COMPARATIVE TECHNO ECONOMIC STUDY OF HVDC TRANSMISSION SYSTEM BETWEEN AN ISLAND GRID AND A MAINLAND GRID

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ABSTRACT

COMPARATIVE TECHNO ECONOMIC STUDY OF HVDC TRANSMISSION SYSTEM BETWEEN AN ISLAND GRID AND A MAINLAND GRID

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Island electricity grids or isolated electricity grids are electrical grids that are not connected to other grids. These grids suffer from low system balance and low power capacity for various reasons (geographical, technical, and other similar aspects). Therefore, all production, transmission, and distribution stages are realized within the network. Electricity generation on an island grid requires constant transportation of fossil fuel to the island, increasing the cost of electricity, and the volatility of the system. Renewable energy sources received attention in recent years to solve this problem. Still, due to the nature of uncertainty of renewables, it is not possible to use this kind of source in full performance. With the development of advanced power electronics, energy transmission with High Voltage Direct Current (HVDC) to islands has become an option. Due to the expensive nature of this option, detailed analysis and comparison are required for island grids. In this thesis, a North Cyprus island grid model is developed with an HVDC interconnection option to Turkey and used for the techno-economic study to compare HVAC and traditional fossil fuel investments. The mentioned techno-economic analysis combines optimal power flow with traditional economic cost calculation methods. Ultimately, a better option among the suggested scenarios is evaluated for further research.

Keywords: HVDC, island grids, interconnector

ÖZ

BİR ADA İLE ANAKARA ELEKTRİK ŞEBEKESİ ARASINDA KURULAN HVDC TEKNOLOJİSİNİN KARŞILAŞTIRMALI TEKNO EKONOMİK ANALİZİ

Dinç, Barış Çağrı
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği
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Eylül 2021, 82 sayfa

Ada elektrik şebekeleri veya izole elektrik şebekeleri, çeşitli nedenlerle (coğrafi, teknik vb.) tüm üretim ve tüketimini şebeke içerisinde gerçekleştirmektedir. Bu durumun sürekliliğinin sağlanması için fosil yakıtların adalara sürekli taşınmasını gerekmektedir, bu da ada elektrik maliyetini, sistemin dengesizliğini arttırmakta ve enerji güvenliğini azaltmaktadır. Bu sorunu çözmek için yenilenebilir enerji kaynakları daha çok tercih edilmeye başlamıştır. Yine de yenilenebilir enerji kaynaklarının enerji üretiminin belirsiz doğası nedeniyle bu tür kaynakları tam performansta kullanmak mümkün değildir ve farklı çözümler ile birlikte kullanılması gerekmektedir. Güç elektroniğindeki gelişmelerle birlikte, adalara Yüksek Gerilim Doğru Akım (HVDC) ile adalar için enerji iletimi bir seçenek haline gelmiştir. HVDC teknolojinin pahalı doğası nedeniyle, ada şebekeleri için ayrıntılı ve karşılaştırmalı analiz gereklidir. Bu tezde, HVDC içeren bir Kuzey Kıbrıs ada şebeke modeli geliştirilmiş ve bu model HVDC teknolojisinin HVAC ve geleneksel fosil yakıt yatırımları ile karşılaştırılması için tekno ekonomik analiz kapsamında kullanılmıştır. Bahsedilen tekno ekonomik analiz, optimum güç akışını geleneksel ekonomik maliyet hesaplama yöntemleriyle birleştirmektedir. Sonuç olarak, önerilen senaryolar arasındaki daha iyi bir seçenek daha ileri araştırmalar için belirlenmiştir.

Keywords: HVDC, islands, interconnector

Dedicated To My Cats Misha and Kurabiye

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CHAPTER 1

INTRODUCTION

As geographical limitations exist for islands, islands usually rely on imported diesel and fuel oil to supply their energy needs. The situation causes high economic and environmental costs. On many islands, near 100% of electricity is generated with diesel and fuel oil. Due to the high transportation costs of oil transportation to remote islands and the relatively small quantities purchased because of lack of deposit, islands pay above global market prices for oil. Because of this, islands face energy security challenges in the form of high costs, vulnerability to oil price changes and, significant trade imbalances. Island governments worldwide are looking for alternative solutions to fossil fuels, mainly renewable energy, to address these problems.

Interconnection technologies are considered one of the possible solutions for islands, used for a couple of decades. This technology is used to power connected several islands electrically to the mainland. The importance of these interconnections is they give more energy security and power range for islands, and island to mainland interconnection numbers are steadily increasing [1]. After all these years, with the lower costs for High Voltage Direct Current (HVDC) based interconnectors with still growing technology and will continue to play a vital role in interconnecting various power grids and offshore renewables [2].

HVDC is used in many different applications to transport energy, interconnection two different grids, and many more with the increased research focus. It was assumed to be expensive and not easy to control technically; semiconductor improvements changed HVDC technology. It is a better choice in some cases than traditional High Voltage Alternating Current (HVAC) transmission. Island to mainland interconnectors is one of the HVDC application areas where its global share increases dramatically [3].

Although initiating a HVDC or HVAC-based interconnector project requires a high amount of investment, this investment is logical and economically beneficial in many cases. Benefits apply, especially if the island’s demand growth is hard to supply for electricity authorities only using fossil fuel-sed generation [4]. A project of such nature shall be initialized after a detailed feasibility analysis since the consequences of any damage affect a severe number of people and government [5]. Also, because of the low economic capacity of islands, sound planning is required.

1.1 Island Grids

Island electricity grids or isolated electricity grids are electrical grids that are connected limited or not connected to another grid with low system balance and production power due to various reasons (geographical, technical, etc.). Therefore all production, transmission, and distribution stages are realized within the network. Such grids generally have low generation capacity and a low number of users.

Although various technologies can generate electricity in island grids, the diversity of generation on an island is generally limited. These methods are fossil fuel-based generation (usually diesel generators) [6], hydroelectric-based generation, and renewable energy generation. In island grids, generation, transmission, and distribution are typically managed by a single institution, and there is no electricity trading market with more than one stakeholder.

Island or isolated grid systems usually meet the energy demand with the low number of power plants with limited capacity and located at a single point. Due to the increase in renewable energy generation in island networks, a transition from the traditional generation model to the distributed generation model can be observed.

Island grids have different characteristics compared to conventional electricity networks due to their limitations. Limited or no connection to other grids, all production and consumption take place within the grid itself, and there is no energy trade most of the time. This situation necessitates the real-time balance of supply and demand in island networks with limited storage facilities and may pose risks in maintaining the network balance. Examples of these risks are the inability to respond to instantaneous load changes due to the lack of generation diversity in island grids or the interruption caused by power plant maintenance [7].

Island grids also experience a lot of load variation compared to a standard grid in periodic and daily time intervals. This situation may cause energy quality problems in the system [8].

Also, island grids have turned to renewable energy sources due to easy accessibility and lack of fuel needs. However, due to the nature of these energy sources, technical constraints and problems occur in island networks with limited generation power. This situation led to the development of many projects and research about integrating renewable energy [6].

Another aspect of islands is ensuring the instantaneous production-consumption balance, which requires implementing the traceability of the network and the possibility of rapid intervention. This situation increases the importance of the supervisory control and data acquisition infrastructure (Supervisory Control and Data Acquisition - SCADA) used in island networks.

1.2 Island Grid Problem Identification

Some difficulties experienced by island and isolated networks and some problems brought about by these difficulties are given in Table-1.1.

Table 1.1. Island and Isolated Network Problems [9]

Difficulty	**Result**	**Impact**
Level of decrease of synchronized energy production	Reduction of system stability and system inertia	- More fluctuation in frequency, load shedding, and increased risk of system failure - To provide more system stability, decrease in energy production, and increase in system operating costs - Increased risk of load shedding
	Decrease of reactive power resources	- Increased loss in energy transmission - Frequency disturbance due to changes in power flows - Decrease in formal voltage level protection
	Decrease of short-circuit level	- Decreased protection of grid error detection and maintain equipment - The risk of destabilization of grid system created by asynchronous production
Transformation of production to a dispersed model and change of demand models	In case of grid system failures, high power phase fluctuation	- Disturbances in frequencies due to changes in power flows. - Decreased protection of grid error detection and maintain equipment
	Due to the limitations of power grid systems, excess regional energy production	- Decrease in low carbon energy production due to stabilization process, and increase in system operating costs
	Excess regional energy production due to low demand	
The effect of load and energy changes to the main power plants usage patterns	While restoring an idle grid power system (black start), the insecurity of energy because of not ready central stations	- Increased risk of failures while restoring idle grid system as desired - Increase in idle grid system restore costs

To solve the problems given in the table, many studies are carried out across the island and isolated grids. However, the problems in every island network do not happen simultaneously; island conditions may cause case-specific issues. For the solution of these problems, knowing the characteristics of the island network is essential.

1.2.1 Possible Improvements for Island Grids

Many possible improvement scenarios and methods were developed and applied to different islands. Because of environmental concerns and the non-dependency of renewables, applications favoring this technology became the focal point of projects.

Besides renewables, many investment options exist to solve the problems mentioned earlier. While these solutions aim to solve specific problems, they also increase each other's efficiency and success. One report [10], offered solutions grouped in two; infrastructural and operational solutions.

Infrastructure investments:

- Diversification of Renewable energy system installations
- Flexible generating units
- Energy storage systems
- Interconnection with neighboring systems
- Distribution automation and smart grid technologies

Operational measures:

- Demand-response programs
- Enhanced generation dispatch and control
- Enhanced defense plans
- Automatic power controller and network monitoring
- Short-term VRE production forecast
- Grid code requirements for integration of VRE generators

While any of the solutions mentioned increases the performance of islands, this study focuses on HVDC-based interconnections. Different investments need to be analyzed well and applied to achieve the best possible solution for island grids.

1.3 Aim of the Study and Approach

The fundamental aim of the study is to analyze HVDC interconnections between islands and mainlands by combining steady-state analysis with economic analysis. To see improvements achieved with interconnection, a comparative case study on North Cyprus-Turkey interconnection was conducted.

This research can answer the questions mentioned below:

- How much HVDC interconnectors improve grid stability compared to the isolated grid?
- How much economic improvement can be achieved with different interconnection investments done on the island grid?
- What is the better solution for the given island-mainland case?

1.4 Study approach

HVDC interconnections are expensive investment projects, and there is a definite possibility that they could not be helpful for all islands around the world. So comparative technology analysis should be done.

In this study, a steady-state model of the selected island is developed and validated. Then HVDC and other possible systems were added to the island grid. Different analyses with different bus connections were done to achieve the best possible grid stability. The prepared model was used to get the correlation between technical and economic properties of the system in Optimal power flow analysis.

Also initial and yearly cost of all possible solutions for a given case is calculated. Obtained results combined with technical benefits and primary payback times calculated and HVDC payback times compared with different island energy solutions. Mentioned analysis expanded with the addition of the social cost of CO_2 to see difference HVDC interconnection can make.

CHAPTER 2

HVDC TECHNOLOGY BACKGROUND

2.1 HVDC Technology Historical Background

The conversion of primary energy into electrical energy is an undeniable event in the formation of today's modern life and industry. Today, daily life is not possible without electrical energy, which is used for telecommunications, heating, transportation, medical care, water supply and is essential for the economy. Countries depend on a reliable energy source and a secure, stable power system for the stable continuation of society. The first power system built by Thomas Edison in New York in 1882 was a direct current (DC) system. However, the DC system could not carry power over longer distances due to the lack of technology to convert DC voltage to higher voltages. With a polyphase AC system developed by Nikola Tesla and the development of the transformer, the AC system became preferable for transmitting power over long distances [11]. In the near future, the first thyristor-based HVDC transmission line, called a current source converter-based HVDC (CSC-HVDC), was operated in the spring of 1970, connecting the island of Gotland to mainland Sweden [12].

The tremendous development of semiconductor technology has allowed the voltage level to increase as well as the power level. One of the milestones in the energy field is the commissioning of 6300 MW HVDC connections from the Itaipu power plant to Sao Paolo in the mid-80s. This event proved that the CSC-HVDC connection is a reliable technology. Following the further development of other semiconductor elements such as insulated gate bipolar transistors (IGBTs), ABB ushered in a new era for HVDC transmission by energizing the first voltage source converter-based HVDC (VSC-HVDC) junction on the island of Gotland in 1996. Much research has been done on this technology, mainly because it can improve the integration of renewable energy sources and solve transmission problems.

2.2 HVDC Converter Technologies

HVDC converter technologies are divided into two. These are the current source converter (CSC) and voltage source converter (VSC) mentioned in the previous section. The difference between these two techniques is mainly terminal voltages and current waveforms on the DC side.

For CSC technology, the polarity of the DC voltage determines the direction of the power flow while the DC keeps the same polarity. These converters are made with semi-controllable switches, like thyristors. Thyristors can be controlled with a given impulse(fire angle) signal to the gate. Nonetheless, the current interruption is only achieved with the zero-crossing of the AC voltage. Voltage and current harmonics are generated for these converters, and large AC filters are required [13]. Also, large smoothing reactors are used to maintain DC on the DC side of these converters. Examples of HVDC CSC systems with a DC voltage of ±1 100 kV and a transmission distance of more than 3,000 km, power values up to 10,000 MW exist [14].

As for the VSC, DC voltage is kept in the same polarity. The polarity of the DC determines the direction of the power flow. These converters are built with IGBTs which are fully controllable semiconductors compared to thyristors. It is possible that with a signal to the IGBT gate, the current can be conducted or interrupted at any time. The DC side of VSCs is connected in parallel to a relatively large capacitor that acts similarly to the voltage source [13]. Multiple levels of capacitors can be used to decrease AC side harmonics on the DC side. This technology is called modular multilevel converters(MMC) [15] [16]. The VSC produces much less voltage and current harmonics on the AC side. Therefore, only smaller filters are needed. Even in some cases, no filter is required. As a result, the size of converter stations is significantly reduced, such as the construction of offshore converters or the installation to urban areas became possible. Recently, it has been possible to create VSC-HVDC connections up to 2,600 MW with DC voltage up to ±525 kV and transmission distance of more than 1500 km [17]. In Figure 1.1, the differences in the structures of a CSC and a VSC are compared.

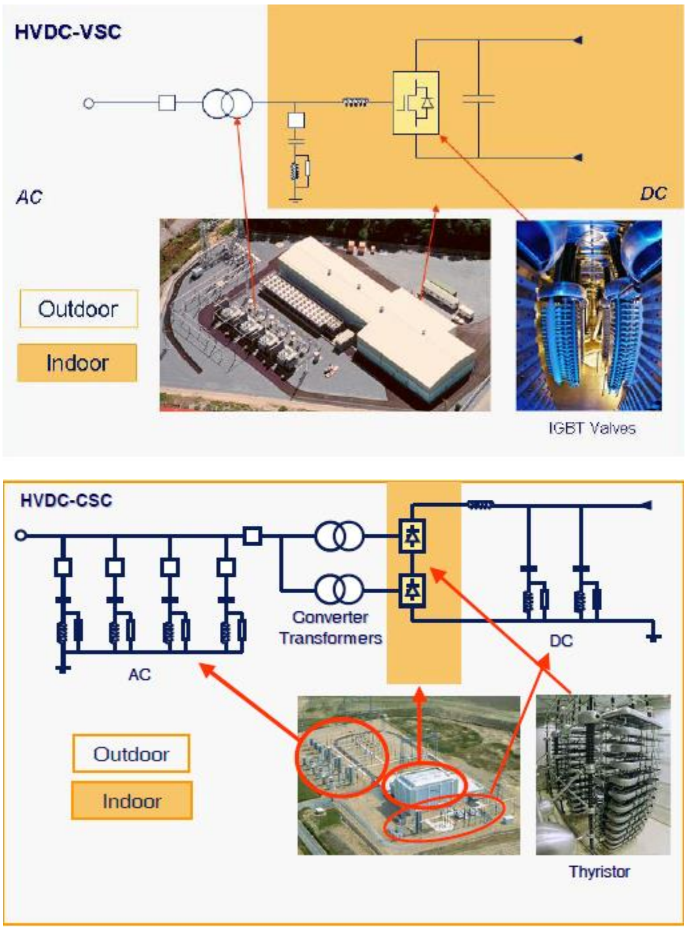

Figure 2.1. HVDC VSC and CSC Structures

Table 2.1 gives a brief comparison of the two technologies.

Table 2.1. Comparison of HVDC VSC and HVDC CSC [18]

Current Source Converter (CSC-LCC)	**Voltage Source Converter (VSC)**
It is a technology that has completed its development.	Its development continues.
It uses thyristor valves connected to AC voltage.	It uses IGBT and is self-contained.
Current regulation problems (thyristor not closing) may occur.	No current regulation problems.
Reactive energy compensation may be required.	No need for reactive energy compensation.

When CSCs and VSCs are compared, it can be said that the most fundamental difference between them is that VSCs can control active and reactive power injections independently from each other. This feature makes VSC-HVDC connections more interesting for real-time power system control. In addition, power can be reversed faster than CSC-HVDC connections since they do not need to change the voltage polarity of the DC cable [19] [20]. Also, as a further advantage, VSCs can be connected to weak AC networks. In theory, it can be connected to an AC bus with a short-circuit rate of 0, but in practice, CSCs need a short-circuit rate of at least around 2 [21]. Voltage source converters play a crucial role during the restoration of a grid. They can be activated immediately to provide voltage support because they do not need any short-circuit capacity to connect to the grid [22].

Today, both VSC and CSC are used to create different applications of power systems. However, the main application is power exchange between the HVDC lines with control of converters. A HVDC converter can help different aspects of the line other than the DC line's power. For example, frequency, voltage magnitude, or power factor can be controlled with HVDC. The usage areas of high voltage DC transmission systems can be in different lengths and power ratings.

HVDC configurations can vary according to the connection method like monopole, bipolar, and back-to-back connection. Connection types can be expanded with the type of return cables. Figure 2.2 shows different HVDC connection configurations.

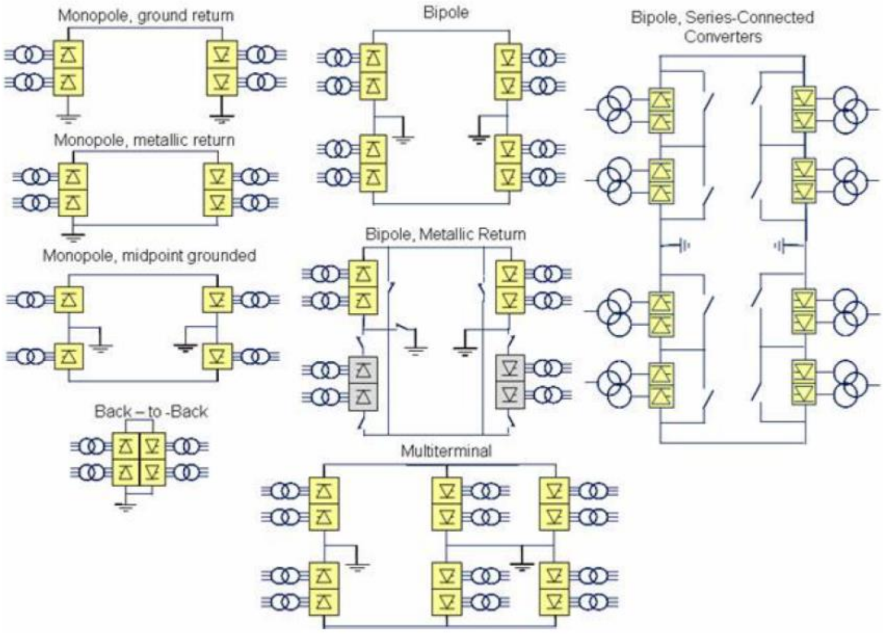

Figure 2.2. HVDC Connection Types [23]

2.3 HVDC and HVAC Comparison

While more detailed and parametric comparisons can be made, we can show the main technological advantages of HVDC over HVAC as follows; [24]

- More control over power
- No limit on cable length (Less interference to telecommunication lines also)
- Asynchronous transmission is possible between networks.

- Less loss on transmission lines (Less corona effect)

While this holds excellent ground, HVDC has some disadvantages compared to HVAC;

- More complicated and expensive conversion stations
- Design and operation on multi-terminal HVDC are sophisticated.
- The design of circuit breakers for HVDC is complex.

Besides technical differences, economic comparison can be made where HVDC shows promise compared to the HVAC connection. Research done on HVDC and HVAC costs show a break-even distance where one technology becomes cheaper than the other one [25]. Figure 2. shows the change in cost based on transmission line distance. Another research calculates that this breakeven distance is about 80 km for submarine transmission. [26].

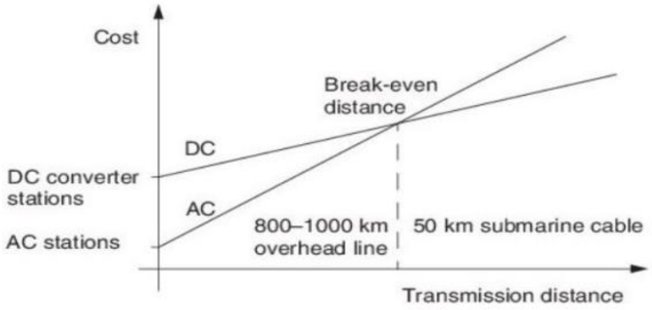

Figure 2.3. HVDC and HVAC Cost Relationship [27]

CHAPTER 3

LITERATURE REVIEW

3.1 Island Energy Generation Methods

Energy planning in an island environment is complex and requires rigorous planning and appropriate tools of evaluation to aid in decision making. The critical aspects are supply security, economic viability, social acceptability, and environmental protection. These critical aspects can be hard to maintain with economic and geographical limitations for islands.

Selecting generation investments for the island can be a complex procedure. This choice can be affected by the island's natural sources, geographical limitations, and demand. However, it can be seen that island grids generally use easy transport-based fossil fuel generators like diesel generators or non-fossil energy generation methods. Methods used can be listed as [10];

- Diesel Generators
- Steam Turbines
- Renewables
- Other Generation Methods;
    - Hydropower
    - Geothermal

Every generation method listed here has its advantages and disadvantages in the scope of island electricity generation. This situation makes a perfect solution for islands is near impossible to establish.

3.1.1 Fossil Fuel Based Power Plants

With the invention of engines, fossil fuels have become an essential part of the economy. This technology is used nearly in all of humankind's different processes. Energy generation is one of the central areas fossil fuels are used. Coal, oil, natural gas can be given examples of fossil fuels used for electricity generation. Synchronized generation capability makes fossil fuel-based generation crucial to systems we use, but increased environmental concerns push people to seek different generation methods [7].

Many of the diesel generators are used to backup or startup solutions to conventional fossil fuel generators. Nevertheless, in islands, this technology is used as the primary generation method of electricity. This is because [28];

- Fast up-down ramping speeds
- Suitable for small or medium-sized energy requirements of islands
- Ease of construction
- Cheaper initial costs
- The global supply chain for fuel
- Developed knowledge for operation and maintaining

Today, most island grids use diesel generators as their primary energy supply method because of the mentioned reasons. But this technology comes with significant disadvantages in islands without diversity of generation methods;

- Volatility to oil prices
- High operation and maintenance costs
- Low energy security
- Limited working time and capacity

To reduce the effects of mentioned disadvantages, many case studies were conducted around to world. Literature consists of renewable integration to generation mix, different diesel generation control [29] and interconnection systems.

3.1.2 Renewable Energy Systems

Today with the growing population, energy requirements caused overuse of natural resources and high amount of greenhouse gas emissions. With that, much research and technological exploration moved fossil fuels to renewable energy [30]. Provided that 80% of the world’s total energy is produced by fossil fuel causing greenhouse gas emissions, the transition towards renewable energy is required [30]. Regarding research conducted, solar energy systems and wind turbines are the most preferred and geographically possible renewable generation methods on islands, while hydro and wave energy applications can be found.

While this case applies worldwide, islands tend to suffer more from this problem because of dependency on fossil fuel-based generation. Besides environmental concerns, the disadvantages of fossil fuel-based sources mentioned before led islands to add more renewable energy sources to their generation mix. Different solutions which renewables could solve can be listed as [28];

- Mitigate high electricity generation costs
- Good local availability of renewable energy sources like solar, wind, geothermal and hydroelectric
- Reduction of greenhouse gas emissions
- Easy to find political and economic support

Even though many advantages come with renewables, it is not possible to generate electricity %100 with renewables. The output of renewable energy generators is challenging to control and difficult to predict with high accuracy. These generators are more challenging to integrate into power systems than other types of technologies, such as conventional fossil-fuelled generators or dispatchable renewable energy generators (e.g., biomass, geothermal, and reservoir hydropower).

Battery usage is an option to overcome this problem, but it is an expensive technology to use on islands.

Reasons that renewables are hard to use can be summarized as [10];

- Non-synchronous nature of renewables
- Hard to find suitable locations and infrastructure for renewable generation
- Uncertainty related to their generation or unexpected changes to their output power
- Variable resource effect on output power (e.g., solar irradiation, wind speed)

To see effects of renewables on island grids many case studies and research conducted. Generally research focuses on technical effects on island grids [7] [8] [31] [32] [33] [34] or economic benefits it can bring [35] [36] [37] [38] [39] [40] [41] [42] [43] [44] [45] [46].

One research study shows that energy storage systems are essential [32]. While uncertainty is an aspect of renewables, another research [33] shows that using essential forecasting and implementing load regulation can decrease losses 13.26% to 2.66%. Another research [37] shows that with smart grid application for an island, renewable penetration can reach up to %40. Mentioned studies show that renewable usage can be increased with various methods.

Economic case studies and feasibility studies show that the island energy economy can benefit from renewables and hybrid systems. A feasibility study done in Hainan island [36] shows that near 50% renewable penetration can decrease energy costs by 32%. Another case study [41] done in Australia island shows that generation only with renewables decreases the cost of energy by about %30. In contrast, combining existing solutions with renewables decreases the energy cost even further, about %60.

It can be seen from the literature that adding more renewables to the grid with different inclusion methods can dramatically increase the feasibility of renewables drastically. Even though intense research is done for renewable inclusion, research

[31] shows synchronous generation is required for grid stability with renewable penetration.

3.2 Island to Mainland Interconnectors

Adding new generation methods to islands inspected in the previous section, interconnecting grid with mainland grid is a possible solution for islands with suitable geographical properties. This requires submarine electricity cables most of the time, and a suitable converter or substation is required based on the technology. Using submarine cables to connect island grids to mainland grids is a common practice today [4] and many more projects are still in development around the world.

The first natural rubber insulated submarine electric power cable was laid in 1811 in Germany, and over the years, with the advancement until 1952, oil-filled insulated submarine cables were introduced [47]. As mentioned before, the first HVDC submarine electric power cable was installed to connect the island of Gotland with Sweden mainland.

Submarine interconnectors are used today to transfer offshore renewable energy sources like wind turbines, electrification of remote areas, and multiple grid interconnection. With the ever-growing consumer demand and increased greenhouse gasses, renewable energy use requirement increases. To utilize offshore-based renewable energy resources that save space, submarine power cables became essential for renewables [48]. Also, the grid connection for islands and other systems can increase grid penetration, another reason interconnectors are vital to power infrastructure. One of the reasons of particular interest towards the renewable energy is 20/2020 targets set by European Commission as well as the 2030 climate and energy framework whose key targets include a 40% decrease in GHG emissions (from 1991 levels), 32% increase in renewable shares and 32.5% improvement in energy efficiency [49]. Mentioned targets require higher renewable usage, which increases interconnector submarine cables.

Worzyk [50] mentions that interconnectors are feasible to connect isolated island grids to mainland grid to overcome problems and increase island energy quality. HVDC and HVAC could be used to connect mainland grids to island grids.

Besides HVDC and HVAC, low-frequency AC technology is being developed [51] [52] as an alternative to HVDC-VSC. However, this technology is used for offshore wind farm energy transmission, and no application between two grids has been made yet.

3.2.1 HVAC Based Connectors

As mentioned in Chapter 2, HVDC and HVAC transmission systems have a cost break-away point based on the distance. This distance changes based on submarine cable or land cable. Because of this, it can be assumed that based on the distance to the mainland, the obvious choice can be made directly. Nevertheless, example projects are given in the study [53] show that improvements on cable technology and case-specific factors need to be considered other than distance between two points.

For example, the DC transmission scheme will not always result in lower power losses if the interconnection is characterized by low power transfer. For high power flows and long distances, lines with higher voltages are desirable. Because of that, case-by-case analysis needs to be done both technical and economical.

One example of island-mainland HVAC interconnection is done between Malta and Sicily [54]. Pollutant power plants produce most of the electrical power within the island. Moreover, the Maltese system is characterized by poor robustness, limited reliability, and high energy costs like many island grids. Interconnection allowed up to 225 MW of power transmission and helped production decrease of Malta power plants. Another example of the interconnection between the island and mainland grid is the Isle of man-UK interconnection [55]. The electricity demand on the Isle of Man is supplied with diesel and gas turbines, with very high electricity costs like Malta. The AC submarine cable was commissioned to reduce the cost and emission of energy generation and improve network stability. It has an undersea length of 104 km and a land length of approximately 4 km, making this connection one of the longest HVAC interconnectors. Other examples can be seen in research done by Pedrazzoli and Rinzo [53].

3.2.2 HVDC Based Connectors

Today, HVDC transmission lines are used on many occasions, like power delivery from wind turbines or the connection of different grid systems. These connections also help usable renewable potential because renewable energy generation on one network is limited and requires a robust electrical grid due to the nature of renewable energy. For example, Denmark has achieved extreme wind power thanks to its connection with Germany and other countries [56].

Considerable research can be found on the improvement of this technology and its economic effects on application areas. Also, many studies and analyses were conducted before and after the HVDC interconnector project completion.

Most of the case studies for HVDC interconnection focuses on renewable penetration change on islands and this situation’s economic benefits. One study [57] focused on long-term submarine transmission between the Greek islands and the mainland uses PLEXOS software. The results show that generation costs are drastically reduced from 200-600 €/MWh to 20-100 €/MWh, and with an increase in renewable energy generation, carbon emissions are reduced up to 60%. Similar research focuses on the interconnection between Greek islands and the mainland and the effect on renewables. Study shows that Greece can achieve %56 renewable penetration on islands with interconnection planning [58]. Another study focused on Crete [59], with bipolar HVDC VSC connection between the island and mainland grids. The study estimated an increase in renewables by 22% to 71% for wind and 5.5% to 11.5% for PV systems, which decreased annual costs for HVDC links, but no general generation costs were estimated. A similar study [60] focuses on Aegean islands with a similar approach, where island and mainland connection is assumed to be a submarine HVDC cable. The results show a 20% cost deduction and twice as wind power usage through the islands.

Besides economic analysis, energy quality analysis was also conducted for islands with HVDC interconnection. One research focuses on frequency improvement of Sardinia Island grid under high penetration of renewable with HVDC transmission and achieved 0.47 Hz improvement [61]. Another example research for Cycladic Islands [62], where the authors examined different submarine cable scenarios and estimated improved energy quality and fewer environmental impacts than the diesel generation implementation.

3.3 Gap

As mentioned in previous sections, many studies were conducted for interconnection systems between islands and the mainland. These studies include economic benefits, technology comparison, or technical changes to island grid properties.

For the economic analyses done, the most crucial comparison factor is the cost of the system as expected. However, such information is difficult to obtain for islands: lifecycle, deployment, installation, maintenance, and operation costs. The inclusion of these could be crucial to the techno-economic analysis of an interconnection project. Also, it is too simplistic, basing the choice of technology on a simple cost vs. distance diagram. Combining these aspects for a case is a complex but critical task to observe and compare HVDC performance with different technologies.

Many of the research mentioned before only focus on one aspect of islands to mainland interconnection. However, comparative analysis with a combination of technical and economic analysis is required to see the performance and benefits of the island to mainland interconnectors.

In addition, many possible interconnection cases did not get research attention before. North Cyprus in the Mediterranean Sea, islands in the Indian Ocean like

Madagascar can be given as an example. While it is easy to guess that interconnections benefit islands in any circumstance, maybe unique aspects of the island can result in a different outcome. So individual research is required for each island case to detect specific outcomes.

3.4 Contribution

A unique case should be chosen to contribute research done for the island to mainland interconnectors, and a combination of different analyses should be conducted.

As explained in the previous section, very little research was conducted on North Cyprus to Turkey interconnection. A few feasibility studies conducted can be found in the literature [63] [64]. However, other studies fail to provide the HVDC interconnector's techno-economic analysis with a comparative analysis of its steady-state effect on the North Cyprus grid.

Also, very little up-to-date information and data can be found like many island grids for the North Cyprus grid. This research also aims to help other researchers who want to work on the North Cyprus grid with grid data and the developed grid model.

CHAPTER 4

CASE STUDY COUNTRY CONTEXT

In this chapter, info about North Cyprus and Turkey will be given. Like many island grids, up-to-date information about the North Cyprus grid is hard to obtain. A good amount of literature research was conducted, and a connection with governmental institutes was established to solve this problem. Some of the given info in this chapter is not used for this research directly, but it is included to close the gap on the island grid of North Cyprus

4.1 North Cyprus Grid

The island of Cyprus, with an area of 9,251 km^2, is the third-largest island after Sicily and Sardinia [65]. 3,355 km^2 of the island belongs to the Turkish Republic of Northern Cyprus (TRNC), and the rest belongs to the Greek Cypriot Administration (KRY) [65]. In the Turkish Republic of Northern Cyprus, the governing organization in the network is the Cyprus Turkish Electricity Authority (KIB-TEK). Energy in North Cyprus is supplied with diesel and steam generators, some renewable energy sources, and the energy taken from the KRY. There are approximately 186,000 different types of consumers managed by KIB-TEK [66].

4.1.1 Total Power

Diesel generators, which are generally the preferred generation type in island networks, are also used as the primary electricity generation source of the North Cyprus grid. Apart from this source, there are also steam turbines and solar energy systems. Currently, the island has about 404 MW of conventional installed power and about 60 MW of renewable energy installed power [67]. The distribution of installed power by institutions can be seen in Figure-4.1.

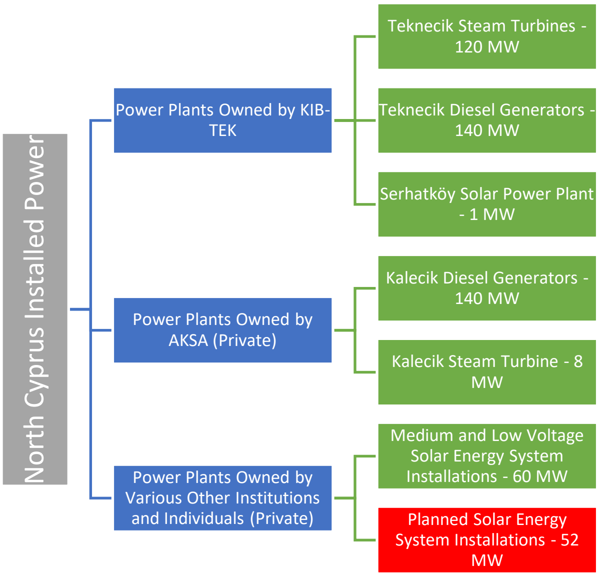

Figure 4.1. North Cyprus Major Power Plants

In order to meet the demand in North Cyprus since 1995, KIB-TEK has been making investments to increase the conventional type installed capacity. The change of the installed power excluding renewable energy in the TRNC by years is given in Figure-4.2. The change of all installed power according to the sources is given in Figure-4.3.

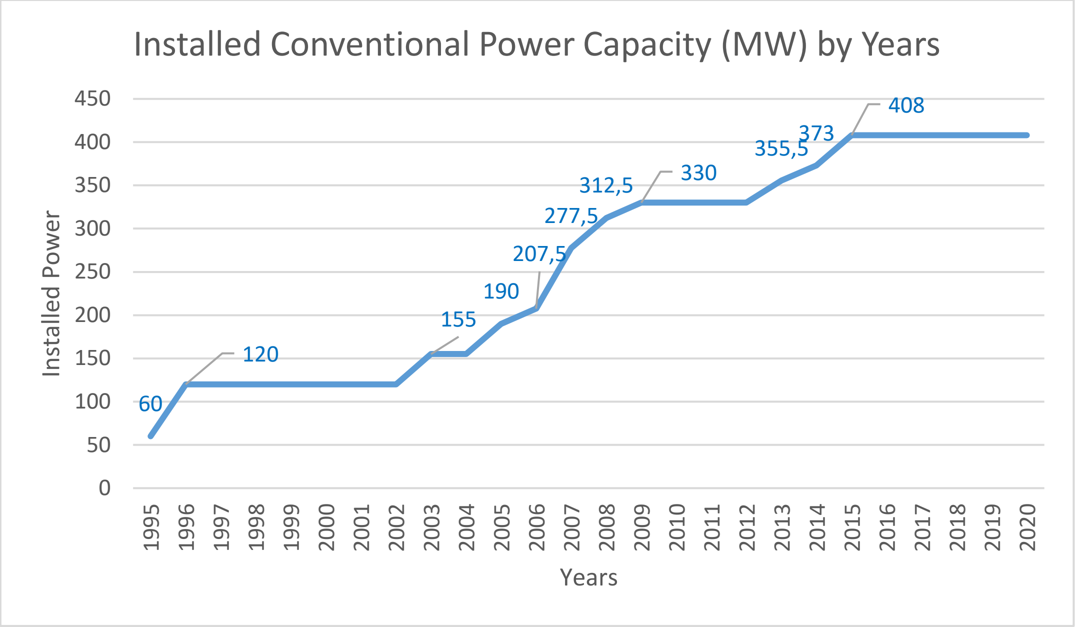

Figure 4.2. Installed Conventional Power Capacity [66]

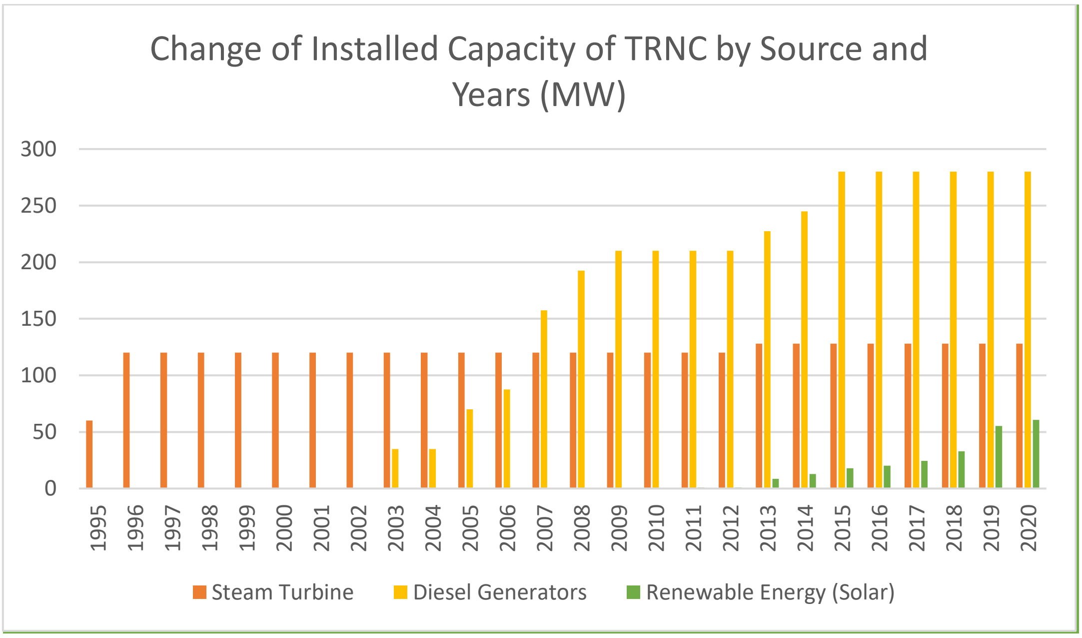

Figure 4.3. Change of Installed Capacity of TRNC by Source

4.1.2 Generation and Consumption

Despite the fluctuations, the North Cyprus electricity consumption amount tends to increase continuously, and this value reached the level of 1.664 GWh in 2019 [66]. The change in the annual production and consumption of electrical energy in North Cyprus by years is shown in Figure-4.4.

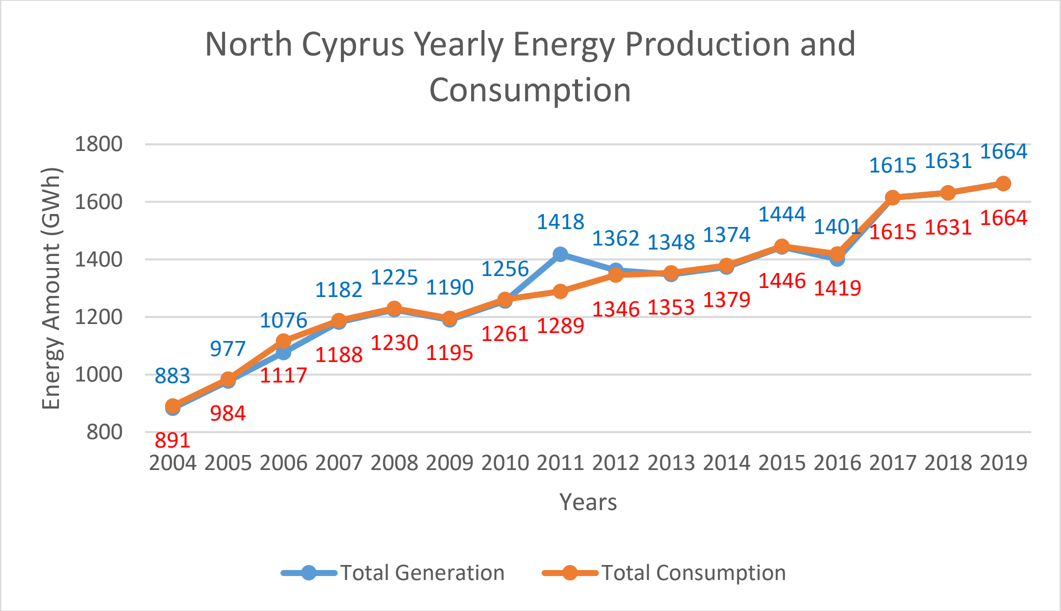

Figure 4.4. North Cyprus Production and Consumption Values

Consumption throughout the year is increasing due to the increase in air conditioning systems brought about by the hot summers. The North Cyprus monthly consumption trend graph can be seen in Figure-4.5.

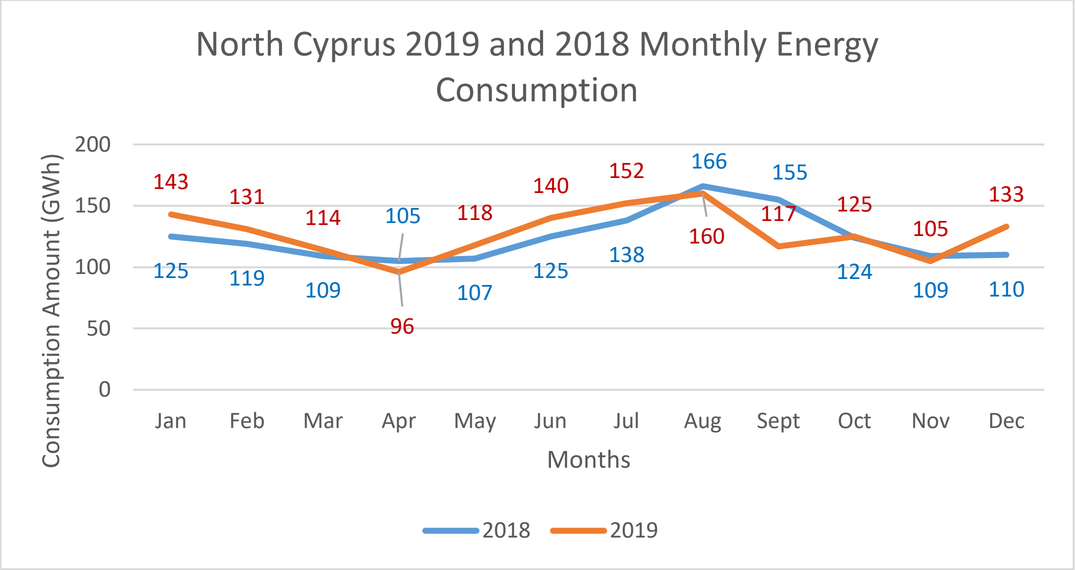

Figure 4.5. North Cyprus 2019 and 2018 Monthly Consumption Amount

Conventional resources under the control of KIB-TEK and Serhatköy PV power plant produced 1664 GWh of electrical energy in 2019 and 406 GWh in the first quarter of 2020. The energy provided to the grid by the renewable energy systems belonging to the Low Voltage and Medium Voltage institutions is received by offsetting. Therefore, there is no record/source of the production of these resources. The distribution of KIB-TEK's production according to resources is given in Figure-4.6.

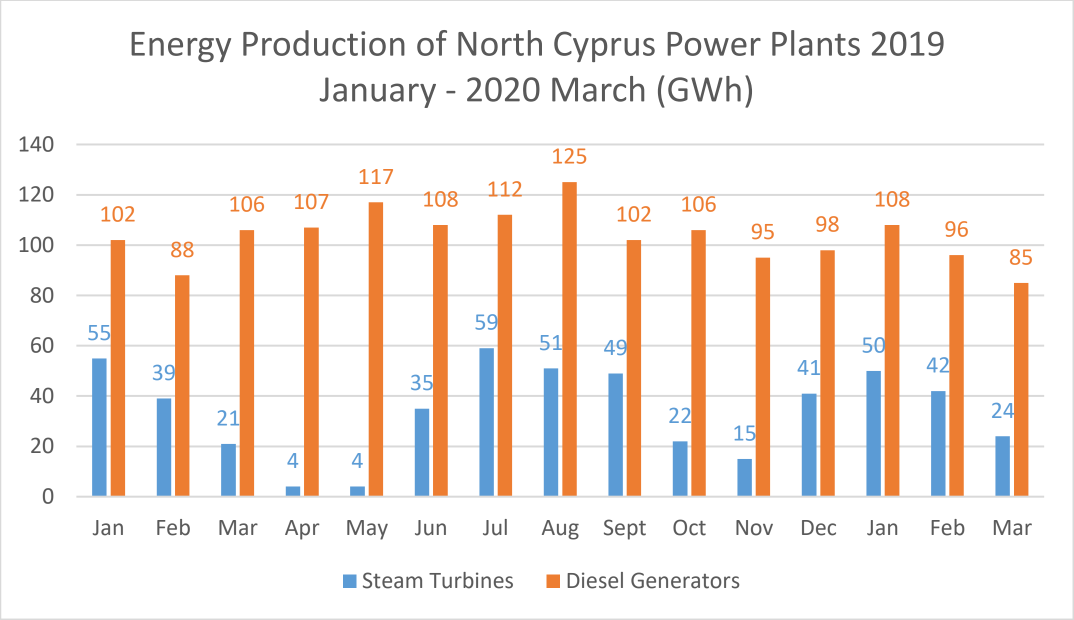

Figure 4.6. Energy Production of North Cyprus Power Plants

In North Cyprus, energy production is carried out at two main points, the Teknecik power plant and the Kalecik power plant. Teknecik Power Plant has eight diesel generators with 17.5 MW power and two steam turbines with 60 MW power. Kalecik Power Plant has eight diesel generators with a power of 17.5 MW and a steam turbine with a power of 10 MW [67]. While the traditional generation model constitutes the primary generation on the island, the residential solar energy systems also constitute the distributed generation model.

Although the diesel generators used to constitute the primary energy production source of the island, there are technical limitations such as taking maintenance for a certain period due to the nature of the devices. Such technical constraints increase the need for backup resources that can be quickly deployed on the island.

4.1.3 Renewable Energy

Due to global warming and limited resources, renewable energy power plants have increased their popularity globally, and serious investments have been made in different facilities and research. The island of Cyprus has also invested in these energy resources because of the island's high solar radiation.

On the island of Cyprus, between 1900 and 2500 kWh of solar radiation per square meter occurs throughout the year. This amount is measured as the best solar energy potential in Europe [68]. In order to use this potential, many solar panel applications and investments have been made on the island. As of the end of September, there are 60.64 MW renewable energy installations in the TRNC. Renewable energy installations to be realized in the TRNC are subject to the permission of the Renewable Energy Board of the TRNC Ministry of Economy and Energy. There is 52.75 MW of renewable energy capacity allowed by this board and not yet installed. New installations made annually to date can be seen in Figure 4.7.

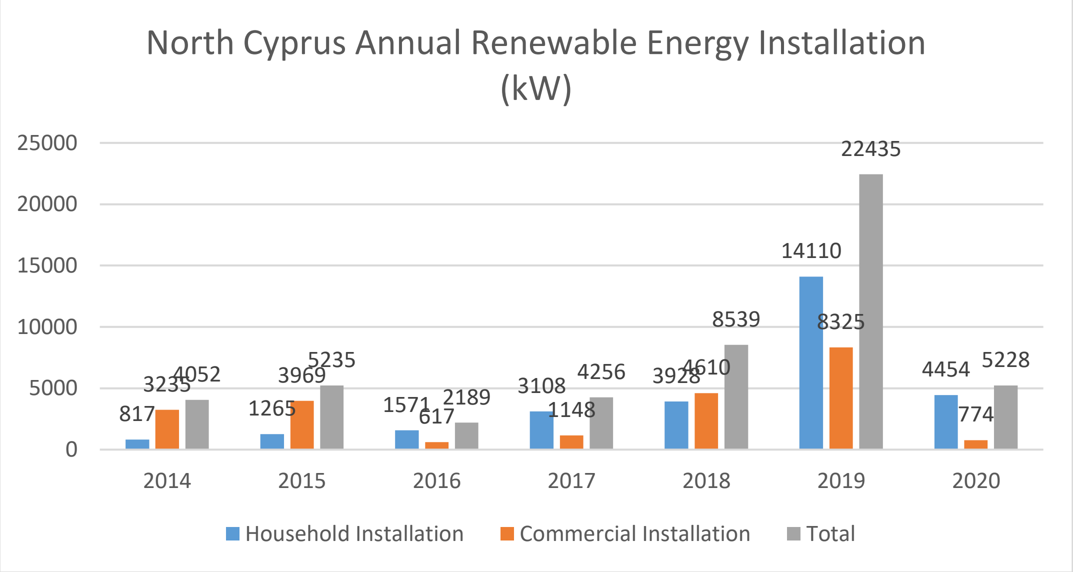

Figure 4.7. North Cyprus Annual Renewable Energy Installation

The ratio of renewable power plants to the resources in North Cyprus by years can be seen in Figure 4.8.

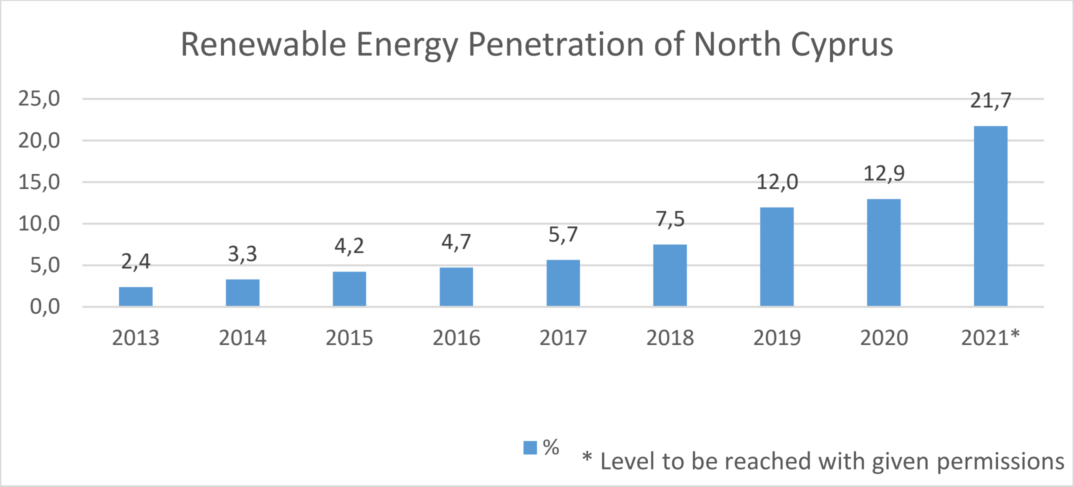

Figure 4.8. Renewable Energy Penetration of North Cyprus

As seen in the graph, even the completion of the power plants with renewable energy power plants, which have reached the level of 13%, is expected to reach 22%.

The amount of energy produced by most of the renewable energy sources in North Cyprus is not directly measured. This result in the small number of input data, the decrease in the performance of the analyzes that can be made, or the prevention of various analyzes. The estimated North Cyprus renewable energy production amount graph prepared based on the generation amounts shared by KIB-TEK for the Serhatköy PV plant can be seen in Figure 4.9.

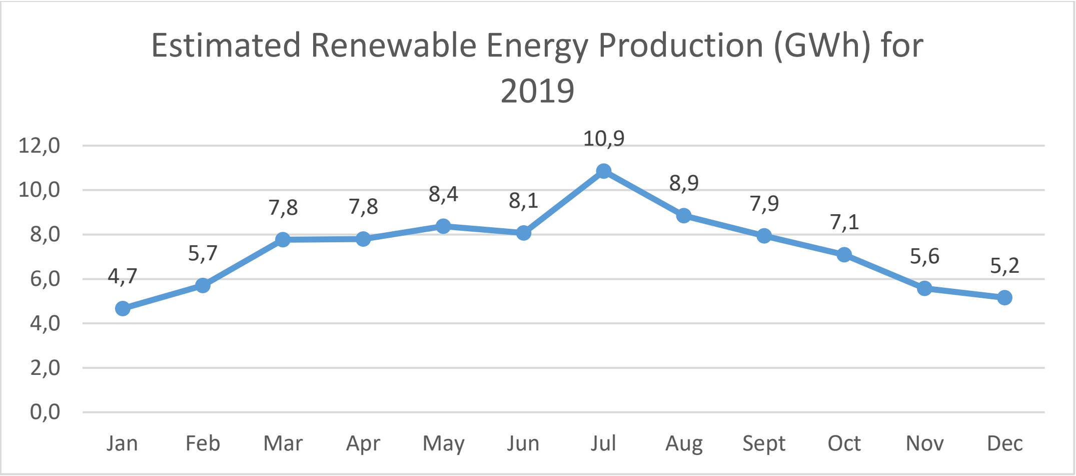

Figure 4.9. Estimated Renewable Energy Production [66]

4.1.4 Transmission

The Cyprus electricity grid operates at four different voltage levels, two high and two medium voltages for transmission. Substations are operating at two levels, 132 kV and 66 kV at high voltage levels. In order to reduce losses throughout the island and increase efficiency, studies are continuing to increase the transmission lines operating from 66 kV to 132 kV. A single line drawing of the island network is given in Figure 4.10 [69].

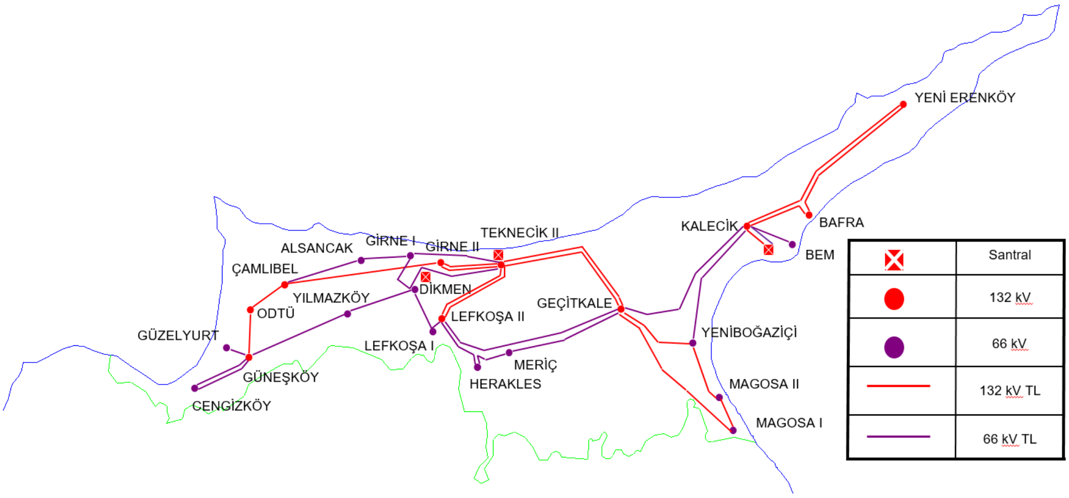

Figure 4.10. North Cyprus Transmission Lines

As seen in the single line diagram in Figure-4.10, there are 32 high voltage transformer centers throughout the island. Between these substations, 545 km of voltage transmission lines have been established. The transmission lines on the island operate at 132 kV and 66 kV levels. Table-3.1 includes HV transformer centers and operating voltage levels.

Table 4.1. North Cyprus Main Transformer Centers

Bus Name	*Voltage Level*	Bus Name	*Voltage Level*
Teknecik ST 1	132 kV – 66 kV	Herakles	66 kV
Kalecik	132 kV – 66 kV	Lefkoşa	132 kV - 66 kV
Yenierenköy	132 kV	Cengizköy	132 kV
Bafra	132 kV	Güneşköy	132 kV
BEM	66 kV	ODTÜ	132 kV
Yeniboğaziçi	132 kV	Çamlıbel	132 kV - 66 kV
Geçitkale 1	132 kV – 66 kV	Alsancak	66 kV
Magosa 2	66 kV	Girne 1	66 kV
Magosa 1	66 kV	Girne 2	132 kV
Meriç	132 kV	Dikmen	66 kV
Haspolat	132 kV	Yılmazköy	66 kV

4.1.5 Distribution

The electrical energy delivered to the high voltage centers is reduced to 22 kV or 11 kV medium voltage levels in the system, and regional distributions are carried out. The energy that has been reduced to these levels is delivered to MV-LV transformer centers, and distribution is carried out by reducing it to 240 V or 415 V voltage levels.

4.1.6 Grid Network Traceability

With a project in 2007 for the first time in the North Cyprus grid, the necessary devices and equipment were installed in 11 high voltage centers. The first system was used with a one-year trial version provided by SIEMENS, and then SCADA was installed with the software and hardware of MIKRONIKA with the financing of the European Union. SCADA system interface is given in Figure 4.11.

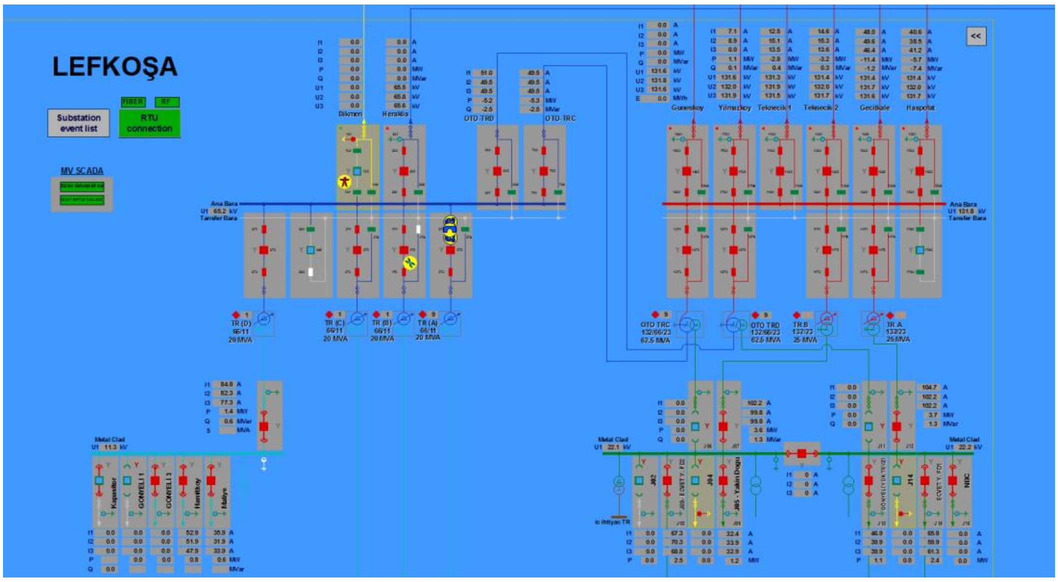

Figure 4.11. Example SCADA System Monitoring Screen

Currently, the KIB-TEK SCADA System performs the following functions:

- Monitoring Functions (Event, Alarm and instant data monitoring)
- Control Functions (Control of control units)
- Data Collection (Transferring instant data to the system)
- Recording and Storage of Data (Recording and archiving the collected data)

This system was used to establish a model for this research.

4.1.7 Grid Code

There is no network operating regulation, standard, or grid code for the network managed by KIB-TEK. The network is managed under laws and general regulations.

Because of this situation, there are excessive renewable penetration, lack of grid data measurement, bad investment planning, and many other problems.

4.1.8 Demand Increase Near Future

In most island cases, investment in energy generation is made in long time intervals compared to the constantly growing mainland grid. While forecasting demand is essential for all electricity grids, islands require more careful demand analyzes. Because nature of islands, making grid investments is expensive and challenging.

It is known that North Cyprus requires improvements to its grid. This situation can be observed from the Renewable Energy Board's allowance for renewable solar installations until further notice [70] because of declining grid stability. Another example of an improvement requirement is after a generator failure, KIB-TEK had to apply load shedding to the grid, which caused blackouts around the island [71].

It can be seen from Figure 4.4 energy demand increases every year while synchronous generation capacity does not change. Demand increase created a non-sustainable situation for North Cyprus where renewable penetration reaches dangerous levels for an island while synchronous energy generation stays the same. Another risk for the North Cyprus grid is the deadline for the energy generation contract made with AKSA until 2024.

Under these circumstances, North Cyprus has very few options: extension to the power plant capacity of KIB-TEK, or extending the AKSA contract of energy production, connecting the electric grid system to the mainland with the means of a submarine electricity cable. All proposed methods have their pros and cons based on different factors such as political, financial, and environmental risks.

4.2 Situation of Turkish Electric Energy

Turkey is a country between Europe and Asia with near 80 Million population. This high population makes energy demand considerably high, and many generation plants are established because of that. Turkey has the second-largest installed power in Europe after Germany. In the case of Turkey, the increase in energy demand has been 5.5% annually since 2002. As of July 2019, Turkey has reached an installed capacity of 90.4 GW, which corresponds to an almost three-fold increase in 17 years [72]. Since the TRNC is an island country, it has a small electricity grid compared to Turkey, with an installed power of 404 MW.

While the installed clean energy potential in the world is about 23%, Turkey's installed renewable energy potential is more than 40% of its total installed power [72]. From this, we can see that Turkey has a lot of clean energy potential and performance compared to other countries in the world. Despite having excellent potential, Turkey still imports an increased amount of natural gas for electricity. Figure 4.12 shows the Turkey generation mix.

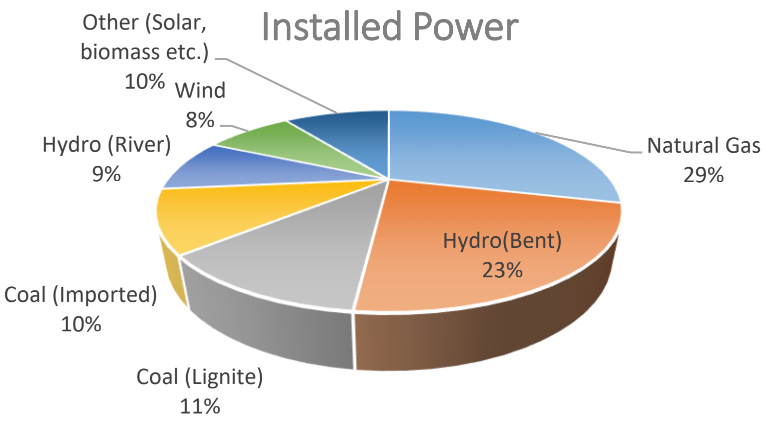

Figure 4.12. Turkey Energy Generation Mix [72]

In this aspect, a transmission line between Turkey and North Cyprus potentially increases renewable energy usage for both countries. For North Cyprus with interconnection, renewable energy pressure on the grid will decrease, and more renewable energy investments can be made. Also, the energy transferred from Turkey will have a better generation method mix which can be counted as renewable usage. For Turkey, North Cyprus's outstanding solar energy potential can be used. Turkey can export excess renewable energy from North Cyprus with interconnection, increasing renewable energy in the generation mix.

For simplicity and scale of power capacity compared to North Cyprus, it is assumed that Turkey's electricity grid can supply an infinite amount of energy.

4.3 EuroAsia Interconnector

For Cyprus island, there is another interconnection project in progress. The EuroAsia Interconnector will start near Hadera in Israel, and after stopping by the island of Cyprus, it will end over Greece. The EuroAsia Interconnection is planned to be 1518 kilometers long with three sections [73]. The Israel-Cyprus section is 310 kilometers, the Cyprus Island-Crete section is 898 kilometers, and the Crete-Attica section is 329 kilometers. The lowest submarine point to be installed will be 3,000 meters below sea level. Submarine cables must be placed at this depth to avoid technical difficulties on the planned route due to the nature of the sea floor. The interconnection capacity planned as two phases is planned to be 2000 MW. The connection can be seen in figure 4.13.

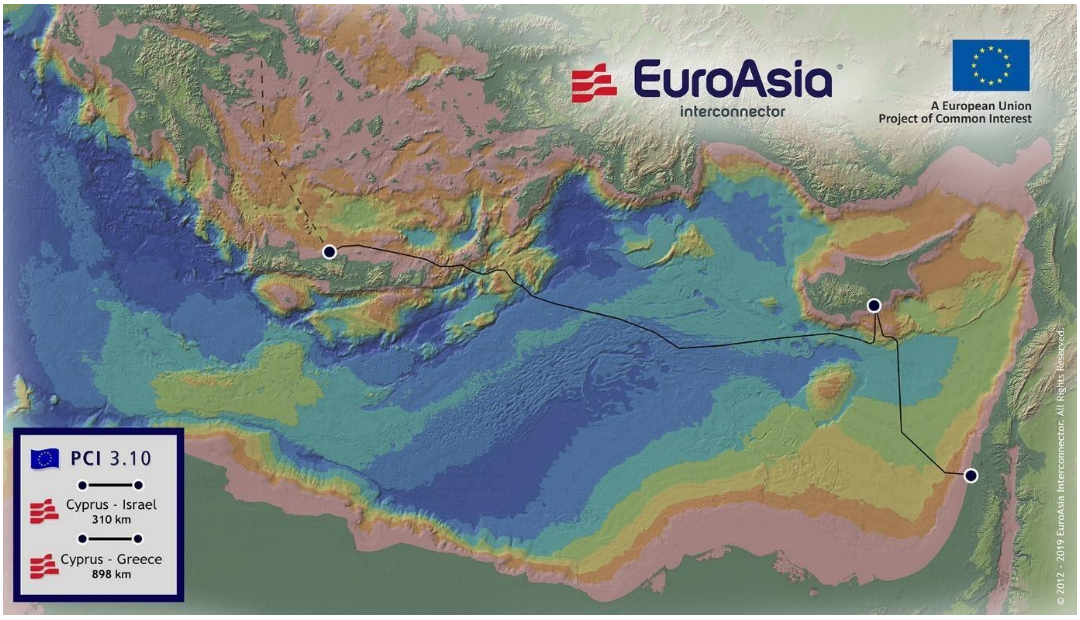

Figure 4.13. EuroAsia Interconnector [73]

Given properties of the project poses severe legal and geopolitical risks for the EuroAsia Interconnection due to legal uncertainty regarding the free passage of submarine cables and the dispute over the delimitation of maritime zones.

The economic, technical, legal, and geopolitical barriers of EuroAsia Interconnector automatically raise the feasibility of the North Cyprus – Turkey interconnector. This connection will comparatively only be 80 to 100 kilometers long and will not pass through the deep sea, ultimately costing much less considering the 1200 kilometers of EuroAsia interconnector. Turkey signed an interconnection agreement with the TRNC in 2016, and an already established connection with the south Cyprus grid will increase interconnection feasibility for the whole island.

CHAPTER 5

METHODOLOGY

For this case study, North Cyprus and Turkey were selected because of acquired data. Analyses conducted in this research focus on two main aspects: technical aspects of interconnection with grid analysis methods for HVDC, HVAC, and new diesel generator cases. The second one focuses economic effects of interconnection with HVDC, HVAC, and new diesel generator cases.

5.1 Grid Analysis Methods

Various methods have been developed to analyze electricity networks in the world, see the current situation of the grid, and try different scenarios. These methods generally enable to foresee the problems to be experienced during the operation of the networks. The main methods are as follows;

- Power Flow
- Continuous Power Flow and Voltage Stability Analysis
- Optimal Power Flow
- Small Signal Stability Analysis
- Time Domain Simulation
- Error Analysis
- Grounding Systems
- Harmonic Analysis
- Protection Analysis and Coordination
- Graphical User Interface

This thesis studied the steady-state properties of the cases, so power flow analysis and optimal power flow analysis are used. In the next section, a more detailed explanation of these analyses is given.

5.1.1 Power Flow Analysis

Power flow analysis is one of the primary tools used in any power system analysis. This analysis is used in planning and design studies to determine whether a particular element in the infrastructure is at risk of overloading.

For operations, power flow analysis studies are performed to ensure that each generator reaches its optimum operating capacity, can be safely maintained, and that the power supply can satisfactorily meet the demand.

A power flow analysis refers to a steady-state analysis of a power network. It is used to determine how the system will work depending on the given installation.

Theoretically, a load flow analysis provides a mathematical description of an electrical network. Usually, an iterative approach is used where unknown values such as currents and voltages are solved. Numerical analysis methods such as Newton-Raphson and Gauss-Seidel help to find values.

Power flow studies are done to plan for various scenarios and hypothetical situations that put the operation of a power system at risk of disruption and damage. For example, scenarios such as performing maintenance activities on transmission lines, removing elements from the network are used within the scope of this analysis. In such cases, it is observed whether loads of the remaining lines exceed their nominal values.

Power flow analysis is also primarily used to develop the plan and design of future power system expansions. It also allows new generator sites that can meet the increase in load demand and identify new transmission areas.

We can summarize the importance of this analysis basically as follows.

- Provides a benchmark to compare changes in voltage and mains flows under abnormal conditions
- Assists in the design of protective devices and explore a system's ability to deal with problems of all types and sizes
- It reveals how new lines to be added can reduce overloads occurring on adjacent lines.
- Facilitates necessary economic evaluations; showing how much of the losses have been reduced by the installation of the new line
- It plays a fundamental role in the planning, control, operation, and economic programming of existing power systems.
- Enables future expansions by understanding the impact of adding new components to the infrastructure
- Helps determine optimal capacitor size and location to improve power factor and increase network bus voltages
- A power system consists of busbars to which lines, generators, and loads are connected.

Each bus has four main variables in power flow analysis: voltage magnitude, phase angle, real power, and reactive power. Each bus has two power flow equations that make the analysis nonlinear.

Two of the four variables are identified in a load flow study, while the remaining two are unknown. This way, the equations are equal to the number of missing values. In the general system, these equations are created, and the solutions that determine the system are found with the mathematical iteration methods given above.

To achieve the results of power flow analysis, there are many options. For this research, open-sourced MATPOWER is used, and prepared grid models with bus, branch and generator data are used in this program. A detailed explanation of the calculation principles of this program can be found in the program’s manual [74].

5.1.2 Optimal Power Flow Analysis

The development of optimum power flow (Optimal Power Flow, OPF) has a long history. It was first evaluated by Carpentier in 1962 [75].

OPF is often used to calculate the minimum cost of production while balancing the entire power flow simultaneously as the optimization calculation. The grid balance can be established in different ways to minimize the production cost. OPF can also be expressed as the minimum shift of generation and other controls from the optimum operating point or minimizing electrical losses in the transmission system. It is also used to adjust loads to determine the minimum load reduction program in emergencies.

Many "control" variables can be identified in the OPF analysis compared to standard analyses. Such variables can be summarized as follows;

- Generator voltage.
- LTC transformer tap position.
- Phase shift transformer tap position.
- Modified capacitor settings.
- Reagent injection for a static VAR compensator.
- Load reduction.
- DC power flow.

OPF has many applications, including:

- Calculation of all control variables as well as optimum production model to achieve minimum production cost while meeting transmission system limitations
- Estimate a "preemptive shipment" using the current state of the power system or a short-term load forecast, including OPF, safety constraints
- In an emergency, i.e., when some system components are overloaded or experience a bus voltage violation, the OPF calculates a "corrective send"

that tells the operators of the system what adjustments they need to make to mitigate the overload.

- Use of OPF to find the optimum setting for generation voltages, transformer stages, and switched capacitors or static VAR compensators (sometimes called "voltage-VAR" optimization)
- The OPF is routinely used in planning studies to determine the maximum voltage that a planned transmission system can withstand. For example, OPF can calculate the maximum power that can be safely transferred from one network area to another.
- OPF is used to provide “bus incremental costs” (BICs) in the economic analysis of the power system. BICs are useful for determining the marginal cost of power on any bus in the system. Similarly, OPF can calculate the incremental or marginal cost of transferring power from one external company through the system to another external company.

Optimal power flow is a vast and complicated mathematical programming problem. Almost every mathematical programming approach that can be applied to this problem has been tried, and it took developers decades to develop computer code that would reliably solve the OPF problem. Lambda-iteration methods, gradient method, Newton's method, and two relatively new techniques, linear programming (LP) and interior-point methods, are used in OPF analysis.

For an economic analysis of HVDC between Turkey and North Cyprus, we used MATPOWER's own Optimal Power Flow algorithm with North Cyprus Grid Model and generator cost function results obtained accordingly.

The MATPOWER AC OPF algorithm optimizes generator cost functions based on real and reactive power injections for each generator. The standard version of Optimal Power Flow can be summarized as [74];

$$min_x f(x) \tag{1}$$

Subject to;

$$g(x) = 0 \tag{2}$$

$$h(x) \leq 0 \tag{3}$$

$$x_{min} \leq x \leq x_{max} \tag{4}$$

Where objection function Eq. (1) is the summation of cost functions of real and reactive power injections, optimization variable x is defined as a matrix where voltage angle, magnitude, real power, and reactive power for each node (node) and generator follows. Equality constraints Eq. (2) consists of nodal power balance equations where voltage angle and magnitude are used with real and reactive power. Inequality constraints Eq. (3) consists of branch flow limits based on voltage angle and magnitude. Eq. (4) variable limits include reference node angle and voltage upper and lower limits for all node voltage magnitude and real and reactive generator injections. Detailed explanations for optimal power flow used in this study can be found in [74].

5.2 Modeling North Cyprus Electricity Grid

5.2.1 Available Data

The island grid model was established by combining different resources from KIB-TEK and North Cyprus Energy Ministry.

For this model, load and generator variables were taken from the High Voltage SCADA system. KIB-TEK shared generation capacities, screen shots of grid observations with low, high and average load cases. Transmission line variables are taken from the grid plan, which has information on cable type and length to calculate required values. Taken grid data can be seen in figure 5.1.

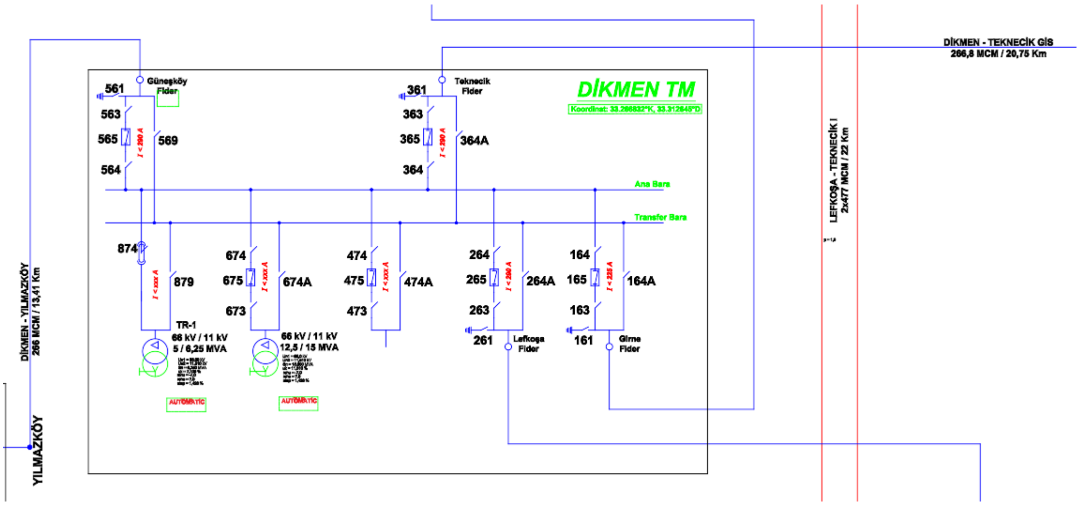

Figure 5.1. Example North Cyprus Grid Data

After cable type and length are acquired from shown data, tables given in [76] were used to obtain required branch values like resistances and capacitances. Load values of busses were taken from the North Cyprus SCADA system, where instant power values were used. It is possible to improve the model with renewable generation and grid extension plans, but shared data for these properties is insufficient.

To conduct optimal power flow analysis, economical properties of generation are required. However, KIB-TEK does not share prices of oil and other expenses because of their policy. To solve this problem, values included in research conducted for Malta island [54] were used for optimal power flow analysis and other economic calculations.

Like many Mediterranean islands, North Cyprus has seasonal characteristics. Rising temperatures in the summer months lead to high air conditioning use. This usage can be seen in electricity generation numbers as they increase. Synchronous generation methods in North Cyprus all use Fuel Oil No. 6. The national electric company, KIB-TEK, does not share the specific type of fuel oil information, so the average price for

Heavy Fuel Oil is used in the analysis. Table 5.1 shows the generation capacity and characteristics of North Cyprus provided by KIB-TEK [67].

Table 5.1. Generation Capacity and Characteristics of North Cyprus

Technology of Generation	Nominal Capacity [MW]	Internal Consumption [MW]	Fuel Rate [kg/MWh]	Fossil Fuel Type	Avg Marginal Cost [€/MWh]	Lowest Marginal Cost [€/MWh]	Highest Marginal Cost [€/MWh]
Teknecik Steam 1	60	5	270	HFO	118,125	67,5	168,75
Teknecik Steam 2	60	5	270	HFO	118,125	67,5	168,75
Teknecik Diesel	140	5	180	HFO	78,3	44,74	111,86
Kalecik Diesel	140	5	180	HFO	78,3	44,74	111,86

Because Malta and North Cyprus island networks have similar configurations and share very similar properties, cost data taken from Malta should result similarly in the North Cyprus case. Fuel data taken from [54] can be found in Table 5.2.

Table 5.2. Fuel Price

	Fuel Price [€/kg]	[€/MWh]
Base (Avg) Oil Price	0.42	35
Low Oil Price	0.24	20
High Oil Price	0.6	50

Table 5.3 shows the monthly electricity generation of North Cyprus for 2019 [66]. Values-based on generators owned by KIB-TEK. These values were used to calculate the generation cost for North Cyprus.

Table 5.3. Monthly Energy Generation

Month	Teknecik Steam 1	Teknecik Steam 2	Teknecik Diesel	Kalecik Diesel
1	27255	27930	59065	42597
2	20796	18150	59005	28755
3	0	21053	59425	47040
4	0	4124	59459	47407
5	0	3668	59676	57024
6	8735	26830	59929	47520
7	29180	29798	60135	52180
8	21493	29602	64259	60526
9	24538	24058	59950	42247
10	21940	0	59666	45334
11	0	15020	59886	35506
12	13929	27235	39386	58710

5.2.2 Developed Model

The developed model of the North Cyprus island electricity grid consists of 32 busses. The island's general load is taken from a high-demand scenario of 289.5 MW, and the generation capacity without renewable sources is 404 MW. The model is built compatible with MATPOWER software which is given in Appendix A. The prepared model is illustrated in Fig. 5.12.

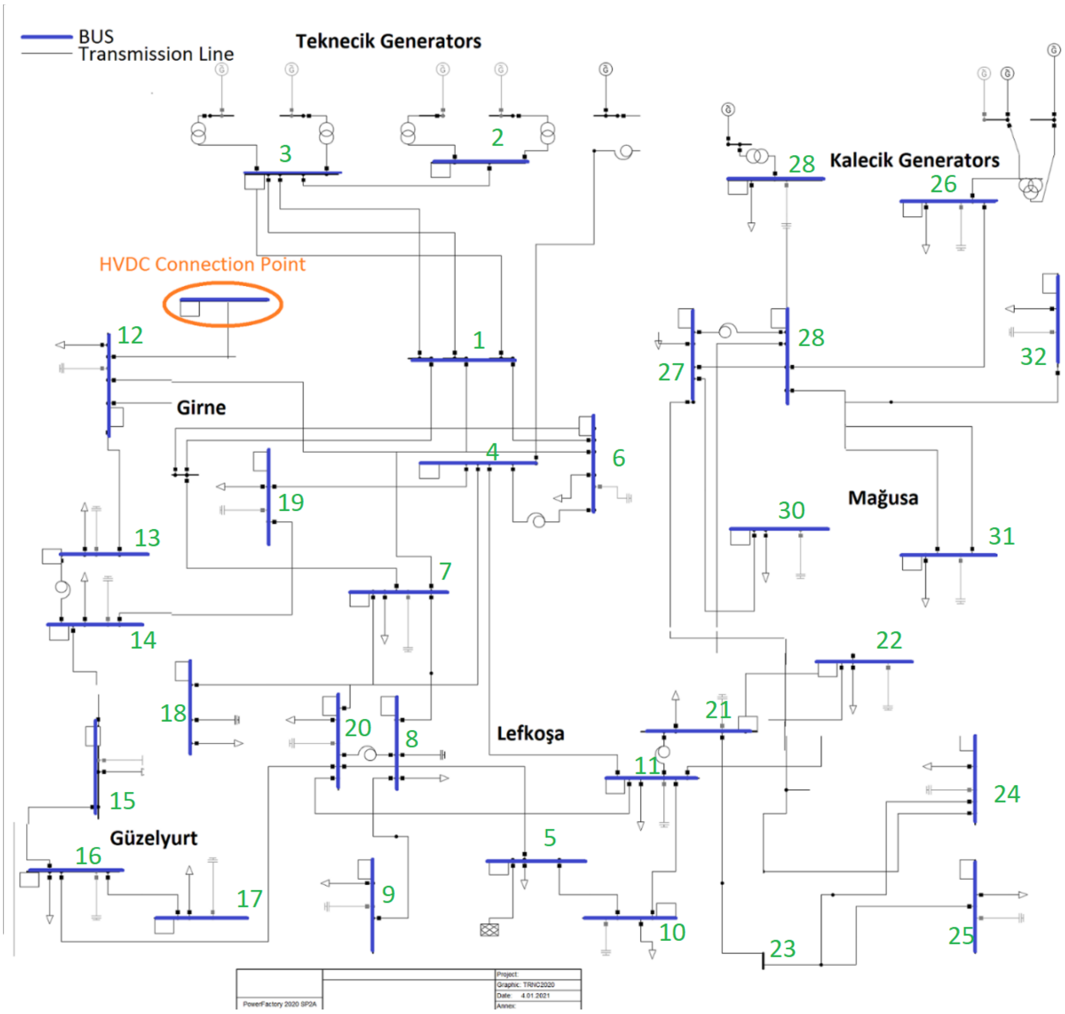

Figure 5.2. Developed North Cyprus Grid Model

Power flow analysis was done with this model compared with the North Cyprus SCADA system to determine the model's accuracy.

5.3 HVDC VSC Inclusion to Developed Model

When North Cyprus’s geography is considered, a transmission line can be established with a certain amount of busses. Figure 5.13 shows the geographical locations of busses on the island.

Figure 5.3. Geographical Locations of Considered Busses

To decide the connection point of transmission line series of load flow analyses conducted with different possible connection point cases and loss values obtained. These cases used are as following;

- Alsancak (66 kV)
- Girne 1 (132 kV)
- Girne 2 (66 kV)
- Teknecik HV (132 kV)

The connection point with the lowest loss on the system is considered the connection point of the HVDC system and used in other analyses.

5.4 Interconnector Initial Cost Analysis

For economical analysis for this type of research, the initial cost is essential. While interconnection projects can bring many benefits, these investments are one of the costliest energy investments for islands.

To see approximate initial cost for HVDC and HVAC interconnections multiple methods developed [38], [52], [77], [78], [79], [80], [81], [82], [83], [84] in literature.

While nearly all of the methods can be used in this research, the method given in [52] is the best choice among them. This is because this research includes more parameters and input values to developed equations than other ones, giving more correct results.

Basically, this method develops empirical formulas for both HVDC and HVAC initial costs. These formulas combine capital costs and the cost of power losses to estimate the cost of the system. Formulas are given as;

$$C_{HVDC} = CC_{HVDC} + LC_{HVDC} = 25 + 0.011S_T + 0.08148S_T + t_c * l_c * nc_c + 0.02610S_T + 3.03534\left(\frac{0.9828S_T}{nc_c*V_n}\right)^2 * r_c * l_c * nc_c + 0.02747\left[0.9828S_T - \left(\frac{0.9828S_T}{nc_c*V_n}\right)^2 * r_c * l_c * nc_c\right] \tag{5}$$

$$C_{HVAC} = CC_{HVAC} + LC_{HVAC} = 5 + 0.045S_T + 0.02621S_T^{0.7513} + t_c * l_c * nc_c + 0.02V_n^2 * 2\pi f_n C * l_c + 0.00911S_T + 1.51767\left(\frac{0.994S_T}{nc_c*V_n}\right)^2 * r_c * l_c * nc_c + 0.00911\left[0.994S_T - \left(\frac{0.994S_T}{nc_c*V_n}\right)^2 * r_c * l_c * nc_c\right] \tag{6}$$

Where;

$CC = Capital\ costs$

$LC = Power\ Loss\ costs$

$S_T = Power\ rating$

t_c= cable cost per set

l_c= Distance

nc_c= Cable set number

V_n=Voltage

r_c= Resistance

$f_n = frequency$

C= capacitance

For diesel generator costs, KIB-TEK [67] for previous diesel generator installation projects were adjusted with inflation and used directly.

5.5 North Cyprus – Turkey Interconnector Case Study Characteristics

As mentioned earlier, the research analyzes the project with an assumed HVDC transmission line of 95 km (80 km subsea and 10 km overhead cable) length with a rated transmission capacity of 800 MW and 200 MW HVDC VSC substations installed on both ends of cable for the initial startup. The submarine cable capacity is initially set high at 800 MW to keep a margin for any future growth of electricity exchange by simply adding more substations on both sides of the cable without replacing the cable. Also, Turkish spot market prices [85] are used when electricity is transferred from the mainland.

All of the parameters used in this research are based on assumptions explained previously and the most commonly used parameters in literature.

Table 5.4. Interconnection Cable and Other Parameters

Parameter	*HVAC*	*HVDC*
Distance	95 km	95 km
Voltage	132 kV	132 kV
Power Rating	200 MW	200 MW
Cable Cost per Set [52]	1105 k$/km	1188 k$/km
Number of Cable Sets	2	1
Capacitance [52]	217 nF/km	-
Resistance [52]	32.4 mΩ/km	22.4 mΩ/km

CHAPTER 6

RESULTS AND DISCUSSION

6.1 North Cyprus Grid Model Power Flow Results

Power flow analysis is conducted with a developed grid model and obtained results compared with measurements in the SCADA system to see if the model is accurate.

Table 6.1. Power Flow System Summary

Type of Travel	*Power Flow Results*	*SCADA Data*
Generation P (MW)	294.24	287.9
Generation Q (MVAr)	106.7	111.7
Loss	4.737 MW 17.98 MVAr	-

The table shows that generation values have high similarity, but detailed examination shows that generators used in the two cases are different. Because SCADA reads values from the optimized system, this difference is expected since power flow analysis does not consider generator differences like real applications. Figure 6.1 shows visualized results of power flow analysis are given.

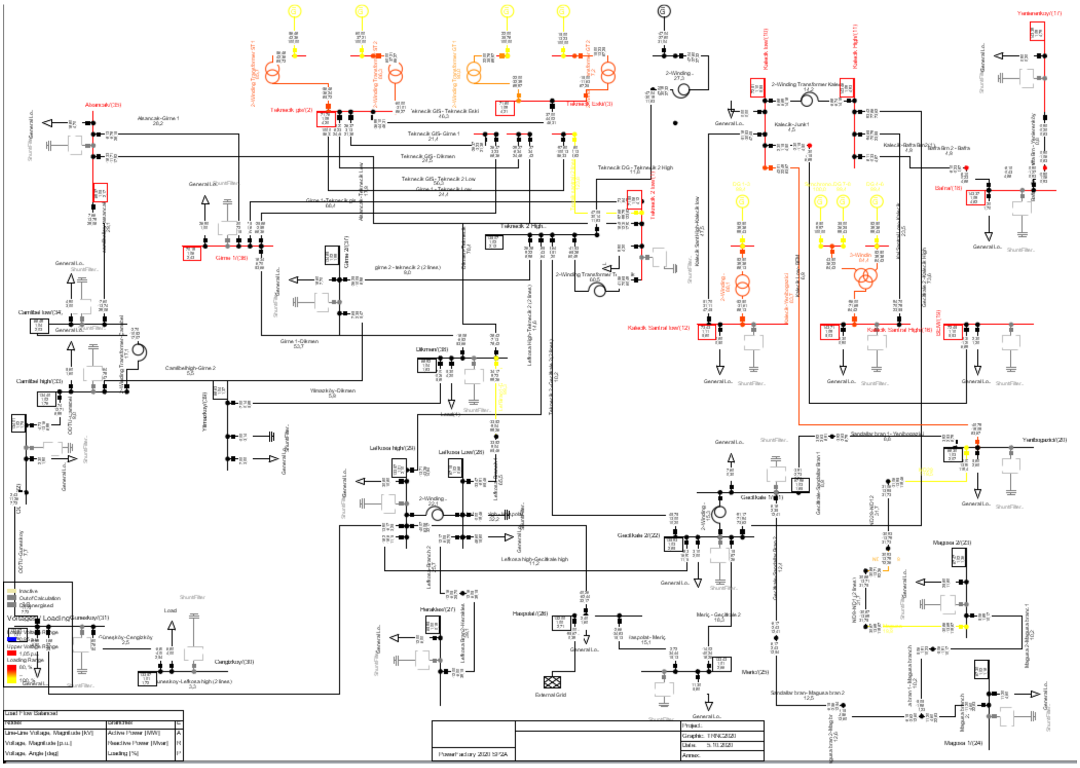

Figure 6.1. Power Flow Results

With similar results obtained in power flow compared to the SCADA system, this model can analyze interconnector systems. Nevertheless, for more accurate results, extended analyses on Chapter 5 should be conducted.

6.2 HVDC Transmission Line Bus Selection

Power flow analysis was done with different cases mentioned in section 5. Change in results can be found in table 6.2.

Table 6.2. Interconnector Connection Bus System Analyze Results

Case	*Loss (MW)*
Alsancak	3.26
Girne 2	8.32
Girne 1	Did not Converge
Teknecik High	7.566

Based on results, HVDC or HVAC interconnections are assumed to be made with Alsancak Bus.

With these results also we can see that with HVDC or HVAC, interconnection losses can be reduced. Fewer losses can be interpreted as increased grid stability. However, a comparison between HVDC and HVAC cannot be made only with these results. Significant differences between these solutions come from their economic properties.

6.3 Optimal Power Flow of Island Grid

As explained in previous sections, OPF takes generation costs and classic power flow parameters to achieve the best-case scenario for a given grid case.

OPF is done based on generation prices and spot prices given in the previous sections. HVDC interconnector to the North Cyprus grid is added based on the method explained in the MATPOWER manual, which is described as adding another generator. System summaries with and without the HVDC interconnector cases can be found in Table 6.3.

Table 6.3. Island Grid OPF System Results

	Without Transmission Line	With Transmission Line
Total Gen. Capacity (MW)	404	604
Total Load (MW)	289	289
Losses (MW)	5,86	3,26
Nodes	32	33
Generators	5	6
Lambda P $/MWh	95,98	88,40
HVDC Utilization (MW)	-	200 MW (100%)

It can be seen that Lambda P decreases nearly 10% for the maximum value of a node. Also, system loss decreases with the interconnector by nearly half, compared to the case without HVDC.

Monthly generation costs were calculated after the fundamental analysis was conducted on available data given in the previous sections. Results for both cases with and without HVDC can be found in Figure 6.1.

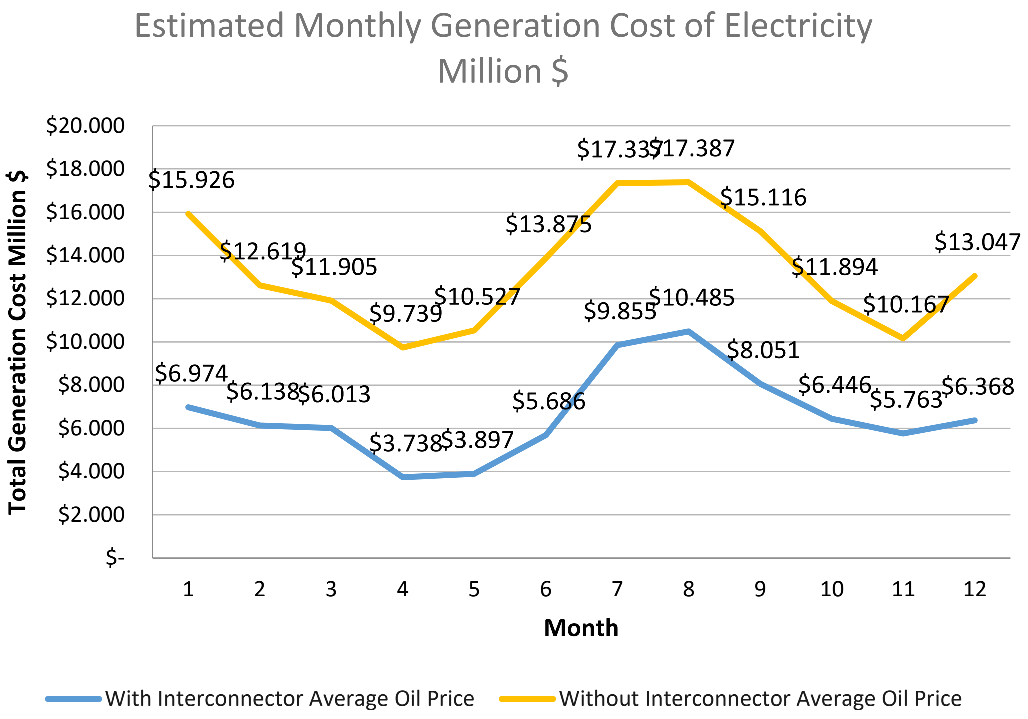

Figure 6.2. Estimated Monthly Generation Costs of Electricity

Based on the values found, a near 48% decrease can be observed based on the average oil price at a specific time. This dependency makes the North Cyprus grid very volatile against oil prices. While this calculation is fundamental and requires further research for more accurate results, we can say that a considerable generation cost reduction can be achieved.

6.3.1 Investment and Annual Cost Calculation Results

Parameters used to calculate initial costs with the formula mentioned in Chapter 5 are given in Table 5.5.

Based on formulas (5 and 6), cost calculation results for HVDC and HVAC are given in Table 6.4.

Table 6.4. Initial Costs

Solution	*Cost*
HVDC	359.843 million $
HVAC	373.076 million $
Diesel Generator	132 million $

The annual cost is calculated by adding system maintenance costs and loss costs for each year. System maintenance cost is taken 0.5% of the total components cost for all solutions to calculate the annual cost. Substations, cable installments, and STATCOM are the main cost parameters for the HVAC and HVDC systems. For diesel generators, maintenance costs are assumed to be the same. Figure 6.3 gives a comparison between annual expenses.

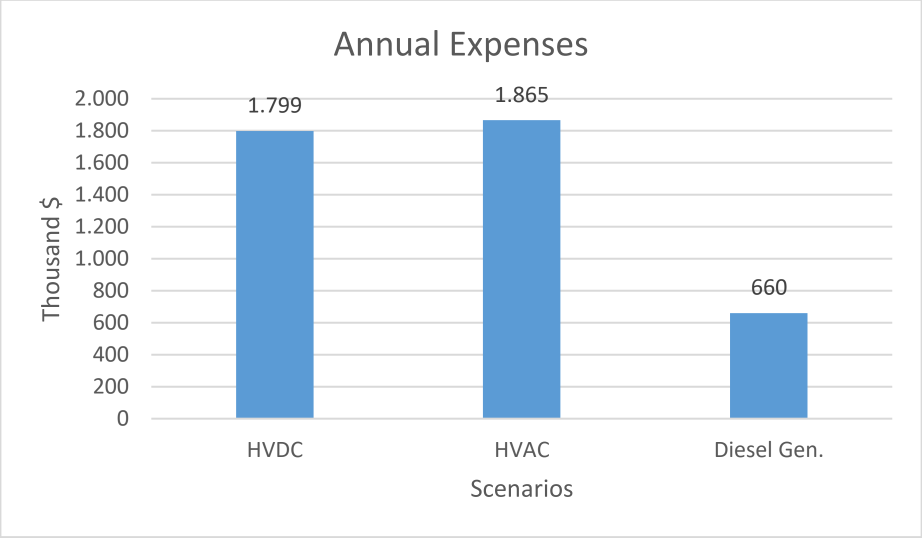

Figure 6.3. Annual Expenses

6.4 Conceptual Return of Investment Comparison of HVDC, HVAC and Diesel Generators

The generation cost difference between energy generated on the island and the mainland is used to calculate estimated payback periods for different scenarios.

HVDC and HVAC cases do not have a significant difference when comparing optimal power flow analysis since the steady-state nature of these two technology assumed similar. Since energy generation costs for diesel generators will be very similar to current energy generation values, it is assumed to cost savings will be zero through the year. While new technology generators can work with higher efficiency, the lack of different generation methods and CO_2 release nullifies this advantage. Even in the long run, this solution can cause increased generation costs because of these reasons.

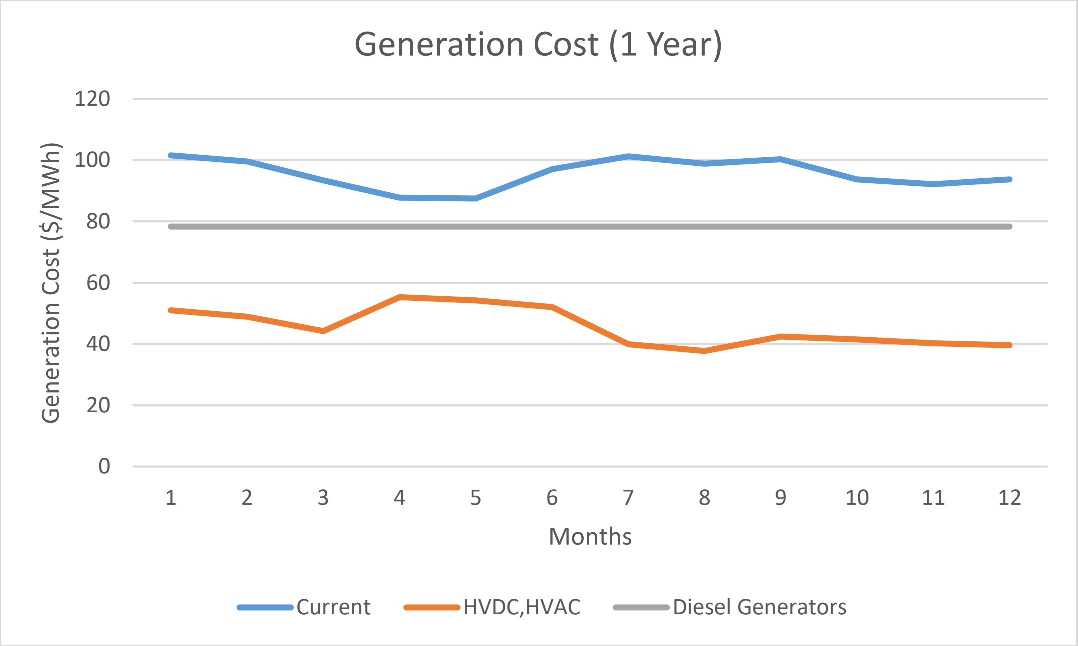

Figure 6.4. Generation Costs per MWh for 1 Year

Table 6.5. Total Savings per Scenario

Month	***Energy Generated [MWh]***	***Interconnector Cost Difference [$/MWh]***	***Diesel Generator Cost Difference [$/MWh]***	***Interconnector Total Savings [$]***	***Diesel Generator Total Savings [$]***
1	156847,00	50,99186	23,23717	$ 7.997.920,49	$ 3.644.679,90
2	126706,00	48,91011	21,29434	$ 6.197.204,99	$ 2.698.120,20
3	127518,00	44,24015	15,06172	$ 5.641.414,83	$ 1.920.640,60
4	110990,00	55,26834	9,450248	$ 6.134.233,21	$ 1.048.883,00
5	120368,00	54,25967	9,156799	$ 6.531.128,05	$ 1.102.185,60
6	143014,00	51,98332	18,72127	$ 7.434.342,16	$ 2.677.403,80
7	171293,00	39,8995	22,91313	$ 6.834.505,72	$ 3.924.858,10
8	175880,00	37,71026	20,5549	$ 6.632.480,90	$ 3.615.196,00
9	150793,00	42,47164	21,94471	$ 6.404.426,51	$ 3.309.108,10
10	126940,00	41,5008	15,40017	$ 5.268.110,97	$ 1.954.898,00
11	110412,00	40,2192082	13,7851	$ 4.440.683,22	$ 1.522.040,40
12	139260,00	39,64026	15,38483	$ 5.520.303,04	$ 2.142.492,00
			Total	$ 75.036.754,09	$ 29.560.505,70

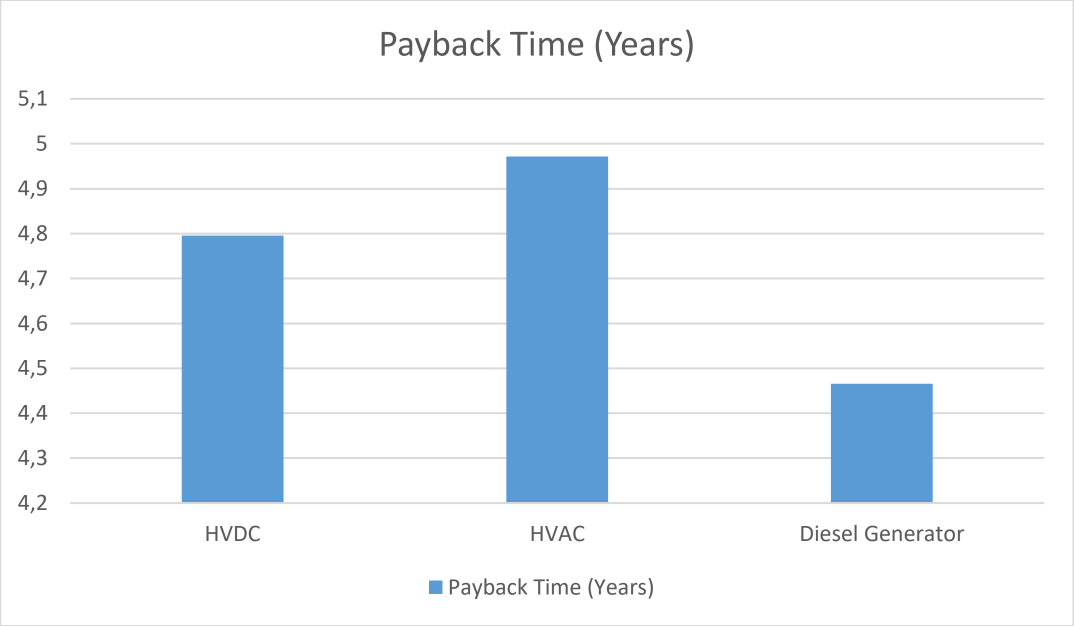

Figure 6.5. Payback Time of HVDC Compared to other Scenarios

It can be seen from simple payback calculations; each solution has a similar payback period of 4 years. Nevertheless, this result only consists of simple generation cost savings. The calculation can be extended with the social cost of CO2 savings achieved with Turkey's healthier generation mix.

Calculations in [63] show that a 200 MW interconnection between North Cyprus and Turkey can save up to %38 of the social cost of CO_2 production. A new payback calculation with the saving mentioned above can be found in table 6.6.

Table 6.6. Extended Cost Saving Calculation Results

Scenario	*Carbon Emission [Million Ton]*	*Percentage Reduction*	*Social Cost [Million $]*	*Savings [Million $]*
Current [Diesel + Steam]	0.685	-	27.412	-
HVDC	0.426	38	16.995	10.417
HVAC	0.426	38	16.995	10.417
Only Diesel Generator	0.675	2	27.037	0.375

As we can see from the table, the social cost of CO_2 benefits HVDC and HVAC while new diesel generator increases cost because of increased CO_2 emissions. Figure 6.6 shows the results of the second analysis.

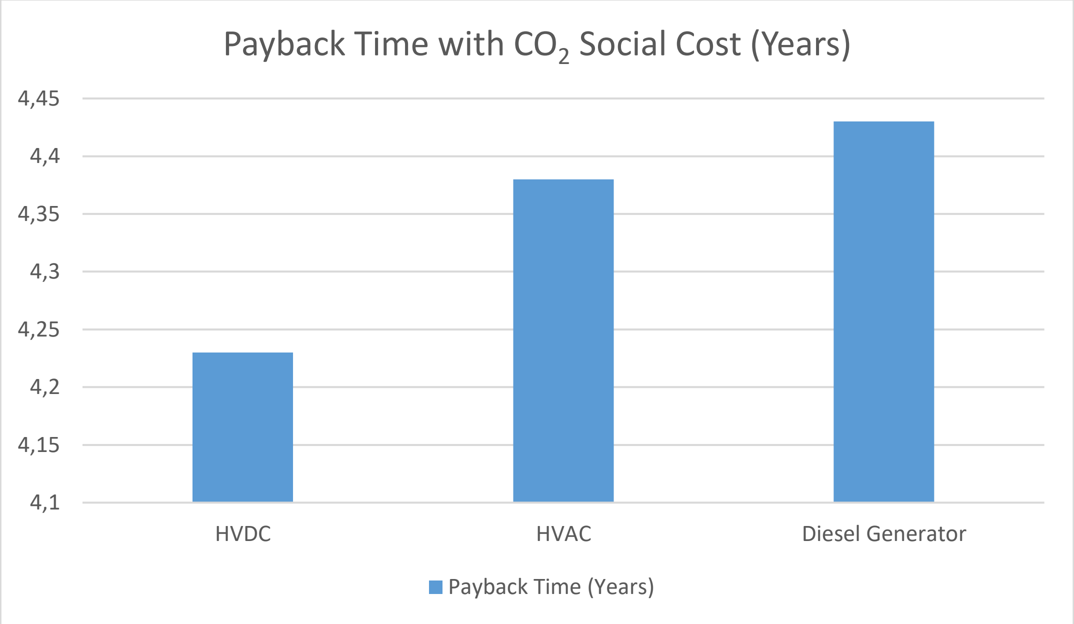

Figure 6.6. Payback Time Obtained with CO_2 Social Cost

Similar payback times are expected from HVDC and HVAC technologies because the distance of North Cyprus to Turkey is very close to the break-away distance given before. For more prolonged distanced cases, HVDC will increase its economic advantages over HVAC. Also, HVAC could require substations after a specific distance that cannot be established for some island to mainland transmission line cases.

6.5 Result Discussion

For this research, every analysis explained in methodology was done to validate proposed models and results.

First given results, validates developed grid model by comparing primary aspects of steady-state analysis results with real-time SCADA readings. The comparison shows that the proposed model can give an idea for possible real-life applications.

Using validated grid model interconnection location on the island decided. Loss amount was used to decide the best location for grid extension for this research. Alsancak bus gave the lowest loss amount and was used in other analyses as a connection point. It is possible to use combined power flow result elements or other analysis methods, but loss comparison will be sufficient for this research. Also, diesel generation addition can be done anywhere on the island compared to interconnection. However, we assumed it would be built in the exact bus location as an interconnector for simplicity and comparison. Research can be extended with analysis of different generation locations and adding renewable energy sources to the model.

With a validated model and chosen interconnection location, optimal power flow analysis was conducted. This analysis is one of the robust steady-state analyses to decide grid extensions and grid response. Results clearly show that interconnection will benefit the island grid in regards to stability with lower losses and healthier line loads and economically, as lambda value shows.

While mentioned results show promise, this research also addresses the literature gap mentioned and includes economic comparison in this techno-economic analysis. To achieve this, investment costs are calculated for each technology. From obtained results, it can be seen that diesel generators require the least amount of initial cost. However, the first analysis only considers reduced fuel cost to see the difference in energy cost. Calculated similar payback times show that while high investment cost interconnector requires it to compensate itself in a similar time frame. This can be interpreted as interconnectors can save more cost in the same time frame.

To extend the analysis, more variables were taken into account. With environmental priority around the globe, the effect of emissions is considered for cost calculation. Only inclusion of this parameter significantly deducted the payback time of interconnectors while no change for diesel was observed as expected. Interconnectors for islands can be more favorable with consideration of the more minor benefits they can bring. These benefits include a possible increase of renewables on grids and stability of grids.

Lastly, it can be seen that the choice between HVDC and HVAC cannot be made directly with similar results since steady-state grid properties and economic benefits of these technologies are very similar in our research’s scope. Also used case’s distance between the island and mainland is very close to the breakeven distance mentioned in chapter 2, which explains why very similar economic results were obtained. To improve the comparison between selected technologies, dynamic state analyses can be conducted. Also, consideration of the socio-economic benefits of each technology can be beneficial. For example, ENTSO-E interconnection rules are critical for the countries in our case, which can affect the project directly. Another angle to see this case benefit is comparing it with similar projects like EuroAsia Interconnector, which connects Cyprus to Israel via HVDC transmission lines.

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

Today’s islands suffer from many electrical system problems due to their limitations. Most islands use fossil fuel-based diesel generators due to ease of construction and low initial cost. However, limited capacity that comes with this technology creates problems for island grids. These include high electricity prices, low-quality power, hard-to-maintain generation, a limited number of possible generation methods, and volatility to high oil prices. Renewable energy generation usage is increased to overcome these problems and provide a better future for the earth’s ecology. Still, the nonpredictable properties of renewable energy sources make using 100% renewables for energy in the near future a complex task to achieve.

One possible solution to island grid problems is establishing a transmission line to a mainland electricity grid. This is possible by using a high voltage alternative current line or a high voltage direct current line. In both possibilities, different aspects come into play, both technical and economical, so multiple analyses and studies are required to decide. There is a chance that any of the possible interconnection technologies will not be suitable for the given case.

In this study, optimal power flow analysis with developed North Cyprus grid model shows HVDC and HVAC technologies bring more stability to the grid than isolated systems. While the steady-state analysis does not give much information about differences between these two technologies, economic analysis shows that HVDC is a slightly better option. The similarity of expenses is expected between the two technologies since selected interconnection requires similar distances to break-even distances found in the literature.

Interconnectors most certainly help island grids, but high initial cost requires multiple feasibility and technical analysis. People can use this research to gather information regarding HVDC, and this knowledge can be used for other island cases or other interconnector projects. Nevertheless, steady-state analysis and main economic calculations are one piece of the puzzle. Other properties of interconnectors need to be observed through dynamic analyses or different studies required on secondary benefits like increased renewable penetration.

For this case, the electric power generation of North Cyprus is not enough to export it. The interconnector will majorly be used to import electricity, thus providing sufficient energy to meet increasing demand. If in the future, with the help of increasing solar energy power plants, the interconnector can export electrical energy, which is a benefit this research did not include.

With the increase in research conducted on HVDC technology, island grids can solve problems, as mentioned earlier. Many current applications worldwide show that interconnectors help the island grid; this can be maximized with cheaper HVDC solutions.

7.1.1 Future Work

As mentioned in this research multiple times, explained analyses are only usable for a start of an interconnector project. Results show that the North Cyprus case is feasible at the start, but this can change with different studies and analyses. So given model can be improved with the inclusion of dynamic properties of generators and other grid elements. Also, secondary benefits of interconnectors and risks involved can be included in the research to observe the accurate feasibility of this case study.

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APPENDIX

A. Developed Grid Model for Power Flow

```
function mpc = TRNC_Model_22July
clear
clc

%% MATPOWER Case Format : Version 2
mpc.version = '2';

%%-----  Power Flow Data  -----%%
%% system MVA base
mpc.baseMVA = 100;

%% bus data
%   bus_i   type    Pd      Qd      Gs      Bs      area    Vm      Va      baseKV  zone    Vmax    Vmin
mpc.bus = [
    1       1       9.9     4.2     0       2.998   1       0.9997  -0.018  66      1       1.05    0.95;
    2       3       1       1       0       0       1       1.0     0.0     11      1       1.05    0.95;
    3       1       0       0       0       0       1       1.001   0.286   15      1       1.05    0.95;
    4       2       1       1       0       0       1       0.9996  -0.022  132     1       1.05    0.95;
    5       1       12.5    4.2     0       5.797   1       0.9809  -1.771  132     1       1.05    0.95;
    6       1       26.9    1.0     0       9.684   1       0.9841  -1.878  66      1       1.05    0.95;
    7       1       5.3     4.2     0       9.651   1       0.9824  -1.826  66      1       1.05    0.95;
    8       1       48.6    15.8    0       18.848  1       0.9908  -0.977  66      1       1.05    0.95;
    9       1       2.4     1.6     0       5.797   1       0.9829  -1.833  132     1       1.05    0.95;
    10      1       11.3    5.8     0       5.824   1       0.9852  -1.726  132     1       1.05    0.95;
    11      1       7.6     0.3     0       2.966   1       0.9944  -0.221  66      1       1.05    0.95;
    12      1       18.8    4.7     0       5.8     1       0.9832  -2.149  66      1       1.05    0.95;
    13      1       4.9     3.0     0       2.911   1       0.985   -1.863  66      1       1.05    0.95;
    14      1       5.6     1.6     0       2.911   1       0.985   -1.861  132     1       1.05    0.95;
    15      1       2.3     1.9     0       1.157   1       0.982   -2.21   132     1       1.05    0.95;
    16      1       9.5     6.9     0       1.15    1       0.979   -2.55   132     1       1.05    0.95;
    17      1       6.8     4.0     0       2.873   1       0.9786  -2.779  132     1       1.05    0.95;
    18      1       4.2     2.3     0       2.869   1       0.978   -2.425  66      1       1.05    0.95;
    19      1       18.6    7.7     0       5.965   1       0.9971  -0.319  132     1       1.05    0.95;
    20      1       30.8    10.8    0       9.818   1       0.9909  -0.966  132     1       1.05    0.95;
    21      1       3.1     2       0       2.966   1       0.9944  -0.217  132     1       1.05    0.95;
    22      1       5.8     2.6     0       2.934   1       0.989   -0.691  66      1       1.05    0.95;
    23      1       0       0       0       0       1       0.9809  -1.771  66      1       1.05    0.95;
    24      1       25.8    11.8    0       9.639   1       0.9818  -1.731  66      1       1.05    0.95;
    25      1       11.2    4.6     0       5.773   1       0.9809  -1.773  66      1       1.05    0.95;
    26      2       0       0       0       0       1       1.0     1.344   15      1       1.05    0.95;
    27      1       6.2     1.6     0       2.995   1       0.9992  1.153   66      1       1.05    0.95;
    28      1       0       0       0       2.995   1       0.9992  1.144   132     1       1.05    0.95;
    29      2       0       0       0       2.995   1       0.9992  1.153   66      1       1.05    0.95;
    30      1       2.3     1.2     0       1.198   1       0.999   1.108   66      1       1.05    0.95;
    31      1       7.2     1.7     0       1.195   1       0.9981  1.007   132     1       1.05    0.95;
    32      1       0.9     0.2     0       2.979   1       0.9964  0.821   132     1       1.05    0.95;
 %%HVDC BUS%%  %  33      2       0       0       0       0       1       0.9996   -0.022  132     1       1.05    0.95;
    ];

%% generator data
%   bus Pg      Qg      Qmax    Qmin    Vg      mBase   status  Pmax    Pmin    Pc1 Pc2 Qc1min  Qc1max  Qc2min  Qc2max
ramp_agc    ramp_10 ramp_30 ramp_q  apf
mpc.gen = [
    2   30      31.7    80      -40     1.0     100     1       120     0      0    0   0       0       0       0       0
0       0       0       0;
    3   5     -16.5     75      -21     1.001   100     1       37      0      0    0   0       0       0       0       0
0       0       0       0;
    4   50  20      112     -40     1.0     100     1       140     5      0    0   0       0       0       0       0
0       0       0       0;
    33  150     40      150     -100    1.0     100     1       200     5      0    0   0       0       0       0       0
0       0       0       0;
    26  40    -40     100      -21  1.001   100     1       70     10      0    0   0       0       0       0       0
0       0       0       0;
    29  40    -40     100      -21  1.001   100     1       200     10      0   0   0       0       0       0       0
0       0       0       0;
];

%% branch data
%   fbus    tbus    r           x           b       rateA   rateB   rateC   ratio   angle   status  angmin  angmax
mpc.branch = [
    1       4       0.00109     0.18799     0       0       0       0       1       0       1       -360    360;
    1       2       0.00090     0.00265     0       0       0       0       1       0       1       -360    360;
    3       1       0.00285     0.00531     0       0       0       0       1       0       1       -360    360;
    4       21      0.00502     0.03103     0.0302  0       0       0       0       0       1       -360    360;
    4       20      0.00757     0.02488     0.0223  0       0       0       0       0       1       -360    360;
```

```
    6      2       0.08145     0.14481     0.0020  0       0       0       0       0       1       -360    360;
    6      12      0.06503     0.11561     0.0016  0       0       0       0       0       1       -360    360;
    7      6      0.07765     0.09193     0.0012  0       0       0       0       0       1       -360    360;
    7      8      0.06017     0.07976     0.0011  0       0       0       0       0       1       -360    360;
    7      2       0.10717     0.19054     0.0026  0       0       0       0       0       1       -360    360;
    8      20      0.00138     0.18767     0       0       0       0       1       0       1       -360    360;
    8      9      0.09200     0.11744     0.0016  0       0       0       0       0       1       -360    360;
    5      10      0.00501     0.03094     0.0075  0       0       0       0       0       1       -360    360;
    5      20      0.00343     0.02120     0.0052  0       0       0       0       0       1       -360    360;
    10      21      0.00741     0.04577     0.0111  0       0       0       0       0       1       -360    360;
    11      23      0.07377     0.22772     0.0035  0       0       0       0       0       1       -360    360;
    11      22      0.04446     0.13726     0.0021  0       0       0       0       0       1       -360    360;
    11      21      0.00109     0.18799     0       0       0       0       1       0       1       -360    360;
    12      13      0.02800     0.08645     0.0013  0       0       0       0       0       1       -360    360;
    13      14      0.00138     0.18767     0       0       0       0       1       0       1       -360    360;
    14      19      0.01934     0.06356     0.0018  0       0       0       0       0       1       -360    360;
    14      15      0.00639     0.02101     0.0047  0       0       0       0       0       1       -360    360;
    15      16      0.00658     0.02162     0.0048  0       0       0       0       0       1       -360    360;
    16      17      0.00413     0.01357     0.0122  0       0       0       0       0       1       -360    360;
    18      7      0.06926     0.12314     0.0017  0       0       0       0       0       1       -360    360;
    19      4       0.00293     0.00963     0.0086  0       0       0       0       0       1       -360    360;
    20      4       0.00757     0.02488     0.0223  0       0       0       0       0       1       -360    360;
    20      21      0.01426     0.08806     0.0214  0       0       0       0       0       1       -360    360;
    21      28      0.01783     0.05859     0.0131  0       0       0       0       0       1       -360    360;
    22      27      0.06441     0.19884     0.0031  0       0       0       0       0       1       -360    360;
    23      25      0.00008     0.00025     0       0       0       0       0       0       1       -360    360;
    23      24      0.02324     0.12547     0.0011  0       0       0       0       0       1       -360    360;
    24      22      0.01905     0.05127     0.0027  0       0       0       0       0       1       -360    360;
    26      28      0.00038     0.00239     0.0023  0       0       0       0       0       1       -360    360;
    27      30      0.02892     0.03390     0.0004  0       0       0       0       0       1       -360    360;
    27      29      0.02892     0.03390     0.0004  0       0       0       0       0       1       -360    360;
    27      28      0.00138     0.18767     0       0       0       0       1       0       1       -360    360;
    28      31      0.00903     0.02966     0.0066  0       0       0       0       0       1       -360    360;
    31      32      0.01688     0.05546     0.0124  0       0       0       0       0       1       -360    360;
];

runpf(mpc);
```

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