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PERT/CPM Techniques: A Pragmatic Approach
Case study of the installation of an industrial photovoltaic plant for self-consumption

Dissertation to fulfill the Master's degree in Engineering and Management of Physical Assets

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ABSTRACT

The global rise of renewable energy investment shows one of the urgent needs, the mitigation of climate change, reduction in the burning of fossil fuels, and transition towards sustainable energy systems. In Portugal, the industrial PV self-consumption systems have been seen as a very promising solution for energy cost reduction and carbon neutrality goals by 2050. However, the deployment of such systems faces many significant challenges, including cost overruns and schedule delays due to poor planning and resource management. This Investigation reviews the integration of Critical Path Method and Program Evaluation and Review Technique to tackle such problems, taking a case study regarding the installation of a photovoltaic system on São Miguel Island, Azores. It assesses the effectiveness of such tools on project management, underlining whether it was able to reduce the length of delays, optimize resource use, and enhance project performance. The results bring out that despite the deficiency in early-stage planning, CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique) techniques improved the predictability and efficiency of the project to achieve a 25% reduction in energy consumption along with significant CO_2 mitigation. Key learnings from this will target proper planning, strong risk analysis, and training on the use of project management tools within the team. These findings also go further to advance renewable energy initiatives in insular regions and beyond, with sustainable and cost-effective solutions for industrial energy challenges.

Keywords: Photovoltaic Systems, Project Management, CPM, PERT, Renewable Energy, Sustainability.

RESUMO

O aumento global do investimento em energias renováveis demonstra uma das necessidades urgentes, a mitigação das alterações climáticas, a redução da queima de combustíveis fósseis e a transição para sistemas energéticos sustentáveis. Em Portugal, os sistemas industriais de autoconsumo fotovoltaico têm sido vistos como uma solução muito promissora para a redução dos custos energéticos e para os objetivos de neutralidade carbónica até 2050. No entanto, a implantação de tais sistemas enfrenta muitos desafios significativos, incluindo derrapagens de custos e atrasos no calendário devido a um planeamento e gestão de recursos deficientes. Esta investigação analisa a integração do Método do Caminho Crítico e da Técnica de Avaliação e Revisão de Programas para resolver esses problemas, tomando como caso de estudo a instalação de um sistema fotovoltaico na ilha de São Miguel, Açores. Avalia a eficácia destas ferramentas na gestão de projetos, sublinhando se foram capazes de reduzir a duração dos atrasos, otimizar a utilização dos recursos e melhorar o desempenho do projeto. Os resultados revelam que, apesar da deficiência no planeamento da fase inicial, as técnicas CPM (Critical Path Method) e PERT (Program Evaluation and Review Technique) melhoraram a previsibilidade e a eficiência do projeto, de modo a obter uma redução de 25% no consumo de energia, juntamente com uma mitigação significativa das emissões de CO_2. As principais aprendizagens deste projeto visam um planeamento adequado, uma forte análise de riscos e formação sobre a utilização de ferramentas de gestão de projetos no seio da equipa. Estas conclusões também contribuem para o avanço das iniciativas de energias renováveis em regiões insulares e não só, com soluções sustentáveis e económicas para os desafios energéticos industriais.

Palavras-chave: Sistemas Fotovoltaicos, Gestão de Projetos, CPM, PERT, Energias Renováveis, Sustentabilidade.

The future belongs to those who believe in the beauty of their dreams.
Eleanor Roosevelt

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LIST OF ACRONYMS AND ABREVIATIONS

ACC	Autoconsumidores Coletivos
ACI	Autoconsumidores Individuais
ACT	Autoridade para as Condições do Trabalho
AI	Artificial Intelligence
BIPV	Building Integrated Photovoltaics
CER	Comunidade de Energia Renovável
CO_2	Carbon Dioxide
CPM	Critical Path Method
DGEG	Direção-Geral de Energia e Geologia
DL	Decreto Lei
EF	earliest finish
ERSE	Entidade Reguladora dos Serviços Energéticos
ES	earliest start
EU	European Union
FMEA	Failure Mode and Effects Analysis
GERT	Graphical Evaluation and Review Technique
IoT	Internet of Things
IU	Instalação elétrica de utilização
LF	latest finish
LS	latest start
PERT	Program Evaluation and Review Technique
PV	Photovoltaic
R&D	Research and development
RBS	Risk Breakdown Structure
RCM	Resolução do Conselho de Ministros
REC	Renewable Energy Communities
RESP	Rede Elétrica de Serviço Público
RNC2050	Routeiro para a Neutralidade Carbónica 2050
SDG	Sustainable Development Goals
SOA	State of the Art
SWOT	Strengths, Weaknesses, Opportunities and Threats Analysis
TSST	Técnico Superior de Segurança no Trabalho
UPAC	Unidade de Produção para Autoconsumo
UPP	Unidade de Pequena Produção
US	United States

1 INTRODUCTION

The increase in global investment in renewable energies reflects the urgent need to mitigate the impacts of climate change, reduce dependence on fossil fuels and promote a sustainable energy transition. In Portugal, photovoltaic energy has established itself as a promising alternative, standing out for its role in reducing energy costs and contributing to achieving carbon neutrality targets by 2050 [1].

However, the implementation of self-consumption photovoltaic plants faces critical challenges, such as cost overruns and schedule delays, often associated with failures in planning, resource allocation and risk management. Established methods such as the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) have emerged as fundamental tools for improving predictability, identifying bottlenecks and optimizing critical activities in complex projects [1], [2].

Despite their potential, the application of these methodologies in photovoltaic projects is still incipient in Portugal, which reinforces the relevance of this research.

This study seeks to analyze how the integration of these tools can promote efficiency in the management of costs and deadlines, thus contributing to more robust management practices in the energy sector.

1.1 Research questions

Given the complexity of self-consumption industrial photovoltaic plant projects, fundamental questions emerge for efficient management. This work sets out to investigate:

- **How can the application of PERT and CPM techniques help to reduce delays and costs in industrial photovoltaic projects?**
- **What are the main challenges and opportunities for implementing these techniques in the specific context of the Portuguese energy sector?**

These questions guide the research throughout the study, providing practical and theoretical insights for the advancement of project planning and control practices in the renewable energy sector.

1.2 Motivation

The relevance of this study is underpinned by the strategic role of renewable energies in the global climate agenda and in Portugal's strategy to achieve carbon neutrality. National legislation, namely Decree-Law no. 162/2019, has created favorable conditions for the expansion of self-consumption systems. However, the effectiveness of these initiatives depends on management practices that ensure economic and operational viability.

The choice of this topic was influenced by my direct contact with a project to install self-consumption photovoltaic plants in the Azores, in which I observed significant challenges, such as time and cost overruns. This experience awakened in me the need to deeply understand what could have been done to mitigate these problems. In addition, I wondered whether these difficulties are common in other projects in the national and international context and how this research could contribute to improving the management of these ventures.

In this sense, this work aims to fill an important gap: while the PERT and CPM methodologies are widely recognized in sectors such as construction, their application in renewable energy projects is still incipient, especially in Portugal. The purpose of this study is to investigate how these tools can be adapted and applied to the energy sector, offering practical solutions for managers and decision-makers.

In addition, this study is also an opportunity for my own development as a manager. I intend to deepen my knowledge and skills in the application of project management tools, with the aim of becoming a professional better prepared to face the complex challenges of this sector. Believing that best management practices are fundamental to the success of projects of great strategic importance, this work represents not only a contribution to the sector, but also an essential step in my career as a manager.

Finally, I believe that efficient management of these projects will not only boost the energy transition in Portugal but will also contribute to consolidating the country as a benchmark in renewable energies. This personal and professional commitment reinforces my determination to be an active part of the solution, helping Portugal to achieve its climate targets and managers to deal with the sector's challenges.

1.3 Objectives

Following on from the research questions above, this study also proposes complementary specific objectives:

Specific Objectives:

- Analyze the direct impacts of using PERT and CPM techniques to reduce delays and costs in photovoltaic projects.
- Identify the main technical, cultural and organizational challenges in adopting these tools in self-consumption energy projects.
- Assess the specific opportunities in the Portuguese context for integrating these methodologies into the planning and control of photovoltaic projects.
- Propose practical guidelines and strategies to facilitate the effective implementation of PERT and CPM techniques in future projects, improving predictability and operational efficiency.

1.4 Work structure

This study is structured in five chapters, organized as follows:

- **Chapter 1: Introduction** - Presents a theoretical and contextual framework of the problem, defines the research questions and the objectives of the study, as well as justifying the relevance of the topic.
- **Chapter 2: State of the Art** - Explores the theoretical basis of the PERT and CPM techniques, their applications and relevance in the energy context, with an emphasis on renewable projects in Portugal.
- **Chapter 3: Methodology** - Details the design of the study, including the case study, the methods of analysis and the tools used to collect and process data.
- **Chapter 4: Results and Discussions** - Presents the main findings, analyzing the impact of the techniques on the case studied and discussing the results in the light of the research questions.
- **Chapter 5: Conclusions and Recommendations** - Summarizes the main results, discusses their practical implications and offers suggestions for future studies.

2 STATE OF THE ART

In the rapidly evolving field of project management, methodologies such as the Project Evaluation and Review Technique (PERT), the Graphical Evaluation and Review Technique (GERT) and the Critical Path Method (CPM) have emerged as fundamental tools in the planning, execution and optimization of projects in all industries. This introduction explores the genesis, development and current applications of these methodologies, focusing particularly on their importance in the photovoltaic sector. By examining their roles in improving project efficiency and effectiveness, this State of the Art (SOA) aims to provide a comprehensive analysis of these techniques, highlighting their contributions to the successful management of photovoltaic projects. Through critical comparison and evaluation, we seek to understand the strengths, weaknesses and adaptability of PERT, GERT and CPM to meet the unique challenges of renewable energy projects, setting the stage for a detailed exploration of their impact on current project management practices.

2.1 Description PERT / GERT / CPM

Historically, the development of project planning methods marked a change in project management. PERT was fundamental in the Polaris missile program, demonstrating its usefulness in environments of great risk and uncertainty. Similarly, CPM transformed the construction industry by optimizing workflows on large-scale projects. These methodologies have not only simplified processes but also laid the foundations for future innovations in project scheduling.

The genesis of project planning techniques dates back to the efforts of Gantt in the 1950s, who introduced the Gantt chart to estimate project duration. This innovative chart was designed to calculate project completion time by analyzing the sequential relationships between activities.

Despite its usefulness for illustrating the sequence of tasks within an activity, the Gantt chart's ability to represent the relationships between activities is limited. To fill this gap, the Critical Path Method (CPM) and the Project Evaluation and Review Technique (PERT) were developed, which improve the visualization of the interdependencies between the various project activities. Both CPM and PERT, as network-based methodologies, aim to facilitate project planning, coordination and control by incorporating the priority relationships between activities into the design of the project network.

The essence of these methodologies lies in the creation of a network diagram, represented by arrows (**activities**) and nodes (**events**), to illustrate the precedence relations among tasks, thereby aiding in the computation of the project's completion timeline[3]. The Critical Path Method (CPM), specifically, proves invaluable when activity durations are precisely known, enabling the determination of the project's completion time by identifying critical paths and activities.

Originally developed by Kelly and Walker to optimize maintenance schedules in chemical plants and expedite project completion, CPM focuses on calculating the project's end date through the longest sequence of dependent tasks, known as the critical path, and its associated critical activities [4],[3].

Identifying the critical path and activities within a project is crucial for managing potential shortcomings, as the aggregate duration of critical tasks directly corresponds to the overall project timeline. Delays in these critical activities could result in project setbacks, influencing the final completion date. Hence, project managers seeking to introduce schedule flexibility must concentrate their efforts on adjusting the durations of non-critical activities, thereby maintaining the integrity and timeliness of the project's execution.

The Critical Path Method (CPM) is a deterministic project management technique widely used to identify and manage critical activities that directly influence a project's completion time. Developed in the 1950s by James E. Kelley Jr. and Morgan R. Walker [4], CPM emerged as an innovative tool for optimizing schedules, initially applied to chemical plant maintenance management. Since then, it has been adopted in various sectors, including construction, engineering and technology, due to its ability to offer clarity and precision in planning.

The CPM is based on creating a network that models the project through activities (represented as arrows) and events or milestones (represented as nodes). This network illustrates the precedence relationships between activities, identifying those that must be carried out sequentially and those that can be carried out in parallel. The main objective of the CPM is to determine the critical path, i.e. the longest sequence of dependent activities, which defines the minimum project duration.

2.1.1 CPM structure

CPM analysis begins by breaking down the project into discrete activities. Each activity is defined by a fixed duration, considered deterministic, which differentiates CPM from other methodologies, such as PERT, which uses probabilistic estimates. Once the activities and their precedence relationships have been defined, the project's network diagram is built, which serves as the basis for calculating the start and finish times for each activity.

The calculations in CPM involve two main phases: the **forward pass** and the **backward pass**. These phases make it possible to determine the earliest and latest start and finish times for each activity, providing information on the flexibility (or "**slack**") available.

In the forward pass, the earliest start (ES) and the earliest finish (EF) of each activity are calculated, starting from the initial activity and progressing to the last activity. For any activity j, these variables are calculated as:

$$ES_j = \max(EF_i)\,, \forall i \; predecessors \; of \; j \tag{2.1}$$

$$EF_j = ES_j + t_j \tag{2.2}$$

Where t_j represents the duration of activity j.

In the backward pass, calculations start from the last activity and proceed backwards, determining the latest start (LS) and latest finish (LF) for each activity. For any activity i, these variables are determined as:

$$LF_i = \min\left(LS_j\right), \forall i \; successors \; of \; i \tag{2.3}$$

$$LS_i = LF_i + t_i \tag{2.4}$$

The critical path is then identified as the sequence of activities whose earliest finish time coincides with the latest finish time ($EF = LF$), indicating that these activities have no slack. Any delay in critical activities directly results in delays to the project.

2.1.2 Benefits of CPM

CPM is particularly useful for identifying and managing critical activities, ensuring that resources are allocated efficiently to minimize delays. It also helps in evaluating alternative scenarios, allowing adjustments to the schedule to accommodate unexpected changes. In addition, CPM is widely supported by project management software such as Microsoft Project, making it easy to apply to large-scale projects.

2.1.3 CPM limitations

Although effective, CPM has some limitations. It assumes that all activity durations are fixed and known, which may not reflect the reality of many projects, especially in contexts of high uncertainty. In addition, it does not explicitly consider limited resources, which can lead to unfeasible schedules in situations of labor or material constraints.

2.1.4 PERT structure

The Program Evaluation and Review Technique (PERT) is a probabilistic methodology developed in 1958 by the US Navy in partnership with Booz Allen Hamilton, with the aim of assisting in the planning and management of complex projects, such as the development of the Polaris missile. This technique marked a significant advance in the area of project management, by incorporating uncertainties and variability into the calculation of deadlines, making it an indispensable tool for projects characterized by their complexity and uncertainty [5].

PERT uses network diagrams to represent the project's activities, making it possible to map the precedence relationships between tasks and estimate the project's total duration. The main innovation of this methodology is the introduction of a three-point estimation system for each activity: the optimistic time (a), the most probable time (m) and the pessimistic time (b). Based on these estimates, the expected duration (μ) and variance (σ^2) of each activity are calculated using the formulas:

$$\mu = \frac{a + 4m + b}{6} \tag{2.5}$$

$$\sigma^2 = \left(\frac{b - a}{6}\right)^2 \tag{2.6}$$

This approach makes it possible not only to calculate the weighted average of activity durations, but also to integrate uncertainties into the planning. In the context of PERT, it is assumed that activity durations follow a Beta distribution, while the total project duration follows a Normal distribution. The expected time to complete the project (μ_p) is obtained by adding up the expected durations of the activities along the critical path:

$$\mu_p = \sum \mu_i \tag{2.7}$$

The total variance (σ_i^2) is calculated by adding up the variances of the critical activities:

$$\sigma_p^2 = \sum \sigma_i^2 \tag{2.8}$$

With these values, you can assess the probability of completing the project within a specific timeframe (X) using the Z-value formula:

$$Z = \frac{X - \mu_p}{\sigma_p} \tag{2.9}$$

The Z value is then compared to a normal distribution table to determine the cumulative probability.

This methodology is particularly useful in pioneering projects or activities with high uncertainty, such as research and development, where activity durations can vary significantly. In addition, PERT makes it possible to analyze alternative scenarios and assess delay risks in a quantitative way, integrating statistical analysis with project planning[6].

2.1.5 GERT structure

The Graphical Evaluation and Review Technique (GERT) is an advanced project planning and management methodology that goes beyond the limitations presented by more traditional tools such as CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique). Developed to model processes involving uncertainties, conditional decisions and iterative cycles, GERT is particularly relevant in complex projects, such as those associated with research and development or industrial processes with high variability.

GERT uses a probabilistic approach to represent activities and events in graphical networks. These networks are made up of nodes, which represent events or decision points, and branches, which connect these nodes and represent activities or transitions. Each branch is associated with a probability of occurrence and a transfer function, which describes the impact of its execution in terms of time or cost. In this way, GERT allows uncertainties to be incorporated into the model, something that the CPM and PERT methodologies are unable to do accurately, as they assume that all activities follow deterministic durations or simplified Beta distributions.

One of GERT's main differentials is its ability to model alternative paths and loops within a network. Alternative paths allow multiple scenarios to be considered simultaneously, weighting the probability of each one occurring. For example, in a product development project, different approaches can be tested with different probabilities of success. Similarly, loops make it possible to model iterations, such as design revisions or additional validations, which are common in research and development projects.

Analysis in GERT begins with the construction of the graphical network, where the probabilities associated with the branches and the time or cost distributions of the activities are defined. Based on this structure, simulation or analytical methods are used to calculate the project's expected times and costs. The expected completion time of a project in GERT is calculated by the weighted sum of the completion times of all possible paths, using the probabilities associated with each path. Similarly, the total expected cost is obtained by weighting the costs of the different scenarios by the same probabilistic factors.

In addition, GERT offers a way of calculating the probability of completing the project within a specific timeframe or budget. To do this, the time and cost variables are assumed to follow probabilistic distributions, allowing the use of statistical models, such as the normal or exponential, to calculate cumulative probabilities.

However, GERT presents significant challenges. Its flexibility and analytical capacity come at the cost of greater computational complexity, which can limit its application in very large projects. In addition, the need for precise data on probabilities and distributions for activities represents an obstacle in projects where such information is scarce or difficult to estimate.

In the context of project management, the use of GERT can be exemplified by engineering projects in which different paths are possible, each with different costs, times and probabilities of success. For example, in a construction project, the choice between different material suppliers or construction methods can be modeled in GERT, allowing managers to identify the most efficient and least risky approach.

2.2 Literature review on CPM, PERT and GERT

In recent decades, the literature on project management, especially around the CPM (Critical Path Method), PERT (Program Evaluation and Review Technique) and GERT (Graphical Evaluation and Review Technique) techniques, has evolved significantly. Recent research highlights the impact of emerging technologies, such as predictive analytics based on artificial intelligence, on the accuracy and efficiency of these methodologies. For example, Ren and Li (2023) [7] demonstrate how integrating PERT with machine learning models improves the prediction of project delays. Tao et al. (2017) [8] expand the application of GERT by including characteristic functions for risk analysis in new product development, highlighting its usefulness in iterative workflows. These contributions illustrate the evolution of classic tools in response to contemporary demands.

The following Table 2.1 presents the most relevant articles on these methodologies, organized in a visually appealing way and based on the SCImago categorization, with a focus on publications that offer robust and applicable insights in different project management contexts.

Table 2.1 – Most relevant articles on CPM, PERT and GERT

Title	**Link:**	**Scimago**	**year**
Optimization Of Distributor Operations Using PERT/CPM To Determine Critical Activities [9]	https://doi.org/10.48204/j.tecno.v26n1.a4656	Q4	2023
Project Planning With CPM And Pert Methods: Example Of Defense Industry [10]	https://www.researchgate.net/publication/368601637	N.A.	2022
Comparison Of The Benefits Of CPM And PERT To Project Partners On Different Projects [11]	https://www.researchgate.net/publication/364753742	N.A.	2022
Mastering Construction Schedules: The Power Of CPM And Pert Integration [12]	https://www.researchgate.net/publication/375113692	N.A.	2023

Network Planning Analysis Using CPM And PERT Methods On Optimization Of Time And Cost [13]	https://doi.org/10.33395/sinkron.v8i1.11961	N.A.	2023
Comparison Of PERT/CPM And CCPM Methods In Project Time Management [14]	https://www.researchgate.net/publication/354800256	N.A.	2021
Simplified CPM/PERT Simulation Model – Closure [15]	https://www.researchgate.net/publication/238179289	Q1	2000
Research On Software Project Schedule Planning Technology Based On The Integration Of PERT And CPM [7]	https://doi.org/10.1016/j.procs.2023.11.029	N.A.	2023
Advancement In Construction Management [16]	Conference Full Paper template (qu.edu.qa)	N.A.	2023
PERT And CPM In Project Management With Practical [17]	https://doi.org/10.4236/ajor.2021.114013	N.A.	2021
Project Management Model For Constructing A Renewable Energy Plant [18]	https://doi.org/10.1016/j.proeng.2017.01.186	N.A.	2017
CPM, PERT And Project Management With Fuzzy Logic Technique And Implementation On A Business [19]	https://doi.org/10.1016/j.sbspro.2015.11.378	Q1	2015
A Dependent Project Evaluation And Review Technique: A Bayesian Network Approach [20]	https://doi.org/10.1016/j.ejor.2019.07.051	Q1	2020
Comparison Of Different Algorithms For Time Analysis For CPM Schedule Networks [21]	https://doi.org/10.1016/j.autcon.2021.103697	Q1	2021
Dynamic Planning Of Construction Activities Using Hybrid Simulation [22]	https://doi.org/10.1016/j.autcon.2014.08.011	Q1	2015
PERT 21: Fitting PERT/CPM For Use In The 21st Century [23]	https://doi.org/10.1016/j.ijproman.2011.09.004	Q1	2012
Schedule Risk Analysis For New-Product Development: The GERT Method Extended By A Characteristic Function [8]	https://doi.org/10.1016/j.ress.2017.06.010	Q1	2017
Application Of Critical Path Method To Stochastic Processes With Historical Operation Data [24]	https://doi.org/10.1016/j.cherd.2019.06.027	Q2	2019
Hart And Mas-Colell Consistency In PERT Problems [25]	https://doi.org/10.1016/j.dam.2017.08.012	Q2	2018
Improvement In Sealing Assembly Process Using Project Management Techniques [26]	https://doi.org/10.1016/j.matpr.2021.11.231	Q2	2022
Network Planning Analysis On Road Construction Projects By CV. X Using Evaluation Review	https://doi.org/10.30880/ijie.2022.14.04.029	Q4	2022

Technique (PERT) - Critical Path Method (CPM) And Crashing Method [27]			
Limitations Of Pert/ CPM In Construction Management Planning: Inputs To Mathematics In Architecture Education [28]	https://doi.org/10.17762/turcomat.v12i10.5313	Q4	2021
Construction Project Evaluation Using CPM - Crashing, CPM pert And CPM For Minimizing Project Delays [29]	https://iopscience.iop.org/article/10.1088/1742-6596/1933/1/012096/pdf	Q4	2020
A Simulation Study Of Duration-Budget Trade-Off In Home Renovation Project Management [30]	https://iopscience.iop.org/article/10.1088/1742-6596/1817/1/012018/pdf	Q4	2021

2.3 CPM, PERT and GERT Comparative Analysis

A deeper comparison of PERT, CPM, and GERT highlights their unique advantages and limitations across different project scenarios. While PERT excels in managing projects with significant uncertainty, such as R&D or innovation-driven projects, CPM is more suited for projects with fixed and well-defined tasks, like construction or manufacturing. GERT, on the other hand, stands out in iterative and probabilistic workflows, offering a dynamic approach to projects requiring feedback loops. For example, [21] analyzed the use of CPM in construction, demonstrating its efficiency in identifying bottlenecks, whereas [8] explored GERT's application in new product development, emphasizing its flexibility in handling uncertain timelines. By integrating these methodologies, project managers can tailor approaches to the complexity and nature of their projects, leveraging the strengths of each technique.

Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM) are prominent techniques in project management. PERT, a brainchild of the US Navy in the 1950s, is adept at handling complex projects with uncertain elements. It assesses various time scenarios, attributing probabilities to different time estimates. Conversely, CPM, developed concurrently by DuPont, is tailored for projects with clear tasks and fixed timelines.

The core principle of both PERT and CPM is to depict project tasks as nodes on a diagram, linked by arrows that depict the order of operations. This setup is crucial for pinpointing the critical path - the chain of tasks that directly impacts the project's overall timeline. Any hold-ups on this path can delay the entire project.

PERT is particularly effective in managing uncertainties. It employs a triad of time predictions for each task: optimistic, most likely, and pessimistic. By applying a specialized formula to these timeframes, PERT computes an average duration for each task and the project, including a variance measure.

In contrast, CPM operates on fixed timeframes, focusing on finding the project's most efficient route. With precise duration estimates, it calculates the earliest and latest start times for each task. This helps identify both the critical path and the leeway in tasks that are not on this path.

Each method brings its unique strengths: PERT is ideal for projects with uncertain elements, while CPM suits projects with strict deadlines and defined tasks. The fusion of these two, known as PERT/CPM, forms a holistic approach to project management, integrating the handling of both uncertain and fixed project timelines [31].

2.4 Current Context and Importance

Renewable energy projects, particularly photovoltaic systems, present significant challenges due to the variability of weather conditions and interruptions in the supply chain. In these circumstances, the use of methodologies such as PERT (Program Evaluation and Review Technique) and CPM (Critical Path Method) is essential to mitigate risks and optimize execution schedules. A recent study by [13] demonstrated the successful application of CPM in optimizing construction schedules for solar installations, which resulted in a significant reduction in costs and delays. In addition, the iterative nature of GERT (Graphical Evaluation and Review Technique) allows for robust risk assessment in projects involving experimental technologies, increasing the resilience and flexibility of schedules.

In the contemporary industrial project management landscape, the PERT, GERT and CPM methodologies remain central due to their ability to adapt to a wide range of project sizes and types. In industrial photovoltaic installations, for example, where there are complex technical challenges and significant uncertainties, these techniques have proved indispensable. The introduction of emerging technologies, such as artificial intelligence (AI) and machine learning, has the potential to further revolutionize these methodologies. Ren and Li (2023)[7] Renhighlight how integrating machine learning models with PERT improves accuracy in predicting delays, enabling proactive adjustments and optimizing results.

In addition, CPM has been widely used in renewable energy infrastructure projects to identify bottlenecks and optimize the use of resources. For example, [21] highlighted the effectiveness of CPM in managing construction schedules, allowing for agile adjustments in the face of unforeseen events. However, when combined with PERT, these methods offer a holistic approach, incorporating both deterministic and probabilistic elements into planning. This combination is particularly useful in photovoltaic projects, where weather uncertainties and logistical challenges can have significant impacts.

GERT, on the other hand, presents a distinctive approach by allowing iterative workflows and alternative paths to be modeled. Its application is especially valuable in projects involving technological innovation or experimental validation, such as the development of new solar panel designs or energy storage systems. [8] demonstrated the effectiveness of GERT in new product development projects, where probabilistic and iterative modeling allowed for greater precision in managing dynamic schedules.

As industrial project management continues to evolve, these methodologies are expected to adapt to new demands, integrating advanced technologies to deal with the challenges of modern projects. Combining classic techniques such as PERT, GERT and CPM with emerging technologies such as AI and predictive analytics can transform the way projects are planned and executed, increasing efficiency and reducing risks. This transformation will be crucial to meet the growing demands for sustainability and efficiency in renewable energy projects, especially in a context of global energy transition.

2.5 The Evolution of Photovoltaic Panels

The evolution of photovoltaic (PV) panels (Table 2.2) dates to Edmond Becquerel's discovery of the photovoltaic effect in 1839, marking the beginning of a technological transformation that would redefine sustainable energy production. Since then, continuous progress in materials, design and efficiency has taken PVs from niche scientific applications to one of the main sources of renewable energy on a global scale.

Table 2.2 – The Evolution of Photovoltaic Panels

year	
1839	**Discovery of the Photovoltaic Effect** Edmond Becquerel observed that certain materials generated electric current when exposed to sunlight, discovering the photovoltaic effect. This scientific milestone provided the theoretical basis for the future development of the technology.
1954	**First Silicon Solar Cell** Bell Laboratories introduced the first functional silicon-based solar cell, achieving an efficiency of approximately 6%. This innovation marked the beginning of modern solar technology.
1970s	**Oil Crisis and Technological Advances** During the oil crisis, the urgent need for energy alternatives drove research into renewable technologies. Thin film cells emerged, such as

	those made of cadmium telluride (CdTe), offering a lighter alternative to crystalline silicon cells.
1980s	**Growth and Government Incentives** Advances in semiconductor manufacturing reduced production costs and increased the efficiency of solar cells to more than 15%. Incentive programs in the United States and Europe drove large-scale adoption.
2000s	**Crystalline silicon dominance** Crystalline silicon (c-Si) panels have established themselves on the market, achieving efficiencies of over 20%. At the same time, perovskite materials began to be investigated, promising greater flexibility and efficiency in future generations of PV.
Present	**Advanced Technologies and Sustainability** Innovations such as bifacial panels, tandem solar cells and building-integrated photovoltaics (BIPV) are revolutionizing the sector. Commercial efficiencies already exceed 25% in crystalline silicon panels, while perovskite technology is approaching commercialization. These innovations respond to the growing global demand for sustainable energy solutions.

2.6 Recent Trends and Innovations in Photovoltaic Technologies

The solar energy sector has experienced rapid evolution, with the emergence of advanced technologies that are transforming the efficiency and versatility of photovoltaic systems. These innovations not only increase energy production but also meet the demands of sustainability and integration into urban environments. The main trends include bifacial panels, tandem cells, building-integrated photovoltaics (BIPV) and the incorporation of artificial intelligence (AI) and Internet of Things (IoT) technologies.

2.6.1 Bifacial panels

Bifacial panels are a significant innovation that allows sunlight to be captured on both sides of the module (Figure 2.1).

Figure 2.1 – Photo of Bifacial panels.

This configuration takes advantage not only of direct light, but also that reflected by the ground and nearby surfaces, increasing energy production by up to 30%, depending on site conditions and the inclination of the panels.

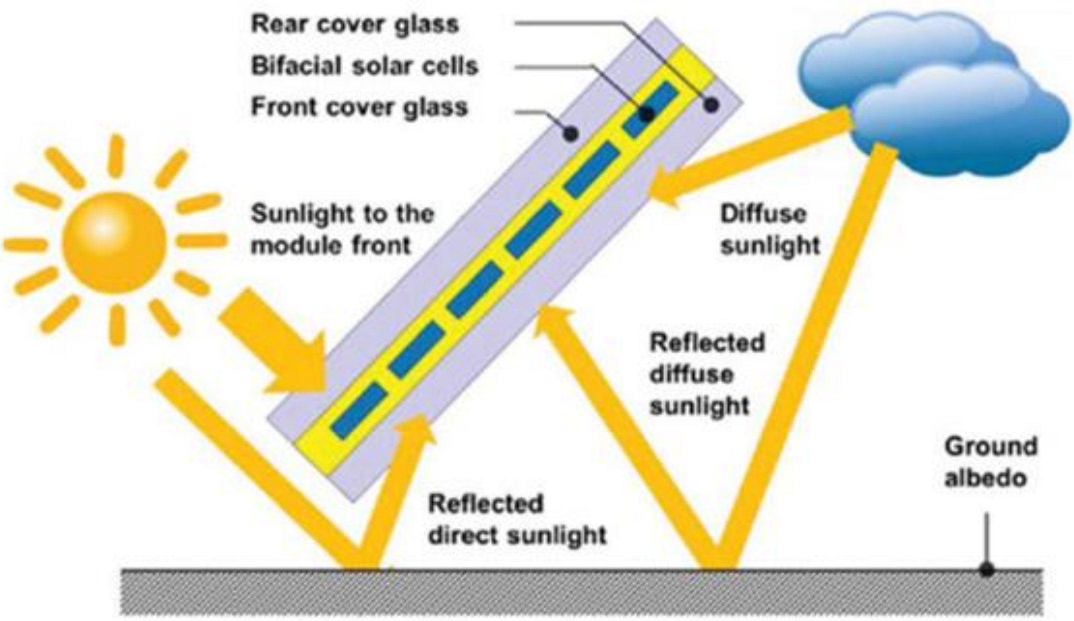

Figure 2.2 – Bifacial panels solar absorption scheme

These systems have been particularly popular in large-scale solar installations, such as photovoltaic parks, where the prepared terrain optimizes the reflected light. Recent studies show that bifacial panels are ideal for regions with high ground reflectivity (albedo), such as desert and snow-covered areas.

2.6.2 Tandem cells

Tandem cells (Figure 2.3) represent a crucial technological advance in the photovoltaic sector. Combining materials such as silicon and perovskite, these cells achieve efficiencies of over 30% under laboratory conditions.

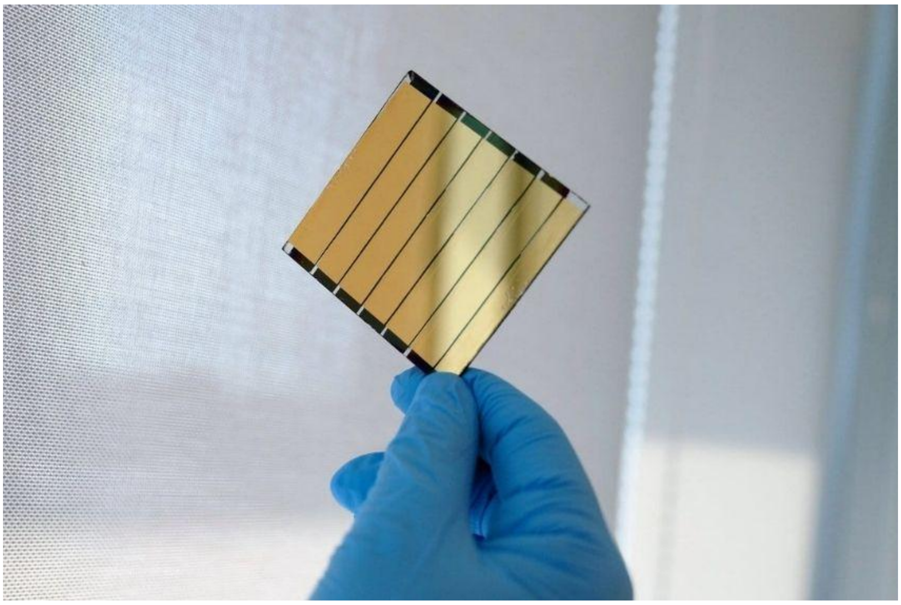

Figure 2.3 – Photo of a Tandem cell.

The tandem structure allows different wavelengths of sunlight to be absorbed more efficiently by specific layers, maximizing energy generation in limited areas. This progress is vital in dense urban contexts, where the space available for solar panels is restricted. In addition, the combination of materials in the tandem cell offers the potential to reduce costs and improve the sustainability of photovoltaic modules.

2.6.3 Building Integrated Photovoltaics (BIPV)

Building-integrated photovoltaics (BIPV) are an innovative solution that combines functionality and design. These systems are integrated directly into facades, roofs and even windows, allowing buildings to generate their own renewable energy while maintaining a modern architectural aesthetic.

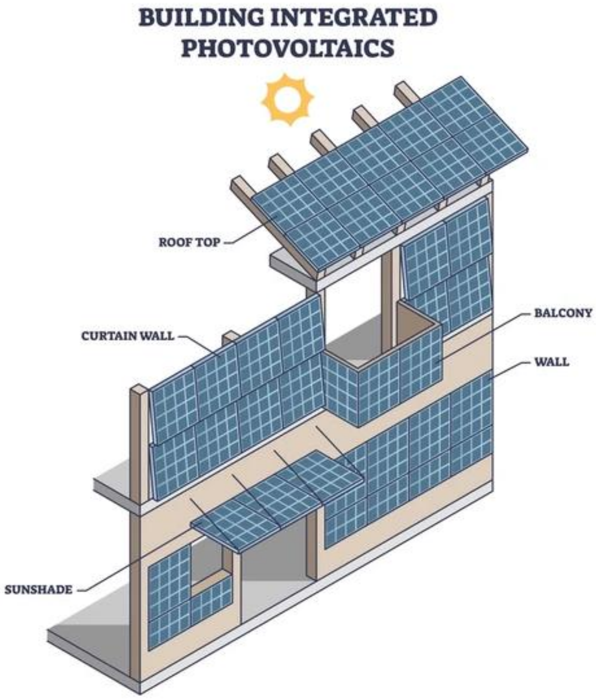

Figure 2.4 – Facade of a hypothetical BIPV.

BIPVs are particularly relevant in the context of sustainable urbanization, promoting energy efficiency in commercial and residential buildings. This technology also reduces the ecological footprint by replacing conventional building materials with functional solar panels.

2.6.4 Integration with AI and IoT

The combination of artificial intelligence (AI) and the Internet of Things (IoT) with photovoltaic systems is redefining the way solar energy is managed and used. These technologies enable accurate predictions of energy production, adjusting systems in real time to optimize performance. In addition, IoT facilitates the integration of solar systems with smart electricity grids and storage batteries, enabling efficient management of the energy generated and consumed. AI, meanwhile, is used to analyze large volumes of data, predicting system failures and improving predictive maintenance. This integrated approach increases the reliability and sustainability of solar systems.

Technological innovations in the photovoltaic sector are boosting the efficiency and accessibility of solar energy. These solutions not only respond to the global demand for cleaner and more sustainable energy sources but also offer flexibility and adaptability to meet the needs of different geographical and urban contexts. The future of renewable energies is intrinsically linked to these technologies, which will continue to evolve and shape the global energy landscape.

2.7 Evolution of Legislation on the Photovoltaic Sector in Portugal

The evolution of photovoltaic legislation in Portugal (Figure 2.5) reflects the country's commitment to energy transition and carbon neutrality. From a historical perspective, we look at how structural reforms have facilitated the adoption of renewable energies and boosted citizen and business participation.

Portugal has set clear targets for decarbonization. The Roadmap to Carbon Neutrality 2050, approved by RCM no. 107/2019, proposes an emissions reduction of between 85% and 90% by 2050, while the National Energy and Climate Plan 2030 (RCM no. 53/2020) calls for at least 80% of electricity to be produced by renewable sources by 2030.

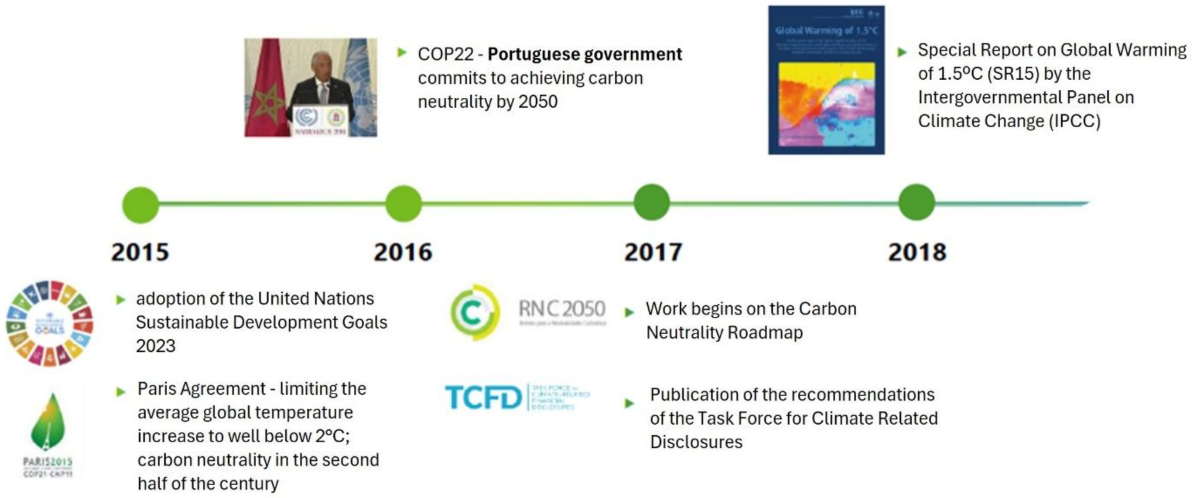

Figure 2.5 – Evolution of Legislation on the Photovoltaic Sector in Portugal (1/2)

In line with these targets, Portugal has transposed European directives such as 2018/2001, which promotes decentralization through Renewable Energy Communities (RECs), and 2019/944, which focuses on modernizing the electricity market.

2.8 Evolution of Legislation on the Photovoltaic Sector in Portugal

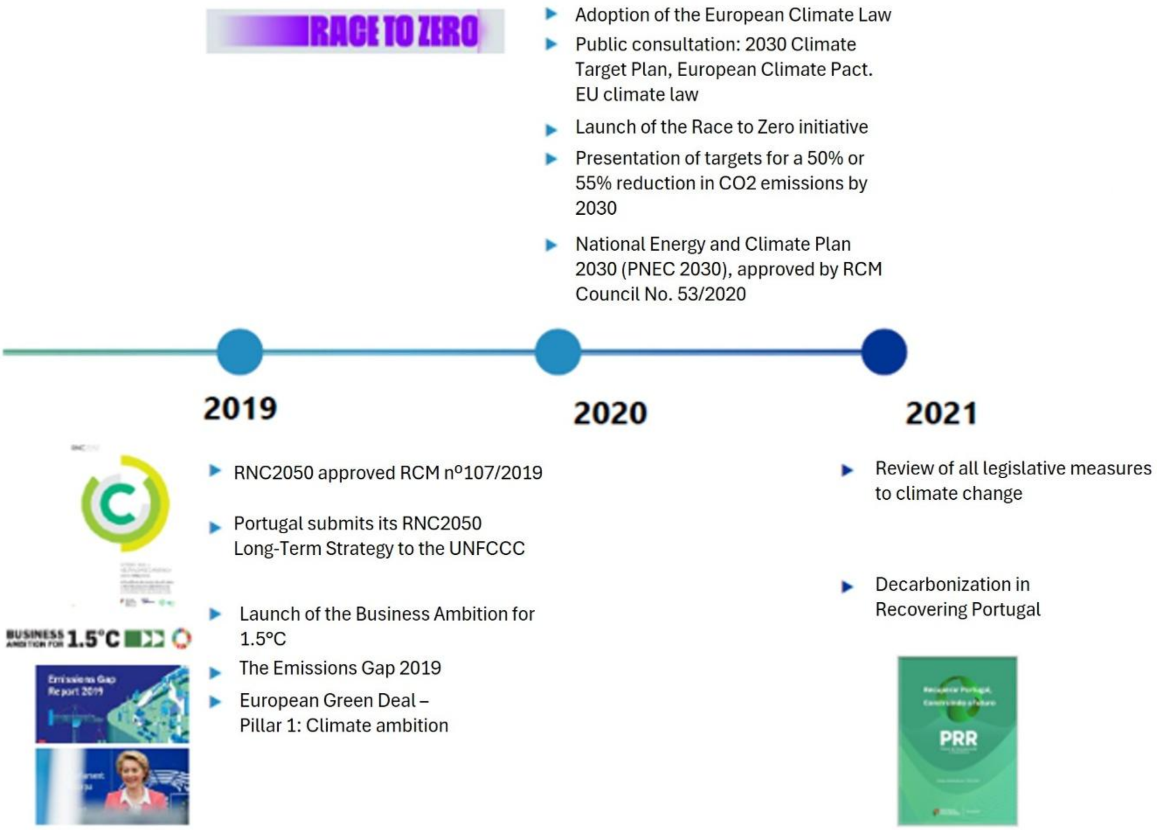

Figure 2.6 – Evolution of Legislation on the Photovoltaic Sector in Portugal (2/2)

In legislative terms, Decree-Law 153/2014 was the first relevant milestone, simplifying administrative procedures for Small Production Units (UPP). However, the real transformation began in 2019, with Decree-Law no. 162/2019, which introduced CERs and UPACs (Production Units for Self-Consumption). This legal regime consolidated the possibility of self-consumption, encouraging the participation of small producers and consumers. Complemented by Ministerial Order no. 16/2020 and ERSE Regulation no. 373/2021, the procedures for licensing, tariffs and regulation of the sector were defined.

With recent reforms, Decree-Law 15/2022 unified and reorganized the National Electricity System, expanding support for technologies such as energy storage. On the other hand, Decree-Laws 30-A/2022 and 72/2022 implemented exceptional measures to speed up renewable projects, while Regulation 815/2023 updated the self-consumption regime, replacing previous regulations.

The results are clear: the installed capacity of decentralized photovoltaics reached 1,675 MW in 2023, and is expected to grow to an additional 800 MW by 2025.

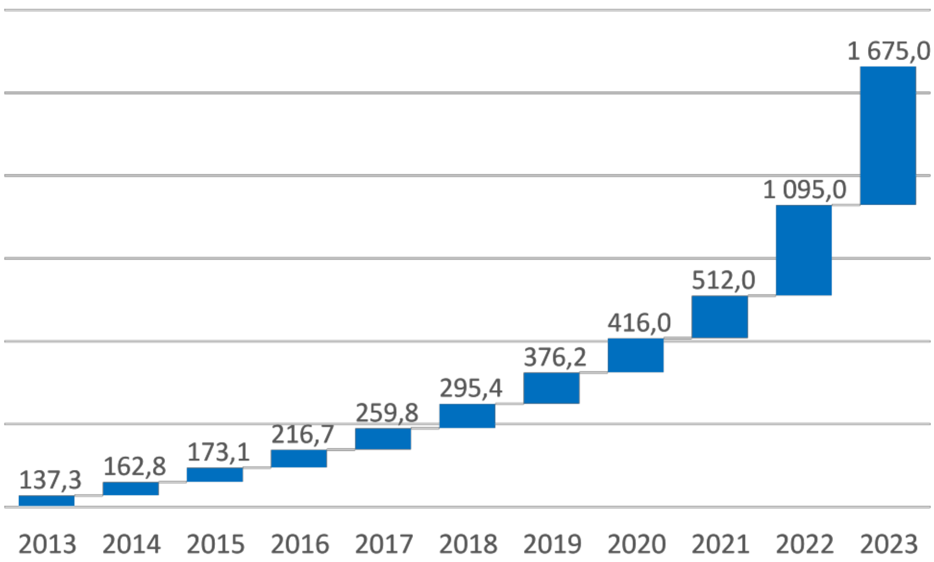

Figure 2.7 - Installed capacity of decentralized photovoltaics, in Portugal (MW)

Decentralization has also been boosted, allowing RECs and self-consumers to gain prominence, promoting energy independence at the residential and business level. In addition, the integration of smart grids and storage systems is essential to sustain this growth.

However, challenges remain. Integrating decentralized energy into the electricity grid requires substantial investment in infrastructure, and the pace of technological innovation requires constant updates to legislation. Despite this, the scenario is promising, with prospects for expansion in techniques such as green hydrogen and advanced storage, reinforcing the competitiveness and sustainability of the national energy sector.

2.9 Photovoltaic Self-consumption in Portugal: Context, Definitions and Implications

Photovoltaic self-consumption in Portugal has been consolidated as one of the most important strategies for the energy transition and the decentralization of energy production. This model enables end consumers, be they residential, business or community, to produce renewable energy to meet their own needs, with significant economic, social and environmental impacts. Portuguese legislation, in line with European guidelines, reflects a commitment to sustainability and carbon neutrality, promoting a more efficient and accessible energy system (DGEG, 2023).

Decree-Law 15/2022 establishes the current legal framework for self-consumption in Portugal. This law defines self-consumption as the consumption of electricity generated by one or more Self-Consumption Production Units (UPAC), used directly by one or more self-consumers of renewable energy (Diário da República, 2022). A self-consumer is described as a final consumer who produces renewable energy for their own use, and can store or sell the surplus, as long as this activity does not constitute the core of their commercial activity. UPACs, on the other hand, are production units using renewable sources, installed at or near the place of consumption, and designed primarily to meet their users' own energy needs.

The legal framework for self-consumption in Portugal includes three main types. Individual self-consumption (ACI) applies when energy is produced and consumed in a single electrical installation (IU), connected to the Public Service Electricity Grid (RESP), to an internal grid or by direct line (DL no. 15/2022, Article 3). On the other hand, Collective Self-Consumption (CSA) involves the sharing of electricity generated between two or more UIs, and is implemented in contexts such as condominiums, business parks or residential neighborhoods. Renewable Energy Communities (RECs) represent a broader collective approach, allowing groups of consumers, organized as legal persons, to produce and share renewable energy with the main aim of generating environmental, economic and social benefits (DGEG, 2023).

Data provided by the Directorate-General for Energy and Geology (DGEG) shows that installed capacity in decentralized photovoltaic systems reached 1,675 MW in 2023, with a target of reaching 2,475 MW by 2025. This growth reflects the increasing adoption of self-consumption by individual and business consumers, driven by tax incentives and lower electricity costs (DGEG, Renewable Energy Report, 2023). However, the success of self-consumption is not limited to numbers. It also promotes greater energy autonomy, democratizes access to energy and significantly reduces greenhouse gas emissions, contributing to national decarbonization goals (RCM no. 107/2019).

Despite the obvious benefits, self-consumption faces challenges. The national electricity infrastructure needs to be adapted to accommodate growing decentralized production, requiring significant investments in the Public Service Electricity Grid (ERSE, 2023). In addition, the licensing processes and the definition of sharing coefficients in ACC and CER still present regulatory complexities that can make it difficult for new consumers to join. Finally, the initial cost of installing photovoltaic and storage systems is still a barrier, especially for small consumers (ERSE, Tariff Report, 2023).

Photovoltaic self-consumption in Portugal is clearly aligned with the objectives of the National Energy and Climate Plan 2030 (RCM no. 53/2020) and the Roadmap to Carbon Neutrality 2050 (RCM no. 107/2019). These initiatives have made significant progress but also require constant adaptation to meet the challenges posed by technological advances and regulatory requirements. Promoting CERs and ACCs is essential to expanding the self-consumption model, making it more inclusive and accessible, while strengthening the sustainability of the national energy system.

2.10 General and Legal Framework for "TSST"

The occupational health and safety landscape in Portugal has undergone several changes over the years. Historically, the professions of Occupational Safety and Hygiene Technician and Senior Technician were initially regulated by DL 110/2000. However, with the passage of time, this decree was later revoked and replaced by DL 42/2012. This legislative change not only altered the nomenclature of the professions to Occupational Safety Technician and Senior Occupational Safety Technician, but also reframed certain parameters associated with these functions.

The vast amount of legislation, from EU directives and national and international regulations, requires constant improvement and updating on the part of Safety Technicians. From this point on, this term will be used to refer to both Technicians and Senior Technicians.

A notable challenge in the legal context of this profession lies in the lack of specific regulations on the conditions for practicing it, especially with regard to ethical and deontological issues. Existing legislation focuses more on the technical side, leaving gaps in the areas of ethics and deontology. It is therefore clear that there is a need to establish a set of rules and guidelines that guarantee the integrity and technical autonomy of the profession, always with the primary focus on safeguarding human life.

In today's constantly evolving labor landscape, Safety Technicians need a robust regulatory body. The Authority for Working Conditions (ACT), the government body responsible, has insufficient resources to adequately supervise the conditions for accessing and remaining in the Safety Technician profession. Although some Safety Technicians have formed associations, these organizations have no effective regulatory power and act more as discussion groups with limited action.

Considering the current scenario, there is an urgent need to create an autonomous body to regulate the profession, suggesting the creation of a "Chamber of Safety Technicians". This body should be responsible for establishing ethical, deontological and technical standards and procedures, as well as guaranteeing the dignity of the profession's salaries.

Certification for the position of Senior Occupational Safety Technician Level VI (TSST) is provided by the ACT (Authority for Labor Conditions). This certification confers on the trainee the degree of Senior Occupational Safety Technician - level VI. It is important to note that if the higher education course was taken outside of

Portugal, it must be recognized by a Portuguese university before admission to the course. On successful completion of the course, the Professional Title of Senior Occupational Safety Technician is issued by ACT.

The profession of Senior Occupational Safety Technician in Portugal is complex and requires continuous improvement, both in terms of training and legislative updates. The creation of a specific regulatory body could be a solution to many of the challenges currently faced.

3 METHODOLOGY

The installation of photovoltaic (PV) systems in industries has grown significantly in Portugal, especially in regions with high energy costs, such as the Azores archipelago. High energy dependence, combined with the challenges of transporting energy to island regions, makes PV systems a viable solution for achieving energy autonomy, reducing costs and promoting sustainability.

3.1 Project Background

This case study focuses on the implementation of a PV system in a local industry, with the aim of reducing electricity consumption costs by 25%, contributing to the environmental and economic sustainability of the region. In addition, it aims to align with global efforts towards energy transition, an essential commitment to mitigating the effects of climate change and meeting carbon neutrality targets.

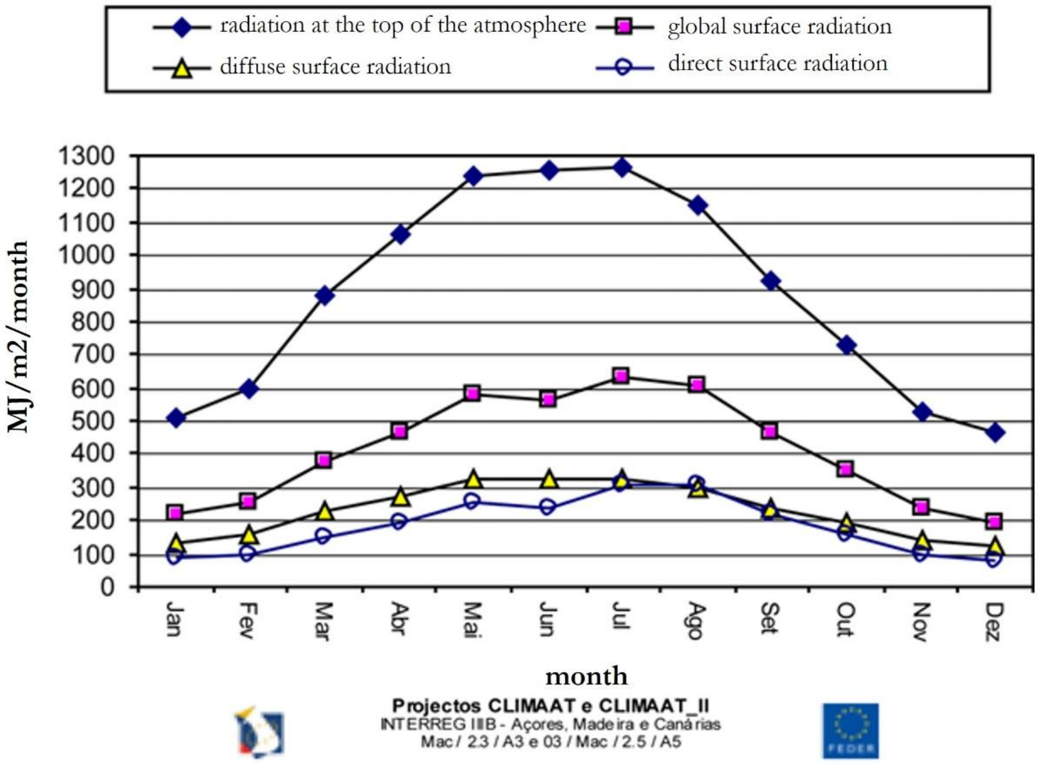

Figure 3.8 – Graph showing the average monthly radiation in the Azores, Portugal

The choice of target industry was based on its critical dependence on high-cost traditional energy sources and the feasibility of switching to a sustainable energy matrix. Recent studies corroborate that PV systems offer considerable benefits in regions such as the Azores, where the availability of sunlight, despite climatic variations, is sufficient to justify the installation of photovoltaic systems [32] [33]. In addition, the introduction of self-consumption systems can drastically reduce dependence on fossil fuels, promoting the economic and environmental resilience of the industry.

The implementation of this system is designed to meet the industry's long-term objectives, including greater energy independence and a sustainable reduction in operating costs. Additionally, some research indicates that similar projects have been successful in reducing carbon emissions and promoting significant energy savings in critical industrial sectors [34].

Island regions, such as the Azores, face specific challenges related to energy infrastructure, as evidenced by feasibility studies on photovoltaic microgeneration in island contexts [1]. These challenges reinforce the need for innovative and resilient solutions, such as the introduction of PV systems to meet local energy needs.

In this way, the project also represents a model for future energy transition initiatives in island regions, contributing to national and international sustainability goals. The combination of local efforts and technological advances in photovoltaics points to a promising future in the integration of renewable energies into the regional and industrial energy matrix.

3.2 Challenges encountered

3.2.1 Resource Planning and Management

The initial planning of this project was carried out rudimentarily in Excel, with substantial limitations in identifying critical activities and their precedents. Studies indicate that the use of management tools such as Microsoft Project, integrated with methodologies such as CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique), is essential to improve accuracy in planning and monitoring complex projects [1]; [2]. The initial approach lacked sufficient detail to predict possible delays and mitigate risks related to resource allocation, a common flaw in projects using non-specialized tools.

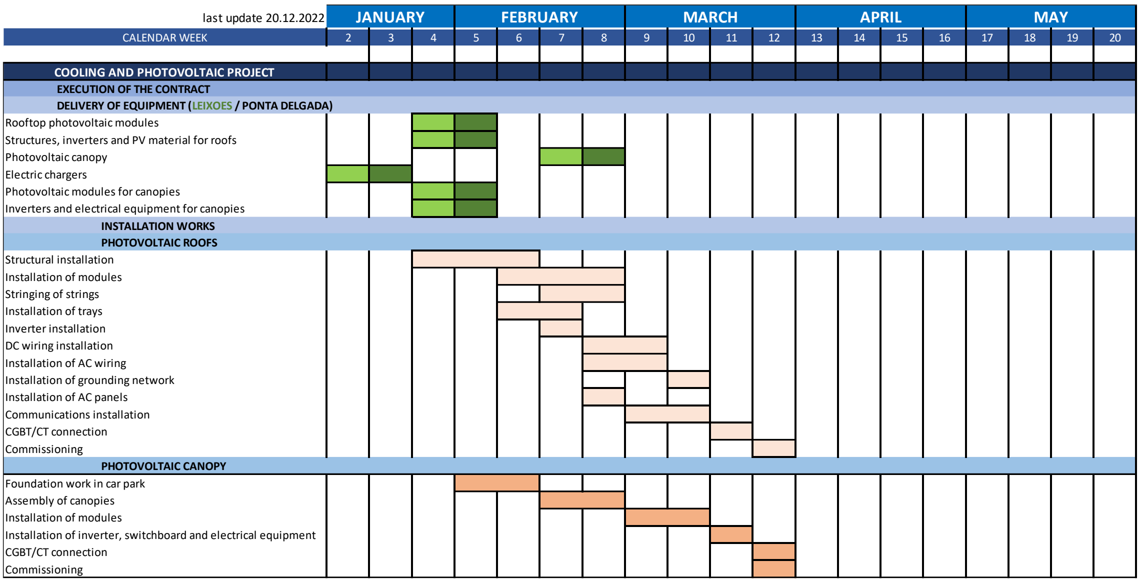

Figure 3.9 – 1st project planning

Figure 3.9 exemplifies these shortcomings, highlighting the lack of detail in interdependent activities and the absence of an integrated vision of the project. Excessively "global" planning resulted in critical omissions that hindered efficient execution, generating delays and a negative financial impact. A recent study on industrial projects confirms that inadequate definition of precedence can cause operational bottlenecks and compromise deadlines and costs [29]

The migration to **Microsoft Project** in January 2023, Figure 3.10, was an attempt to improve project management.

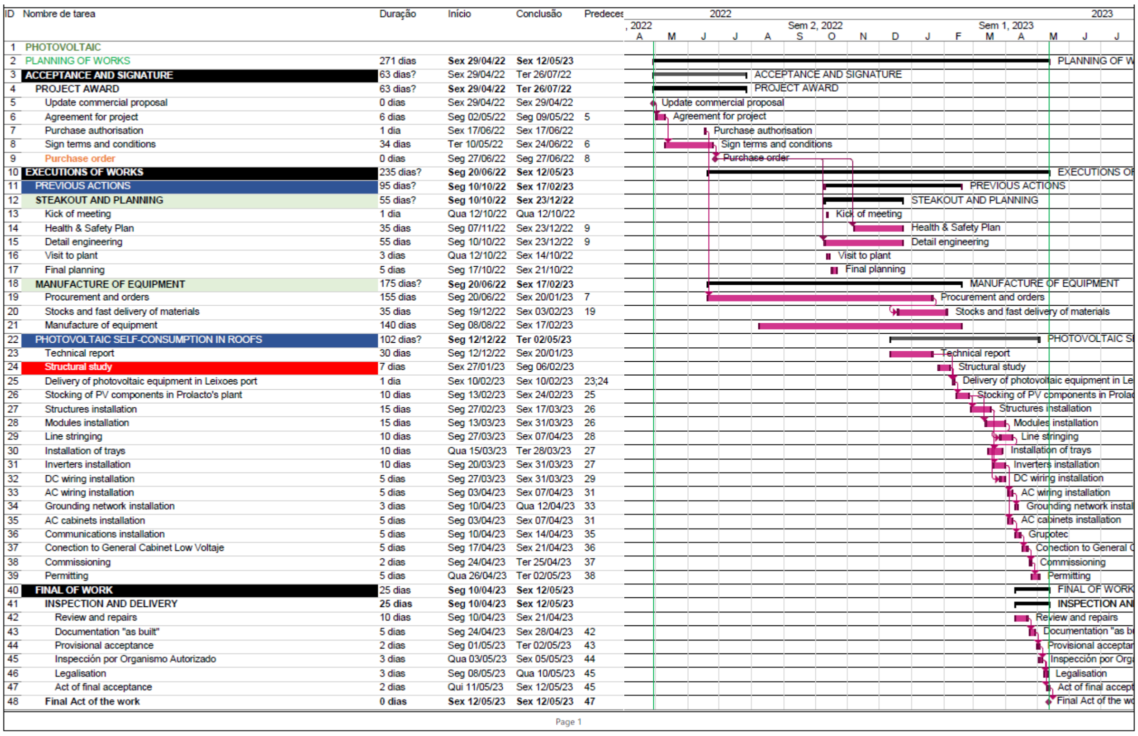

Figure 3.10 – 2nd Project planning (1st on MS Project).

However, the absence of a complete critical path and clear precedences compromised the ability to predict and mitigate new delays.

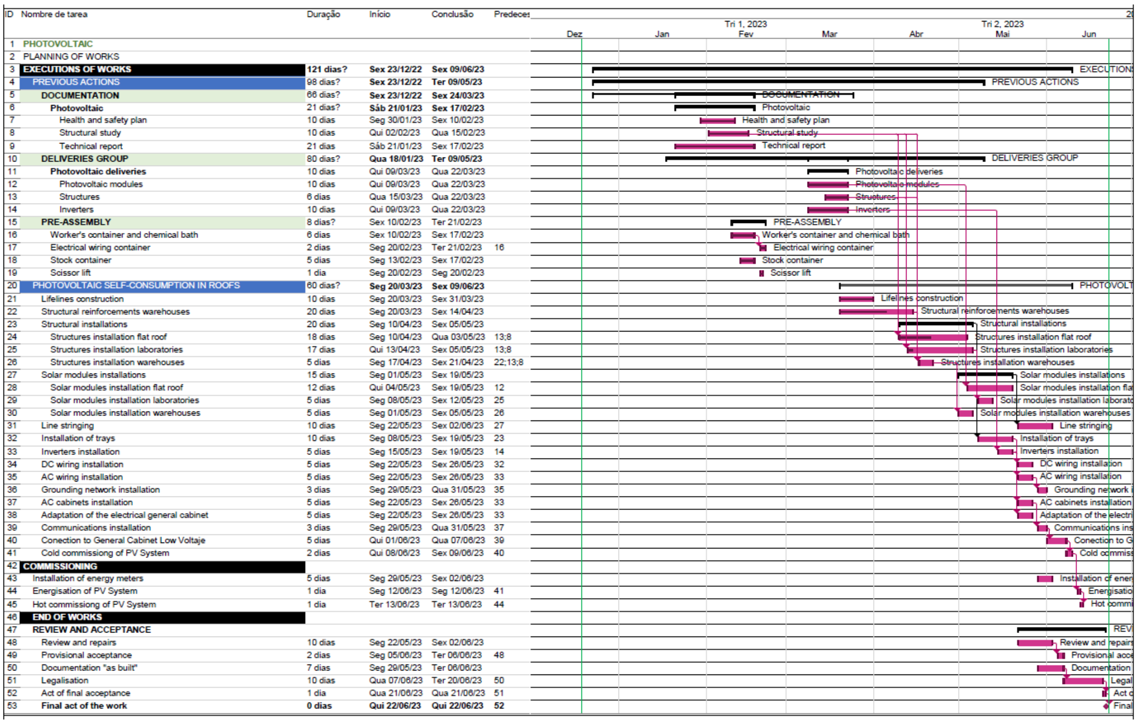

Figure 3.11 – 3rd Project planning

In addition, logistical factors associated with the island location and adverse weather conditions contributed to further delays, resulting in the project only being completed in November 2023, 8 months after the initial estimate.

REGIÃO AUTÓNOMA DOS AÇORES
SECRETARIA REGIONAL DO TURISMO, MOBILIDADE E INFRAESTRUTURAS
Direção Regional da Energia

Averbamentos
1. -

Certificado de Exploração emitido nos termos do disposto do n.º 3 do artigo 11.º do Decreto-Lei n.º 15/2022, de 14 de janeiro.

Nota: As informações relativas às características da Unidade de Produção/Sistema de Contagem estão em conformidade.

Ponta Delgada, 21 de novembro de 2023

A Diretora Regional da Energia

Assinado por: **Joana Ferreira Rita**
Num. de Identificação: 13072102
Data: 2023.11.21 14:52:42-01'00'
Certificado por: **Governo Regional dos Açores**
Atributos certificados: **Diretor Regional da Energia**

CHAVE MÓVEL

Joana Ferreira Rita

Figure 3.12 – FV project operating certificate.

Current literature highlights that tools such as CPM, when used effectively, can predict delays more accurately and align resources to mitigate their impacts [35] [1]

In addition, the lack of key metrics and performance indicators in the initial planning prevented effective monitoring of the project's progress. The implementation of indicators such as milestones and measurable objectives is essential to assess the status of the project in real time and correct deviations before they compromise deadlines and costs [1]. Recent studies suggest that integrating PERT/CPM networks with simulations such as Monte Carlo can offer more robust forecasts for projects with complex variables [36]

In addition, the lack of a holistic approach to the project life cycle resulted in an inadequate allocation of financial and human resources. This failure compromised not only the schedule, but also reduced the overall efficiency of the project. Research in the area reinforces, as already mentioned, that the combination of advanced methodologies, such as PERT/CPM, with robust software such as Microsoft Project, is essential for managing the interdependence of tasks and optimizing the use of resources[37].

Analysis of the tools used in the current project highlights the need for a more structured and integrated approach. Investing in training on project planning and management tools, as well as the adoption of performance metrics, could have minimized delays and additional costs.

3.2.2 Time slippage

The delays observed in the project underline the need for robust monitoring and control tools, which are essential for mitigating the impact of external variables. In this case, the logistical difficulties associated with transporting equipment to an island region, adverse weather conditions and a lack of synchronization between scheduled activities contributed to significant delays. For example, heavy rains at critical times made it impossible to carry out tasks on schedule, leading to increases in financial and time costs.

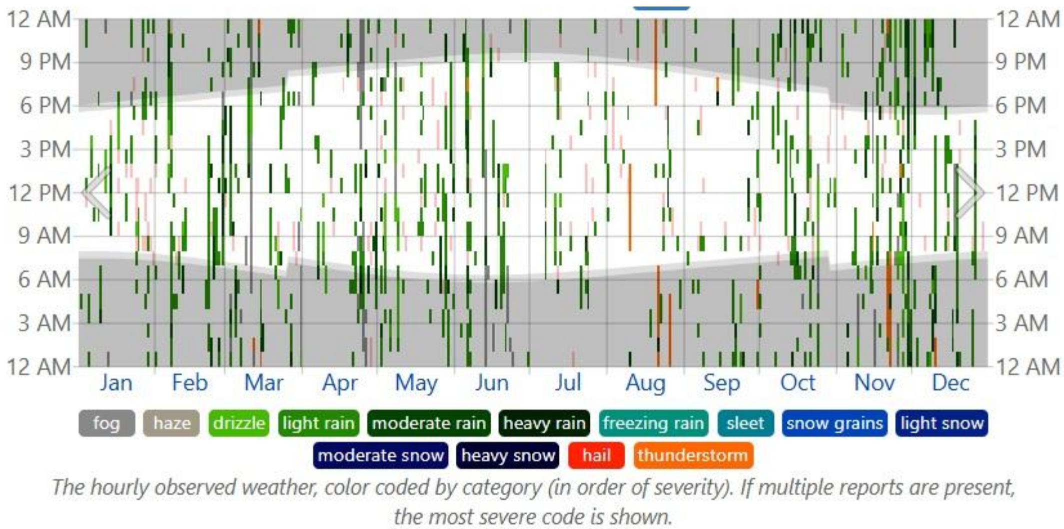

Figure 3.13 – Graph describing the climate in the Azores in 2023

Indeed, some studies indicate that delays caused by weather conditions and logistical problems are recurrent in projects located in island regions, where limited accessibility and a lack of adequate infrastructure exacerbate the challenges[38] These delays have also generated additional costs, including expenditure on prolonged storage of equipment and renegotiation of contracts with suppliers. The literature highlights that a lack of contingency planning is one of the main causes of delays in projects with complex external variables, such as the weather [39]

In addition, the unavailability of specialized technical support in the region led to improvised solutions, compromising the efficiency of the project. Detailed risk analysis during initial planning would have allowed such challenges to be anticipated and preventive strategies to be implemented. Tools such as probabilistic analysis and impact simulations are recommended for projects in remote contexts or vulnerable to external conditions [40]

A preventive approach could have included defining strategies to deal with climatic and logistical disruptions.

According to [41], integrating risk models into initial planning helps to significantly reduce delays, while solutions based on efficient logistics networks can minimize the financial impact of disruptions. These challenges reinforce the importance of adopting modern project management practices, ensuring greater resilience and predictability.

3.2.3 Coordination between teams

Effective coordination between the technical and management teams and suppliers was identified as a critical factor in the project's success. The lack of alignment between the parties involved resulted in delays in the delivery of essential materials, compromising deadlines and increasing costs. In particular, the absence of regular meetings and the lack of a centralized communication system exacerbated disconnections, culminating in cumulative delays.

Recent studies highlight that centralized communication management systems can mitigate these problems by facilitating real-time coordination between geographically dispersed teams [42]. Digital collaboration tools, when used properly, help to align objectives, reduce ambiguity and ensure that stakeholders remain informed and integrated.

Internal coordination also faced challenges due to the lack of adequate training in project management tools, limiting the ability to respond to operational problems. Without this knowledge, the solutions adopted tended to be short-term, without addressing the root causes of the difficulties faced. The literature suggests that continuous training in modern management tools, such as Microsoft Project and Slack, can significantly increase the efficiency and resilience of teams [43]

In addition, the absence of a clearly designated project leader contributed to fragmented management. The lack of a central authority made it difficult to make quick and effective decisions, especially at critical moments. Studies indicate that appointing a project manager with robust communication and leadership skills is essential to ensure team alignment and reduce the likelihood of coordination failures.

3.3 Critical Analysis

3.3.1 Communication Efficiency

Coordination between the different teams was compromised by various factors that significantly impacted the efficiency of the project. The use of multiple avenues of communication, without a centralized structure, made alignment between stakeholders difficult. This disorganized approach was compounded by the absence of a project manager with the authority to make strategic decisions and operationalize a clear and effective communication flow.

In addition, language difficulties between teams, some of whom spoke in Portuguese and others in Spanish, created additional barriers, hindering smooth interactions. The appointment of a bilingual manager, with proven experience in similar projects, could have mitigated this problem, guiding the work and ensuring more efficient alignment between the parties. The lack of adequate leadership and a single line of communication contributed to the EPC company losing control of the project at certain times, resulting in delays and additional costs.

The urgency to complete the project was another negative factor. As delays accumulated, the attempt to speed up execution increased the likelihood of errors, which indeed occurred. Studies show that rushing through delayed projects can lead to operational failures and hasty decisions, further compromising quality and deadlines [44].

The use of collaborative digital tools, such as **Microsoft Teams** or **Asana**, could have reduced disconnections by providing a centralized platform for monitoring progress and facilitating the exchange of information in real time. These platforms also allow for the definition of tasks, timelines and responsible parties, promoting greater transparency and accountability between teams [45]. However, their effectiveness depends on strong leadership capable of integrating and managing the different parts of the project.

The lack of a structured approach and a project manager capable of centralizing strategic decisions was therefore one of the most damaging factors for the project's overall performance. The absence of a robust communication system and the reliance on improvised methods reflect a "facilitism" that ultimately compromised the control and success of the venture.

3.3.2 Risk analysis

The absence of a structured risk analysis during the initial planning was a determining factor in the problems faced throughout the project. In island regions like the Azores, where adverse weather conditions are predictable, the lack of robust planning made the project vulnerable to delays and financial impacts. Studies show that the integration of tools such as Failure Mode and Effects Analysis (FMEA) and SWOT Analysis is essential for anticipating and mitigating risks associated with external and logistical factors [46]

The logistics of delivering materials and equipment was another critical element that did not receive enough attention. This type of challenge is magnified in remote locations with limited infrastructure, such as the Azores, where the communication route used is by sea, with a delay of at least a week between order and delivery.

The adoption of methods such as Failure Mode and Effects Analysis (FMEA) and SWOT Analysis for risk analysis would have made it possible to plan alternative solutions and ensure greater efficiency in the use of resources [47].

In addition, the absence of scenario-based simulations and probabilistic analysis contributed to the inability to predict interruptions. The use of tools such as Monte Carlo analysis, combined with risk mapping through the Risk Breakdown Structure (RBS), could have provided a detailed view of the project's potential critical points[48], since the RBS could have highlighted the risks and the Monte Carlo tool could have helped predict the likelihood of the project being delayed due to these factors, and could also have made it possible to quantify their financial impact.

3.3.3 Environmental and Social Impact

The delays in the project represented a substantial challenge for the efficiency and costs of implementing the photovoltaic plant. However, the results obtained show significant environmental and social benefits, highlighting the strategic role of this project in the energy transition in island regions.

3.3.4 Environmental contributions

The photovoltaic system installed exceeded expectations, reaching the initial target of reducing the plant's electricity consumption by 25%. This result contributed directly to reducing the industrial operation's carbon footprint, reinforcing the project's alignment with the Sustainable Development Goals (SDGs), especially with Goal 7 (affordable and clean energy) and Goal 13 (action against global climate change).

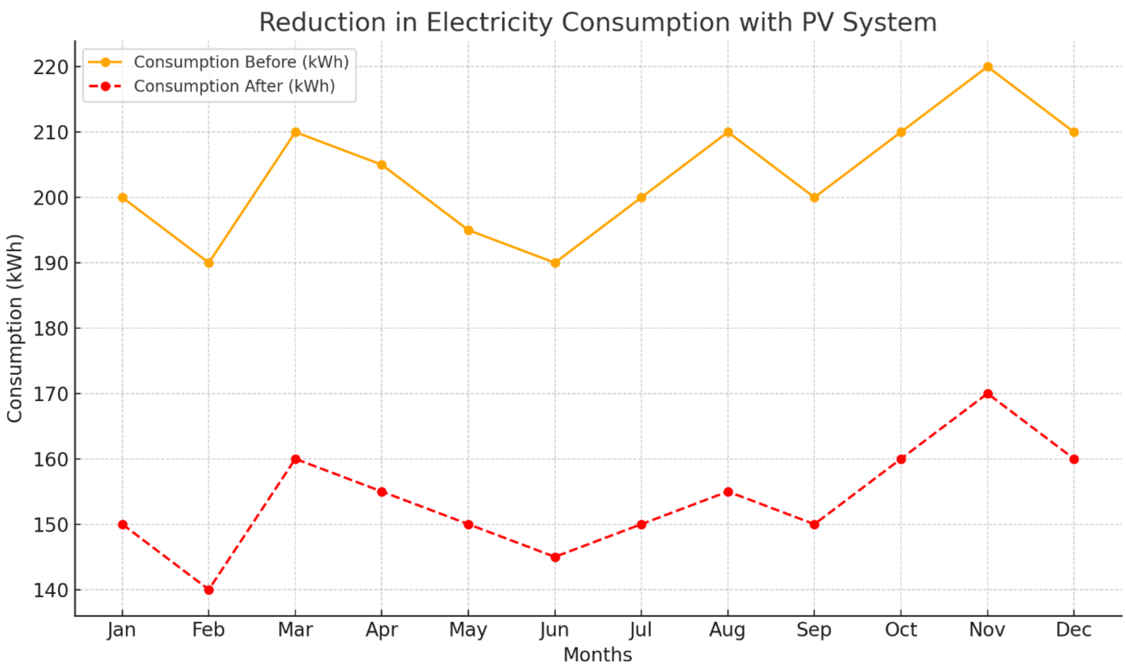

Figure 3.14 – Reduction in electricity consumption with the PV system

The graph (Figure 14) shows the monthly evolution of electricity consumption before and after the installation of the photovoltaic system. There has been a consistent reduction over the months, demonstrating the effectiveness of the solution in achieving the stipulated target of a 25% reduction in energy consumption.

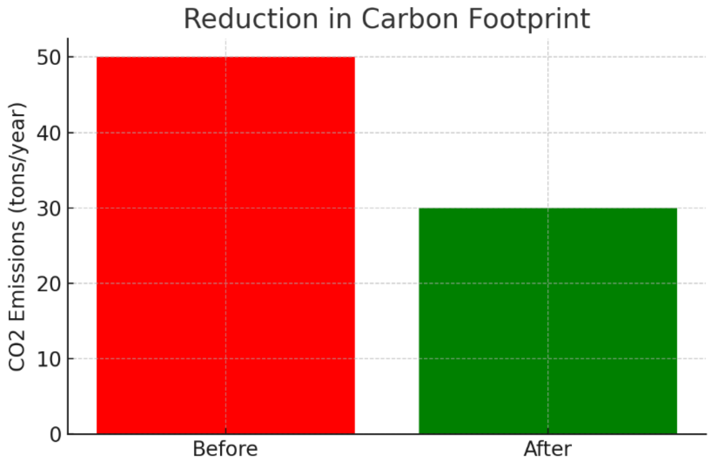

Figure 3.15 – Reduction in Carbon Footprint with the PV system.

The graph (Figure 3.15) illustrates the reduction in annual CO_2 emissions, showing the transition to a cleaner energy matrix. Emissions were reduced from 50 to 35 tons of CO_2 per year, which reinforces the project's positive impact on the environment and its contribution to mitigating climate change.

Studies corroborate that self-consumption energy solutions, such as photovoltaic systems, have significant positive environmental impacts. According to Fragkos et al. (2023), the implementation of renewable energies in island contexts promotes the reduction of greenhouse gas emissions, while increasing the resilience of local energy infrastructures.

3.3.5 Social repercussions

In addition to the environmental gains, the project boosted the local economy, creating jobs during the installation and maintenance of the system. In addition, the promotion of sustainable practices has raised awareness in the community about the relevance of renewable energies, in line with the literature that highlights the social benefits of the energy transition in local economies [49].

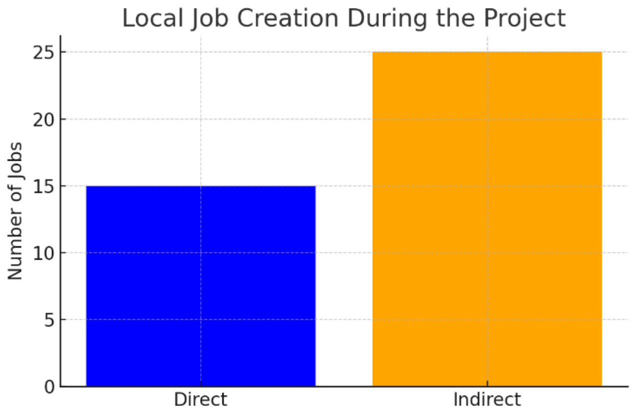

Figure 3.16 – Local Job Creation with the PV system project.

The graph (Figure 3.16) demonstrates the social impact of the project by highlighting the number of direct and indirect jobs generated. During installation and maintenance, 15 direct jobs and 25 indirect jobs were created, representing a significant boost to the local economy.

This project also had a multiplier effect, serving as a model for other local industries which, upon seeing the demonstration of the economic and environmental viability of self-consumption systems, began to adopt sustainable technologies in the Azores archipelago, contributing to the promotion of energy independence and increased regional resilience. Demonstrating the economic and environmental viability of self-consumption systems has the potential to encourage greater adoption of sustainable technologies in the Azores archipelago, promoting greater energy independence and regional resilience.

3.4 Examples of Application of Project Management Techniques

Below are some examples that illustrate the practical application of Project Management Techniques. These concrete cases demonstrate how theoretical concepts can be implemented in real contexts, highlighting their impacts and benefits. The analysis of examples provides a better understanding of the feasibility and adaptability of the proposed solutions, as well as highlighting the potential of these techniques to address challenges in different sectors and promote effective results.

3.4.1 CPM Application Example

Considering a hypothetical project made up of the following activities and durations:

Table 3.3 – Project activities and durations.

Activity	Duration (days)	Predecessors
A	3	-
B	5	A
C	2	A
D	4	B, C

Now generating the network diagram and calculating the critical path:

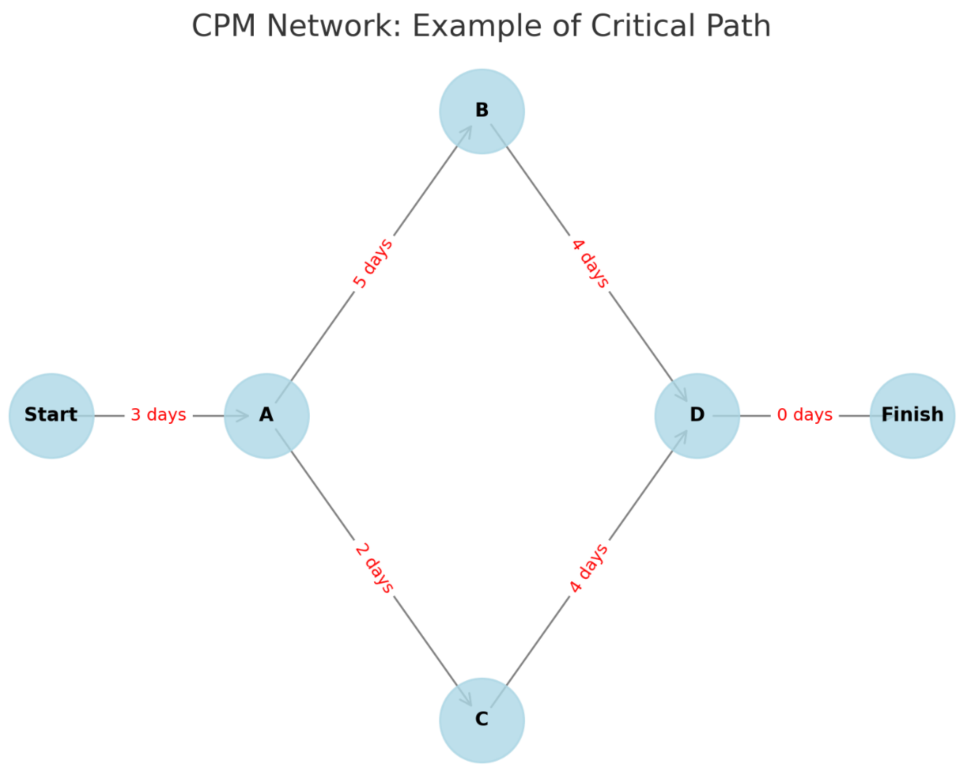

Figure 3.17 – Project Diagram.

The diagram above represents the activity network of the fictitious project. Each node (blue circle) represents events or activity start and end points, while the edges (lines) represent the activities, with their respective durations indicated in days.

Critical Path Interpretation

1. Calculating the critical path involves:

o Determine the earliest (ES, EF) and latest (LS, LF) times for each activity.

o Identify the activities that have no slack $(EF = LF)$.

2. In the example, the critical path would be the sequence of activities that determines the total duration of the project.

performing the step-by-step calculations to determine the earliest (ES, EF) and latest (LS, LF) times for each activity we have:

1. Calculating the Earliest Times ($\boldsymbol{ES}$ and $\boldsymbol{EF}$)

The earliest times are calculated starting with the first activity and progressing to the last.

- **Activity A:**

$$ES_A = 0\ (start\ of\ the\ project). \tag{3.10}$$

$$EF_A = ES_A + t_A\ = 0 + 3 = 3 \tag{3.11}$$

- **Activity B:**

$$ES_B = EF_A = 3\ (starts\ after\ the\ end\ of\ A). \tag{3.12}$$

$$EF_B = ES_B + t_B\ = 3 + 5 = 8 \tag{3.13}$$

- **Activity C:**

$$ES_C = EF_A = 3\ (starts\ after\ the\ end\ of\ A). \tag{3.14}$$

$$EF_C = ES_C + t_C\ = 3 + 2 = 5 \tag{3.15}$$

- **Activity D:**

$$ES_D = max(EF_B, EF_C) = \max(8{,}5) = 8\ (starts\ after\ the\ end\ of\ B\ and\ C). \tag{3.16}$$

$$EF_D = ES_D + t_D\ = 8 + 4 = 12 \tag{3.17}$$

- **End:**

$$ES_{END} = EF_D = 12 \tag{3.18}$$

2. Calculating the Latest Times ($\boldsymbol{LS}$ and $\boldsymbol{LF}$)

The earliest times are calculated starting with the first activity and progressing to the last.

- **End:**

$$LF_{END} = EF_{END} = 12 \tag{3.19}$$

- **Activity D:**

$$LF_D = LF_{END} = 12\ (last\ activity). \tag{3.20}$$

$$LS_D = LF_D - t_D\ = 12 - 4 = 8 \tag{3.21}$$

- **Activity B:**

$$LF_B = LS_D = 8\ (D\ depends\ on\ B). \tag{3.22}$$

$$LS_B = LF_B - t_B\ = 8 - 5 = 3 \tag{3.23}$$

- **Activity C:**

$$LF_C = LS_D = 8\ (D\ depends\ on\ C). \tag{3.24}$$

$$LS_C = LF_C - t_C\ = 8 - 2 = 6 \tag{3.25}$$

- **Activity A:**

$$LF_A = min(LS_B, LS_C) = \min(3,6) = 3\ (A\ is\ predecessor\ of\ B\ and\ C). \tag{3.26}$$

$$LS_A = LF_A - t_A\ = 3 - 3 = 0 \tag{3.27}$$

3. **Determining the Critical Path**

The critical path is made up of activities whose Slack) is zero, i.e. where:

$$Slack = LS - ES = 0 \tag{3.28}$$

$$Slack = LF - EF = 0 \tag{3.29}$$

- **Activity A:** $Slack = 0$
- **Activity B:** $Slack = 0$

- **Activity C:** $Slack = 0$

The critical path is the sequence **A ⟶ B ⟶ D**, and the total duration of the project is **12 days**.

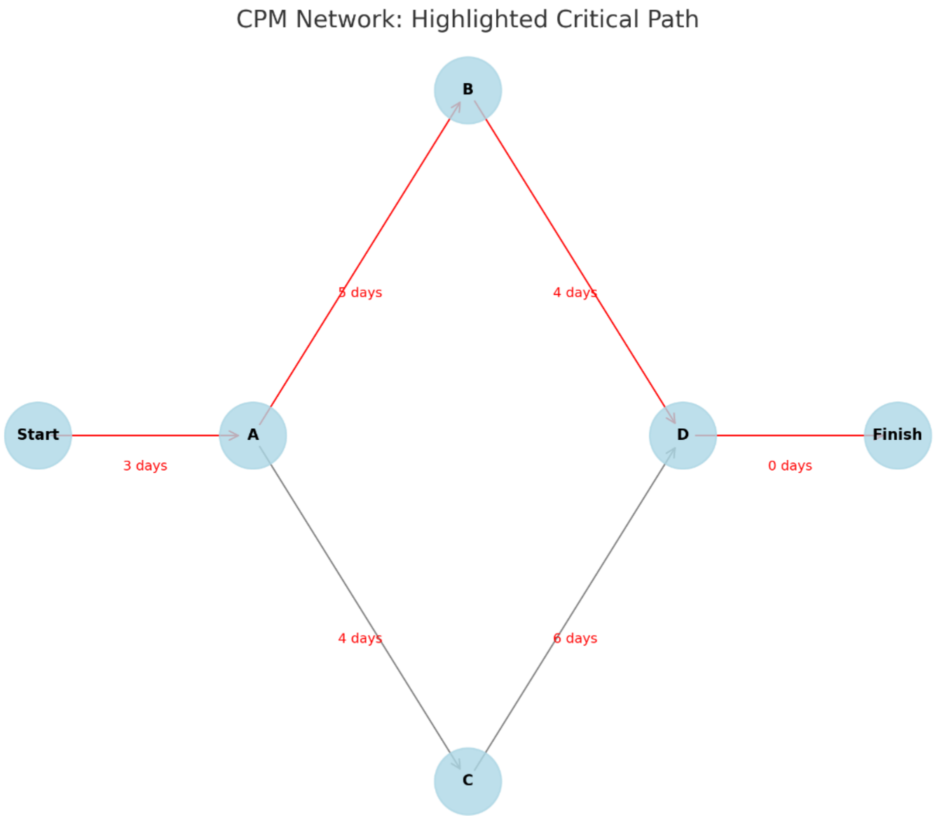

Figure 3.18 – CPM network with highlighted critical path.

In the updated chart, the critical path (A ⟶ B ⟶ D) is highlighted in red, indicating the activities that determine the minimum project duration, with the times calculated for each activity:

- **START:** $ES = 0, LF = 0$
- **Activity A:** $ES = 0, EF = 3; LS = 0; LF = 3$
- **Activity B:** $ES = 3, EF = 8; LS = 3; LF = 8$
- **Activity D:** $ES = 8, EF = 12; LS = 8; LF = 12$
- **FINISH:** $ES = 12, LF = 12$

Activities outside the critical path (such as C) have slack, offering flexibility in the schedule. For example, activity C has $Slack = 3\ days\ (LS - ES)$.

3.4.2 PERT Application Example

Considering the same hypothetical project created for the CPM Method, now adjusted to apply the PERT Method, we have:

Table 3.4 – Project activities and durations.

Activity	Duration (days)	Predecessors	a (days)	m (days)	b (days)
A	3	-	2	4	6
B	5	A	3	5	9
C	2	A	1	3	5
D	4	B, C	4	6	10

Based on the formulas presented, we calculated the following expected durations and variances:

Table 3.5 – Project activities and durations statistical data.

Activity	Expected duration (μ)	Variance (σ^2)	Critical path
A	4,00	0,44	yes
B	5,33	1,00	yes
C	3,00	0,44	no
D	6,33	1,00	yes

The critical path is made up of activities **A → B → D**, with an expected total duration of:

$$\mu_p = 4 + 5{,}33 + 6{,}33 = 15{,}66\ days \tag{3.30}$$

The total variance of the project is:

$$\sigma_p^2 = 0{,}44 + 1{,}00 + 1{,}00 = 2{,}44 \tag{3.31}$$

The standard deviation (σ_p) is:

$$\sigma_p = \sqrt{2{,}44} = 1{,}56\ dias \tag{3.32}$$

Probability of Completion

Suppose we want to evaluate the probability of completing the project within 16 days. The Z value is:

$$Z = \frac{16 - 15{,}66}{1{,}56} = 0{,}22 \tag{3.33}$$

Consulting the normal distribution table, the value Z=0.22 corresponds to a cumulative probability of approximately **58.71%**, indicating that there is around a **59%** chance of completing the project on time.

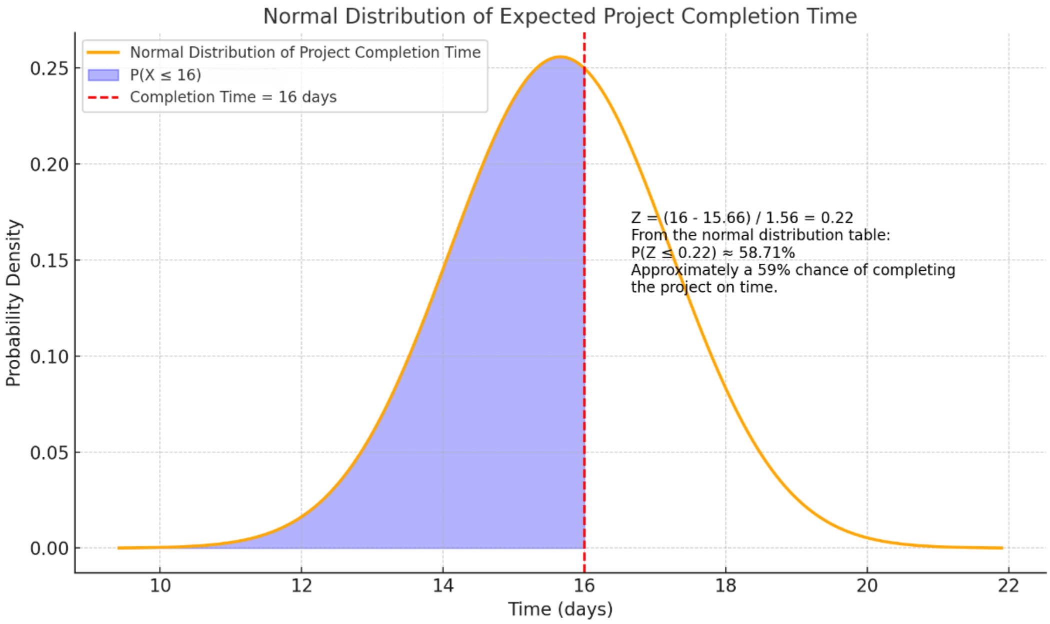

Figure 3.19 – Normal Distribution of Expected Project Time (PERT).

The graph above represents the normal distribution of the expected project time, with an average (μ_P) of 15.66 days and a standard deviation (σ_p) of 1.56 days. The area shaded in purple corresponds to the probability of the project being completed within 16 days. This probability was calculated as approximately 58.71%, indicating a moderate chance of completing the project within this timeframe.

This visually demonstrates the variability in the project schedule and how PERT can be used to quantify uncertainty in probabilistic terms.

3.4.3 GERT Network Example

To illustrate the practical application of GERT, below I present a graphic that exemplifies a GERT network with different alternative paths and loops, along with a detailed explanation of its interpretation.

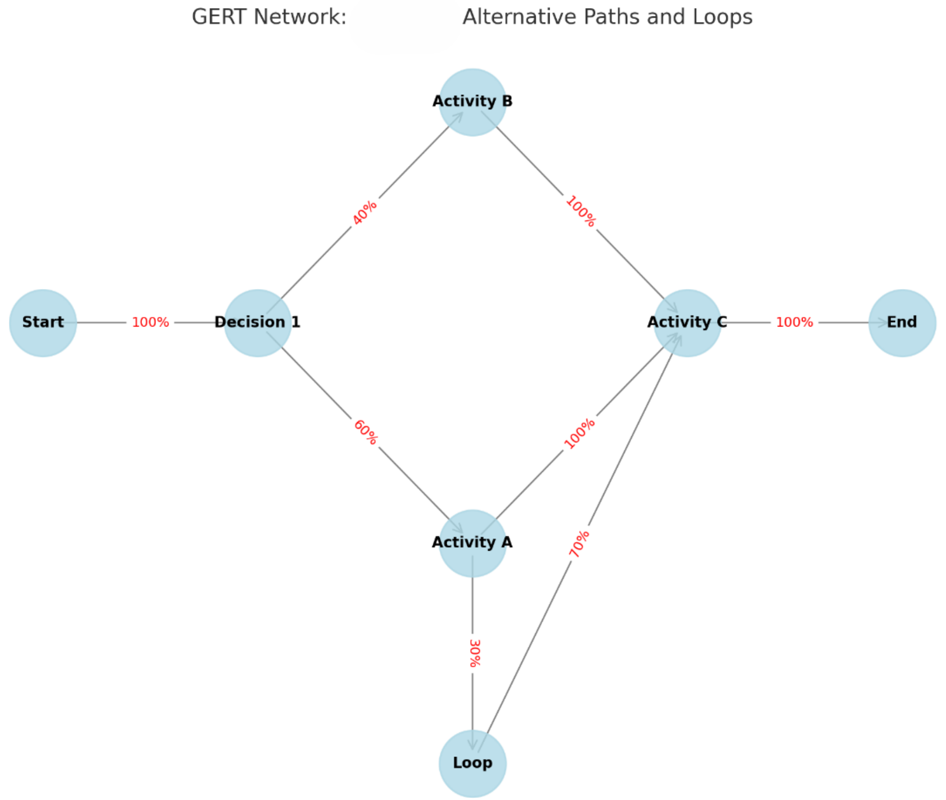

Figure 3.20 – GERT Network with Alternative Paths and Loops.

The graphic above illustrates a typical GERT network, where each node represents events and each branch represents activities with associated probabilities. The network includes alternative paths and a loop, which reflects GERT's flexibility for modeling iterative processes and uncertainties.

- **Nodes (Events):** Represent stages of the project, such as "Start", "Decision 1" and "End".
- **Branches (Activities):** Connect the nodes and have associated probabilities. For example, from "Decision 1", there is a 60% chance of moving on to "Activity A" and 40% to "Activity B".
- **Loop:** After "Activity A", the project can return to the same activity (30% chance) or move on to "Activity C" (70%).

Interpretation

- The **expected average** project completion **time** can be calculated by weighting the probabilities of each path by the sum of the durations of the corresponding activities.
- The **total expected cost** is calculated in a similar way, adjusting for the costs associated with each activity.

- The **probability of success** within a specific time can be estimated by integrating the times of the paths and their probability distributions.

4 RESULTS AND DISCUSSIONS

This chapter presents a critical and detailed analysis of the results obtained in the project to install an industrial photovoltaic plant for self-consumption, focusing on the impacts of the PERT and CPM techniques. The aim is to contextualize the data in the light of the challenges faced, identify gaps in the process and propose solutions for future improvement. The economic, environmental and organizational impact of the project is discussed, addressing the problems faced, their causes and the lessons learned.

4.1 Analysis of results

4.1.1 Planning and execution

The project revealed significant flaws in the initial planning, such as the use of rudimentary tools (Excel), which did not make it possible to identify critical activities and predict delays accurately. The migration to Microsoft Project brought improvements, but did not eliminate the bottlenecks resulting from lack of training and lack of integration between teams. In addition, using a more automated and less error-prone approach would have made it possible to identify critical paths more accurately, avoiding the delays observed. Studies indicate that implementing robust tools such as CPM and PERT from the outset would have made it possible to identify critical paths, mitigating delays and reducing costs [1]

4.1.2 Impact of delays

The delays resulted in a significant increase in costs, reducing the expected profit margin from 20% to just 4%. These delays were attributed to adverse weather conditions, logistical problems and the absence of a comprehensive risk analysis. This situation also highlighted the need for forecasting and contingency, which could be achieved by integrating Monte Carlo simulations and Risk Breakdown Structure techniques, making it possible to predict and mitigate the impacts of these variables [36]. In addition, it was observed that delays related to logistics could have been mitigated with the use of integrated supply planning, including more efficient local partnerships.

4.1.3 Environmental and social benefits

Despite the challenges, the project exceeded its target of reducing electricity consumption by 25%, contributing to the reduction of 15 tons of annual CO_2 emissions. This achievement reflects not only the efficiency of the technology used, but also the project's commitment to sustainability. In addition, the creation of local jobs and increased community awareness highlighted the project's positive impact, bringing it in line with the Sustainable Development Goals [49]. This impact not only benefited the local economy but also reinforced the perception of the importance of investments in renewable energies.

4.2 Discussion

4.2.1 Critical Evaluation of the PERT and CPM Techniques

The use of PERT and CPM proved essential in dealing with the complexity of the project. However, the late application of these techniques limited their impact. Integrating them from the start would have allowed for greater predictability and a better allocation of resources, including the definition of clear critical milestones that could be monitored throughout the schedule. Studies corroborate that their use from the outset could have provided greater predictability and a better allocation of resource [50]. In addition, the techniques could have reduced the impact of external factors, such as logistical and climatic delays [39]. The post-project analysis reinforces that greater dedication to training teams in the application of these tools could also have avoided errors and omissions in planning.

4.2.2 Coordination problems

The lack of a centralized communication system and an experienced project manager resulted in disconnects between the teams, contributing to cumulative delays. In addition, the absence of regular meetings and a clear flow of information compromised the alignment of those involved. Collaborative tools, such as Microsoft Teams, could have mitigated these disconnects by ensuring greater transparency and accountability [43]. These studies highlight the importance of fostering a culture of collaboration that includes a continuous feedback loop, allowing for quick problem solving and improved synergy between teams.

4.2.3 Lessons learned

The experience gained over the course of the project highlighted several key lessons for improving future initiatives. Firstly, the importance of detailed planning proved essential, highlighting the need for a structured approach that includes simulations and risk analysis from the outset. This planning must go beyond simply mapping out critical activities and also incorporate the definition of intermediate targets and clear performance indicators that can be monitored regularly to assess progress and anticipate possible deviations.

Another key point was the need to train the teams involved in carrying out the project. Specific training in the use of project management tools, such as PERT and CPM, is essential to maximize their effectiveness. It is not enough to provide access to the tools; it is essential to ensure that team members fully understand the fundamentals of these techniques so that they can apply them efficiently and appropriately. This understanding not only improves the accuracy of planning but also increases the confidence and operational efficiency of those involved.

These lessons learned represent a solid basis for continuous improvement and the success of future initiatives.

5 CONCLUSIONS AND RECOMMENDATIONS

This research has shown that, despite the challenges faced, the project has achieved significant environmental and social results. The critical analysis reinforces the need to improve initial planning, train teams and adopt advanced technologies to optimize future projects.

This chapter discusses the opportunities for progress and the gaps identified during the project to install the self-consumption industrial photovoltaic plant, exploring how these experiences can serve as a basis for developing more efficient and sustainable solutions in the energy sector. As well as identifying the challenges faced, it presents proposals for future work that broaden the scope of the techniques used, suggesting applications in other contexts and sectors. The potential of these techniques to improve forecasting, productivity and sustainability is at the heart of this discussion.

One point of note is the absence of a structured risk analysis, a factor that limited the project's predictability and resilience. In this sense, the adoption of more robust methodologies, such as Failure Mode and Effect Analysis (FMEA) and Risk Breakdown Structure (RBS), could have improved risk identification and mitigation. Future work could explore these techniques and their impact on complex projects, particularly in island regions or those with limited infrastructure. Furthermore, the integration of advanced technologies such as the Internet of Things (IoT) and systems based on artificial intelligence can bring greater visibility and control to the progress of projects, contributing to more innovative and effective solutions.

CPM and PERT techniques can also be adapted and applied in other sectors, such as construction, the automotive industry and logistics, where accurate forecasting of deadlines and costs is essential. Studies can assess how these techniques can be adjusted to deal with the specificities of these sectors, promoting efficiency and productivity gains. In addition, the integration of photovoltaic systems with other renewable energy sources, such as wind and biomass, is also an area of great potential. Hybrid systems can increase resilience and sustainability and are especially relevant for island regions facing specific infrastructure challenges.

In conclusion, the gaps identified in this project represent a rich basis for future research. The integration of emerging technologies, the improvement of the methodologies employed and the training of teams are essential elements for significant advances in project management. These efforts will pave the way for more efficient and sustainable projects, in line with the growing demands for innovative solutions in the energy sector.

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