

Bachelor's Thesis

Bachelor's degree in Industrial Technologies and Economic Analysis

Offshore Wind Park Optimization

June 2024

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Call: Spring 2023-2024



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ETSEIB

Abstract

Short and must include results.

Keywords: offshore wind power plant, power flow, renewable energy, HVAC, transmission system, optimization, mixed-integer programming, genetic algorithms.

MSC codes: 90C11, 90C15, 90C29, 90C30, 90C59

Resum

Short and must include results.

Paraules clau: parc eòlic marí, flux de potència, energia renovable, HVAC, sistema de transmissió, optimització, programació enter mixta, algoritmes genètics.

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Resumen

Short and must include results.

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Nomenclature

The next list describes several abbreviations and symbols that will be later used within the body of the thesis.

AC Alternating Current

DC Direct Current

HVAC High Voltage Alternating Current

HVDC High Voltage Direct Current

MVRSM Mixed-Variable ReLU-based Surrogate Modelling

N-R Newton-Raphson Method

OPF Optimal Power Flow

OSS Offshore Substation

OWF Offshore Wind Farm

OWPP Offshore Wind Power Plant

PF Power Flow

SCR Short Circuit Ratio

XLPE Cross-Linked Polyethylene

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1 Preface

Arguably, climate change is one of the most pressing challenges we are facing today as humanity. That's why I wanted to develop a project revolving around sustainable solutions for the energy system of the future. As an engineering student I wanted to explore how renewable energy sources can be integrated into the grid and what challenges it poses, that's why I contacted Oriol Gomis to explore thesis topics within this field.

He introduced me diverse research areas and also eRoots, a spin-off from the UPC-CITCEA that develops software solutions for modern grid modelling, analysis and optimization. Then Josep Fanals, my supervisor and eRoots CEO, presented to my various topics that they would be potentially interested to develop a thesis on. This is when he introduced me to the topic of design, sizing and optimization of the transmission system of offshore wind power plants. The research group CITCEA-UPC has been working in this area [2] and further development on this field was the breeding ground for this proposal. The topic immediately caught my attention and that is how I ended up as an intern at eRoots developing software solutions for the optimization of offshore wind power plants.



Figure 1: Una imatge del logo de l'ETSEIB

Per referir-se a la Fig.1. Per no repetir informació és millor referir-se a altres apartats 6.

I recorda, sempre és important citar a la bibliografia [2].

La bibliografia ha d'estar ordenada, en tengu un exemple a la pàgina 30

2 Introduction

2.1 Motivation

During the industrial engineering studies you get in touch with a wide range of topics that can be applied to different fields. During the last years to get introduced to electrical engineering fundamentals and its applications. I discovered a deep interests for those topics and realized is a key tool for ensuring a future towards energy systems that can inegrate renwable energy sources.

The main driving force behind choosing this topic is the need to develop a sustainable energy system that can ensure a future for the next generations. The energy system is a key player in the fight against climate change. Moreover, the last report on global sustainable development [1] highlights how *Goal 7: Affordable and clean energy* is failing to meet its targets. In fact, it actually notices a backward trend in the 2020-2023 period when it comes to this goal targets, which signals that it is an area where efforts have to be put in.

This thesis is my modest and passionate contribution to provide sustainable solutions for our future.

2.2 Scope

This work will limit its study to the optimal design of HVAC transmission systems, without considering the cost comparision with HVDC. Moreover, it will limit its study to the steady-state of balanced three phase load systems, without considering unbalanced or transient states.

2.3 Objectives

The main objectives of the thesis are the following:

- Model all the elements of the transmission system of an offshore wind power plant and find its equivalent circuit.
- Implement a power flow solver with Python.
- Formulate the optimization problem to minimize all types of costs taking into account the technical constraints of the system.
- Benchmark different optimization algorithms thar find solutions faster than state of the art methods.
- Study some specific cases applicable to real offshore wind power plants.

2.4 Outline

The thesis is structured as follows:

- Chapter 3 introduces offshore wind power plants, the problem we want to tackle and models the elements that we find in a HVAC transmission system.
- Chapter 5 formulates the minimization problem, including objective functions and constraints. In this section we also build the power flow solver that deals with the equality constraints and the algorithm for computing objective function values.
- Chapter 6 explains state of the art methods to solve the problem, its limitations, and our new approaches involving surrogate models, genetic algorithms and optimal power flow.
- Chapter 7 showcases results for different OWPP's sizes and distance to shore and compare it with existing results in terms of validity and computational time.
- Chapter 8 collects the main outcomes of the thesis and proposes future lines of work.
- Chapter 9 presents the planning and viability studies for the project.

3 Technical background: grid to study

3.1 Offshore wind power plants

As global energy demands surge and the pressing need for sustainable development becomes ever more urgent, the quest for renewable energy sources has intensified. Among these, wind power has emerged as a frontrunner due to its potential to generate substantial amounts of clean electricity. While onshore wind farms have been widely implemented, their offshore counterparts are gaining increasing attention for their ability to harness the stronger and more consistent winds found over the oceans.

Offshore wind power, defined as the use of wind turbines located in bodies of water to generate electricity, presents several advantages over onshore installations. The primary benefit lies in the higher wind speeds and lower turbulence experienced offshore, which contribute to greater energy yields. Additionally, offshore wind farms can be situated closer to urban centers located along coastlines, thereby reducing transmission losses and enhancing energy efficiency. The development of offshore wind technology has seen rapid advancements in recent years. From the deployment of the first offshore wind farm in Denmark in 1991 to the establishment of massive installations such as the Hornsea Project in the UK, the scale and capacity of these projects have grown significantly. Technological innovations, including larger turbines, floating foundations, and improved grid integration techniques, have further propelled the industry forward.

3.2 Transmission systems design and reactive power compensation problem

When designing the transmission system of an OWPP, several factors must be considered to ensure optimal performance and efficiency. The system must be capable of transmitting the generated power from the wind turbines to the onshore grid while trying to be as energy and cost-efficient as possible. There are two main types of technologies that can be used, HVDC and HVAC. In this thesis we will focus our study to the HVAC technology.

To put in context the relevance of this topic, the work and software developed in this thesis will be used as the breeding-ground of a partnership between eRoots and Acciona, a leading infrastructure company in Spain that has shown interest in developing a tool for the optimal design of OWPP's transmission systems.

One drawback of using HVAC cables is the high shunt capacitance they have, which is even larger in underground cables, which are the ones used for OWPP.

	Overhead Lines	Underground Lines
Capacitance per unit length ($\mu\text{F}/\text{km}$)	0.01 - 0.02	0.3 - 0.6

Table 1: Comparison of Capacitance per unit length of Overhead and Underground Lines

The charging current of this capacitance limits the active power transfer capacity of the line and in-

creases power losses and voltage across the line due to the Ferranti effect[3]. This effect can be described by the voltage difference between the sending and receiving end of transmission line under no-load conditions:

$$\frac{V_o - V_i}{V_o} = \omega^2 CL \frac{l^2}{2} \quad (1)$$

where V_o and V_i are the receiving and sending end voltages respectively, ω is the frequency, C is the capacitance per unit length, L is the inductance per unit length and l is the length of the line. Note that the voltage difference is proportional to the square of the length of the line which leads to overvoltages for long transmission lines.

However, the possibility to include reactive power compensation elements helps reduce the reactive power generation. Figure 2 shows how including this compensation reduces power losses, especially when we approach the no-load condition, which is equivalent to not having any type of active power injection from the OWPP, i.e. the wind speed is very low.

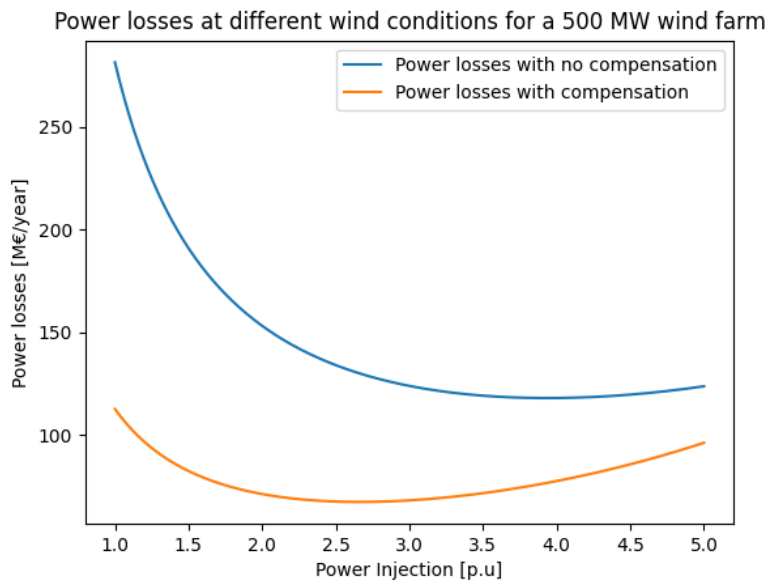


Figure 2: Power losses comparison when including reactive power compensation

The goal of the project is to determine where this compensation has to be placed and how to size it. But this is only part of the design characteristics we want to optimize. A full description of the optimization variables will be presented in Chapter 5.

3.3 Grid elements

To be able to do a steady-state analysis of the transmission system we need to model all the elements in the grid. This section models these elements and presents some important concepts to understand

the grid.

3.3.1 Cables

Cables are an essential part of HVAC transmission systems. We will consider three-core cross-linked Polyethylene (XLPE) cables, which are the most common type of cables used in OWPP's. The equivalent circuit of a cable is shown in Figure 3. We will use a model

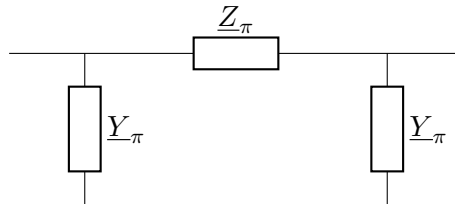


Figure 3: Pi model transmission line

3.3.2 Transformers

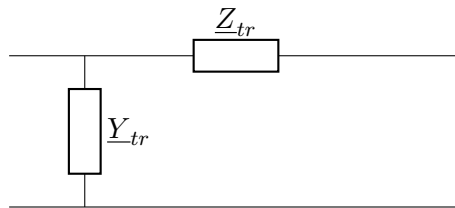


Figure 4: Transformer model

3.3.3 Shunt reactor: reactive power compensation

To compensate reactive power generation we will use shunt reactors. They are reactive power absorbers and in our case will be connected from the line directly to the ground. The equivalent circuit is shown in Figure 5.

$$\underline{y}_{sh} = \frac{1}{j\omega L} \quad (2)$$

where L is the inductance of the reactor.

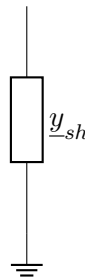


Figure 5: Shunt reactor model

We will consider the possibility to include 5 different shunt reactors in the system. Further development on the reasoning of this scheme on 4

3.3.4 Main grid

It will be the slack bus.

We will model the grid we are connected to using a Thévenin equivalent circuit where \underline{u}_g is the Thévenin voltage and \underline{z}_g is the Thévenin impedance:

$$\underline{z}_g = R_g + jX_g \quad (3a)$$

$$R_g = \sqrt{\frac{\frac{U_g^2}{SCR} powf S_{base}}{(\frac{X_g}{R_g})^2 + 1}} \quad (3b)$$

Note that we need the short circuit ratio (SCR) and the $\frac{X_g}{R_g}$ ratio as parameters to the equivalent circuit.

- The SCR is the ratio of the short circuit apparent power in the case of a line-line-line-ground fault at the location in the grid where some generator is connected to the power rating of the generator itself. It is somehow a measure of the grid strength to small disturbances.

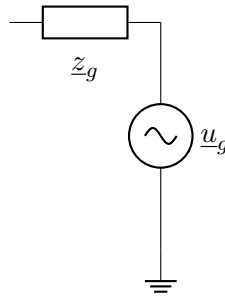


Figure 6: Main grid model

3.3.5 Power plant

We will model our OWPP as a simple power injection at one end of the transmission line. For our analysis we will consider that there is no reactive power generation, therefore $q_{owf} = 0$. p_{owf} will be the active power generation that will depend on the wind conditions of the plant. The reach of the work will limit its analysis to a fix power generation.

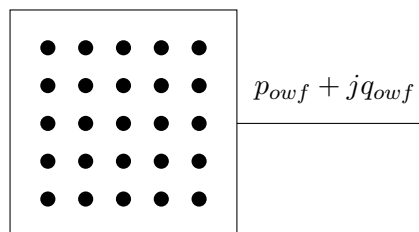


Figure 7: Power plant

3.4 Costs modelling

3.4.1 Cables

3.4.2 Transformers

3.4.3 Shunt reactor

3.4.4 Switchgears

3.4.5 Substation platform

4 Power flow analysis

Now we can fully define the power flow analysis. This approach will allow us to model the transmission system as a set of buses (or nodes) interconnected by transmission links. This will allow us to solve for the steady-state powers and voltages of the system. This step is crucial to latter on formulate our optimization since power flow equations will be the equality constraint of the optimization problem, 9, and the objective function will also depend on the solution of the power flow (PF).

4.1 Types of buses

In this section we will briefly describe what is a bus and what types we have.

Buses are points of the grid which either supplied by generators, *generator buses*, or those without generators, *load buses*. More formally, a n -bus system, $N = \{B_1, \dots, B_i, \dots, B_n\}$ where N is the set of n -nodes, is defined as:

$$\forall B_i \in N, \begin{cases} S_i = P_i + jQ_i, & \text{where } S_i \text{ is the apparent power at bus } i \\ V_i = |V_i|e^{j\theta_i}, & \text{where } V_i \text{ is the complex voltage at bus } i \end{cases} \quad (4)$$

As we can see, for each bus i we have 4 variables:

- P_i and Q_i are the active and reactive power at bus i respectively.
- $|V_i|$ and θ_i are the voltage magnitude and angle at bus i respectively.

It is important to note that in general we cannot specify all the P_i 's independently since there is a constraint imposed by the need to balance active power. In our case, a transmission system with losses, which are unknown before the PF, the sum of P_i 's must be equal to losses. To tackle this we will define one bus as the *slack* bus, where power injection is left free. Taking all of this account, depending on the variables are known and unknown for a certain bus we can classify them as:

- **Slack bus:** The slack bus is the reference bus of the system. It is the bus where the voltage magnitude and angle are known, typically $|V_i| = 1, \theta_i = 0$. All other buses angles will be referenced to the *slack*. It is used to balance the active and reactive power in the system.
- **Generator bus (PV):** The generator bus is the bus where the active and reactive power are known. The voltage magnitude and angle are unknown.
- **Load bus (PQ):** The load bus is the bus where the active and reactive power are unknown. The voltage magnitude and angle are known.

In summary:

	Slack Bus	Generator Bus	Load Bus
Voltage Magnitude ($ V_i $)	Yes	No	Yes
Voltage Angle (θ_i)	Yes	No	Yes
Active Power (P_i)	No	Yes	No
Reactive Power (Q_i)	No	Yes	No

Table 2: Known and unknown variables for each type of bus

4.2 Per unit system (p.u.)

In power systems analysis, it is common to use the per unit system to normalize the magnitudes of the variables. This is very useful when we are dealing with several transformers and voltage levels. The per unit system is defined as:

$$\text{Per unit value} = \frac{\text{Actual value}}{\text{Base value}} \quad (5)$$

In our case we will use $S_{base} = 100 \text{ MVA}$ and $V_{base} = \text{transmission voltage in kV}$ as the base values. This means that the per unit system will be defined as:

$$\begin{cases} I_{base} = S_{base} / V_{base} \\ Y_{base} = \frac{S_{base}}{V_{base}^2} \end{cases} \quad (6)$$

Using the per unit system will be particularly useful for analyzing the results and for dealing with the inequality constraints 5.2.2.

4.3 Admittance matrix

The admittance matrix encodes all the information of the elements of the grid and the relationship between them and allows us to perform the steady-state analysis of the grid. Now we can build the full HVAC transmission system model and find its admittance matrix \underline{Y}_{bus} , which will be essential for the power flow solver.

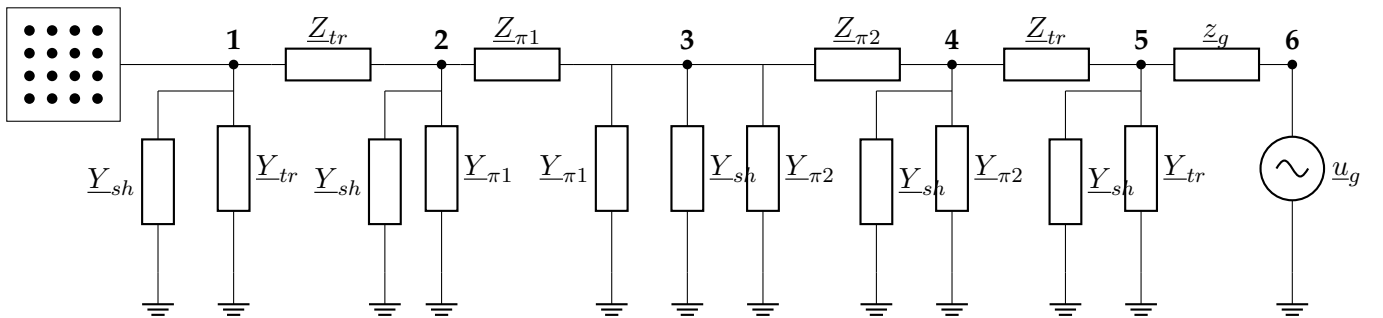


Figure 8: Transmission system model

$$\mathbf{Y}_{\text{bus}} = \begin{bmatrix} (2\underline{y}_{tr} + \underline{y}_{sh}) & -\underline{y}_{tr} & 0 & 0 & 0 & 0 \\ -\underline{y}_{tr} & (2\underline{y}_{\pi 1} + \underline{y}_{sh} + \underline{y}_{tr}) & -\underline{y}_{\pi 1} & 0 & 0 & 0 \\ 0 & -\underline{y}_{\pi 1} & (2\underline{y}_{\pi 1} + 2\underline{y}_{\pi 2} + \underline{y}_{sh}) & -\underline{y}_{\pi 2} & 0 & 0 \\ 0 & 0 & -\underline{y}_{\pi 2} & (2\underline{y}_{\pi 2} + \underline{y}_{sh} + \underline{y}_{tr}) & -\underline{y}_{tr} & 0 \\ 0 & 0 & 0 & -\underline{y}_{tr} & (2\underline{y}_{tr} + \underline{y}_{sh} + \underline{y}_g) & -\underline{y}_g \\ 0 & 0 & 0 & 0 & -\underline{y}_g & \underline{y}_g \end{bmatrix} \quad (7)$$

4.4 Grid parameters

We will use the following set of grid elements parameters for the transformers and the main grid:

Parameter	Value
SCR	5
$\frac{X_g}{R_g}$	10
P_{Cu}^{loss}	60 kW
P_{Fe}^{loss}	40 kW
u_k	18 %
i_o	1.2 %

Table 3: Grid parameters [2]

4.5 Power flow equations and solver

The power flow solver is described in Algorithm 1.

Algorithm 1 Newton Raphson Solver

```

1: procedure RUN_PF
2:   Initialize  $V$  with ones and  $\theta$  with zeros
   Set  $V[\text{slack}]$  to 1,  $\theta[\text{slack}]$  to 0
   Set  $P, Q$  based on OWPP data
   Set  $iter = 0, tol$  and  $k = 0$ 
3:   while  $iter < max\_iter$  and  $\Delta PQ > tol$  do
4:     Compute  $P\_present, Q\_present$  using  $V, \theta, Y_{bus}$ 
5:     Compute mismatch  $\Delta PQ = [dP, dQ]$  as difference between calculated and given  $P, Q$ 
6:     Compute the Jacobian matrix  $J$ .
7:     Solve the linear system  $J \cdot \Delta x_k = -\Delta PQ$ .
8:     Compute the updated  $x_{k+1} = x_k + \Delta x_k$ .
9:     Update  $V, \theta$  using  $dP, dQ, Y_{bus}$ 
10:    if  $\max(\Delta PQ) < tol$  then
11:      break
12:    end if
13:  end while
14:  return  $V, \theta$ 
15: end procedure

```

5 Optimization problem formulation

Explicar pq separem en multiobjective, ventages respsecvte soluci3 tradicional, etc

$$\mathbf{x} = \left[vol_{tr}, n_{cables}, react_{bi1}, \dots, react_{bi5}, react_{cont1}, \dots, react_{cont5}, react_{bi5}, S_{trafo} \right] \quad (8)$$

In equation 8 we define the vector of unknowns that we want to find the optimal values for. The vector includes the voltage of the transformer, the number of cables ...

5.1 Objective function: multiobjective and mixed-integer

5.2 Constraints

5.2.1 Equality: Power Flow

Now we define de equality constraints as seen in Eq. 9

$$\mathbf{h}_m(\mathbf{x}) = \mathbf{0} \quad (9)$$

$$\mathbf{S}_i = \mathbf{V}_i \left(\sum_{j=1}^{N_{nodes}} \mathbf{Y}_{ij} \mathbf{V}_j \right)^* \quad (10)$$

$$\begin{aligned} \underline{s}_1 - (p_{owf} + jq_{owf}) &= 0, \\ \underline{s}_1 - \underline{u}_1 [(2\underline{y}_{tr} + \underline{y}_l)\underline{u}_1 - (\underline{y}_{tr})\underline{u}_2]^* &= 0, \\ \underline{s}_2 - \underline{u}_2 [-(\underline{y}_{tr})\underline{u}_1 + (2\underline{y}_{\pi 1} + \underline{y}_l + \underline{y}_{tr})\underline{u}_2 - (\underline{y}_{\pi 1})\underline{u}_3]^* &= 0, \\ \underline{s}_3 - \underline{u}_3 [-(\underline{y}_{\pi 1})\underline{u}_2 + (2\underline{y}_{\pi 1} + 2\underline{y}_{\pi 2} + \underline{y}_l)\underline{u}_3 - (\underline{y}_{\pi 2})\underline{u}_4]^* &= 0, \\ \underline{s}_4 - \underline{u}_4 [-(\underline{y}_{\pi 2})\underline{u}_3 + (2\underline{y}_{\pi 2} + \underline{y}_l + \underline{y}_{tr})\underline{u}_4 - (\underline{y}_{tr})\underline{u}_5]^* &= 0, \\ \underline{s}_5 - \underline{u}_5 [-(\underline{y}_{tr})\underline{u}_4 + (2\underline{y}_{tr} + \underline{y}_l + \underline{y}_g)\underline{u}_5]^* &= 0 \end{aligned} \quad (11)$$

5.2.2 Inequality: Technical constraints

$$\mathbf{g}_n(\mathbf{x}) \leq \mathbf{0} \quad (12)$$

$$U_{kj} - U_{max} \leq 0 \quad (13)$$

$$U_{min} - U_{kj} \leq 0 \quad (14)$$

$$I_{kj} - I_{max} \leq 0 \quad (15)$$

$$Q_{min} - Q_{gj} \leq 0 \quad (16)$$

$$Q_{gj} - Q_{max} \leq 0 \quad (17)$$

$$Y_{l-ij} - Y_{l-i}^{max} \leq 0 \quad (18)$$

$$N_{react} - N_{react}^{max} \leq 0 \quad (19)$$

$$(20)$$

5.3 Algorithm overview

H

6 Optimization methods

6.1 State of the art: interior point method

6.2 NSGA-II: Genetic algorithm

6.3 Optimal Power Flow approach for compensation sizing

h

7 Case study

7.1 500 MW OWPP

h

8 Conclusions

8.1 Outcome

8.2 Future work

h

9 Planning and viability studies

9.1 Time Planning

Figure 9 shows the time distribution for the tasks carried out in the thesis.

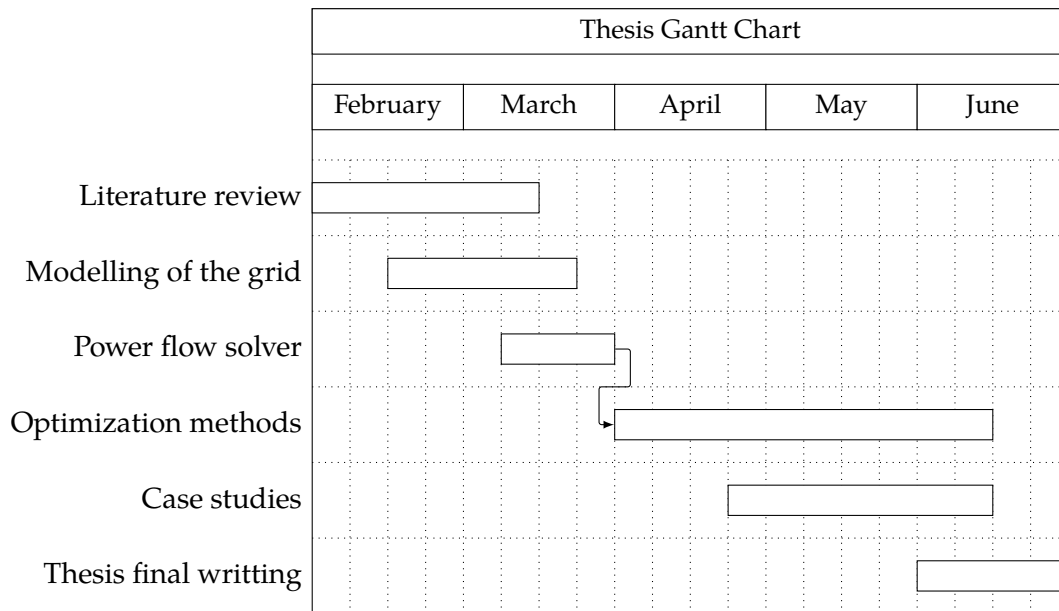


Figure 9: Thesis Gantt Chart

9.2 Economic assessment

Concept	Cost
Computer	\$XXX
Working hours	\$XXX
Tutor supervision	\$XXX
Total without IVA	\$600
Total with IVA (21%)	\$720

Table 4: Thesis Costs

9.3 Environmental assessment

This environmental assessment evaluates the energy costs incurred during the development of a thesis over five months, using a computer as the primary tool. The primary energy consumption arises from the computer's usage, which includes writing, research, data analysis, and communication.

Assuming an average laptop with a power consumption of 60 watts, used for approximately 6 hours daily, the total energy consumption over five months is around 54 kWh. This consumption translates to roughly 30 kg of CO₂ emissions, assuming the average emission factor for electricity generation.

To reduce these energy costs and associated environmental impacts in future thesis projects, several

strategies can be employed. Utilizing energy-efficient computers, enabling power-saving modes, and limiting usage time can significantly lower consumption. Additionally, adopting renewable energy sources, such as solar panels for charging devices, further reduces the carbon footprint, contributing to a more sustainable academic practice.

9.4 Social and gender equality assessment

This assessment evaluates the social and gender equality aspects of a bachelor's thesis focused on developing a tool for optimizing renewable energy system design, authored by a 22-year-old white engineering student. While the thesis itself addresses a critical area in sustainable development, examining its social dimensions is essential to ensure inclusivity and equality.

The demographic profile of the author reflects broader trends in STEM fields, where women and minority groups remain underrepresented. This lack of diversity can influence the perspectives and priorities embedded in the research. Ensuring diverse representation in such projects is crucial for incorporating a wide range of insights and addressing the needs of various communities.

To promote social and gender equality, the research should consider the differential impacts of renewable energy systems on diverse populations. Inclusive design processes involve consulting with and incorporating feedback from women, marginalized communities, and other underrepresented groups. This approach ensures that the developed tools and technologies are accessible and beneficial to all segments of society.

Moreover, educational institutions should encourage and support participation from diverse backgrounds in engineering and renewable energy fields. Mentorship programs, scholarships, and targeted recruitment can help bridge the gender and social gap, fostering an environment where innovative solutions for renewable energy are developed through diverse and inclusive contributions.

Acknowledgements

Primer de tot vull agrair profundament el suport constant del Josep, el meu tutor, que m'ha donat consell i ajuda quan l'he necessitada cada dia des de que vaig entrar a eRoots. Per extensió, agrair la rebuda i suport de tot l'equip d'eRoots durant aquests mesos, especialment a l'Oriol Gomis que ha proporcionat noves idees i enfocs al desenvolupament de la tesi.

Aquest TFG tanca un capítol de quatre anys de la meva vida que han sigut molt feliços gràcies als meus amics del grau; gràcies a tots nou. Finalment, agrair a la meva família i a la Mire el seu suport incondicional cada dia i a ensenyar-me a estimar.

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