POLITECNICO DI TORINO

Master Degree in Electrical Engineering

Master Degree Thesis

Analysis, Simulation with PyPSA, and Comparison of Scenarios with High Penetration of Renewables and Bitcoin Mining. Case study: Pantelleria Minor Island

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Abstract

Pantelleria is a minor island in the Mediterranean Sea that is renowned for its stunning natural landscapes and volcanic hot springs. Despite its small size, meeting the island's energy needs presents a significant challenge. Due to its remote location, the island is not connected to the mainland grid, and the majority of its electricity is generated using generators powered by fossil fuels.
In response to the growing concern over climate change and the need to reduce carbon emissions, the community of Pantelleria has set a goal of transitioning to a renewable energy system by 2050. This is a trickier proposition for the island, as it necessitates a complete overhaul of its existing energy infrastructure and the adoption of new technologies and management strategies.
The transition to a renewable energy-based system also presents a number of obstacles, including the variability and unpredictability of renewable energy sources, which can lead to a lack of control over the energy supply and the need for curtailment. In order to ensure a stable and reliable energy supply, the effective management of the grid becomes essential.

This thesis investigate the process of integrating renewable energy sources, specifically the utilisation of curtailed energy, into bitcoin mining. The aim of this study is to compare four scenarios involving different components, such as energy storage units, thermal and renewable energy generators, and mining farms. By investigating the integration of renewable energy and bitcoin mining, this paper seeks to identify opportunities for increased efficiency, decreased costs, and decreased energy waste. The analysis of various scenarios will reveal the optimal component combination for the integration of renewable energy and bitcoin mining.
To achieve the integration of these diverse components into a single electrical grid, a simulation software was developed.
The simulation software requires the precise hard-coding of optimization functions to ensure the proper functioning of the system and investigate the scope of the thesis, utilizing only renewable energy for bitcoin mining.

This is a crucial aspect, even if thermal generation is more convenient and abundant in the grid, as it restricts the use of renewable energy sources, limiting the potential of the bitcoin mining operation. By optimising the combination of energy storage units, renewable energy generators, and mining farms, this solution seeks to maximise energy efficiency and reduce the environmental the concern about the environmental impact of bitcoin mining.

In order to evaluate the efficacy of the proposed solution, four distinct but realistic scenarios were compared.
The first scenario depicts the current energy situation of the minor's island, which relies primarily on generators powered by fossil fuels imported from Italy.
The second scenario illustrates the 2050 energy scenario based on renewable energy sources and energy storage systems. The third scenario expands on the second by integrating bitcoin mining with renewable energy and storage.
The fourth scenario is differentiated from the third by the elimination of energy storage units.
Given the significant variability of the extrapolated reality, the findings of this study highlight a number of critical factors that could provide valuable guidance during the decision-making process.

One of the results of this study is the significant reduction of storage units by over 85% in the third scenario after the addition of mining facilities, which is due to the new network dynamics determined by the relationship between installation costs, marginal costs, and revenue obtained from the energy produced.
In particular, the reduction of the objective function was found to follow a quadratic trend in relation to the variable capacity of mining farms installed in the network, saturating after a certain level of installation is reached.
This saturation occurs due to the optimization of curtailed energy utilization by the mining farms and the associated cost of managing the network.

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Chapter 1

The Minor Islands

1.1 European Minor Islands

The European Union has more than 2,400 minor islands, which are small, delicate, and complex systems with multiple criticalities. These territories face several challenges, including disconnection from the national transmission grid, reliance on the supply of raw materials, and isolation that renders them inaccessible at times. Because of these problems, many of the smaller islands in the European Union have to use diesel and fossil fuels based power plants to make electricity. This has a big effect on the fragile ecosystems of these islands.
In response to these challenges, the European Commission and 14 member states, under the Maltese Presidency, signed the "Political Declaration on Clean Energy for the Islands of the European Union" [1]. In this document, the will to:

- Promote and support the energy transition in islands while preserving security of supply.
- Initiate a forum to bring together interested Member States to share best practices with respect to financial and regulatory instruments and promote the best available technologies. Support the EU's Clean Island Energy Initiative with a view to establish a long-term framework to promote replicable and scalable projects.

- Support the EU's Clean Island Energy Initiative with a view to establishing a long-term framework to promote replication.

In 2018, the Commission, in collaboration with the European Parliament, established a secretariat titled "Clean Energy for the EU's Islands" in order to assist those islands that, due to their unique geographical, climatic, and strong sense of community characteristics, have the potential to generate a significant portion of the energy they consume from renewable sources. The Secretariat provides advisory services and serves as a platform for the exchange of best practices. The Aran Islands in Ireland, CresLoinj in Croatia, Salina in Italy, Culatra in Portugal, La Palma in Spain, and Sifnos in Greece were initially chosen to host pilot projects. Twenty additional European islands, including Pantelleria and Favignana, were subsequently identified as having begun their own path toward energy transition and environmental sustainability. The Clean Energy for EU Islands Secretariat's project is based on the development of a "Clean Energy Transition Agenda" (CETA) by each island [2].

The agenda intends to outline a pathway containing credible and strategic energy transition objectives. The transition must prioritize the production of energy from renewable sources, energy efficiency, the development of electric mobility and more efficient transport solutions, and the creation of more engaged and conscious local communities able to exploit local resources in a balanced and circular manner. Along with the integration of renewable systems, the core would be if the pre-existing grid is able to sustain their unpredictable behaviour. This is particularly true for the PV panels that have been implemented in the residential realities; they provide energy as long as there is sun available but once the sun sets it is requested to the public grid to ramp in order to satisfy the energy demand.
The secretariat provided a model structure of the CETA that was tailored to each island's unique requirements. The template calls for the writing of two sections: one describing the current situation on the island and the other detailing the future of the island and the actions to be taken.

The first section is composed by:

1. A general description of the island's geography, economy, and population;
2. A description of the island's current energy system;
3. A stakeholder mapping that identifies relevant stakeholders for the island;
4. An analysis of the policy and regulations guiding the plan;

The second section include:

1. A vision statement for the entire island;
2. A description of the governance of the transition process;
3. An identification and description of the transition process's primary pathways;
4. A monitoring strategy;

1.2 Italian Minor Islands

There are 30 minor Italian islands with a population of approximately 200,000, or 0.3% of Italy's total population. These islands are dispersed throughout seven Italian regions: Campania, Latium, Liguria, Apulia, Sardinia, Sicily, and Tuscany. Since 1986, the 35 island municipalities have formed the Associazione Nazionale Comuni Isole Minori (ANCIM). A cohesive and unified association has greater strength than a single municipality.

Twenty-one of the thirty smaller Italian islands are not interconnected to the national electricity transmission grid, resulting in a severe economical-energetic aspect: the cost of electricity is the highest in all of Italy.
Electricity costs are up to three times higher than the national average. This is due to the fact that the majority of this energy is generated by inefficient, highly polluting and expensive external fossil fuel supplies. In addition to diesel for electricity generation, other critical issues involve the supply of gasoline and diesel for transportation, water for civil use, and waste disposal from the islands to the mainland.

The islands' economy is primarily dependent on tourism; summer months see a three to fourfold increase in admissions compared to winter months. This results in a seasonal variation in electricity demand.
In order to meet the peak demand during the summer, fuel-based plants are frequently oversized, and in order to maintain stability and avoid grid outages, they operate at close to nominal power during the winter months.
The majority of the non-interconnected islands are operated by Enel Production, while twelve islands are operated by local companies, eleven of which have joined the "Unione delle Imprese Elettriche Minori" (UNIEM).
The association's goals are as follows: "Promotion of sustainable development in the minor islands in which they operate and the guarantee of the security of the supply of electric energy in territories that present important criticalities both on the demand side and on the front of the supply of energy resources" [3].

The islands' electricity is sold under the same economic conditions as the rest of the country. The difference between production costs and revenues is distributed to all Italian consumers through the Auc4RIM tariff component of the system charges, the 2019 amount was 104.5 million euros. This component accounts for approximately 1% of total system costs [4].

Despite the fact that many of the islands have some of the highest solar irradiance and wind values in Italy, the number of installed renewable energy plants is presently quite low.
As of 2019, only the island of Capraia is able to generate all of its electricity from renewable sources, primarily due to the 3.2 MW biodiesel power plant, which is fueled by the processing of soy, rapeseed, and sunflower oil.
Even in this instance, however, land dependence is not eliminated because the raw materials are still transported by ship. On the other islands, the average coverage is less than 2%, while Ventotene has the highest coverage at 4.91% [5].
The minors islands are the ideal laboratory for implementing models for closing energy, water, and waste cycles; the technologies to be used for this process are mature and economically viable.
What is still lacking is a decisive political vision on the part of local administrations and the active participation of citizens.
As cited by [5]: "The Mediterranean can and must play a leading role in this process by enhancing local natural resources and promoting the economies of the area, involving the local communities. The goal of our work is to make people understand how today it is possible and necessary to achieve a deep and positive environmental change in these specific areas. The main reason why we need to accelerate this perspective is because it brings together goals of general interest, both for residents and tourists, the environment, and the economy".

1.3 Decree Promotes Renewable Energy in Minor Islands

The Ministerial Decree of 14 February 2017 on "Disposizioni per la progressiva copertura del fabbisogno delle isole minori non interconnesse attraverso energia da fonti rinnovabili" [6] was enacted to encourage the gradual spread of renewable plants on the territories of unconnected minor islands. The Decree encourages the installation of solar thermal panels, heat pumps for the production of domestic hot water only, and electricity production plants powered by renewable sources that are connected to the island's grid by domestic and non-domestic users. Specific minimum objectives were established to be achieved by 31 December 2020.
The measure affects a total of 20 islands, each of which has an area greater than 1 km^2, a distance greater than 1 km from the mainland, and a population of at least 50 residents. Regarding the remuneration of interventions, the energy produced by solar thermal panels is proportional to the cost of the fuel saved for the lower efficiency produced; each square metre of panel is estimated to produce thermal energy equivalent to a 600 kWh/year electrical energy savings.

The electrical energy produced by plants fueled by renewable sources is compensated with incentive tariffs proportional to the cost of the fuel saved, both for the portion of electricity fed into the grid and for the portion of electricity self-consumed.
Among the objectives of the decree are the modernization of the electricity networks on the island, so as to permit a high penetration of renewables, and the implementation of pilot projects aimed at a high utilisation of renewable sources and a reduction in the annual production of conventional electricity.

1.4 ARERA Resolution

ARERA (Autorità di Regolazione per Energia, Reti e Ambiente) is the Italian regulatory authority for energy, networks, and the environment. It is responsible for ensuring fair competition in the energy and water markets, protecting consumers' rights, and promoting sustainable energy and environmental policies. It also monitors the performance of the national and regional transmission and distribution networks and ensures that tariffs for electricity and natural gas are fair and transparent.
The incentives promoted by Ministerial Decree 14/02/2017 were defined from ARERA with the Deliberazione 558 of 6/11/2018 by ARERA that sets the rules for the remuneration of electricity and thermal energy produced by renewable sources on non-interconnected islands [7]. This decision was made with the goal of increasing the use of renewable energy in smaller islands that are not connected to the main electricity grid. The decision establishes the criteria for remuneration for the production of energy from renewable sources, such as wind and solar, on non-interconnected islands. Additionally, the decision lays out the methods for assigning energy efficiency credits, which can be used to fund investments in renewable energy sources.
The compensation established by ARERA, in the case of power plants electricity, only applies to plants with a minimum capacity of 0.5 kW that are fueled by renewable sources and put into operation after the date of the measure's entry into force.
The portion associated with the obligation to integrate renewable sources into new buildings is not eligible for compensation. The remuneration specified by the resolution only applies to thermal energy produced by thermal solar panels and heat pumps used for the coverage of domestic hot water consumption after the date of the measure's implementation. The period of compensation entitlement is twenty years, net of any shutdowns. In the event an island is interconnected to the national electricity grid, these provisions only apply to plants that come online within two years of the date Terna notifies the Authority of the interconnection.
The remuneration for electricity produced from renewable sources is:

- of the feed in tariff variety for the portion of subsidized electricity that is actually fed into the grid. This portion of electricity is compensated at the same rate as the base tariff.
- a feed-in premium for the portion of subsidized electricity consumed immediately on-site. The compensation for this portion of electricity equals, if positive, the difference between the base tariff and the value assigned to the electricity produced and immediately consumed.

The base tariff is paid for by two distinct mechanisms:

1. The base tariff is equal to the avoided cost efficiency, within the minimum and maximum value differentials by power class. The efficient avoided cost is the cost of fuel saved due to the lower consumption of efficiently produced electricity as a result of replacing electricity production from fossil fuels with an equivalent amount of electricity from renewable sources using the best available technology. It is determined, for each non-connected island, based on the industrial price of diesel for cars and is updated annually based on the average industrial price of diesel for cars in the previous year.

2. The basic tariff is equal to a fixed value, which is differentiated by power class and by group of islands, as shown in the table below.

   The selected mechanism is applicable for the entire period of compensation entitlement and cannot be altered. The value of the instantaneously produced and consumed electricity is equal to 104.27 €/MWh for the year 2021.

1.5 Incentives and Funding for the Minor Islands

Compared to the first-time horizon on which to measure the achievement of the objectives i.e. 31 December 2020, there has been a considerable delay, by virtue of the fact that the decree Ministerial Decree 14/07/2017 only came into force on 10 August 2019. On the other hand, with respect to the power values to be installed provided for in the decree, UNIEM has highlighted the critical issues related to compatibility with absorption and grid balance. In 2016, the association presented a 'feasible plan' for the deployment of renewables, in which the short-term targets are about half in terms of installations compared to what is envisaged by the Decree.
This capacity was sized considering a load associated with photovoltaic power equal to 20% of consumption in periods of low demand, so as to ensure the stability of the grid.
The RES power targets set out in the DM imply an overproduction that can only be reduced only with storage systems.
In order for distributors to become active managers of a complex system where simultaneously maximise the objectives of environmental sustainability, service quality and cost-effectiveness at the same time, the MISE had provided with the "Programma Energia e Sviluppo dei Territori 2014-2020" [8] a total financial allocation of 120.4 million euro in the less developed regions under thematic objective 4 (Supporting the transition towards a low-carbon economy) of the European Union's Cohesion Policy.
In the last year, with the goal of making smaller islands more independent, productive of non-fossil fuel-dependent energy and with environmentally respectful interventions, the PNRR (NextGenerationEU) has foreseen, through the program "Isole Verdi", with the approval of the Directorial Decree No. 219 of September 27, 2022, admitted for registration by the Court of Auditors on October 28, 2022 at No. 2934, the financing of approved projects for a value close to 200 million euros is granted to the municipalities of the 19 non-interconnected minor islands.
In conclusion, as the text above demonstrates, there is a growing focus on addressing the unique energy needs of smaller islands, particularly in terms of increasing independence and transitioning towards non-fossil fuel-dependent energy sources.

The PNRR's recent allocation of nearly 200 million euros in funding for approved projects for non-interconnected minor islands is a significant step towards achieving these goals. Furthermore, the available technology allows for the improvement of the reality of minor islands. The "Programma Energia e Sviluppo dei Territori 2014-2020", which provides a total financial allocation of 120.4 million euro in the less developed regions of the European Union's Cohesion Policy, is a clear indication of the importance of this issue for the country. Overall, it is clear that addressing the energy needs of smaller islands is becoming an increasingly important priority, and that the necessary resources and technology are being made available to achieve this goal.

1.6 Relation between Minors Islands and National Authorities

In order to clearly establish the economic and technical relationships that occur between the energy managers of the non-interconnected minor islands, and thus effectively contextualize the work that this thesis will promote in the subsequent chapters that compose it, a summary investigation is carried out on how local energy management and subsequent economic accountability takes place.
Local managers of minor islands work to ensure the quality of the electricity supply services for all loads connected to the network, receiving incentives, as seen in the previous chapter, for the adjustment of the energy price to the national average through ARERA, according to the previously reported tables. The dispatch service, carried out by Terna, is the coordinated management of electricity injections and withdrawals on the national transmission network to ensure the balancing of the electrical system.

Electricity is not a stored commodity, therefore it is necessary to produce, instant by instant, the amount of energy required by the final consumers and manage its transmission in such a way that supply and demand are always in equilibrium. This will ensure continuity of supply in safe conditions.
The dispatch service, carried out by Terna in the national grid, is the coordinated management of electricity injections and withdrawals on the national transmission network to ensure the balancing of the electrical system.
In real time, Terna monitors the electrical flows and corrects the injection and withdrawal levels by balancing them at all times. If necessary, Terna sends specific orders to reduce or increase the energy injected into the network to production units.

As cited in Resolution 111/06 [9] by ARERA, the various phases of opening the market to final customers have thus defined the conditions for the provision of the electricity dispatch service on national territory - currently regulated by deliberation no. 111/06 - limiting its application, for reasons of gradual implementation, to portions of territory on which interconnected electric networks are located, even if not directly connected to the national transmission network.

This limitation particularly affects the electric systems of minor islands and has mainly been dictated by reasons of simplicity of management of these systems in the delicate start-up phase of the market.
The extension of the rules of the electricity market to these territorial areas must, in fact, take into account the physical peculiarities of these networks that make it impossible to apply the management methods of electricity injections and withdrawals adopted for the dispatching points connected to the networks interconnected with the national transmission network.

The proposed provision scheme therefore regulates the dispatch service for the non-interconnected networks of the minor islands of the national territory; it identifies the methods of participation in the electricity market with reference to the resources connected to these isolated electric systems, also in order to allow the provision of protection and safeguarding services to all final users who have the right.

There is the possibility of participation in the electricity market of the injection and withdrawal points belonging to non-interconnected networks is allowed through:

- creation of isolated dispatching points, that is, distinct from all other dispatching points, for each non-interconnected network;
- identification of a "balancing user", to whom the programs of injection or withdrawal will automatically be attributed by the electricity market manager, in order to balance the overall program resulting from the other dispatching points belonging to the same network;

Such isolated dispatching points, for the purposes of participation in the electricity market and the determination of the economic items relative to the dispatch service, are considered included in a relevant network zone identified by Terna.
With reference to the production and consumption units related to isolated dispatching points, the presentation of offers in the day-ahead market and participation in the Energy Account Platform (PCE) is allowed, while participation in the balancing market and in the market for dispatch services is excluded.

Currently, the electric service on non-interconnected networks is managed according to a different mode depending on whether the same networks are part of an electric system under the ownership of a minor electricity company.

Given that in these non-interconnected systems, the generation and consumption are not necessarily balanced and the technical and economic management is not necessarily centralized, the proposed provision scheme allows the participation of the isolated dispatching points in the electricity market, while maintaining the technical and economic management of the system under the responsibility of the local manager.

Considering that in these non-interconnected systems, the electricity generation as well as the supply of all the necessary ancillary services for the safe management of an electric network (reserve, regulation, black-start) are necessarily dependent on the production units connected to the same network, the Authority intends to propose that Terna, in the role of responsible for the dispatch service for the entire national territory, identify for each system the units to be considered essential for the electrical safety of the non-interconnected network.

With the regulation provided for by deliberation 111/06 for the essential units for the system's safety, it would therefore be possible to guarantee the coverage of the recognized generation costs of the essential production units of the isolated networks by providing recognition of rewards in the protected market through the isolated network manager as the service provider.
To summarize:

- Terna identifies and publishes the list of essential units for the system's safety for each non-interconnected network;
- Terna creates, for each non-interconnected network, a virtual dispatching point for consumption units with withdrawal capacity equal, in absolute value, to the injection capacity of the dispatching point for production units related to the essential units for the safety of the non-interconnected network;
- Terna takes on the role of market operator for each virtual consumption unit;

- For the purpose of participating in the day-ahead market, Terna associates the isolated dispatching points of each non-interconnected network referred to in Article 3 to a relevant network zone;
- Terna takes on the role of dispatching user and market operator for the essential units for the safety of non-interconnected networks managed by minor electricity companies;
- Terna takes on the role of dispatching user and market operator for the essential units for the safety of non-interconnected networks managed by minor electricity companies;

1.7 Pantelleria Island: Balancing Tourism, Agriculture and Energy Sustainability

Pantelleria is the largest of Italy's non-interconnected minor islands, located approximately 110 kilometres from Sicily and 65 kilometres from Tunisia. The area of Pantelleria is approximately 84.5 km^2, with a maximum length of 13.7 km and a maximum width of 8 km. It is Italy's fifth largest island. Permanent island residents number 7,665 individuals, fluctuateing a lot during the different seasan of the year due to the influx of tourists.

The things that most characterise the island outside of technical themes are agriculture and tourism. The first one is mainly focused on the cultivation of capers and grapes, which are used to produce the famous Pantelleria wine and the typical capers in salt. This traditional activity has been passed down for generations, and it still represents one of the main sources of income for the island's inhabitants.

On the other hand, tourism is mainly concentrated in the summer months, when the island is visited by thousands of tourists from all over the world, who are attracted by its natural beauty, its crystal clear sea, and its rich cultural heritage. Both agriculture and tourism play a vital role in the island's economy and are an integral part of its identity.

Volcanic activity formed the island approximately 30.000 years ago. On the island, secondary volcanic phenomena are currently observable.
With the "Decreto del Presidente della Repubblica 7/10/2016 n. 235 [10], Istituzione del Parco nazionale «Isola di Pantelleria» e dell'Ente Parco nazionale «Isola di Pantelleria»" National Park was established. The island's highest point is the so-called "Montagna Grande," which rises approximately 836 metres above sea level. In Pantelleria, there are two valleys ('Valle di Ghirlanda' and 'Valle del Monastero'), exploited to viniculture. The only natural lake on the island is the so-called "Lago di Venere," which has a volcanic origin and is fed by meteoric waters and thermal springs.
The climate of Pantelleria is Mediterranean, with hot summers and mild winters.

The average annual temperature ranges from 11 °C to 30 °C, rarely falling below 8 °C or rising above 34 °C. The average annual precipitation is approximately 352 millimetres.
Due to the island's isolation and lack of connection to the national electric grid, its energy supply is costly. It is dependent upon fossil fuels, SME. D.E. Pantelleria S.p.A. owns the diesel-powered power plant and It is responsible for the management of the electricity network from generation to distribution. The facility consists of eight diesel generators with a total output of 23 MW. The fuel is imported via ferries from Sicily. Not only is this costly, but it is also extremely polluting.

However, the island is characterised by a high availability of renewable energy sources, particularly solar and wind. Seasonally varying, Pantelleria's annual solar radiation is 1.69 MWh/m^2. Regarding the wind source, its location ensures favourable wind conditions, which can be utilised with a vertical-axis wind turbine. On the entire island, the average wind power density is 850 W/m^2. The installed capacity of RES is 750 kW, which is comprised of 720 kW of PV, with the largest plant measuring 90 kW, and 32 kW of wind turbines. 38% of total electricity consumption is accounted for by the residential sector, which includes both permanent and seasonal homes. In reality, the majority of the energy required to heat, cool, and produce hot water at home is provided by electricity.

1.8 Pantelleria's Renewable Energy Potential: A Closer Look

Pantelleria's heavy reliance on fossil fuels for transportation and electricity production not only contributes to the island's carbon footprint but also exacerbates the effects of climate change. As a small island, Pantelleria is particularly vulnerable to the impacts of rising sea levels, ocean acidification, and extreme weather events, which are becoming more frequent and severe due to climate change.
Moreover, the island's Mediterranean climate is already experiencing hot summers and mild winters, with temperatures ranging from 11 °C to 30 °C, but these weather patterns are projected to intensify due to climate change, resulting in more frequent and severe heat waves, droughts, and floods [11].
In this context, transitioning to renewable energy sources and implementing sustainable agricultural practices are crucial to reducing Pantelleria's carbon footprint, increasing its resilience to climate change, and promoting sustainable development on the island.

One of the consequences of climate change that Pantelleria is experiencing is an increase in the frequency and intensity of wildfires. The island is susceptible to wildfires due to its dry and arid climate, which is becoming increasingly severe due to drought caused by climate change. This phenomenon not only threatens the island's biodiversity and natural landscapes but also poses a significant risk to human settlements and infrastructure.
Pantelleria, has been receiving increased attention from the academic community for its potential to serve as a case study for investigating new energy systems strategies. Despite its current reliance on fossil fuels for energy generation and distribution, the island's high availability of renewable energy sources and its isolated location make it a prime candidate for exploring innovative solutions for energy management.

In this context, this study will focus on the potential of integrating Bitcoin mining as a way to exploit the curtailed energy from the RES. This thesis aims to understand how this technology could be integrated in a sustainable and efficient way on the island. The study will provide valuable insights into the potential of Bitcoin mining as a solution to energy management in remote and isolated areas. However, before proposing any new layout, it is essential to conduct a thorough analysis of the island's renewable energy potential and identify the most suitable sources for integration.

As can be observed in the Figure 1.1 from [12], Pantelleria exhibits distinct characteristics regarding its energy consumption and production patterns.

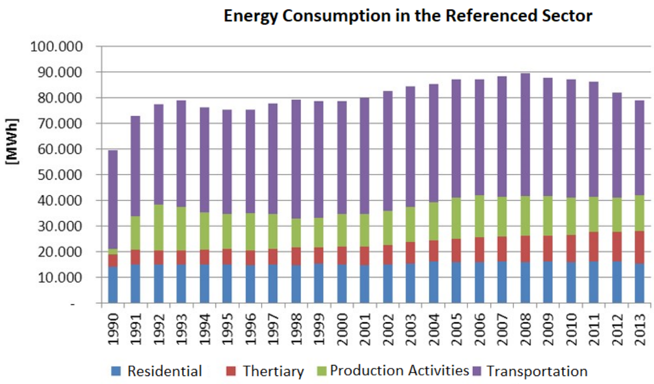

Figure 1.1: Energy Consumption in the Referenced Sector [12]

Analysis of recent data reveals that the island's energy consumption is primarily driven by the tertiary sector, specifically the tourism industry, and the electrical source is the only sector experiencing an increase. This can be attributed to several factors, including a shift towards electric-only utilities for heating and cooking among residents.

The utilization of electric energy for these end-uses is becoming more prevalent and it will have an impact on the energy consumption pattern of the island.

As can be observed in the Figure 1.2 from [12], the breakdown of energy consumption on Pantelleria during the last 20 years:

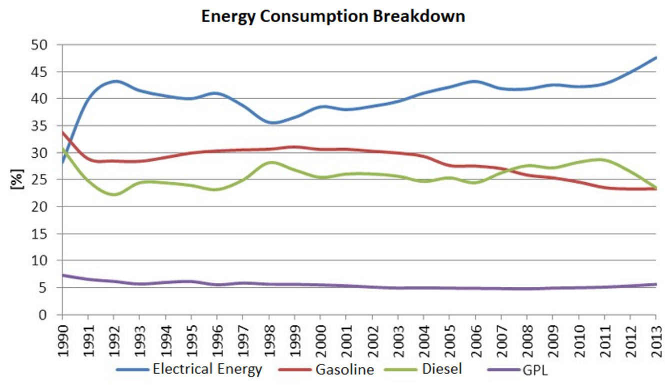

Figure 1.2: Energy Consumption Breakdown [12]

1.8.1 Utilizing Solar Energy for Sustainable Power Generation

The photovoltaic plants present on the minor island are represented in the following figure 1.3, extracted from the GSE [13]. They are concentrated in the North of the island, where the main port and commercial center of the island are located.

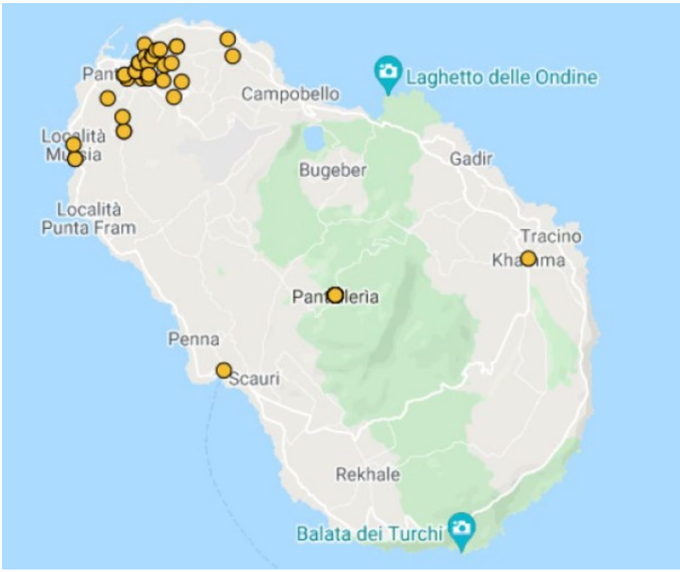

Figure 1.3: Distribution of Photovoltaic Plants Across the Island

According to [11], the annual solar irradiance on the horizontal plane in Pantelleria is around 1800 kWh/m2, whereas on the optimal inclination plane (32°), it's approximately 2000 kWh/m2. This comparison is graphically illustrated in Figure 1.4.

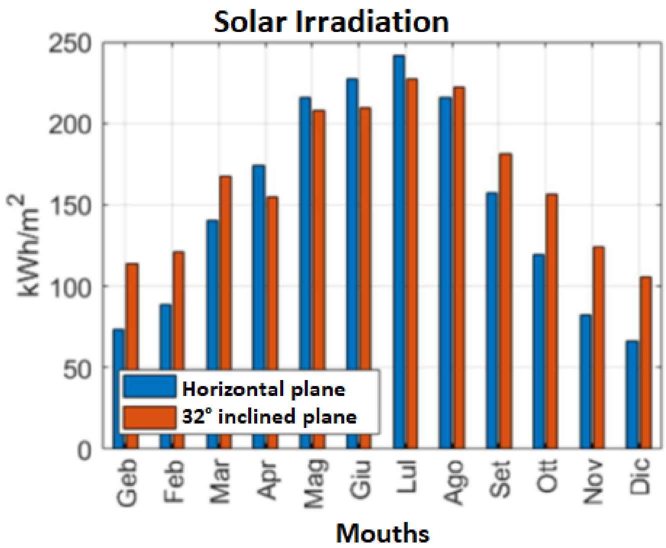

Figure 1.4: Visualization of Monthly Solar Irradiation Throughout the Year [12]

The monthly solar irradiation on the horizonal plane and on the optimal inclination are represented respectively in blue and red in figure above. The annual radiation on the ground, without considering obstacles beyond the ground surface (buildings or trees), is shown in Figure 1.5 from [12], utilizing software ArcGIS,it was possible to determine the annual ground irradiation on the island. This data revealed that the southern region, specifically the southern slope of the mountainous terrain, experiences the highest levels of irradiation.
This information is particularly useful for preliminary assessments of the feasibility of medium-to-large scale photovoltaic systems, as well as identifying the most optimal areas for harnessing solar energy.

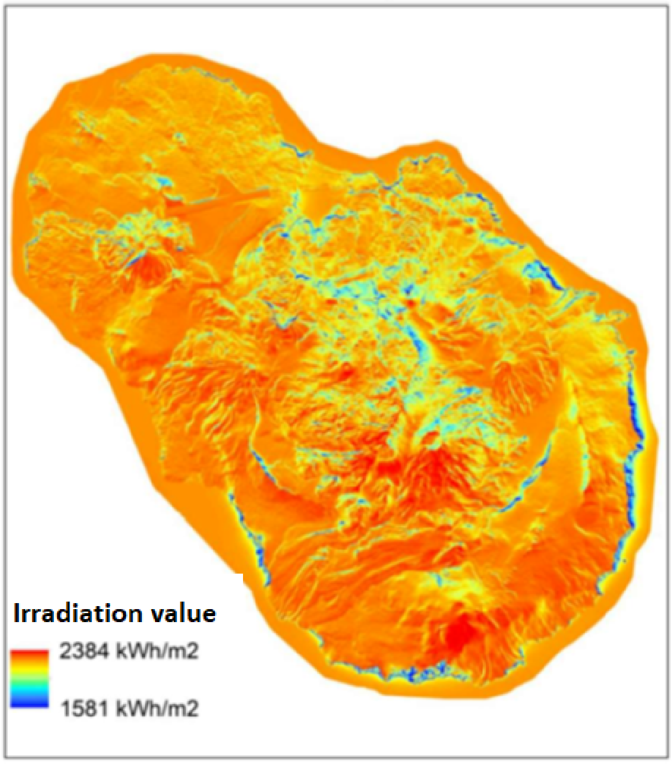

Figure 1.5: Geographical Mapping of Solar Irradiation [12]

1.8.2 Utilizing Wind Energy for Sustainable Power Generation

The on-shore wind energy plants present on the minor island are represented in the following figure 1.6, extracted from the GSE [13].

Figure 1.6: Distribution of Eolic Plants Across the Island

In Pantelleria island, due to its location in the center of the Sicilian Channel the wind blows very strongly.
The average annual wind speed (on and off-shore) at 50 m a.g.l./a.s.l. is shown in Figure 1.7. The annual average velocity, depending on the area, ranges mainly between 7-8 m/s (yellow) and 8-9 m/s (pink).

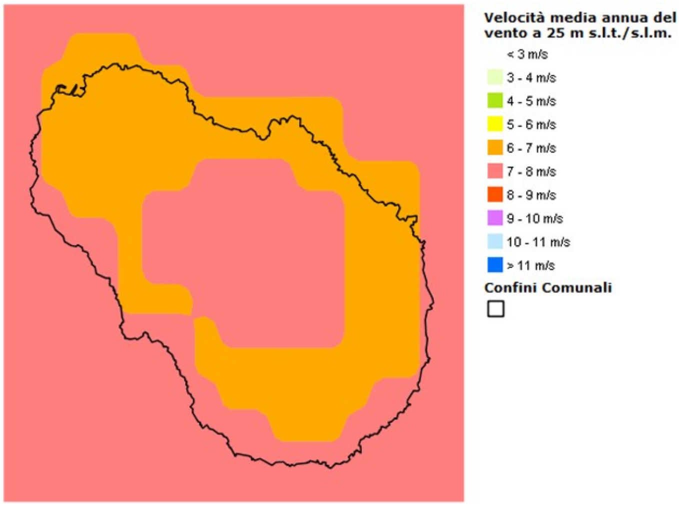

Figure 1.7: Evaluating the Availability of Wind Energy Resources

Floating offshore wind turbine plant is a rapidly developing plant technology that involves the installation of wind turbines on floating platforms anchored to the seabed. This technology has the potential to harness the strong and consistent winds blowing above deeper waters, where traditional bottom-fixed offshore wind turbines are not feasible.

The installation of floating offshore wind turbine plant has gained increasing attention in recent years, as it presents a number of advantages over traditional offshore wind systems. For example, floating offshore wind turbines have a smaller environmental impact, as they do not require the extensive excavation and foundation work needed for bottom-fixed offshore wind turbines [14].
Additionally, floating offshore wind turbines have a lower visual impact and can be located further from shore, reducing conflicts with other coastal uses.
In our case, after a careful analysis of the environmental characteristics of the island of Pantelleria, we have chosen to consider the offshore floating wind energy as the technology more suitable for the area. This technology offers a unique opportunity for energy production in this area and is expected to be a key contributor to the island's energy mix.

Chapter 2

Bitcoin Protocol and Electric Grid Challenges

2.1 Introduction

Bitcoin, the world's only real decentralized digital currency, has captured the attention of the public, governments, and the academic community alike. As the first decentralized digital currency, Bitcoin has not only disrupted traditional financial systems, but also has sparked a global conversation about the potential of decentralized systems and the role of trust in our economy. Understanding Bitcoin, however, is no easy task.
The concept of Bitcoin is multifaceted and complex, encompassing elements of cryptography, timechain technology, and economic theory.
To truly grasp the significance of Bitcoin, one must have a deep understanding of these underlying technologies and their implications.

The history, operation, and ramifications of the Bitcoin protocol will be examined in more detail in the following chapter, with a particular emphasis on how it relates to the electrical grid.
From the beginnings of the cyberpunk movement to how mining and energy use are doing right now. We'll examine the many elements of the Bitcoin ecosystem and the problems they provide for the grid.

In the chapter, as discussed in the original paper, what we know today as blockchain technology, a buzzword created for marketing purposes, is correctly referred to as timechain. The protocol and, consequently, the timechain, are written with a capital "B" following the rules of the protocol, while the currency that can be traded within it is referred to as "bitcoin", as Satoshi Nakamoto intended.

Furthermore, this thesis is being written at the completion of only 14 years of this nascent technology, which has already taken shape as a revolution, albeit a non-violent one, against the previously used system. To be honest, more than a revolution, it is a technological evolution of the way certain things are done based on trust, one of the most important being the exchange of value.

2.2 Historical background

Since the early days of digital communication, people have been searching for a currency that could harness the power of this technology to its fullest potential. One of the major challenges in creating a digital currency was the ease with which digital documents could be copied and replicated endlessly.
In 2002, Adam Back, a computer scientist and cypherpunk, came up with a solution called Hashcash [15]. This method used an algorithm that linked the creation of digital coins to a process called "proof-of-work" which required a significant amount of computational power. This made it so that coins created this way could not be easily replicated without expending the same amount of computational power.
In 2004, Hal Finney, another computer scientist and cypherpunk, created the first reusable proof of work system before Bitcoin, giving digital coins value even after they had been used. While these developments were groundbreaking, they were not sufficient to create a fully functional digital currency that could be used for everyday transactions.

To fully understand the origin of these ideas, it is crucial to grasp the identity and beliefs of the cypherpunk movement.
Cypherpunks are a group of individuals who congregated in the late 20th century to discuss issues related to cryptography, privacy, and online freedom [16].
They were interested in using cryptography as a means of protecting individuals' and groups' privacy against the encroachments of authorities and large corporations. Many of them were also interested in promoting the use of cryptography to create decentralized, trustless systems such as decentralized digital currencies and peer-to-peer networks.
Notable cypherpunks include also Julian Assange, Tim May, Eric Hughes, nick Szabo and the pseudonymous Satoshi Nakamoto. They established a mailing list to discuss these topics and wrote numerous technical papers and manifestos outlining their ideas and vision.
Many of them have since contributed to the development of open-source projects and cryptographic protocols that have been used in numerous modern applications, including the decentralized digital currency Bitcoin.

In 2008, an anonymous group operating under the pseudonym Satoshi Nakamoto released the Bitcoin whitepaper [17], marking a significant advancement in the realm of electronic money. This whitepaper drew upon the work of pioneers such as Adam Back and Alan Finney, linking it to a distributed database storage system first proposed in 1991, later known as the timechain.

The process of writing data to Bitcoin's timechain is incentivized through transaction fees paid by users and the issuance of newly minted digital coins.A block of legitimate transactions can be added to the distributed ledger at any time, but the network will only accept it if it is the first to produce a special digital signature called a "hash" . This process, known as cryptocurrency mining, requires a significant amount of processing power and resources in terms of energy.
In the world of cryptocurrencies, "mining" refers to the process of using computer hardware to solve complex mathematical problems in order to validate and record transactions on the blockchain network. A certain amount of the appropriate cryptocurrency is given as compensation for this process.

The graphics processing unit (GPU) and the application-specific integrated circuit (ASIC) miner are two main types of computer hardware used in mining process.
Although GPUs, which are frequently found in consumer-grade PCs, may mine bitcoins, they are less effective than ASICs. This is due to the fact that ASICs are created and optimised exclusively for mining, whereas GPUs are created for general-purpose computing. ASICs have a greater hash rate and require less power as a consequence, which clearly increases the profitability of miners.
GPUs provide greater versatility in terms of the range of cryptocurrencies that may be mined than ASICs can. Nevertheless, additional parts like a CPU case, wiring, a motherboard, memory, and an external power supply are needed to make a fully working mining setup with GPUs. The higher the hashrate, the more likely the miner is to be the first to solve the mathematical problem and validate the next block, resulting in a reward of cryptocurrency.

2.3 Insight into Mining

Mining is a service that keeps records. It is done through the Proof of Work, which uses computer processing power. Miners keep the timechain consistent, complete, and unchangeable by repeatedly grouping newly broadcast transactions into a block.

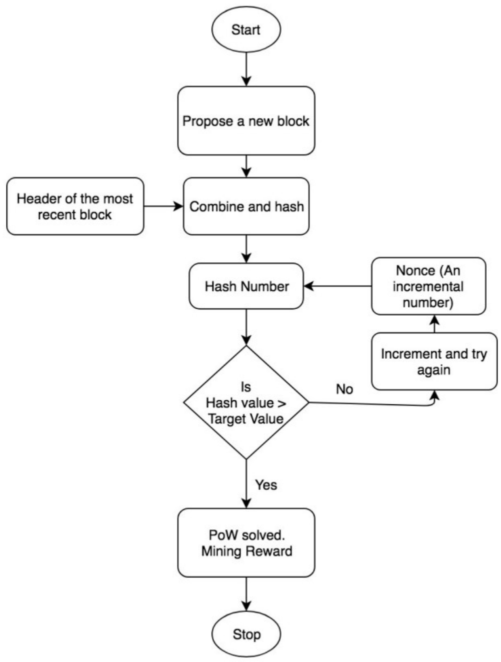

Figure 2.1: Proof of Work flowchart

This list of records called blocks, are linked using cryptography. Each block includes the cryptographic hash, i.e, an output of the SHA-256 (Secure Hash Algorithm) cryptographic function [18], of the prior block in the timechain, linking the two.
The hash of the previous block, the timestamp, and all transaction data are contained inside the new block. Computers connected to the network validate the digital ledger by solving complicated mathematical equations in order to receive the correct hash that contains all the previous block's information.

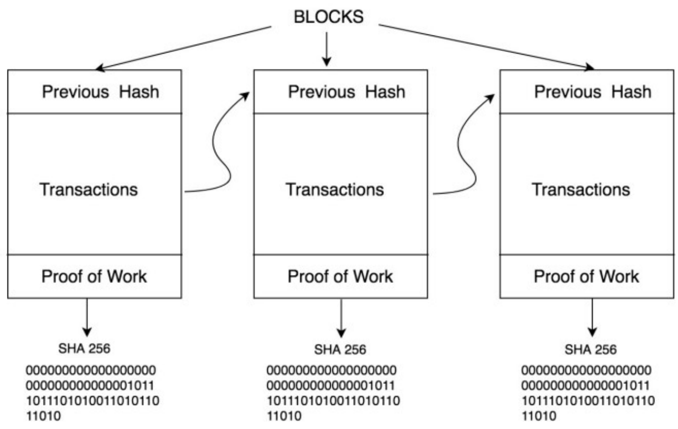

Figure 2.2: Chain of Blocks

As explained in the white paper and has can be seen in the figure 2.2: "New transactions are broadcast to all nodes; each node collects new transactions into a block; each node works on finding a difficult proof-of-work for its block; when a node finds a proof-of-work, it broadcasts the block to all nodes; nodes accept the block only if all transactions initiate valid and not already spent; nodes express their acceptance of the block by working on creating the next block in the chain, using the hash of the accepted block as the previous hash" [17]
When a block is mined, miners are rewarded with not only the release of new bitcoin but also with the transaction fee that each user paid to broadcast their transaction onto the network.

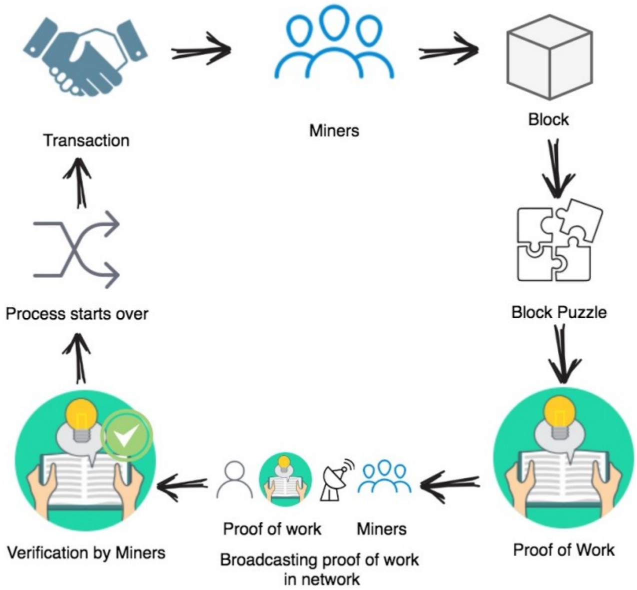

Figure 2.3: Bitcoin protocol Working Loop

Bitcoin emission rates decrease every 210,000 blocks, making it a disinflationary asset. In order to maintain the steady flow of newly mined blocks of approximately one every 10 minutes, the network difficulty, i.e, the measure of how difficult it is to mine a bitcoin, varies proportionally to the computational power dedicated to the network. This feature makes computations harder to do as more miners join the network whilst keeping the network secure and stable.

Anyone can try to add a block of valid transactions to the distributed ledger, but the network will only accept it if it is the first to generate a digital signature called a "hash".
It's easy to figure out how to make a single hash. So, the Bitcoin protocol gradually makes it more difficult to manage the number of Bitcoins created. The proof-of-work is done by adding one to the block's nonce until a value is found that gives the block's hash with the required zero bits at the beginning. A fresh nonce is generated and the hash computation is restarted if the hash does not adhere to the standard. Before finding the right hash, it may take several attempts (the nonce's size is just 32 bits, therefore in fact it is required for the Bitcoin

Protocol and Electric Grid Challenges to modify other information inside the block).

Mining is the term used to describe the energy and power-intensive process of producing a hash. In the world of cryptocurrencies, a "miner" is a computer that is used to solve certain complex problems in exchange for a certain amount of the corresponding cryptocurrency. Computer hardware that is often used for this process includes the graphics processing unit (GPU) and the application-specific integrated circuit (ASIC) miner, as said before. While GPUs can mine cryptocurrencies, ASICs are more effective at it.

Figure 2.4: Antminer S19 pro

In comparison to ASIC miners, GPU miners have a far wider range of coins they can mine. The purpose of ASICs is mining that's why there're ASICs for any algorithm since each of them is designed to mine a certain type of algorithm.
ASIC miners are composed of integrated circuit chips that are built to perform particular functions. They are much more profitable, consume less energy, require-less power and have greater hash rates. Although GPUs need additional funds for

CPU casings, Bitcoin Protocol and Electric Grid Challenges wiring, a motherboard, Memory, and an SSD in order to construct a fully working mining rig while ASICs are self-contained computers.
The more hashrate a participant has, the more likely it is that they will be the first to find the correct digital signature for the next block of transactions.

2.4 Mining Farm Needs and Characteristics

One of the main components to consider in the construction of a renewable energy plant, set in a protected natural environment with multiple regulations that seek to preserve its natural state and avoid excessive anthropomorphizing, is the landscape impact that this plant will have, and thus the excessive volume occupied by the facility [19].
Bitcoin mining fits perfectly into the pursuit of this goal, being both energy and volumetrically intensive. The Antminer S19 Pro can be contextualized as a condensation of the engineering functions of mining, being designed to consume as little energy and space as possible.
The bitcoin mining facility within the facilities where the electricity is produced is called a mining farm. The farm consists of a number of mining rigs, determined by the amount of ASICs to be housed.

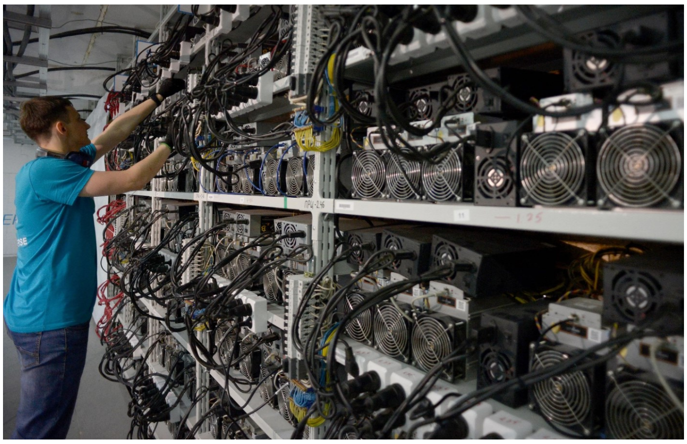

Figure 2.5: Representation of Mining Farm Dimensions

A "mining rig" is a customized personal computer (PC) with all standard PC components, including a CPU, motherboard, RAM, and storage [20]. The primary distinction is that mining rigs use graphical processing units (GPUs) rather than central processing units (CPUs). GPUs are superior at solving the cryptographic equations required to verify timechain transactions. In terms of instructions per clock, a single high-end GPU can outperform a conventional CPU by up to 800 times.

Some things to consider when looking to build a mining rig are:

- ASICs can be pricey, so it is essential to factor in the costs of all necessary equipment.
- Bitcoin mining is an energy-intensive process; therefore, it is crucial to consider the cost of electricity.
- Building a mining rig is not the same as building a custom PC; it can be a trial-and-error process involving numerous tweaks and adjustments.

Components of a mining rig:

- ASICs
  As already explained in this chapter, this is the place and space where the SHA-256 function is performed intensively, searching for the right combination of data to obtain a hash function of the block being processed less than the previous block.
- Motherboard
  The motherboard is the core of any computer, and a mining rig is no exception. It must be capable of supporting all ASICs that will be utilised in the rig.
- CPU
  A basic mining rig utilising ASICs requires only a low-end or moderate CPU, such as an Intel 8th or 9th generation.
- RAM
  Random access memory is necessary for all computers because it is used to temporarily store data while the computer is operating. It is essential for a mining rig to have enough RAM to store the data from all ASICs utilised by the rig.
- PSU
  A mining rig's power supply unit is one of its most vital components. This is because the PSU must be capable of supplying sufficient power to all rig components. A good rule of thumb is to purchase a PSU that can provide at least double the amount of power required by your system.

- Storage
  A mining rig, like any other computer, requires storage. This can be a hard drive or solid-state drive. The storage size will depend on the quantity of data you intend to mine. Generally, any 240 GB or larger storage device should suffice.

It therefore makes sense to quantify the relationship between the energy made available by the renewable source and the space occupied by the equipment that is required, as long as this same energy can be harnessed for bitcoin mining when the network does not need it or, at any rate, when system optimization dictates that it is more efficient to head in this direction.

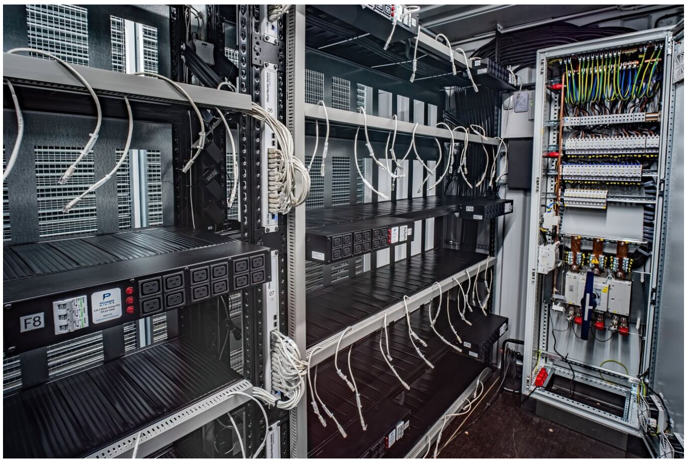

Figure 2.6: Empty structure - cointainer based

The dimensions of an Antminer S19 Pro, the ASIC taken into consideration as state-of-the-art during the course of this thesis work, are 195 x 290 x 370 mm (length, depth, and height).
Considering the arrangement of the latter on a mining rig and taking an example from the leaders in the relevant industry, to optimize space, five ASICs are arranged in parallel on several shelves, according to the height these shelves can reach, referring to the locations where generation takes place.
As can be seen on the above image, the reduction of space would occur as if one were considering a conventional bookcase leaning against the wall, about 30 cm

thick. Except that in this case the avant-garde cryptographic technology we are analyzing would replace the storage of books in a vertical manner, subsequently expanding on the cyberspace that has no physical limits as the latter did.

Considering the structure's height of two meters, on a wall five meters long, covering this wall with three rigs, each composed of five ASICs, and therefore 1.5 meters per rig, would allow the insertion of $25x3 = 75$ Antminer S19 Pro.
With the attached possibility, the consumption of each ASIC being 3250 W, 245 kW could be exploited. As the depth of the miner is 30 cm, taking into account the fans attached in the assembly for cooling, the entire rack would occupy 2.7 m^3.
Rounding all estimates upwards, therefore, with the intention of taking the space occupied by the power units and cabling abundantly into account, we would have the possibility of utilizing 250 KW with only 3 m^3 of volume.
Making the order of magnitude of the example under consideration comparable to the availability of a buildable future facility according to the Agenda della Transizione Energetica in Pallestrina, a 1 MW photovoltaic system would require 12 m^3.

With regard to the cooling that these machines require, which is a fundamental part of the operation, much attention must be paid to this point. Two main techniques are used:

- air cooling
- liquid cooling

Air cooling remains the most widely used technique to this day, as most ASICs available on the market are built this way. The Antminer S19 Pro does not shy away from the category; the latter technique is taken into account in this thesis for both the power consumption calculation and the volume required to implement it. With the most efficient machine cooling, there is no direct dependency on the amount of empty space within the host room of the mining process.

The physical cooling of the miner is crucial to avoid the loss of the properties of the

semiconductors they are composed of, which are necessary to perform the cryptographic work they have to do. Therefore, the fundamental aspect is the convective motion of air to which these machines must be subjected and the ventilation of the room. There is therefore no need to provide additional space for cooling other than the physical space required to house the fans and the synchronous motors that drive them. As with the calculation of energy consumption, in which cooling makes up 20%, the volumetric calculation is done in the same way, taking 20% of the previously predetermined volume into account.
It is useful to point out, for greater contextualization of the choices made previously, how the market is currently heading abundantly towards research and development of mining containers, which present the following advantages.

- Cost containment.
- Containment of space.
- Possibility of being physically moved.
- High convection efficiency of the air flow.

It is therefore almost superfluous to have to emphasize that constricted environments do not equate to excessive heating of the machinery but rather allow heat to be removed more efficiently if the convection flow is designed appropriately.

In conclusion, bitcoin mining is ad hoc engineered for the condensation in space of all its facilities. It does not impact the surrounding environment by exploiting cyberspace, which has no place in the physical dimensioning calculations previously made. The interaction with a naturalistic and tourist-intensive reality abundant in renewable and cost-effective energy, is perfectly suited to the passibility of integration with the electricity grid of this technology, which allows for more efficient facilities that are committed to powering it electrically.

2.5 State of the industry: The horizons and what has existed until this cycle

The approach that has characterised the mining industry to date is the approach that humans use natively in most industries without even realising it. Centralisation.

This in fact facilitates the management dynamics of a business and consequently reduces its risks. But does it actually work in this application?

The past trend has been to build ever larger mining facilities, with the aim of maximising the replication efficiency of a business structure initially created for a smaller mining facility [21]. By centralising many resources to such an extent, economic investments were required, capital gains had to be guaranteed to investors, supply contracts had to be fulfilled, and dividends had to be split within a specific timeframe.

This has led to the emergence of large leaders in the industry in question, with considerable impacts (but no impact at all on the Bitcoin protocol) in the event of problems dependent on the company management itself, which is rigid and sets deadlines that do not coincide with the timing of the protocol or even the free market.

The cyclicality shown so far by this technology, which is not necessarily going to characterise the dynamics of price and hashrate as significantly in the future as it does now, lies in the lines of code still present in the first release of the protocol, i.e., the setting of a halving every 200,000 blocks and the updating of the difficulty every 2,016 blocks.

The conflict between the timings of an immutable protocol chosen for soft- and cryptographic purposes and those related to contract and annual budget stipulation is riddled with immature failures. The year of writing this thesis was permeated by countless episodes of the kind described above, including the bankruptcy of the largest listed company solely structured around the Bitcoin mining business.

On the other hand, in order to escape these problems, but above all due to the economic possibilities of the actors involved, the present shows us how the development of small miners, also located in smaller economic and electrical realities, is increasing. As this thesis aims to investigate, the bottom-up approach, i.e., starting from small renewable energy plants in locations mostly disconnected from the main grid, allows for the evasion of those constraints derived from budget closure precisely because of the greater flexibility of the reality in which micro-mining is implemented.

The choice of putting the power grid first and therefore disconnecting even for long periods of time in the need to feed loads with dispatching priority, or choosing to switch off machines because it is more convenient due to protocol characteristics external to the plant allows for the construction of a system that is anti-fragile and resilient over time, unlike large companies.

The exploitation of resources distributed throughout the territory, and often smaller in size, such as water jumps of a few metres or photovoltaic panels of a few kilowatts, ensures the decentralisation of possible problems and increases the robustness of the network. The change in the perception of the value of energy brought about by the world events of 2022 has further reinforced this ongoing change in the mining sector as well, leading to the increased exploitation of small energy resources located in large industrial centres to create digital scarcity from energy abundance.

Chapter 3

Constructing the Model: Key Considerationsn

3.1 Introduction

In this chapter, following the situational introduction of the aspects that characterise the island of Pantelleria, both those inherent to the energy aspects and those inherent to the policies that intersperse nowadays and create the foundation for the future.
Following recognition of the significance of Bitcoin mining and the technical-industrial characteristics inherent in electrical engineering application [22], the model built specifically to represent the interaction between these two seemingly disparate realities is presented.
All the decision-making components that had to be taken into account in the composition of the model will be considered next, the latter including both long-run economic aspects and technicalities to be considered in order to make sure that the correct decision-making choices to be made by the optimization software were represented at each hour of the year under consideration.

This chapter begins by providing a situational introduction to the various aspects that define the island of Pantelleria. These aspects include energy policies and other key factors that serve as the foundation for the island's future.

Following from the continuos growing significance of Bitcoin mining and the technical-industrial characteristics inherent in electrical engineering, this study aim is to present a model, that has been specifically developed, to represent the interaction between these seemingly disparate realities.
This model is the result of careful consideration of a range of decision-making components.
These components surely incluedes both long-run economic aspects and technicalities but focuses the more on the second one. This because they are critical to ensuring that the optimization software used to make decisions is capable of representing the correct choices at each hour of the year under consideration.

In the following sections, we will explore the facets of energy policies and technical-industrial characteristics that define the island of Pantelleria. Additionally, we will delve into the model that has been developed to represent the interaction between Bitcoin mining and electrical engineering.
By analyzing the various decision-making components that were taken into account during the model's development, we will gain valuable insights into the complexities of this emerging field. Ultimately, this study seeks to contribute to a better understanding of the possible relationship between energy policies, electrical engineering, and emerging technologies like Bitcoin mining.

3.2 PyPSA Introduction

PyPSA (Python for Power System Analysis) is a free and open-source software package for simulating and optimizing power systems [23]. It provides a range of tools for modeling power grids, renewable energy sources, storage systems, and demand-side management strategies. With its modular architecture and user-friendly interface, PyPSA has become a popular tool for researchers, energy analysts, and industry professionals alike.

The capacity of PyPSA to simulate power systems at various sizes, from small microgrids to massive regional or national networks, is one of its important characteristics.
PyPSA enables users to study a variety of situations and to evaluate various optimization techniques since it can mimic both the steady-state and dynamic behaviour of power systems. The Standard Power System Model (SPSM) and the Grid Data Format are popular power system models that PyPSA also supports as input data formats (GDF)
Another strength of PyPSA is its support for renewable energy sources, including wind, solar, and hydroelectric power. PyPSA's renewable energy modeling capabilities enable users to evaluate the potential impact of variable generation on power system stability, and to explore strategies for integrating renewable energy into existing grids. In addition, PyPSA includes tools for simulating energy storage systems, which can be used to mitigate the effects of variable generation and to improve the overall performance of power systems.

PyPSA is also highly customizable, with a wide range of options for adjusting model parameters and configuring simulations. Users can specify optimization objectives, constraints, and algorithms, as well as explore the sensitivity of model outputs to different input parameters. PyPSA can also be integrated with other software packages, allowing users to build more complex models and to explore a wider range of scenarios.

For modelling, simulating, and optimising power systems, PyPSA is a strong tool. It is the perfect option for a variety of energy research and commercial applications due to its flexibility, scalability, and simplicity of usage.

Pypsa allows for the creation of an electrical network model that can be shaped according to the user's needs and analyzed in terms of its functioning.
The interplay between the various components of the network can be created in different ways, such as by creating various nodes and interconnecting them to simulate energy flows, or by simplifying the model such that all components are connected to the same electrical node, applying a simplification to the network and analyzing the energy exchanges between the generators, loads, Bitcoin mining, and storage units (if present in the scenario under study).

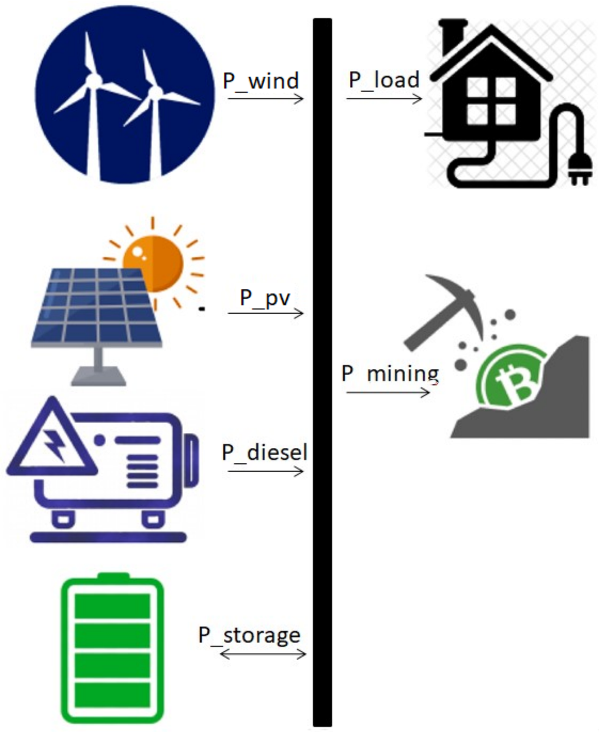

Figure 3.1: Simplified network diagram for analyzing power flows and interactions between components in a PyPSA model of an electrical system with Bitcoin mining and storage units

A schematic example can be seen in Figure 3.1, where loads of the network are represented on the left side by P_{load}, the loads from the connected mining farms by P_{mining}, and on the right side, renewable energy generators are represented by P_{res}, thermal generators by P_{diesel}, and storage units by $P_{storage}$.

By creating a network with this simplification, it is possible to analyze power flows at each snapshot based on the characteristics assigned to each component of the network, such as capacity factors during the year under study for renewable energies (depending on atmospheric conditions for converting solar and wind energy into electricity), installation costs for different components, and also marginal costs, such as in the case of mining, where the marginal cost depends on the characteristics of that particular snapshot of the Bitcoin protocol.

3.3 Adequacy of Electricl Systems Reserve Calculation

The adequacy of the electric system refers to the ability to ensure that the energy demanded by consumers (both households and businesses) is always balanced by the energy produced by power plants. An adequate system is one that has enough resources for production, storage, flexibility (e.g. consumers who are willing to reduce their load), and transportation capacity to meet expected electric demand at all times, including a reserve to account for errors in demand and production forecasting (e.g. from renewable sources) and the consequences of possible network failures and events (e.g. line opening, production plant malfunction, etc.).

One of the main indicators for measuring the adequacy (or inadequacy) of an electric system is known as the Loss of Load Expectation (LOLE) and represents the total number of hours per year in which it is likely that a portion of consumers will be disconnected because expected demand exceeds available resources [24]. This indicator has been adopted as a measure of adequacy at both the European and Italian levels. Generally, an electric system is considered adequate when the LOLE is ≤ 3 hours [25].

This means that there is a 0.03% probability that at least one consumer (but not necessarily all consumers) will be disconnected from the network due to adequacy issues.
In Figure 3.2 is a diagram illustrating how these indices are generated:

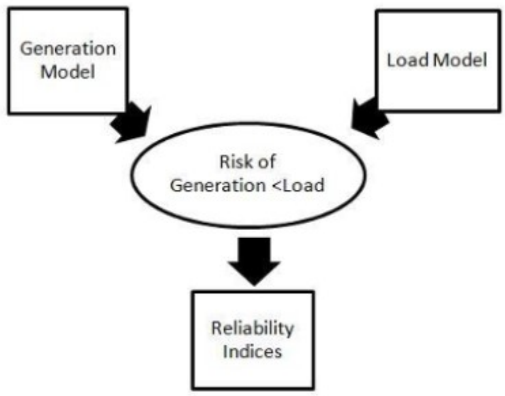

Figure 3.2: Diagram of indices evalutation

Adequacy evaluations are performed using a probabilistic analysis to take into account variations (random and non-random) in key factors, including weather phenomena (temperature, wind, irradiation, etc.).
Due to the operational rate of the diesel generator and the planned installed power, the LOLP (Loss of Load Probability) calculated using the State Enumerations Method [26], along with the LOLE (Loss of Load Expectancy), satisfies the requirements.

The reserve, guaranteed entirely by the thermal power generation of our system, should at each snapshot provide for the satisfaction of primary, secondary, and operational reserve as described in the body of the thesis, all of which are necessary for the correct functioning of the system [27].
So, the reserve that we take into consideration for guarantee the adequacy and security of the system is:

- Primary reserve:

$$P_{min} = PMT + 1.5\% \cdot P_{eff} \tag{3.1}$$

$$P_{max} = P_{max,erogabile} - 1.5\% \cdot P_{eff} \tag{3.2}$$

Where PMT represents the technical minimum power; Peff is the efficient power, so the maximum active power that a CPU can continuously produce (for thermal-electric plants) or for a certain amount of hours (for hydroelectric plants)

- Secondary reserve: The Grid Transmission Operator procures the resources for the secondary power reserve via the ASM. The DSOs make available, at a price offered on the MSD, secondary reserve power of ±15% of the maximum power for hydro units, or ±10 MW to ±6% of the maximum power for thermoelectric UPs.
- The operational reserve will be 5% of the actual load as cited in [28]

This reserve is the one that have to be available at every snapshots in the total installed power of the disel generators configured in the PyPSA simulation.
In conclusion, the power that our electrical system have keep available is:

$$P_{disp,gen,diesel,reserve} \geq Primary_{res} + Secondary_{res} + Operational_{res} \tag{3.3}$$

Where:

$$P_{disp,gen,diesel,reserve} = P_{gen,diesel,installed} - P_{gen,diesel,used} \tag{3.4}$$

In this equation, the reserve power capacity of the diesel generator, denoted by $P_{disp,gen,diesel,reserve}$, is calculated by subtracting the used diesel generator power capacity, denoted by $P_{gen,diesel,used}$, from the total installed diesel generator power capacity, denoted by $P_{gen,diesel,installed}$. It is assumed that the entire installed diesel generator capacity is functional and can be put into operation, and the used capacity represents the power demanded by the network.
This means that if the load exceed the range for what the reserve available is less that the total calculated above, the load supposed to be turn off will be not feed by the grid.

3.4 Capex, Opex and Marginal Costs

The discount rate is a crucial parameter in the economic calculations of renewable energy investments, as it influences the net present value (NPV) and economic attractiveness of a project.
The discount rate used for a renewable energy investment depends on various factors, including:

- the project's risk;
- market and government policies;
- financing;

In general, discount rates for renewable energy investments can range between 3% and 10%, with higher rates for riskier projects and lower rates for projects with more government support and less risk.
Additionally, sector-specific discount rates such as the social discount rate, which takes into account the social and environmental benefits of using renewable energy sources, are often used.
To calculate the NPV of our investment, we calculate the annuity using the formula [29]:

$$a = \frac{1 - ((1 + r)^{-n})}{r} \tag{3.5}$$

where:

- a is the annuity
- r is the discount rate
- n is the economic lifetime

Then use the annuity to calculate the NPV of our investment using the formula [30]:

$$NPV = \frac{CAPEX}{a} \tag{3.6}$$

Where $CAPEX$ is your initial investment.

In economics and finance field, operation and maintenance costs (OPEX) are expenses related to the continuing operation and maintenance for the lifetime of a facility or piece of equipment. These expenses may include things like labour, upkeep and repairs, and utilities.
The financial analysis of renewable energy projects must precisely estimate and take into account OPEX since they have a big influence on the project's overall economic viability.
The method used to include OPEX in the PyPSA simulation was to calculate the expenses as a percentage of the annual energy output and then add that amount to the NPV figure.
The OPEX was specifically estimated to be 2% of each KW produced over the course of a year, and the total was then added to the CAPEX, and finally the capital cost was computed. This was done by creating a new parameter for the OPEX as a percentage of the energy production, as opex percent with a value of 2%. Then, this parameter was used to calculate the annual operational costs using the formula:

$$opex\_annual = opex\_percent * production\_annual \tag{3.7}$$

Finally, this value of opex_annual was added to the CAPEX value and was used to compute the capital_cost.
The choice of installed MW for each resource was based on the Energy Transition Agenda, which foresees the following installed quantities of renewables by 2050, as well as an annual electricity load of approximately 45,300 MWh.

The choice of installed MW for mining would replace the storage that was previously planned for in larger quantities.

The individuation of the installation cost for each resource was informed by various factors, including the "Power Generation Costs" by IRENA regarding the year 2020 [31]. This document provided valuable insights and guidance for the determination of the optimal cost regarding different renewable, incorporating also the trend that this economics factor had in the past.

- The ongoing reduction in solar PV module costs has been a key factor in driving improved competitiveness, with this trend continuing through 2020. Between December 2009 and December 2020, crystalline silicon module prices dropped significantly as can be seen in figure 3.3 and figure 3.4 from [31], with average cost reductions of around 93%. In 2020, the average module price for crystalline modules decreased by between 5% and 15% compared to the previous year.

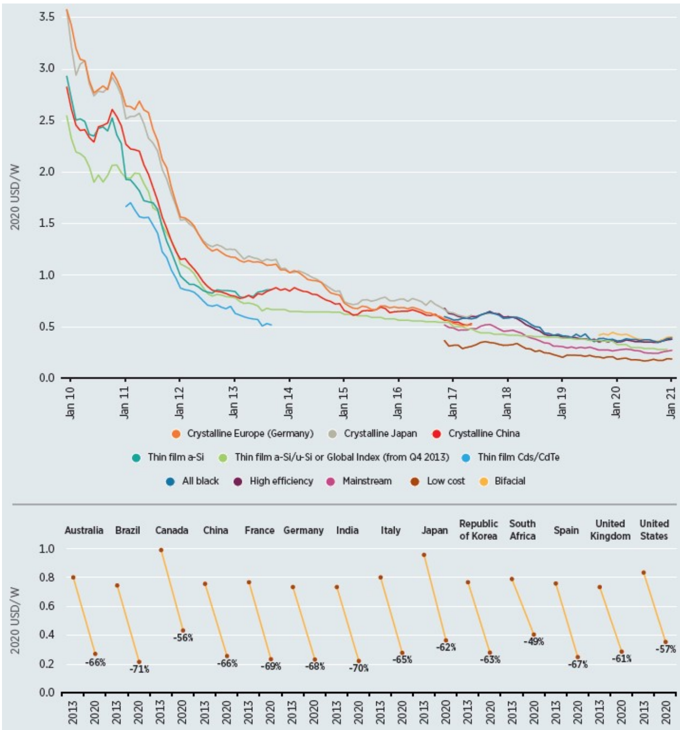

Figure 3.3: Comparing Photovoltaic Costs Across Nations [31]

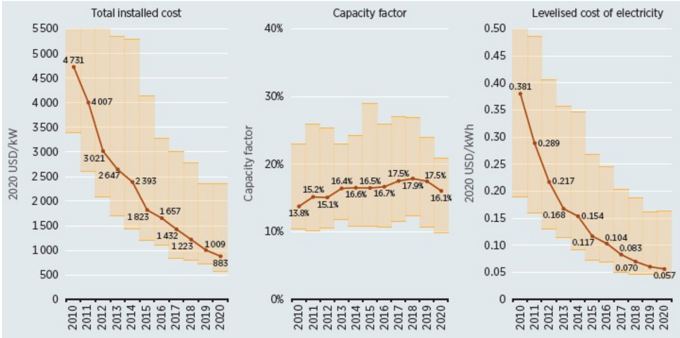

Figure 3.4: Evaluating the Differences in Photovoltaic Costs [31]

- According to the IRENA Renewable Cost Database, the weighted-average total installed cost of onshore wind projects decreased by 74% between 1983 and 2020, from USD 5,241/kW to USD 1,355/kW [31].
  This decline in cost was driven by reductions in both wind turbine prices and balance-of-plant costs, with global average total installed costs falling by up to 9% for every doubling in cumulative onshore wind capacity deployed. From 2010 to 2020, the global weighted-average total installed cost of onshore wind decreased by 31%, from USD 1,975/kW to USD 1,355/kW, with a 10% year-on-year decline in 2020.

Costs	**Off-shore wind**	**Solar photovoltaics**	**Mining farm**
Total installed cost	3185	883	700
O&M cost	80	9	1.5

Table 3.1: Tabella per calcolo del CAPEX e OPEX delle rinnovabili presenti

To calculate the annualized capital cost to be inserted into PyPSA, taking into account a lifespan of 25 years for the renewable energy systems and 4 years for the hardware used for mining, the following equation it's been used:

$$Capital\_cost = \frac{P_{installed} \times Installed_{cost} + P_{installed} \times O\&M_{cost} \times Years}{a} \tag{3.8}$$

Where:

- P_installed is the installed capacity of the renewable energy system, in units of power (MW)
- Installation_cost is the cost of installing the renewable energy system, in units of currency per unit of power (€/MW)
- O&M_cost is the annual cost of operating and maintaining the renewable energy system, in units of currency per unit of power (€/MW-year)
- Years is the number of years over which the OM costs are considered

Due to the numerous factors that need to be taken into consideration, the incorporation of energy storage into a system requires careful attention. The cost of lithium-based battery installations for renewable energy can vary depending on various factors such as the size of the system, battery chemistry, brand, and region. The cost of lithium-based battery installations was declining due to technological advancements and economies of scale in production. According to a report by the International Renewable Energy Agency (IRENA) from November 2020, the global weighted average cost of utility-scale battery storage decreased by 87% from 2010 to 2018, and by 13% from 2018 to 2019.

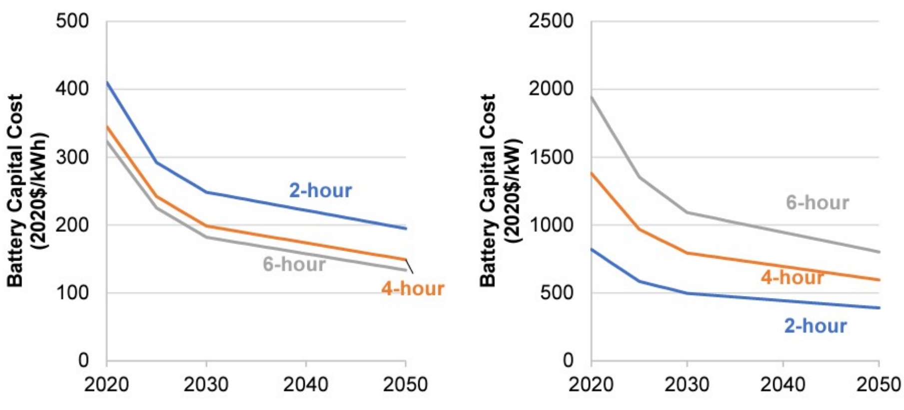

Figure 3.5: Analyzing the Cost of Energy Storage Units [32]

As of February 2023, it is likely that the cost of lithium-based battery installations for renewable energy has continued to decrease due to ongoing advancements in technology and manufacturing.
It's around 700 €/KWh the cost of the modern lithium-based storage system, the only one considered in this simulation. And may be different depending on the number of the cycles the storage have to compute during his life-time.
A higher number of charging and discharging cycles can negatively impact the lifespan of energy storage systems. As depicted in Figure 3.5 from [32], there are significant cost differences between systems with different characteristics. In this study, a 2-hour duration was considered with an annual usage that was less than the 15-year lifespan of the system.

A storage unit represents an energy storage system, such as a battery, that can store electrical energy and release it when needed. The key characteristics of a storage unit include its power capacity and energy capacity. These two characteristics are essential in defining the capabilities and limitations of the storage unit within the power system model.

Power capacity: This represents the maximum rate at which the storage unit can charge or discharge energy. It is typically expressed in units of power, such as kilowatts (kW) or megawatts (MW). The power capacity determines how quickly the storage unit can respond to changes in demand or generation within the power system.

Energy capacity: This is the total amount of electrical energy that the storage unit can store, typically expressed in units of energy, such as kilowatt-hours (kWh) or megawatt-hours (MWh). The energy capacity determines how long the storage unit can provide power at its maximum power capacity before being depleted or fully charged.

One way to describe the relationship between power capacity and energy capacity is through the concept of "C-rate" or battery duration. The C-rate indicates the rate at which a battery can be charged or discharged relative to its energy capacity. For example, a C-rate of 1C means that the battery can be fully charged or discharged in one hour [33]. In this study, a C-rate of 0.5 was considered for the energy storage units, which corresponds to a 2-hour duration of the system when discussing the storage units.

To summarize, the inclusion of the capital cost is an important task to implement in creating the model, with the mentioned value representing an annualized cost:

- Capital cost off-shore wind energy plant = 260’000 €/MW-year

- Capital cost solar energy plant = 55’400 €/MW-year

- Capital cost mining farm = 17’000 €/MW-year

- Capital cost storage units = 55’000 €/MWh-year

3.5 Renewable Capacity Factors

Capacity factor is a measure of the actual output of a power generation facility as a proportion of its maximum potential output.
As it gives a hint as to the dependability and efficiency of the technology, it is frequently used to assess the performance of RES like wind and solar energy. In the case of offshore renewable energy, capacity factor is extremely important in assessing both a project's economic feasibility and environmental effect.
In the case of offshore renewable energy, capacity factor plays a crucial role in determining the economic viability of a project, as well as its environmental impact.

3.5.1 Floating offshore wind turbine plant

For wind energy, depending on the location and weather, offshore wind farms generally have a capacity factor from 35% to 45% . This indicates that an offshore wind farm with a 100 MW capacity will generate 35 to 45 MW of power on average per year.
It is crucial to keep in mind that these numbers might fluctuate significantly depending on the location, the weather, and the particular design of the offshore renewable energy installation. Moreover, capacity factors for certain offshore renewable energy projects, including wave and tidal energy, are currently being considered and are not yet firmly defined.

Renewables.ninja is an online platform that provides real-time information on renewable energy production and availability worldwide. It utilizes weather, production, and market data to provide forecasts and analysis on solar and wind energy.
It also features an interactive map that allows users to view data for specific geographic areas and a section for energy cost analysis. The tool is designed for academic research, and for professional and policy makers in the renewable energy industry.
The platform employs a three-dimensional wind flow model, based on the Navier-Stokes equations, to estimate wind power production. The model also employs an interpolation algorithm to estimate wind power production at points where there

are no meteorological data.

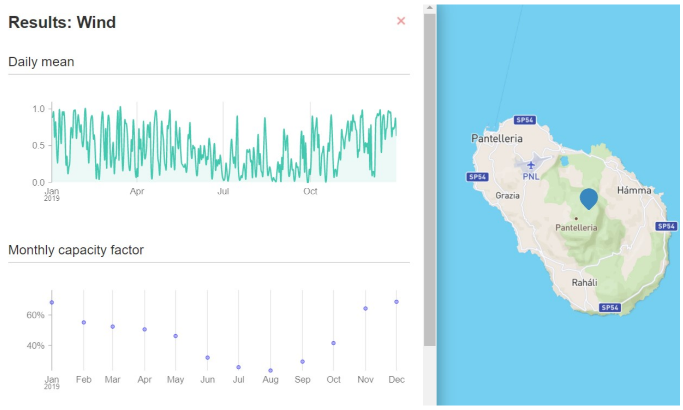

Figure 3.6: An Example of Raw Wind Data Acquisition [34]

One of the main advantages of this technology is that it can be implemented in an environmentally friendly way, as it does not require the installation of poles, which can have a negative impact on the natural landscape.

The capacity factor of offshore wind energy in Pantelleria has been estimated to be within the range of 45% to 48%. Offshore floating wind turbines were considered as the primary wind related technology for this project, due to the fact that Pantelleria is also a national park and it is important to minimize the environmental impact of the project.
The capacity factor data was then used to estimate the production of the proposed offshore wind farm, and to evaluate the economic feasibility of the project.

3.5.2 Photovoltaic power plant

For solar power, capacity factor is typically in the range of 20-25% for solar farms, reflecting the intermittency of solar radiation and the limitations of current technology. In the Pantelleria case study, the capacity factor of solar energy has been estimated to be within the range of 20% to 23%.

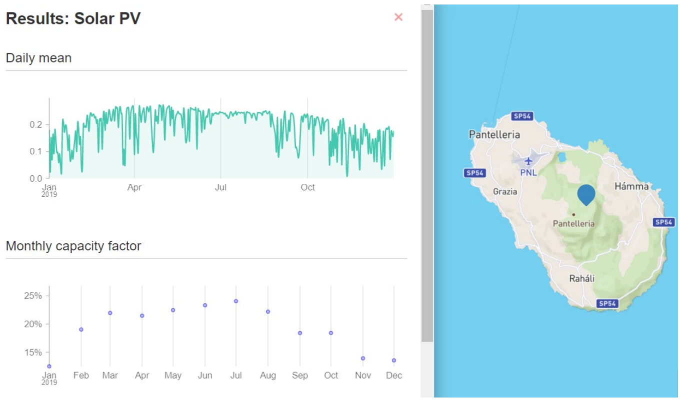

Figure 3.7: An Example of Raw Photovoltaic Data Acquisition [34]

We then incorporated the data obtained from Renewables.ninj into our model built in PyPSA, this allowed us to consider the capacity factor of both offshore floating wind energy and ground-mounted solar energy in our simulation, providing a more comprehensive evaluation of the feasibility and potential of the proposed project.

3.6 Integration in the objective function of the term related to the mining revenue

In this section the key considerations for calculating the revenue of Bitcoin mining using renewable energy sources.
To determine the revenue, one must calculate the total cost of producing the renewable energy, the energy required to power the mining equipment, the mining difficulty, and the current Bitcoin price [35]. By taking all of these factors into account, one can estimate the potential revenue that could be generated through Bitcoin mining using renewable energy.
In the formulation mentioned in the previous chapter, if the manager of the electrical system decides to install the Bitcoin mining facilities, in a configuration as desing in the figure, the formulation would be rewritten to include the profit of mining action, their respective energy consumption, and the depreciation cost mining devices. A typical CMD can mine BTChour number of BTC per one hour [36]:

$$btc\_hour = \left(\frac{3600 * \alpha * \rho_{CMD}}{2^{32} * \delta} \right) \tag{3.9}$$

- α is paid to the miners as the incentive for carrying out the mining action. Currently, it is equal to 6.25 BTC per block, and it will halve every four years, where the next halving step will be done in 2024. Where:

- ρ_{CMD} is the hash rate power of the CMD (in Tera-Hash/sec) [37].
- δ is the difficulty of solving the bitcoin optimization problem in Tera-Hash (TH) at hour t.

Usually, more powerful CMDs with higher hash rates, denoted by ρ_{CMD}, consume more power, denoted by P_{CMD}, to operate. These parameters can vary among CMDs, and the market offers a range of options with different hash rates and power consumption characteristics. As with other computers, running a CMD generates thermal energy, which means that CMD owners must also account for cooling and temperature regulation costs in addition to the energy consumption of the CMDs themselves. Assuming that the total energy available for the mining farm at a given hour, t, is $P_curtailed$ in MW, the number of running CMDs at that time, denoted by $N_{t,CMD}$, can be estimated using the following equation as done in [38]:

$$N_{t,CMD} = \frac{(1 - \gamma_{cool}) * P\_curtailment}{P_{CMD}} \tag{3.10}$$

γ_{cool} represents the ratio of power used to cool down the mining farm. In practice, it is estimated that the mining farm employs about 20% of its input power for cooling purposes. This estimation is higher than the typical 10%-15% reported in the literature. This is partly due to the trend of increasing temperatures worldwide caused by climate change, and partly because the mining farm is located in a hot region, such as Pantelleria.
P_{CMD} stands for the power consumption of one CMD device in MW. The total income of a mining farm in dollars at hour t can be estimated using the following equation:

$$R_t = \frac{3600 * \alpha * \rho_{CMD}}{2^{32} \times \delta_t} * N_{t,CMD} * \lambda_{btc} \tag{3.11}$$

Suppose that λ_{BTC_t} is the price of one BTC in dollars at hour t, and R_{tCMD} is the overall income of the mining farm in euro [39].
Expressing the income of a mining business as a function of the power consumption of the mining farm was fundamental during the model development process.
This approach allowed the optimization function to depend on the curtailment available at every hour in the minor island, referencing the corresponding value and adding it to the optimization function.

$$R_t = C\_marginal * P\_curtailment \tag{3.12}$$

Where:

$$C\_marginal = \frac{3600 * \alpha * (1 - \gamma\_cool) * \rho_{CMD}}{2^{32} * \delta_t * P_{CMD}} * \lambda_{btc} \tag{3.13}$$

As can be seen, β_t depends on the parameters of the installed CMD (ρ_{CMD} and P_{CMD}).
Generally, it is safe to predict that the difficulty and the price of Bitcoin will remain

nearly consistent over a daily time frame. Consequently, in a daily-based investigation, the parameter's temporal dependence can be disregarded. It's important to remember that CMD depreciation costs must be included [40].
In conclusion, a number of variables that might fluctuate over time, but for a certain length of time, can be regarded constants, impact the marginal cost of mining Bitcoin. The elements that influence the marginal cost of mining bitcoin and how they alter over time are listed below:

- The benefit of clearing each block is: Every 210,000 blocks, or roughly every 4 years, this value is cut in half. Hence, it may be regarded as constant for a particular 4-year period.
- The difficulty of solving the cryptography function δ_t: This value is updated every two weeks, but for a given period of two weeks it can be considered constant.
- The exchange value of Bitcoin λ_{btc}: This value is more volatile and can fluctuate more frequently, but for a given day it can be assumed to be fairly constant with good precision.

Chapter 4

PyPSA Simulation

4.1 Data Importing

After importing the necessary packages to utilize the various tools provided by Python libraries, the capacity factors for the two renewable energy sources used in the simulation, floating offshore wind turbines and photovoltaic panels, were also imported.
Reference was made to the year 2019 for the choice of capacity factors, in fact even the first model built is based on the year 2019 and the characteristics of the power grid at that time juncture.
The time interval between one detected data and its next is 1 hour, which then allows it to be used properly with the snapshots that the optimizer takes into account for the calculation of all variables, namely 8760.

The electrical load is always imported in the form of a series punctuated by hourly intervals. The reference load is held constant in the 2019 scenario, instead added a multiplier such that, it is comparable to that estimated in "Agenda per la transizione energetica" [12].
This chapter shows how the various considerations to be taken into account in estimating future electricity load take into account both the decrease in consumption due to increasing electrical efficiency and the increase due to various factors such as electrification of transport and heating.

The load is a strict constraint that the power grid must meet at each time step.

In addition, external parameters of the Bitcoin protocol were imported, such as the difficulty of solving the mining problem [41] and the market exchange price [42] relative to the relevant time period. They will be needed when calculating the marginal cost that mining has within the simulation at each snapshots.

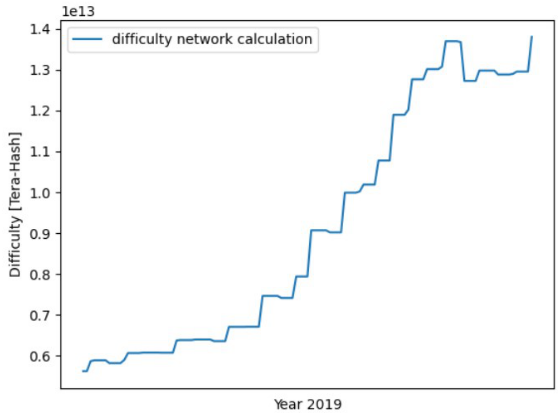

Figure 4.1: Bitcoin difficulty SHA-256 calculation for the year 2019

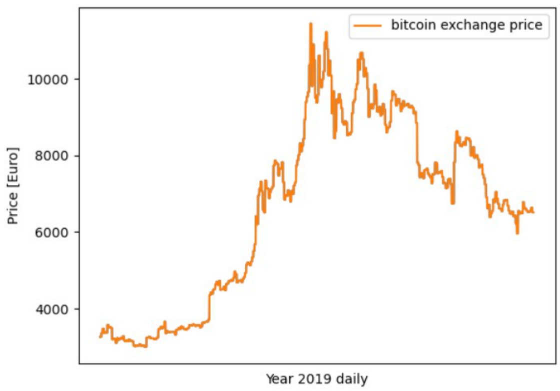

Figure 4.2: Bitcoin exchange market price for the year 2019

4.2 Four Scenarios for Energy System Composition

The purpose of this chapter is to provide a clear explanation of the composition and structure of the electrical network in different scenarios.
It outlines how the scenarios were designed and how the different components were integrated into the network prior to optimization.

In each scenario, nominal power values were assigned to the various components of the electrical network. These values serve as initial estimates that can be further refined and optimized based on techno-economic analysis.
It is important to note that the indicated nominal power values for each scenario will be subsequently optimized to achieve the most efficient and cost-effective system configuration.

4.2.1 Scenario 0: Power Generation Plants in the Year 2019

In this scenario, the load is primarily supplied by diesel generators due to the limited use of renewables.
The share of renewables in the energy mix is minimal and differs significantly by orders of magnitude.

Type of plants	**Nominal Power**
Thermal power plant	23 MW
Solar power plant	720 kW
Wind power plant	32 kW

Table 4.1: Design and Composition of the Electrical System for Scenario 0

This scenario, referred to as Scenario 0, is inspired by the electrical grid composition of the Pantelleria minor island in the year 2019.

The objective function for this scenario is totally positive and free of external dependencies or profitable sources, in contrast to other scenarios.
The power available in this scenario is designed to largely cover the electrical load, resulting in an oversized system that is highly flexible in response to electrical demand.

4.2.2 Scenario 1: Power Generation Plants in the year 2050

In this scenario, which is characterized by a high penetration of renewable sources, in contrast to [12] the programmable generation consists essentially of the diesel generators already present in the grid, as opposed to replacing them with biodiesel-fueled generators as planned. This choice was dictated by the purpose of the investigation, as the stability of the grid is ensured by the presence of the latter, the presence of biodiesel generators is expected to help achieve these goals, while also contributing to important climate objectives.
Additionally, it is important to consider the storage units' C-rate of 0.5, inserted as a parameter during the design phase, which allows them to charge or discharge fully within 2 hours at their maximum power capacity. This characteristic plays a significant role in the flexibility and responsiveness of the storage units within the power system.

Type of plants	**Nominal Power**
Thermal power plant	23 MW
Solar power plant	12 MW
Floating offshore wind turbine plant	6 MW
Storage units with 0.5C	14 MW

Table 4.2: Design and Composition of the Electrical System for Scenario 1

4.2.3 Scenario 2: Power Generation Plants in the year 2050 with mining of Bitcoin

In this scenario, the integration of mining serves as the cornerstone of the investigation.
As the demand for Bitcoin mining increases globally, there is a growing need to investigate the impact of mining on the electrical grid of isolated islands. This scenario, therefore, provides valuable insight into the integration of a mining farm into the electrical system of the Pantelleria minor island.
It is important to note that this scenario also includes an energy storage system with the same characteristics as previously discussed, specifically a C-rate of 0.5, which further influences the system's capabilities.
Through the exploration of various optimization models, the study aimed to understand the impact of mining on the overall performance of the system and identify the optimal configuration for its integration.
The analysis of this scenario thus provides valuable insights into the challenges and opportunities of integrating Bitcoin mining into electrical systems, especially in isolated regions.

Type of plants	**Nominal Power**
Thermal power plant	23 MW
Solar power plant	12 MW
Floating offshore wind turbine plant	6 MW
Storage units with 0.5C	14 MW
Mining farms	9 MW

Table 4.3: Design and Composition of the Electrical System for Scenario 2

4.2.4 Scenario 3: Power Generation Plants in the year 2050 with mining of Bitcoin and absence of storage units

In this scenario, the load is primarily supplied by diesel generators, and the use of renewables is minimal and differs significantly by orders of magnitude.
The behavior of a grid with the presence of bitcoin mining farms, similar to the previous scenario but without storage, was also investigated.
This choice was dictated by the unique characteristics of Bitcoin mining, which presents itself as a buyer of last-resort energy, similar to storage facilities, but differentiated by the non-storage of electricity at the time of lowest production from renewable sources.
The outcomes of this scenario will provide insights into the potential trade-offs and challenges of integrating Bitcoin mining into an energy system that is not supported by storage technologies.

Type of plants	Nominal Power
Thermal power plant	23 MW
Solar power plant	12 MW
Floating offshore wind turbine plant	6 MW
Mining farms	9 MW

Table 4.4: Design and Composition of the Electrical System for Scenario 0

4.3 Incorporating Constraints in Simulation Models: Strategies and Best Practices

The utilization of an open-source tool for simulating particular situations is always a crucial aspect in the success of the investigation of the problem. This is especially true when the "classic" rules of dynamics are modified.
This sub-chapter outlines the constraints that were included in the simulation to ensure the proper functioning of all network components. The instantaneous balance of the system can be expressed as follows:

$$p_{\text{gen\_die}} + p_{\text{gen\_ren}} + p_{\text{sto}} \quad = \quad p_{\text{load}} + p_{\text{min}} \tag{4.1}$$

Where:

- $p_{\text{gen\_die}}$: The power generation supplied by the thermal generators.
- $p_{\text{gen\_ren}}$: The power generation supplied by the renewable energy sources.
- p_{sto}: The available power capacity of the energy storage system can be either positive or negative, depending on the direction of the energy flow. For storage units, if $p > 0$ the storage unit is supplying active power to the bus and if $q > 0$ it is supplying reactive power (behaving like a capacitor).
- p_{load}: The power demand from consumers.
- p_{min}: The power demand of the mining operation, if in operation.

Particularly, two hand-written functions were used, the implementation of which was crucial to ensuring the constant repetition of rules throughout each simulation moment. The primary purpose of the first constraint was to ensure network stability. This function made it possible to prevent any network malfunctions or collapses, thereby increasing the system's dependability.

The objective of the second constraint was to ensure that all of the energy actually used for mining came from renewable sources. This function made it possible to limit the simulation's environmental impact by promoting the use of renewable energy sources and reducing greenhouse gas emissions. The remainder of the chapter describes in detail the two hand-written functions used and their impact on the simulation, as well as the results obtained by applying constraints.

1. Constraints on the mining functionality

   In a system where supplying a load allows for an improvement in the overall objective function, such as Bitcoin mining, where the cost of installation is calculated based on the nominal power, but is represented in the final balance as a "dummy generator," it is viewed as a variable that can be exploited to drastically reduce the objective function result.

   To avoid this issue, especially during the periods of the year where the marginal cost, which is dependent on variables outside the electrical system, is higher than the cost of producing the energy that feeds the system, a restriction has been placed on the thermal generator, which prevents it from participating in the mining process.
   In this way, it was also possible to use exclusively the curtailment energy for mining, as investigated in [38].

   The maximum amount of energy that the mining farms are permitted to use is determined by the following restriction:

   $$p_{\min} \quad \leq \quad p_{\text{gen\_ren}} - p_{\text{load}} \tag{4.2}$$

   In this way seems that only the curtailed energy can be use from the mining. But due to the components of the system, this is not enough for guarantee that the storage act as a bypass to transfer energy from the diesel generator to the mining one.

To accomplish this goal, we introduced constraints on the operating status of both generators. The operational status, denoted as *status*, can be either ON (1) or OFF (0), indicating whether the generator is working or not working, respectively.

The relationship between the two generators can be expressed by the following conditional statements:

- If $p_{\text{gen\_die}}$ is ON, then the *status* of $p_{\min}$ must be set to OFF.
- If $p_{\text{gen}_\text{d}\text{ie}}$ is OFF, the *status* of $p_{\min}$ is not restricted.

This relationship ensures that the two generators do not operate simultaneously. To represent this constraint mathematically, we employ an inequality:

$$status(p_{\text{gen\_die}}) \quad + \quad status(p_{\min}) \quad < \quad 2 \tag{4.3}$$

By incorporating this inequality into the simulation model, we effectively ensure that the two generators are not working together, and the energy used for Bitcoin mining operations is derived exclusively from renewable energy sources.

The rationale behind this inequality is that if both generators were to be in operation simultaneously, their combined status values would be equal to 2 (1 + 1 = 2). However, the inequality requires the sum to be strictly less than 2. Consequently, the condition forces at least one of the generators to be in the OFF state, ensuring that both generators do not operate together.

It is important to note that in cases where the load demand exceeds the capacity of the renewable energy sources, the diesel generator is designed to switch to its operational mode. This contingency ensures the stability of the power grid by providing the necessary energy to meet the load requirements when renewable sources are insufficient. In such situations, the mining generator will remain in the OFF state to prioritize the utilization of the diesel generator for satisfying the load demand, maintaining the constraint established by the inequality.

2. Constraints on the grid stability

   To always be in possession of the energy availability needed to ensure that the system is reliable and adequate, as seen in the previous chapter, it was constrained that a portion of the energy available from the thermal generators, be preserved throughout the simulation. The following inequality has been incorporated:

$$p_{\text{disp\_die}} \geq 1.5\% * p_{\text{eff}} + 6\% * p_{\text{inst}} + 5\% * p_{\text{load}} + 20\% * p_{\text{gen\_ren}} \quad (4.4)$$

   Where:

   - $p_{\text{disp\_die}}$: Is the difference between the installed capacity and the actual used

   - p_{eff}: Is the effective power that a thermal generator can guarantee to produce without limit of time

   - p_{inst}: Is the maximum capacity installed of the plant

   - $p_{\text{gen\_ren}}$: Is the available energy from the renewable source

   This took into account the primary reserve to be available for primary regulation, the secondary reserve, and the operational reserve that takes into account a percentage of the load and renewable sources [43].
   This two terms in fact, presenting inherent unpredictability, are included in the share of programmable energy available to ensure the stability of a system that at high penetration of renewables.

Chapter 5

Result

5.1 Results presentation

During the decision-making phase for establishing the composition of the electrical grid, the decision to compare different situations should serve to provide an overview of some of the numerous potential outcomes.
The purpose of this chapter is not to provide a definitive answer to the question of which case is superior, but rather to highlight the characteristics and advantages of each case.
In every case study will be analyzed data for:

- The objective function results
- The result of the power optimization
- The renewables energy behaviour
- The storage units behaviour
- The potential diesel reduction if any
- The bitcoin mining integration

5.2 Analysis of results: Scenario 0

With the purpose of having a reference on the results obtained from the other scenarios and understanding the current behavior of the grid, the results of this scenario have been reported.
Since renewable resources are present to a much lesser extent compared to thermal generation, which covers the needs of most of the load, from its summer peak to the baseload of winter nights, this have a minor impact on the results of the objective function and the optimization of the optimal power results as:

Type of plants	**Optimized Nominal Power**
Thermal power plant	23 MW
Solar power plant	0.18 MW
Wind power plant	0.85 MW

Table 5.1: Optimized composition of the system - year 2019

Optimized nominal capacities can only further confirm that the reality of the smaller islands, subject to high seasonal load variability, needs to have a margin on nominal power capable of responding readily to increased loads.

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In this scenario, it can be observed that renewable energy sources are utilized almost entirely during times of production availability, particularly photovoltaics which reach their maximum output during peak tourist season and corresponding periods of high energy demand from the grid.

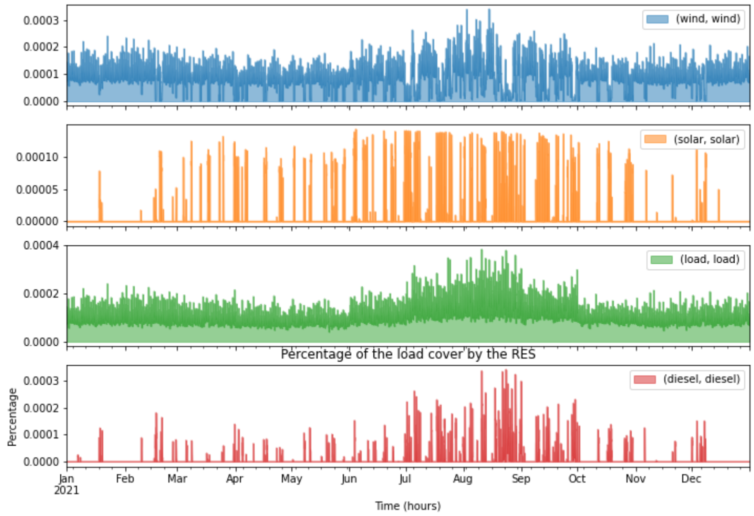

Figure 5.1: Scenario 0: Key Components of the Network Representation

In the analysis, it can be observed that the peak participation of thermal generators in satisfying the electrical load demand coincides with the summer months, which are positioned approximately in the middle of the temporal analysis.
The density of photovoltaic production, represented in orange in the graph, also coincides with the summer season, for both climatological reasons and greater demand for energy from the grid.

As for the participation of onshore wind turbines in the grid, the maximum values are also obtained during the peak summer demand from the grid, since this represents the energy dispatched to the grid, and not just the energy available from nature but converted into electricity and injected into the grid.

5.3 Analysis of results: Scenario 1

In a scenario with high penetration of renewable energy resources, but still experiencing high load variability, it is critical to optimize the installed power to ensure the efficient operation of the energy system.
To this end, the optimization calculations for installed power have produced some noteworthy results.
By incorporating storage solutions to compensate for low production periods and to harness excess energy during peak production, the system becomes more resilient and sustainable.
The results of the optimization calculations for installed power are as follows:

Type of plants	**Optimized Nominal Power**
Thermal power plant	23 MW
Solar power plant	7 MW
Floating offshore wind turbine plant	14 MW
Storage units with 0.5C	17 MW

Table 5.2: Optimized composition of the system - year 2050

The optimizer has clearly given significant consideration to the installation of energy storage, while consistently maintaining the C-rate as previously mentioned. This approach is essential for accurately determining the optimized installation capacity of the energy storage system within the network.
Furthermore, due to its favorable geographical location, the minor island of Pantelleria has the potential to generate electricity from a variety of natural resources, provided that appropriate conversion facilities are installed.

Compared to the previous scenario exploration, the contribution of thermal generation to the electrical system balance has decreased. This can be attributed to the presence of storage units (which were absent in the previous chart) and the increased capacity of renewable energy sources.

In this scenario, the daily demand has increased to an average of around 5 MWh.

However, the energy dispatch mix in the grid has been modified, resulting in reduced thermal generation production.

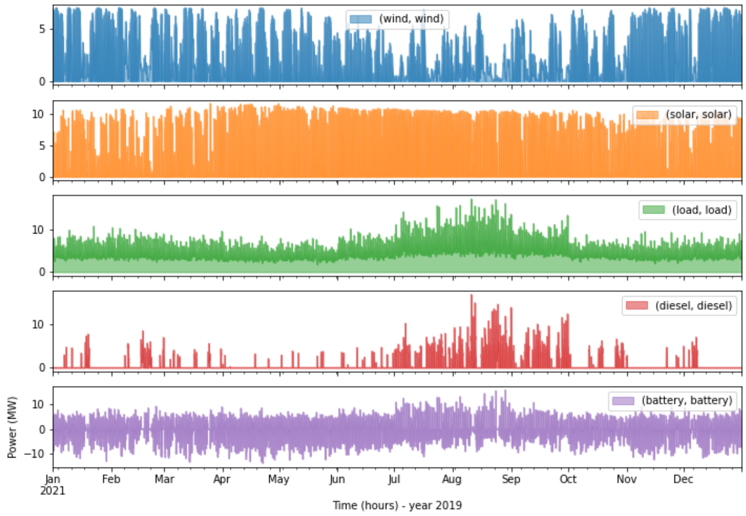

Figure 5.2: Scenario 1: Key Components of the Network Representation

The role of storage in the energy system is of paramount importance, as it is the only component that can shift energy production to periods when it is not immediately required by the load.

This capability can enhance the overall resilience and sustainability of the energy system, particularly in regions with high variability in electrical demand.
As illustrated in the graph in violet, the maximum capacity values achieved by storage units coincide with the peak grid load months, demonstrating the system's ability to utilize available renewable resources during periods of high demand.
Conversely, during the periods when diesel generators are more heavily utilized, the contribution of storage solutions tends to be negligible.

5.4 Analysis of results: Scenario 2

Given the high variability of the load, the ability of renewable energy sources to utilize excess energy provides significant advantages, as evidenced by the results of the optimization function.
By harnessing renewable energy during periods of high production and utilizing storage solutions to compensate for low production periods, energy systems can become more resilient and sustainable.

Moreover, this approach can lead to greater cost savings and a reduced dependence on non-renewable energy sources, making it a compelling option for regions seeking to transition to a more sustainable energy future.

In this scenario the optimal installation power finding are:

Type of plants	**Optimized Nominal Power**
Thermal power plant	23 MW
Solar power plant	7 MW
Floating offshore wind turbine plant	14 MW
Mining farms	15 MW
Storage units with 0.5C	2 MW

Table 5.3: Optimized composition of the system - year 2050 with mining of Bitcoin

The results of the optimization analysis reveal a significant difference compared to Scenario 2050, with storage units reduced by approximately 90%.
However, the inclusion of a network component like mining can enable time-independent operation, similar to storage solutions in some respects, although without the ability to dispatch energy to meet the load.

The following graph showcases the energy storage capacity and the variations in both injected and withdrawn power from the network by the storage units during the simulation.

It is noticeable that during periods of maximum operation of the thermal generators to satisfy the load, the storage unit does not show any activity, as there is no excess energy available to store. This manipulation of the behavior of mining can lead

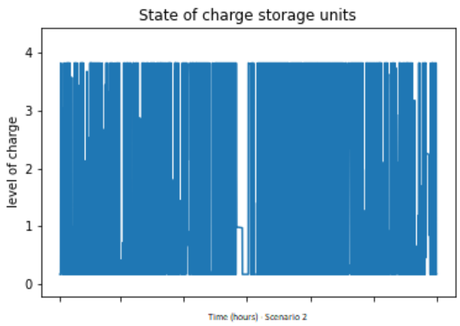

Figure 5.3: Energy Storage Capacity in the Scenario 2

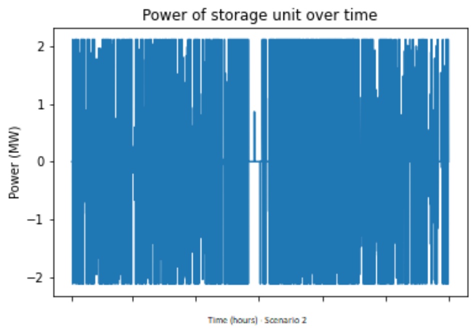

Figure 5.4: Discharge and Charge of Storage Units in Scenario 2

Figure 5.5: Characteristics of the storage units - Scenario 2

to more efficient and cost-effective energy systems, especially in regions with high variability in electrical demand.
The representation of the components in the same chart can be seen below:

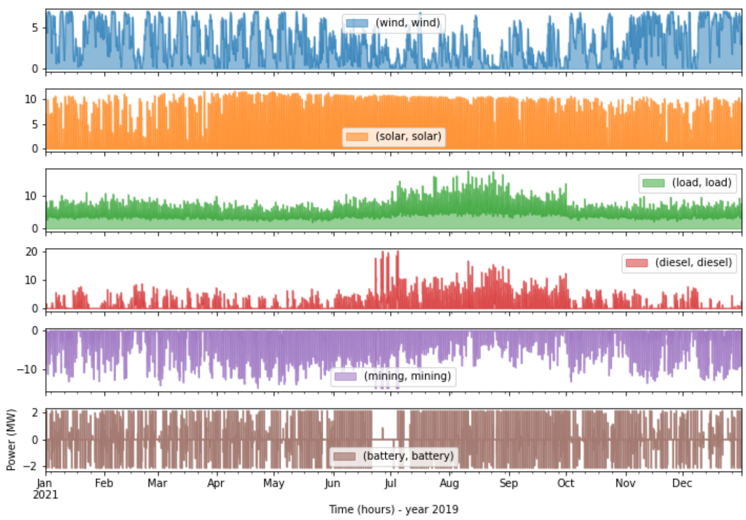

Figure 5.6: Investigating the Benefits of Mining Capacity Optimization in Energy Systems

Analysis of the results obtained from energy system simulations has revealed that mining tends not to operate during periods of maximum renewable energy production, but rather during times of high grid demand when favorable conditions are present.
In this case, the Bitcoin mining process is represented in violet and assumes only negative values during its operation.
This is because it has been incorporated into the energy system simulation as a dummy generator, with a negative value indicating its impact on the overall system.

Despite being represented as a load, mining appears differently than the typical network load, but in practice (and as indicated previously in the balance equations) it is added to the overall load of the system. Additionally, mining activity is highest during periods when there is abundant and low-cost electrical energy available, particularly when renewable sources generate surplus electricity after meeting the system's demand.
Bitcoin mining is properly incorporated into the energy system simulation and assumes variable values that depend on the system's constraints and network characteristics for each snapshot of the system.
Moreover, it is noteworthy that the operation of storage units, highlighted in brown in the graph, is almost absent during peak periods of the network, when thermal generation is utilized to meet the critical energy demands of the system and ensure complete reliance on renewable sources.

The investigation into the optimal installation capacity for mining was based on various factors, as outlined in the third chapter.
The network's objective function was analyzed to determine the lower area closer to the bend elbow, considering the space occupation that this physical dimension would have in the installation process within or near a grid electrical node.
The relation between the objective function and the capacity of mining is shown in the graph below, with the x-axis representing the installed mining capacity and the y-axis representing the values assumed by the optimizer's objective function.

The graph depicts a large slope in the lower installation-region, indicating a

high variation of the objective function at low installed capacity. As the capacity increases, the objective function tends to stabilize, with the increase in capacity resulting in only a slight reduction in the objective function.
This indicates that the optimal installation capacity for mining lies within the elbow region of the graph, where the benefits of increased mining capacity are significant, but the cost of installation and operation remains low.

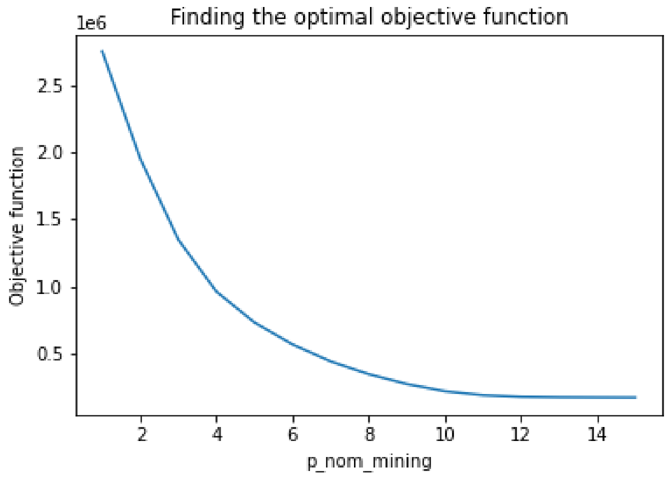

Figure 5.7: Optimal installation mining capacity investigation - Scenario 2

It is evident from the simulation results that a comparison between renewable energy sources and Bitcoin mining highlights the power-intensive nature of the latter.
As a buyer of last resort for electricity, mining adapts to the characteristics of the grid and changes more frequently than sources that are dependent on a single variable, such as the meteorological conditions for renewable sources or the electrical demand for thermal generation.

5.5 Analysis of results: Scenario 3

With the aim of comparing the behavior of the network components between the previous scenario and the current one, a simulation was run without the storage units.
This was done in accordance with the concepts of "Bitcoin Battery" dynamics [44], which involve changing the participation characteristics of the mining component in the network over time.
This led to different considerations and insights into the behavior of the network under different conditions.
The removal of storage units from the network allowed for a clearer understanding of the role of different components in the system.
It is interesting to note that the relation curve between the installed mining capacity and the objective function result is still present in this scenario. However, there are noticeable differences in the behavior of the network components without the presence of storage.

The absence of storage units led to a higher utilization of diesel generators during peak load periods, as observed in the simulation results. Additionally, the mining component's behavior is different from the previous scenario due to its role as a "buyer of last resort" for electricity, which allows it to adapt to the characteristics of the grid more quickly than other components that are dependent on specific external variables, such as weather conditions or electrical demand.

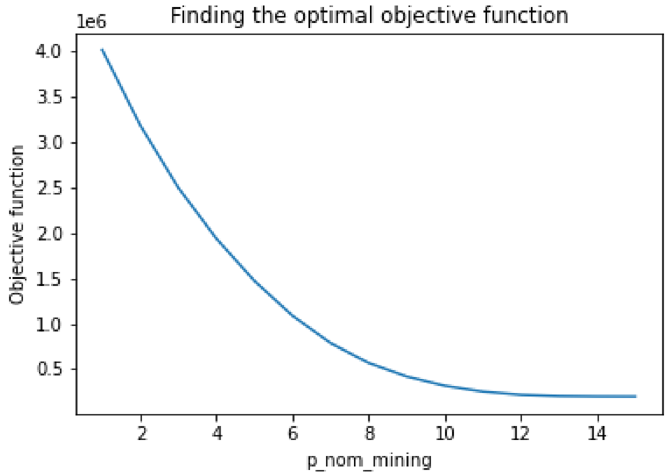

Figure 5.8: Optimal installation mining capacity investigation - Scenario 3

In summary, the removal of storage units from the network has provided valuable insights into the behavior of the different components in the system.
These insights can be used to inform decisions regarding the optimal installation of different components in energy systems.
The comparison of the objective function result between the scenario with and without storage reveals interesting findings.

When comparing the two graphs, it can be noticed that the slope of the curve in the scenario without storage is steeper, indicating a smaller improvement in the objective function result in percentage when increasing the mining capacity.
On the other hand, the slope of the curve in the scenario with storage is less steep, indicating a greater improvement in the objective function result in percentage when increasing the mining capacity.
However, it is worth noting that the value to be optimized is higher in the scenario with storage, with a value of approximately $4 * 10^6$ compared to approximately $2.7 * 10^6$ in the scenario with storage.

Chapter 6

Conclusion

6.1 Results and Analysis

This thesis is centered around the design of an electrical system for a minor island, specifically the island of Pantelleria.
At first the analysis focus on co-understand the energetic reality of the island, simulating and looking forward to investigate different solution, including the one with the integration of the bitcoin mining.
In the first case the work aimed to simulate the existing electrical grid, weakly populated by renewable sources being a fragile and delicate system, so where generation via thermal generator works well for decades.
A relevant part of the thesis is the study of the same electrical system but adjusted for the future trend, based on the document [12], both on the load side and the generation side, taking advantage by the proximity with the sea.

The comparison between the integration of different technologies was at the heart of approving interesting results, once it was ensured that the system thus formulated met the constraints of stability and co-habitation between different technologies.
The inclusion of the mining of bitcoin, brought us the possibility to have an positive member in the objective function, with the constraint of using only the energy that remains available from renewable sources successively to that the electrical load is supplied.

It is crucial to consider this aspect since it is inherent in the design of a system mainly based on renewable energy. The curtailment of energy production must be implemented during times of maximum production and lower demand.
It is not feasible to design a storage system that can absorb all the available energy due to the still high costs associated with the technology of the storage itself. Shifting energy over time is always an expensive application.

When comparing the different scenarios, it was observed that the objective function, which takes into account the differences between the product of the energy generated by various resources and their marginal costs and the fixed costs of the system with the optimized power, proved to be a valuable tool for analyzing the impact of introducing mining in the third scenario.
The repeated iterations revealed significant changes in the function, highlighting the significance of the mining component in the overall system.

The optimization analysis revealed that the introduction of mining resulted in a significant reduction in the storage capacity required. Specifically, the storage units nominal power, with a focus on 4-hour duration systems, which was optimized at 17 MW in the second scenario, was reduced to 2 MW, resulting in a reduction greater than 85% of the total.
In addition, comparing the insertion of different mining farms capacities within a network with constant constant network characteristics, as seen in the chapter of the results, the objective function of scenario 2 is reduced abundantly from an initial value of 2.7×10^6 to a value of 1.67×10^6 by optimizing 9 MW of mining farms nominal power, considering the area below the elbow of the curve, not the oversaturation part of the curve.
Comparing the third and fourth scenarios, on the other hand, it can be seen that the reduction in the objective function, starting from higher values, has a less steep reduction in the initial part of the curve in the fourth scenario, which corresponds to mining nominal power still less than 5 MW.
This highlights the change in the improvement of the objective function with the insertion of mining farms between a scenario in which storage units are included and one in which they are not.

6.2 Conclusions and Future Work

The results of this study show that the integration of bitcoin mining in a renewable energy-based electrical system can provide additional benefits. By using the curtailed energy that would otherwise go to waste, mining farms can act as a "buyer of last resort" and provide a valuable revenue stream.
However, it is important to note that the integration of mining farms requires careful consideration and planning to ensure that it does not adversely affect the stability and reliability of the electrical grid.

Moreover, one aspect that has not been considered in the current analysis is the role of energy storage systems in providing reserve capacity. This omission may have influenced the results, as the optimizer identified the mining component as the sole alternative to the thermal generator for reserve provision.
It is important to acknowledge that, had the energy storage systems been considered as an additional option for reserve capacity, the optimal size of the storage systems might have been larger, potentially reducing the reliance on mining operations for reserve provision. This scenario would likely have resulted in a more balanced distribution of reserve capacity among the various components of the electrical network.

While this limitation should be taken into account when interpreting the findings of the current study, it does not undermine the overall validity of the research. The results still provide valuable insights into the relationship between generators and their roles in the grid. Future work could expand on this study by incorporating energy storage systems as an additional source of reserve capacity, which would help to refine the optimization process and provide a more comprehensive understanding of the most efficient and cost-effective system configurations.

Future research could benefit from considering the production curves of diesel generators while accounting for variations in efficiency. In the current study, the diesel generation unit is treated as a single entity; however, a more detailed analysis could divide the diesel generator into its eight individual units, taking into account the committability of each separate unit.

By incorporating these refinements, future investigations would be able to more accurately represent the dynamics of the diesel generation system and provide a deeper understanding of the interplay between different generator units. This approach would likely lead to more precise optimization outcomes, further enhancing the efficiency and cost-effectiveness of the electrical network configurations.
Future work could build upon the findings of this study by further exploring the technical and economic feasibility of integrating Bitcoin mining into various renewable energy-based electrical systems. The current analysis has been conducted within a specific framework, utilizing a well-defined case study and a set of temporal scenarios to achieve the desired outcomes.

Subsequent research can enhance this existing framework by incorporating the refinements mentioned earlier, such as considering the role of energy storage systems in providing reserve capacity and accounting for individual diesel generation units. These improvements would provide a more comprehensive and accurate representation of the system dynamics and optimization outcomes.
Additionally, future studies could investigate other aspects of integrating Bitcoin mining operations into renewable energy-based electrical systems, such as the potential environmental benefits, grid stability, and the impact on local energy markets.

Bibliography

[1] European Commission. *Clean Energy for EU Island*. 2017. URL: https://energy.ec.europa.eu/topics/markets-and-consumers/clean-energy-eu-islands_en (cit. on p. 1).

[2] European Commission. *Clean Energy Transition Agenda*. 2021. URL: https://clean-energy-islands.ec.europa.eu/system/files/2021-11/CETA_AranIslands_Oct2019_FULL.pdf (cit. on p. 2).

[3] Unione delle Imprese Elettriche Minori. *UNIEM Goals*. 2014. URL: https://uniem.it/chi-siamo/obiettivi (cit. on p. 4).

[4] Arera. *Oneri generali di sistema e ulteriori componenti*. 2017. URL: https://www.arera.it/it/elettricita/auc.htm (cit. on p. 5).

[5] Legambiente. *Rapporto isole sostenibili*. 2020. URL: https://www.legambiente.it/rapporti-e-osservatori/isole-sostenibili/ (cit. on p. 5).

[6] Mise. *Copertura del fabbisogno delle isole minori non interconnesse attraverso energia da fonti rinnovabili*. 2017. URL: https://www.mise.gov.it/index.php/it/normativa/decreti-ministeriali/decreto-ministeriale-14-febbraio-2017-copertura-del-fabbisogno-delle-isole-minori-non-interconnesse-attraverso-energia-da-fonti-rinnovabili (cit. on p. 6).

[7] Arera. *Definizione della remunerazione dell'energia elettrica e termica prodotta da fonti rinnovabili nelle isole non interconnesse*. 2018. URL: https://www.arera.it/it/docs/18/558-18.htm (cit. on p. 7).

[8] Mise. *Energia e Sviluppo dei Territori 2014 -2020*. 2017. URL: https://www.ponic.gov.it/sites/PON/pocenergia (cit. on p. 9).

[9] Arera. *Condizioni per l'erogazione del pubblico servizio di dispacciamento dell'energia elettrica sul territorio nazionale e per l'approvvigionamento delle relative risorse su base di merito economico*. 2006. URL: https://www.arera.it/it/docs/06/111-06.htm (cit. on p. 11).

[10] Decreto del Presidente della Repubblica 7/10/2016 n. 235. *Istituzione del Parco nazionale «Isola di Pantelleria*. 2016. URL: https://www.gazzettaufficiale.it/eli/gu/2016/10/07/235/sg/pdf (cit. on p. 15).

[11] Nature. *Climate change and interconnected risks to sustainable development in the Mediterranean*. 2018. URL: https://trilemma.worldenergy.org/#!/country-profile?country=Italy&year=2021 (cit. on pp. 17, 20).

[12] Clean Energy for EU Islands. *Agenda Per la Transizione Energetica*. 2021. URL: https://trilemma.worldenergy.org/#!/country-profile?country=Italy&year=2021 (cit. on pp. 18, 19, 21, 22, 65, 68, 86).

[13] GSE. *ATLAIMPIANTI*. URL: https://atla.gse.it/atlaimpianti/project/Atlaimpianti_Internet.html (cit. on pp. 20, 23).

[14] Chakalis Georgilakis Zountouridou Kiokes. *Offshore floating wind parks in the deep waters of Mediterranean Sea*. 2015. URL: https://doi.org/10.1016/j.rser.2015.06.027 (cit. on p. 24).

[15] Adam Back. *Hashcash - A Cost-Functionary Model for Spam Control*. 2002. URL: https://www.researchgate.net/publication/2482110_Hashcash_-_A_Denial_of_Service_Counter-Measure (cit. on p. 28).

[16] *A Cypherpunk's Manifesto*. 1993. URL: https://www.activism.net/cypherpunk/manifesto.html (cit. on p. 28).

[17] Satoshi Nakamoto. *Bitcoin: A Peer-to-Peer Electronic Cash System*. 2008. URL: https://bitcoin.org/bitcoin.pdf (cit. on pp. 29, 31).

[18] Marek Grajek Rahul Naik Nicolas Courtois. *Optimizing SHA256 in Bitcoin Mining*. 2016. URL: https://link.springer.com/chapter/10.1007/978-3-662-44893-9_12 (cit. on p. 30).

[19] Michele Marchesi Luisanna Cocco. *Modeling and Simulation of the Economics of Mining in the Bitcoin Market*. 2016. URL: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0164603 (cit. on p. 35).

[20] Rostislav Haliplii and Guegan. *To Mine or Not to Mine? The Bitcoin Mining Paradox*. 2020. URL: http://dx.doi.org/10.2139/ssrn.3583515 (cit. on p. 35).

[21] MDPI. *Hedging renewable energy investments with Bitcoin mining*. 2021. URL: https://ideas.repec.org/a/eee/rensus/v138y2021ics1364032120308054.html (cit. on p. 40).

[22] Gabriela Pohl Peter Phillips. *Bitcoin is Digital Energy*. 2022. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4198698 (cit. on p. 43).

[23] *PyPSA: Python for Power System Analysis*. 2017. URL: https://pypsa.readthedocs.io/en/latest/ (cit. on p. 45).

[24] Journal Electrical and Electronic Engineering. *Effective Simulation Technique to Evaluate Loss of Load Expectation*. 2013. URL: https://www.sciencepublishinggroup.com/journal/paperinfo.aspx?journalid=239&doi=10.11648/j.jeee.20130101.13 (cit. on p. 48).

[25] Terna. *Adequacy*. URL: https://www.terna.it/en/electric-system/dispatching/adequacy (cit. on p. 48).

[26] IEEE. *Sequential Monte Carlo simulation for composite power system reliability analysis with time varying loads*. 2020. URL: https://ieeexplore.ieee.org/document/9079910 (cit. on p. 49).

[27] Terna. *Regole per il dispacciamento*. URL: https://download.terna.it/terna/0000/0108/18.pdf (cit. on p. 49).

[28] IEEE. *A Systematic Comparison of Operating Reserve Methodologies*. URL: https://ieeexplore.ieee.org/document/6939462 (cit. on p. 50).

[29] PyPSA Library. *Cost Assumption*. 2017. URL: https://pypsa-eur.readthedocs.io/en/latest/costs.html (cit. on p. 51).

[30] Pelin Yilmaz and Suleyman Yilmaz. *An economic analysis of renewable energy: A case study for Turkey*. 2017. URL: https://www.sciencedirect.com/science/article/pii/S1364032116307533 (cit. on p. 51).

[31] IRENA. *Power Generation Costs*. 2020. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf (cit. on pp. 52–54).

[32] NREL. *Cost Projections for Utility-Scale Battery Storage: 2021 Update*. URL: https://www.nrel.gov/docs/fy21osti/79236.pdf (cit. on pp. 55, 56).

[33] IEEE. *Optimal Placement and Sizing of Various C-Rate Type of BESS for Minimizing the Impact of Intermittent DG Output on Hourly Peak Load Variation in Radial Distribution Network*. 2022. URL: https://ieeexplore.ieee.org/abstract/document/9847777?casa_token=PyW5qxp5n8cAAAAA:lSWEFMoz2Hd7VLhsSJIi6qnaqliKtLWqHhYtvviE73c3JDyYEnMiY0SVD94OUvZy8qLvXxWvyA (cit. on p. 57).

[34] Renewable Ninja. *Raw Wind and Solar Data Acquisition*. 2019. URL: https://www.renewables.ninja/ (cit. on pp. 59, 60).

[35] IEEE. *Bitcoin mining acceleration and performance quantification*. 2014. URL: https://ieeexplore.ieee.org/abstract/document/6900989?casa_token=bHhE4UxfPekAAAAA:ZmSWv1K5rQYM2rlSFu-dJKdHffMQPQLXRvc_Wbd9JAnczhfWEvkxh2zekfUHEhlVN1o9wOCb7w (cit. on p. 61).

[36] International Journal of Electrical Power and Energy Systems. *An economic evaluation framework for cryptocurrency mining operation in microgrids*. 2022. URL: https://doi.org/10.1016/j.ijepes.2022.108329 (cit. on p. 61).

[37] Asic Miner Value. *Miners Profitability*. 2022. URL: https://www.asicminervalue.com (cit. on p. 61).

[38] Renewable Energy Systems Group Environmental Sciences Division Oak Ridge National Laboratory. *Bitcoin mining to reduce the renewable curtailment: a case study of CAISO*. 2019. URL: https://ssrn.com/abstract=3436872 (cit. on pp. 62, 72).

[39] Shunya Noda Yoshinori Hashimoto. *Pricing of Mining ASIC and Its Implication to the High Volatility of Cryptocurrency Prices*. 2019. URL: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3368286 (cit. on p. 62).

[40] Reier Forradellas RF Jorge azquez J Echarte Fern andez M A. *Cryptocurrency Mining from an Economic and Environmental Perspective. Analysis of the Most and Least Sustainable Countries*. 2021. URL: https://www.mdpi.com/1996-1073/14/14/4254 (cit. on p. 63).

[41] Blockchain.com. *Difficulty Hashrate over time*. 2023. URL: https://www.blockchain.com/explorer/charts/difficulty (cit. on p. 66).

[42] Glassnode. *Market exchange price of Bitcoin over time*. 2023. URL: https://studio.glassnode.com/workbench (cit. on p. 66).

[43] NREL. *Operating Reserves and Variable Generation*. 2011. URL: https://www.nrel.gov/docs/fy11osti/51978.pdf (cit. on p. 74).

[44] Nasdaq. *Bitcoin Is A Green Energy Battery For Wasted Electricity*. 2022. URL: https://www.nasdaq.com/articles/bitcoin-is-a-green-energy-battery-for-wasted-electricity# (cit. on p. 84).