POWER LOSS REDUCTION AND VOLTAGE PROFILE IMPROVEMENT VIA DISTRIBUTED PV SITE AND SIZE SELECTION IN SMART GRIDS: THE CASE OF NORTH CYPRUS

SUSTAINABLE ENVIRONMENT AND ENERGY SYSTEMS
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ABSTRACT

POWER LOSS REDUCTION AND VOLTAGE PROFILE IMPROVEMENT VIA DISTRIBUTED PV SITE AND SIZE SELECTION IN SMART GRIDS: THE CASE OF NORTH CYPRUS

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The increased awareness of communities on climate change, the inefficiencies associated with power-system infrastructure, and the exponential growth in energy demand motivated donors, non-governmental organizations, consumers, firms, and investors to cooperate with governments to establish an efficient and reliable framework that meets all requirements while ensuring user security, known as the Smart Grid (SG). One of the most pivotal enabler-technologies for the transition toward SGs is Distributed Generation (DG) in which power generation is localized through small-scale energy systems that either complement or replace centralized power plants. In the context of SGs, the successful adaptation of DG systems – especially renewable DG systems – helps to eradicate system inefficiencies and all its concomitant challenges such as power quality and reliability, energy security, as well as the detrimental impacts of aging system-infrastructure. However, integrating DG systems into current power systems requires optimal planning in order to extract the maximum benefits of their integration. Therefore, this present thesis aims at proposing a novel method for site and size selection of solar Photovoltaic DG units considering system technical performance. The novelty of this thesis relies on employing

Weak Busbar (WBB) and Weighted Integration (WI) approaches for the site and size selection criteria, respectively. Initially, the solar resource potential is assessed considering the solar irradiation in the desired test case, and then the technical performance of the grid, with the presence of PV DG units, is assessed using the proposed approaches. In addition to the potential of minimizing harmful emissions, the technical performance is investigated through system total active power loss, busbar voltage-profile, and system overloading. The work includes a detailed case analysis performed on the Northern Cypriot power system with promising results that validate the proposed method. It is found that using the WI approach helps to reduce active power loss in the network by 36% at 50% penetration level of PV DG units whereas the potential of active power loss reduction is 32% using the NI approach. Similarly, using the WI approach provides better performance relative to the NI approach in terms of busbar voltage-profile improvement in which at 50% penetration level, all voltage magnitudes (in p.u.) are within the rated values.

Keywords: Smart Grid, Distributed Generation, Solar PV, Power Flow Analysis, North Cyprus

ÖZ

AKILLI ELEKTRIK SEBEKELERINDE, GUC KAYIPLARININ VE VOLTAJ PROFILININ DAGITILMIS FOTOVOLTAIK SAHA VE KAPASITE SECIMI ILE GELISTIRILMESI: KUZEY KIBRIS DURUMU

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İklim değişikliği konusunda toplumsal farkındalıgın artması, elektrik güç altyapılarına bağli verimsizlik sorunu, ve enerji talebindeki devamlı artış tüketicileri, sivil toplum kuruluşlarını şirketleri ve yatırımcıları devlet yönetim ile birlikte hareket ederek yapısal reformlar gerçekleştirmesi husunda teşvik etmektedir. Bu yapısal reformlar çerçevesinde Akilli Elektrik Şebekesi (AEŞ) sistemlerine geçiş ve bu sistemlerin yaygınlaşması enerji sektörüne bağli ortaya çıkan ihtiyacların güvenli ve verimli birşekilde karşılanması açısından önem taşımaktadır. Yapısal reformlar yanısıra, AEŞ sistemlerine geçişin sağlanmasında Dağıtılmış Guç Üretimi (DGU) gibi teknolojilerde en önemli rollerden birine sahiptir. DGU gibi teknolojiler merkezi elektrik üretimine olan bagımlılıgı bolgesel kucuk çaplı enerjı sıstemlerını yaygınlastırarak azaltabılır. Buna mukabil AEŞ konusunda, DGU sistemlerinin başarılı bir şekilde yaygınlaşması – özellikle yenilenebilir DGU sistemleri – yukarıda bahsedilen verimsizlik ve buna bağlı güç kalitesi ve enerji güvenliği gibi eski altyapı sistemlerinin doğurduğu olumsuzlukların ortadan kaldırılmasında yardımcı olmaktadır. Öte yandan, DGU sistemlerinin mevcut güç sistemlerine entegrasyonuyla maksimum düzeyde faydalanılması için en uygun birşekilde planlanması gerekir. Bu yüzden bu tez, yenilikçi bir yaklaşımla sistemin teknik performansını değerlendirerek Fotovolatik DGU sistemi için saha ve kapasite belirlemeyi hedeflemektedir. Bu çalışmanın özgünlüğü saha ve kapasite seçiminde uygulanan Weak Busbar (WBB) ve Weighted Integration (WI) yaklaşımları sayesindedir. Öncelikle, güneş enerjisi potansiyeli Kuzey Kıbrıs durumu için ışıma dikkate alarak değerlendirildi. Sonrasında, bahsedilen WBB ve WI yaklaşımları ile mevcut şebeke sisteminin ve Fotovolataik DGU entegre sisteminin teknik performansı değerlendirilip, karşılaştırıldı. Sera gazı emisyonlarının zararlarının en aza indirgenmesi potansiyeli ile birlikte, sistemdedeki toplam güç kayıpları, busbar voltaj-profili ve sistemdeki aşırı yüklenmeler hesaplandı. Bu çalışma detaylı Kuzey Kıbrıs durum analizi ve önerilen yaklaşımlar ile elde edilen ümit vadeden ve doğrulanmış sonuçlar içermektedir.

Anahtar Sözcükler: Akıllı Elektrik Şebeke, Dağıtılmış Üretim, Solar PV, Güç Akışı Analizi, Kuzey Kıbrıs

DEDICATION

To My Family

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My experience during my Master of Science at Middle East Technical University – Northern Cyprus Campus has been an exciting journey that is full of academic discoveries and personal growth. The journey is extremely worthwhile and supportive to achieve my future endeavors. I would like to take this opportunity to acknowledge the people that help me to reach where I stand today.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ABCA	Artificial Bee Colony Algorithm
AENS	Average Energy Not Supplied
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
AP	Access Point
CE	Combustion Engine
CHP	Combined Heat and Power
CPS	Centralized Power System
CSP	Concentrated Solar Power
CT	Communication Technology
DG	Distributed Generation
DGIG	Doubly-Fed Induction Generator
DR	Demand Response
DSO	Distribution System Operator
EENS	Expected Energy Not Served
EF-PI	Energy Flexibility Platform and Interface
ESS/BSS	Energy Storage System
EV	Electric Vehicle
G2V	Grid-to-Vehicle
GA	Genetic Algorithm
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
HAN	Home Area Network
ICE	Internal Combustion Engine
IPP	Independent Power Producer

IRR	Internal Rate of Return
ISO	Independent System Operator
LCOE	Levelized Cost of Energy
LSF	Loss Sensitivity Factor
MAC	Media Access Control
MCU	Microcontroller Unit
MG	Micro-Grid
NAN	Neighborhood Area Network
NCTS	North Cyprus Transmission System
NF	Nodal Factor
NI	Normal Integration
NPV	Net Present Value
NRPF	Newton Raphson Power Flow
O&M	Operation and Maintenance
OpenADR	Open Automated Demand Response
OPF	Optimal Power Flow
P2G	Power-to-Gas
PBP	Payback Period
PL	Penetration Level
PQ	Power Quality
PV	Solar Photovoltaic
QoS	Quality of Service
RE	Renewable Energy
RES	Renewable Energy Sources
RTC	Real-time Clock
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SG	Smart Grid
SHMS	Smart-Home Management System
SM	Smart Metering
T&D	Transmission and Distribution
THD	Total Harmonic Distortion
USEF	Universal Smart Energy Framework

V2G	Vehicle-to-Grid
V2V	Vehicle-to-Vehicle
VDI	Voltage Deviation Index
VPI	Voltage Profile Index
VPP	Virtual Power Plant
WAN	Wide Area Network
WBB	Weak Busbar
WI	Weighted Integration
WTA	Willingness to Accept
WTP	Willingness to Pay

Chapter 1

INTRODUCTION

The present chapter provides an overview of the content of the thesis and the flow of information. First, the research domain of this research is highlighted by positioning the scope of the study amongst the recently witnessed critical changes in the power system era. Secondly, the motivations behind conducting this particular research are outlined considering the benefits that can be accomplished by adopting the proposed strategy. Subsequently, the chapter provides a detailed description of the study objectives and the type of analysis that is followed in this thesis. Finally, an outline of the rest of the thesis is provided explaining the flow of information in the subsequent chapters.

1.1. RESEARCH SCOPE

Electric power is considered to be one of the most important factors for life quality improvement through expanding countries' economies [1]. Nevertheless, the nature of power systems has been shaped by various aspects. For instance, the exponential growth in electricity demand increases the stress on conventional electricity resources. Despite the availability of fossil-fuel-based centralized generation reserves, they form a significant threat to the environment due to their harmful greenhouse gas emissions. Fossil fuels still have the largest portion of the world's electricity generation mix [2] where coal is estimated to account for 40.9% of this global generation mix (2014) [3]. To this extent, societies started paying more attention to climate change and sustainability, which has led to the emergence of renewable means of energy production. Hence, in order to fasten the movement towards sustainable development and mitigate climate change effects, renewables should be integrated into power systems [4]. The realization of centralized power generation negative impacts has brought attention to distributing the generation process. Distributed generation (DG) technology offers various technical benefits to power systems such as enhancing the robustness of transmission systems [5], minimizing interruptions as a result of T&D outages [6], reducing transmission power losses and improving voltage profiles [7]. However, it is essential that DG units are well-planned when integrated into power systems in order to maintain their maximum technical benefits [8]. In other words, the improper choice of DG's size and location may lead to overvoltages and excessive power losses [9]. The development of a multifaceted integration scheme of DGs in future SGs, while ensuring the provision of quality services that comply with the desired operational standards as well as system technical parameters is essential for the progression towards sustainable and smart power networks.

1.2. RESEARCH MOTIVATION

In an attempt to better prepare for future trends in power generation, the power industry witnessed a vast transition towards distributing the power generation through the power system. The proliferation of DG investments puts a big burden on utilities and service providers to plan the integration in line with the existing grid infrastructure, especially in the case of RE-DGs that are believed to have variable power outputs. The motive for optimal planning of DGs in modern power systems while ensuring the standards of power reliability cannot be denied on a board of in-depth knowledge of the potential advantages such as following subsections (Also see section 3.2).

1.2.1. System operational efficiency

In addition to alleviating the environmental impacts, DGs are seen as a mechanism to offer various benefits for enhancing system operation efficiency. The technical usefulness of DGs is greatly accomplished in 'weak' power systems in some regions across the globe. In terms of efficiency, DGs, for instance, help to reduce active power losses in the network, improve busbar voltage profiles, and reduce system overloading. The shift to fully sustainable and smart power networks may seem disruptive at first due to the complex structure of involved technologies and the requirements of stakeholders. However, there is an urgent need to enforce research and developmental activities to carefully assess the applicability of the technology in the current grid structure and, if necessary, call for upgrading the network accordingly.

1.2.2. Economic profitability

The declining prices of RESs, as well as the DG systems in general, make them attractive solutions not only to utilities and power producers but also to energy consumers such as households, industrial areas, and governmental buildings. In fact, renewable energy investments are perceived as a mechanism for generating revenue owing to the 'renewability' of their resources, that is their total cost is majorly the installation cost with relatively low O&M costs. Governments in some parts of the world offer 'Green Incentives' to consumers as an attempt to promote the usage of clean energy. Despite the validity of the argument that IPPs will be marginalized in the energy market due to the loss of opportunities for selling their power to DSOs since consumers rely mainly on DGs; policymakers may impose temporary regulations (which is currently in practice) on the maximum allowable DG capacity. This can be done to protect IPPs until they find other alternatives or switch to renewable means of energy productions, possibly by offering DG schemes for consumers. Whether or not the integration of DGs brings new challenges to the energy sector, it can be commonly agreed that there is a great potential of generating revenues by investing in RE-based DGs. In fact, this can be more profitable with the presence of net-metering solutions that enable consumers to feed the excess energy generated back to the national grid at agreeable sell back prices (generally specified by the government).

1.2.3. Environment

The unprecedented growth in energy demands creates an additional struggle for utilities, keeping in mind the depletion of natural energy resources and the constraints of available large spaces in modern urbanized societies. Not only it is costly to construct fossil fuel-based power plants but also, their operation is primarily accompanied by harmful emissions that would act as an obstruction toward mitigating global warming. Fortunately, RE-DGs play a vital role in expediting the driving force for meeting the sustainability measures.

Although it is argued that they occupy large spaces and probably require deforestation, photovoltaics, for example, are characterized by zero GHG emissions.

1.2.4. The features of the target case study

The analysis is implemented in the NCTS for the following reasons for support. First, the NCTS is characterized by heavy dependence on fossil fuel power plants (See section 4.6) which is believed to hinder sustainable development. This study examines the benefits of integrating RE-DG units in the system in order to contribute to the overall movement of the country towards sustainability and assist in future RE planning. Secondly and essentially, the strategic location of the NCTS makes it a very attractive location for RE investments. For example, the island is characterized by abundant solar resources that can be directly converted into useful power. Keeping this in mind, the future of the NCTS is expected to accommodate a wide range of power generation schemes, especially PV. Accordingly, the present thesis aims at providing the necessary planning theme of PV integration considering solar resource availability as well as system performance with regard to increasing system efficiency.

1.3. REVIEW OF RELATED LITERATURE

Integrating DG units into power systems have been investigated thoroughly in literature and can be grouped under two categories: 1) The integration into distribution networks, and 2) The integration into transmission networks. Distribution networks, transfer electric power to end-users and are characterized by lower voltage ranges in comparison with transmission networks. Transmission networks, however, are composed of high voltage transmission lines and substations to carry electric power over large distances, from power generation sources to distribution networks. The integration into distribution networks is tackled as an optimization problem in various studies [10]–[18]. Objectives of this optimization problem target improving system technical parameters such as reducing active power loss and improving busbar voltage profiles. To do this, authors employ different methods like deterministic and heuristic algorithms [19] which depends on the target objective. Heuristic Algorithms, for instance, are known for a fact that heuristic algorithms are robust and show dominance in providing near-optimal solutions relative to deterministic algorithms at the cost of computational efforts [20]. On the other hand, integration into transmission networks – the target of this study – is considered to be more complex when compared to integration into distribution networks [21].

However, optimal planning of DG units in transmission networks is observed in several studies. For instance, references [22], [23] target transmission network expansion in the presence of DG units considering installation costs using GA and ABCA based optimization, respectively. References [24]–[26] examine the impacts of large scale PV-DG's on transmission networks considering dynamic & static voltage stability and available transfer capability respectively while others [27] consider enhancing power quality using DG units in sub-transmission networks. Authors in [28] use the varying seasonal load model to show its effectiveness over the constant load model in reducing transmission losses and improving voltage profiles of the IEEE 9 busbar test system by integrating PV and DFIG based DG units. Another study, [29], shows the benefits of integrating a single 80 MW-size large-scale thermal coal DG into the Rajasthan power system. However, such fossil fuel-based DG increases GHG emissions into the environment and therefore, RES-based DG units can be a better alternative as they are environment-friendly. Moreover, the on-grid/off-grid aspect of integrating wind DGs is discussed in [30] where it is found that on-grid shows fewer power losses relative to off-grid connection of a 3 MW wind turbine. Furthermore, reference [31] employs the Penetration Level (PL) criterion for DG sizes to examine the impact of RES-DG units on voltage and frequency stability of the national grid of Jordan. The PL in this study is considered as a percentage of system aggregated demand and two PLs are used, 10% and 40%. The study shows that the PL of RES (PV and wind) should not exceed 10% of Jordan's total annual demand in order to avoid line congestions while the frequency stability analysis on the system shows that RES can be integrated up to a portion of 40% of the total generation. However, the study chooses three candidate busbars in the system for RES-DG placement considering their high potential of RES installations, according to the region's climatic conditions. The placement criterion is as essential as the sizing criterion and should be optimally planned to take into account system technical parameters such as active power loss and busbar voltage profiles. Authors in [32] employ the NF that is used to determine the changes in network operations due to change in active power injections on a certain busbar, caused by DG units. According to this approach, busbars with high NFs indicate high associated power loss and voltage issues, therefore, can be chosen for DG placement in order to improve the network performance. As for DG sizing, authors use a zonal PL approach that considers the aggregated demand of system zones instead of system total aggregated demand in order to determine the sizes of two DG units. Comparatively, authors in [33] employ the PL approach in order to examine the impacts of three DG units (PV, wind, and combustion turbines) on load busbars using PL approach to examine their impacts on transmission networks and determine the maximum PL of the DG units, accordingly. Even so, the transition towards 100% RES-based smart power systems requires considering multiple DG units in RES integration analysis in order to provide more realistic and accurate results considering future smart power systems that are expected to accommodate a large number of DG units. Authors in [34], on the other hand, present LSF and VPI for placement criterion of DG units into power systems. LSF principle determines the effect of injecting a DG unit on candidate busbars considering system power loss. Consequently, busbars are ranked in ascending order and busbars with the lowest LSF are chosen as the best candidates for the placement of DG units. In addition, VPI relies on ranking busbars in terms of their effectiveness in improving the voltage profile of busbars to their desired nominal values. However, the study considers 0.1 to 0.5 p.u range for DG unit size criterion, which is an important factor to be taken into account and might be further enhanced in order to avoid RPF issues in the grid. Consequently, the DG may start back-feeding excess generated power into the grid and, system reliability may degrade accordingly.

On that account, none of the related literature attempts, to the best of our knowledge, discuss the benefits of using PL based WBB and WI approaches for optimal DG placement and sizing in transmission networks. Table 1 categorizes the related literature attempts in comparison with our approach.

Table 1. A comparison of related theoretical approaches.

Ref.	Year	Objective(s)	Method		Type of DG(s)
			Place	Size	
[35]	2011	Loss reduction and voltage profile	LSF and VPI	-	General
[32]	2012	Loss reduction, and congestion reduction	NF	2% and 4% Zonal PLs	General
[36]	2013	Static voltage stability	Single busbar	-	PV
[37]	2014	Voltage stability	Non-generating load busbar	-	PV
[29]	2016	Loss reduction, voltage profile, and line overloading	Case study-specific (GSS Zawar)	80 MW	Thermal coal
[33]	2016	Loss reduction and voltage profile	Load busbars	0 – 100% PLs	PV, Wind, & combustion turbines
[28]	2017	Loss reduction and voltage profile	Load busbars	-	PV & Wind
[31]	2018	Voltage stability and frequency stability	Most candidate busbars for RES installation (3 busbars)	10% and 40% PLs	PV & Wind
This thesis	2019	Loss reduction, voltage profile, and system overloading	WBB (Multiple Units)	WI	PV asynchronous generators

The strategical location of Northern Cyprus motivated citizens to promote the usage of renewable energy. Therefore, several works in the literature discuss the integration of renewable energy into the Northern Cyprus power system. Reference [38] for instance attempts to assess wind and solar energy potentials and hybrid-based renewable installations in the region. The study concluded that wind-assisted solar thermal systems have an advantage of reduced system costs in comparison with constructing a new solar energy storage system. Furthermore, study [39] designs a 1.275 MWp PV system and built-in Serhatkoy, Northern Cyprus. The PV plant is operational since 2011 and feeds the grid of about 2 GWh annually. Reference [40] attempts to assess the profitability of PV investments in Northern Cyprus. This study highlights the potential of integrating PV plants into different cities of the island. They reported that Guzelyurt is the best city in terms of economic profit from PV investments where it provided a cost of energy lower than grid tariff of 0.1035 USD/kWh and a net present value of 3256.1 USD/kWp.

In addition, authors in [41] propose - They suggest using hybrid PV-Wind systems for the residential sector, medium-capacity windmill plants for meeting commercial and trade energy requirements, heating steam boiler’s water from direct sunlight, and utilizing wave energy at the coastal areas. However, the scheme is very broad and does not include the technical impacts on the power system. Another scheme is presented in reference [42] in other to investigate citizens' preferences on having a built-in-PV system that is included in housing construction. The study utilizes building information modeling and contingent valuation method in order to assess citizen-related parameters such as WTP and WTA. They conclude that people showed more acceptance to a lower feed-in-tariff rather than incentives on PV installation costs. references [43], [44] investigate the feasibility of PV power plants in order to meet Middle East Technical University – Northern Cyprus Campus energy demands. Similarly, reference [45] proposes a guide for installing large-scale PV power plants in order to meet Cyprus International University's energy demand. Other studies target different parts of integrating renewables into the island such as study [46] where they examine the impact of dust, tilt angle and orientation on PV plant performance.

Accordingly, none of the aforementioned NCTS-based studies considers optimal planning of distributed PV generations in the country considering different locations and impacts on the power system performance. Therefore, this thesis fills a gap in the literature that is related to this particular power grid, the NCST case, outlines a comparison between the present thesis work and the related literature that target renewable energy planning in the island. The contributions of this thesis are vital for future renewable energy planning in the country.

Table 2. A comparison of related literature associated with the target test case.

Ref.	Year	Area	Brief Description
[41]	2009	Renewable energy feasibility analysis	a scheme for meeting electricity demand in the island for residential, commercial, and coastal areas
[47]	2013	Renewable energy feasibility analysis	Economic comparative analysis
[43]	2013	Renewable energy feasibility analysis	Meeting the energy demand of a university campus (METU-NCC)
[42]	2014	Renewable energy social acceptance	An investigation on citizens’ preferences on having a built-in-PV system that is included in housing construction
[39]	2015	PV project report	A 1.275 MWp PV system installation in Serhatkoy that is operational since 2011
[44]	2015	Renewable energy feasibility analysis	Meeting the energy demand of a university campus (METU-NCC)
[45]	2016	Renewable energy feasibility analysis	Meeting the energy demand of a university campus (CIU)

[40]	2018	Renewable energy feasibility analysis	Economic assessment of PV projects in different locations according to the solar irradiation
[46]	2018	PV plant performance assessment	An investigation on the impact of dust, tilt angle, and orientation on the performance of PV plants
This thesis	2019	1. Renewable energy feasibility analysis 2. Power grid performance assessment 3. PV site and size selection	An investigation on PV plants feasibility and solar resource assessment with detailed performance assessment criteria of increased PV penetration levels on the NCTS considering site and size of integration in the power grid

1.4. RESEARCH OBJECTIVES

Characterized by low prices, RE-based DGs – such as Photovoltaics and wind turbines – assist in modernizing the operations in Centralized Power Systems CPSs through mitigating the reliance of fossil fuels for energy production. Yet, improper integration of those RE-based DGs can create additional challenges to the operations in the grid, e.g. excessive power losses. In addition, even though RE investments can be economically profitable, especially in countries where the solar resource is abundant, power systems respond differently to RE-DG that is characterized by variable power outputs according to weather conditions. Therefore optimal planning of such power generation schemes in future SGs is vital for the provision of a grid structure that not only meets the variable requirements of concerned communities but also ensures the quality of services while maintaining the efficiency of the system. The main focus of this thesis relies on examining the impact of distributed PV generation on the NCTS considering different metrics. Firstly the present work aims at assessing the availability of solar resources in the region by depicting the profitability of investments. Secondly, power system parameters are examined including system active power loss, busbar voltage profiles, and system total overloading. Finally and foremost, the potential of mitigating GHG emissions in the NCTS through leveraging the available solar resources. Accordingly, we provide, through OPF analysis, an optimal placement and sizing criteria of the PV-DG units in the desired system. Thus, the objectives of the study can be outlined as follows, the study aims at:

- Depicting the state of the art of SGs and provides in-depth detail on the relationship between current and future power grids, the involved stakeholders, and key enabling technologies for the successful development of SGs.

- Discussing DG technology as an inseparable segment of future SGs and as a mechanism used in this thesis to enhance the operations in the present power system.
- Assessing the potential of solar resources in Northern Cyprus in order to devise the feasibility and profitability of PV investments in a distributed manner to reduce the reliance on fossil fuel power plants on the island.
- Contributing two analytical approaches in order to assess the impact of increased distributed PV generations on the system, namely Weakbusbar (WBB) and Weighted Integration (WI) Approaches. WBB approach takes into account system busbar voltage magnitudes as a site-selection criterion of PV plants and the second approach deals with determining the size of each PV unit to be placed on the desired busbars.
- Validating the proposed placement and sizing approaches in comparison with the Normal Integration (NI) approach whereby the total PV generation size is shared among candidate busbars evenly.

1.5. THESIS OUTLINE

DG and RE integration into future SGs is considered as a necessity provided that communities are willing to fight global warming and modernize current power systems. Purposefully, Chapter 2 provides useful insights on the SG technology considering the shortcomings in centralized power systems, the involved stakeholders in the SG paradigm, and the essential enabling technologies that make the SG possible. Subsequently, the concept of DG as a pivotal segment of the SG is discussed in Chapter 3 by discussing important aspects such as definition, benefits, and types in order to provide a better understanding of the technology and better explain the type of the used DG in this thesis.

Chapter 3 comprehensively presents the directly related literature works that target solar PV integration status into the NCTS as well as PV-based DG integration into transmission networks to outline the contribution of the present approaches against the methods existing in the literature.

Chapter 4 outlines the necessary theoretical formulations for defining the problem scope theoretically and present the constraints and assumptions used for result interpretations. In this chapter, the proposed approaches for distributed PV plants' placement and size criteria are formulated synergistically and the methodology carried out in obtaining the results is illustrated.

In Chapter 5, the NCTS test system is described by providing necessary system elements and conditions that are important for result comparisons pre and post distributed PV plants.

Chapter 6 presents the research findings in three stages; solar resources potential in Northern Cyprus, distributed PV integration analysis including the impact on NCTS system parameters – total active power loss, busbar voltage profiles, and total overloading –, and maximum allowable PV PL for the systems considering active power loss as well as voltage profiles of busbars. The potential for reducing GHG emissions is also discussed. Finally, chapter 7 concludes this thesis work based on findings in chapter 6 and suggests possible future research directions. Appendix A

1.6. CHAPTER SUMMARY

The preceding subsections provided a general description of the major contents of the thesis. Initially, the research scope, as well as the motivation, have been discussed in order to devise the importance of the present work to the SG community. Then, the research objectives are outlined as will be detailed in the upcoming sections. Finally, the organization of the thesis is illustrated with a general highlight of each of the lateral chapters.

Chapter 2

THE SMART GRID

The main aim of this chapter is to review the recent advancements in SGs in order to devise the importance of integrating DG sources into the system. The essential background on the operations in power systems as well as the associated challenges that helped giving birth to the SG concept is also outlined. This chapter also reviews SG key stakeholders and enabling technologies that are essential for the successful transition towards decentralized generation.

2.1. THE FUTURE OF CENTRALIZED POWER SYSTEMS: THE SMART GRID

Traditionally during the early start of the twentieth century, the power industry relied mainly on large utilities that operated the entire power transaction process from generation to distribution in specific defined territorial divisions [48]. The nature of power system operations then has been shaped by evolving regulatory apparatuses, the emergence of new generation technologies, and societies' efforts to reduce pollution and greenhouse gas emissions. The significant growth in population numbers helped to increase the stress on electric power generation and hence led to disparity forms between the electricity demand and supply chains. Towards the end of the twentieth century, societies started realizing the impacts of fossil fuel-based power plants and as a result, renewable energy generation schemes started to contribute to the available generation mixes worldwide as a movement to enforce sustainability measures. The idea that renewable energy sources should be integrated into power systems became sensible among concerned societies in order to maintain harmful-emissions free grids [4]. It can be observed that the reliance on oil generation significantly decays as the generation from renewables increases. Therefore, this vast acceleration in renewable energy integration will induce big challenges to utilities because renewables are known for their variable power outputs. Undoubtedly, current power grids, as illustrated in Figure 2.1 [49], are characterized by various shortcomings and structural weaknesses [50] in keeping pace with the technological advancements and the new generation schemes. Some of the weaknesses are listed below [51]:

- Grids in some parts of the world are half a century old.
- One directional power flow.
- Overloading and power flow rerouting are managed by operators.
- Access and flexibility limitations to new generation schemes.
- Lack of information about the network conditions.
- High power losses and maintenance costs.
- Costly power interruptions and outages

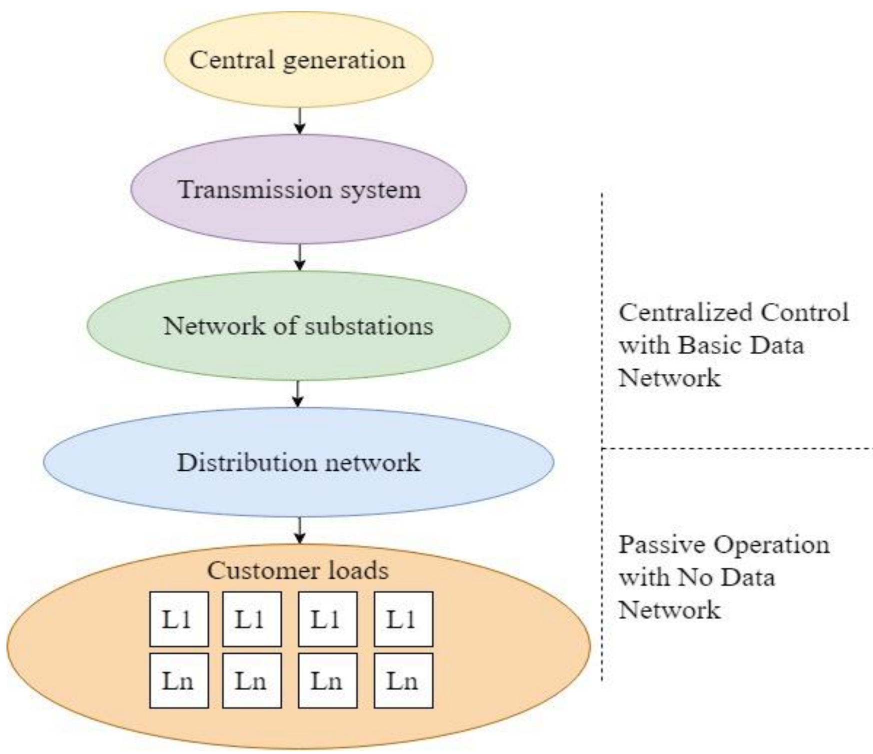

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Figure 2.1. An example of a centralized power system.

To overcome the aforementioned weaknesses, recent efforts strive to modernize the conventional power systems operate by introducing the Smart Grid (SG) concept. Alongside with sustainability, smart grid terminology emerged as a key solution in the early twentieth century. To some extent, the concept nowadays is more popular among academicians, industrial bodies, and political actors. The attributes of a smart grid promote innovating and upgrading current power grids while holding all their existing characteristics [52]. However, smart grids offer a wide range of unique features that enhance both efficiency and reliability in the electric power transaction process. The features of a SG include, but not limited to [53]:

- Distributed Generation technology.
- Smart metering.
- Renewable Energy sources.
- Bidirectional communication systems.
- Self-restoration capability.
- Data security.
- Harmful emissions reduction.
- Energy storage technologies.
- Distribution automation.

Table 3. Comparison between conventional and smart grids.

No.	Scheme	CPS	SG
1	Operation	Electromechanical	Digital in nature
2	Data communication	Unidirectional	Bidirectional
3	Power Generation	Centralized	Distributed
4	Sensory devices	Lack of sensor nodes	Wide usage of sensors across the grid
5	Network monitoring	Manual	Digitalized self-monitoring
6	reliability	Blackouts and faults	Robust, self-restoration, and smart
7	Controllability	Lack of control	Automated intelligent control systems
8	efficiency	High energy loss	Energy efficient
9	sustainability	Difficult to integrate RE	Possible to accommodate wide range or renewables
10	flexibility	Lack of consumer interaction	Frequent interactions with consumers

In comparison with conventional grids, smart grids are believed to have well-structured alternative technologies, as shown in Table 3. Comparison between conventional and smart grids [54], [55], to acquire the most possible benefits. These emerging enabler technologies in smart grids will eventually have significant contributions to society's economies by providing a wide range of projects and collaborations and hence job availability. Apart from the economic development, it is worthwhile mentioning that, through using clean energy sources, smart grids will contribute to fastening the movement towards sustainable development and assist in hindering the increase in climate change impacts [56]. From a power system point of view, the advantages vary along the electricity delivery process. For instance, smart meters will offer an essential role relative to the conventional meters not only in gathering consumption data but also in providing consumers the ability to instantaneously track their consumption patterns and automatically control their electronic devices which require robust communication systems and wireless sensor networks. As for the generation, decentralizing the generation will enhance the operations in the network and reduce power losses. As depicted in Figure 2.2 that shows the conceptual model of the future grid [57]–[59], the new paradigm of electric power transactions requires a well-structured collaboration between the enabler domains. At the bulk-generation stage, power is generated in a centralized model, which may contain large-scale renewables such as hydropower, photovoltaics, and wind farms. As for the transmission and distribution domains, RE-based distributed generations will be dominant relative to fossil fuel-based centralized generations. Moreover, customers in the future grid will have flexibility in choices and will be able to integrate other electrical applications into the system such as electric vehicles, storage systems, and small scale renewable generations. The successfulness of smart grid diverse power generation paradigm relies heavily on optimal planning of generation sources in relation to system response to different power generation schemes.

2.2. STAKEHOLDERS

It can be observed in Figure 2.3 that the SG involves different participants that take different roles in the power delivery process such as energy markets, system operators, service providers, and consumers. The framework implies that large-scale competitiveness amongst the stakeholders – especially service providers and energy markets – will be enabled allowing for innovations and technologies to come up. The decentralized nature of the SG is carefully built taking into account existing and new companies to take part in augmenting a privatized and liberal energy market [60] (see section 3.2.2).

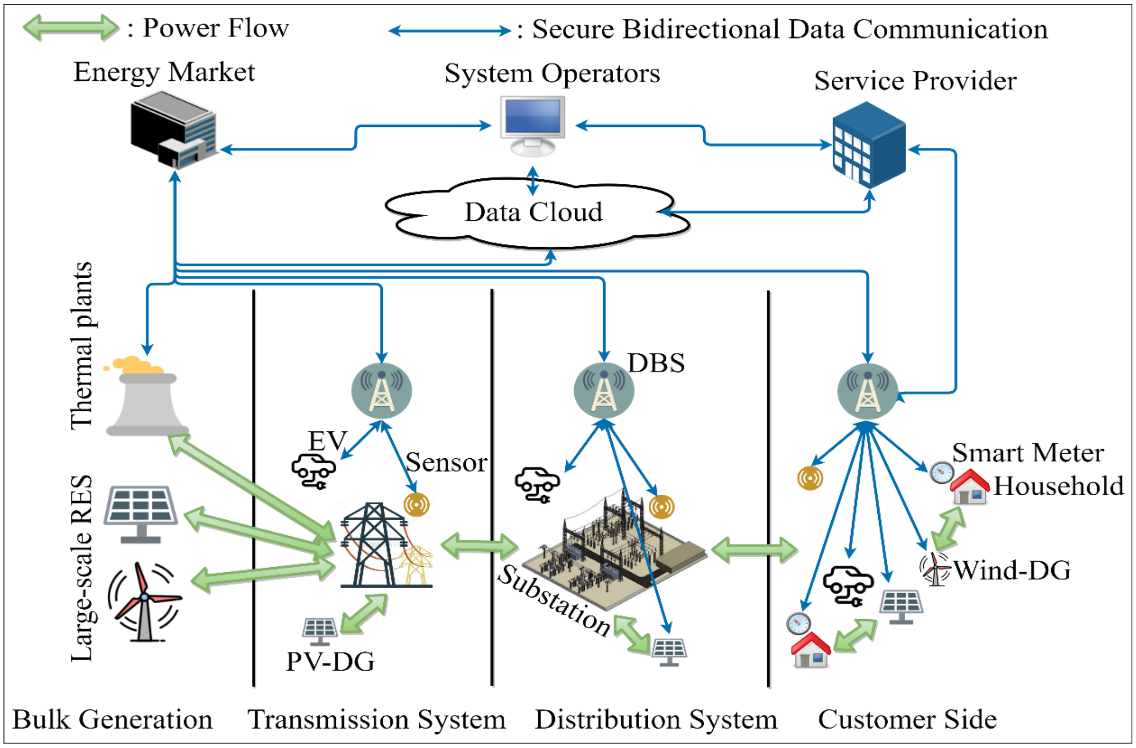

Figure 2.4. A general illustration of a SG model accommodating various modern technologies that operate simultaneously.

Parallel with efficient regulatory frameworks, the governmental bodies are expected to take part in this successful transition to a decentralized system. Governments, for example, prompt the usage of RESs, DGs, as well as other technologies such as EVs and ESSs. This will ultimately contribute to the reduced energy consumption, improved environmental friendliness of the system, and improve system performance. The Paris agreement in 2016 [61] is a good example of how governments take part in the movement towards sustainable societies through setting targets to strengthen the collaborative efforts in responding to the global warming and reduce GHG.

System operators participate in controlling the power transaction process using modern protocols provided that the grid is enabled with a robust bidirectional communication network. Virtual Power Plants VPP, for example, is expected to replace the existing resource control-structure in the network. VPPs make use of data packets in the Data Clouds to improve power production and manage power-sharing among microgrids. This enables integrating different management schemes such as DG control, and DR and energy storage programs at the distribution level [62].

For this, the market competitiveness will exponentially increase for providing flexible services that meet the requirements of both, consumers and system operators. Service providers, therefore, can be responsible for establishing efficient communication networks and enabling devices. For instance, the communication networks can be built as per the requirements of the desired region in the SG, such as bulk generation, transmission or distribution stages. Enabling devices such as SMs can be deployed at the consumer side for energy consumption monitoring. In addition, advanced SM can include SHMSs that do not only monitor energy consumption but also provide additional capabilities such as controlling household premises and lighting control.

2.3. ENABLING TECHNOLOGIES

In the CPSs, it is difficult to have complete information on the power flow in many aspects such as power quality, reliability, energy usage at different loads, etc. With that being said, new technologies can be employed in a synergetic and integrated manner modernize existing power systems and expose hidden network information. AMI offers a sustainable solution in this regard by providing a two-way communication scheme between utilities and consumers. Data including voltage and current readings as well as demand curves will be collected from loads using SMs, then the data is transferred using AMI to clouds and then to utilities in order to process the data and manage transmission and distribution processes. Then feedback is sent back to consumers in order for them to monitor their consumption patterns and check the quality of the power.

2.3.1. Smart Meters

A key enabler device in SGs is the SM where it is installed on the consumer side for collecting real-time voltage and current data. Unlike conventional AMR where data collection is monthly, SMs provide the ability of daily data collection [63] via communication networks. Hence, SMs in SGs are beneficial not only for consumers but also for utilities and environments. The major features of SMs, but not limited to, are listed below [64], [65]:

- Energy billing

- Electricity consumption reduction
- Consumption curves for both ends
- Net metering
- Power reliability monitoring: Outage detection
- Power Quality monitoring: Harmonics and voltage disturbances classification
- Power security monitoring: Fraud and thief detection
- Automated remote control abilities
- Remote appliance control
- Interfacing other devices
- Indirect greenhouse gases reduction as a result of reduced demand
- Fewer utility trucks in the streets for outage allocation and PQ tests.

The aforementioned list implies that AMI, in comparison with AMR technology, is able to enhance the communication between services providers, system operators, and consumers. It can be said that it is expected to have more complexities in the structure of SMs since it requires the integration of high-tech components to provide good functionalities and features as illustrated in Figure 2.5 [66]. SMs mainly consist of an MCU unit, a power supply unit with a complimentary battery, voltage and current sensors for active and reactive energy measurement in the energy metering IC, an RTC, and a communication facility as listed below [67]:

2.3.1.1. Microcontroller

MCU is the heart of a SM where most of the major data processing occurs. Therefore, all operations and functions in the SM are controlled by the MCU including the following:

- Communication with the energy metering IC
- Calculations based on the data received
- Display electrical parameters, tariff, and cost of electricity
- Smartcard reading
- Tamper detection
- Data management with EEPROM
- Communication with other communication devices
- Power management.

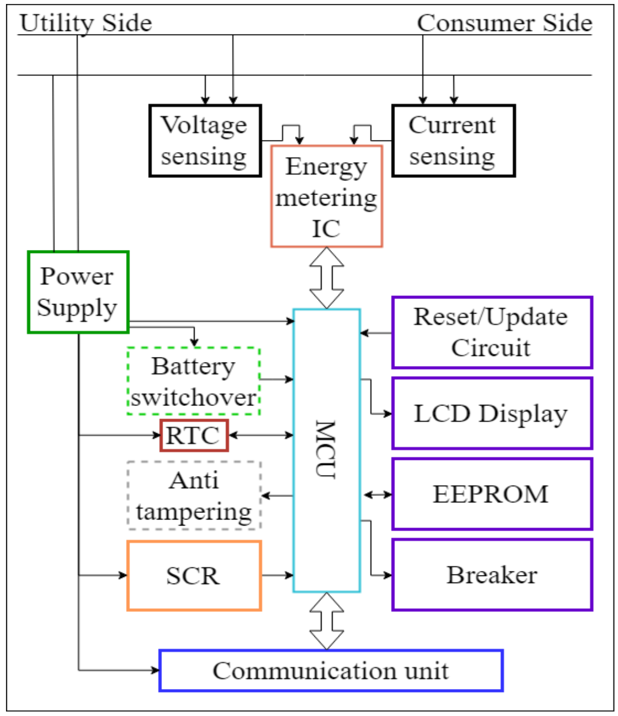

Figure 2.5. SM internal structure

Nowadays, most of the SMs are equipped with LCD interfaces that enable the consumers to not only learn their electricity tariffs and energy consumption patterns but also learn the quality of power delivered from utilities as well as the indication of a power outage when it occurs. The MCU unit also processes such functionalities.

2.3.1.2. Power supply unit

The SM circuit is supplied with power from the main AC lines through AC-DC converters and voltage regulators. A supplemental switchover battery is charged from the main AC lines in order to power the circuit when the connection between main AC and power supply unit is interrupted or a power outage occurs. Solar cells and rechargeable batteries can also be used to supply SM with power during the day [68].

2.3.1.3. Energy measurement unit

Based on the voltage and current readings sensed by the voltage and current sensors, energy measurement units perform signal conditioning, and computation of active, reactive, and apparent powers. Energy measurement units can operate as an embedded chip into the MCU or as a standard separated chip to provide the measurements as voltage or frequency pulses.

2.3.2. Communication Technologies

Enabling CTs can be classified into wired versus wireless technologies in SGs. The importance of choosing the appropriate CT cannot be denied because the SG is segmented into different networks, HAN, NAN, and WANs. The range of coverage, for example, is one of the essential criteria to be taken into account. For each SG network, as depicted in Figure 2.6, different ranges of coverage are required. Unlike NAN and WAN, HAN requires relatively a short range of around 300 m. While coverage range differs from one technology to another, the data rate is another essential factor to be considered, especially around data-heterogeneous areas of the SG network such as APs and clouds. To this extent, these parameters per se affect the performance of the network in many ways. The increased data rate, for instance, would introduce additional overhead in which results in increased energy consumption or delayed message delivery time.

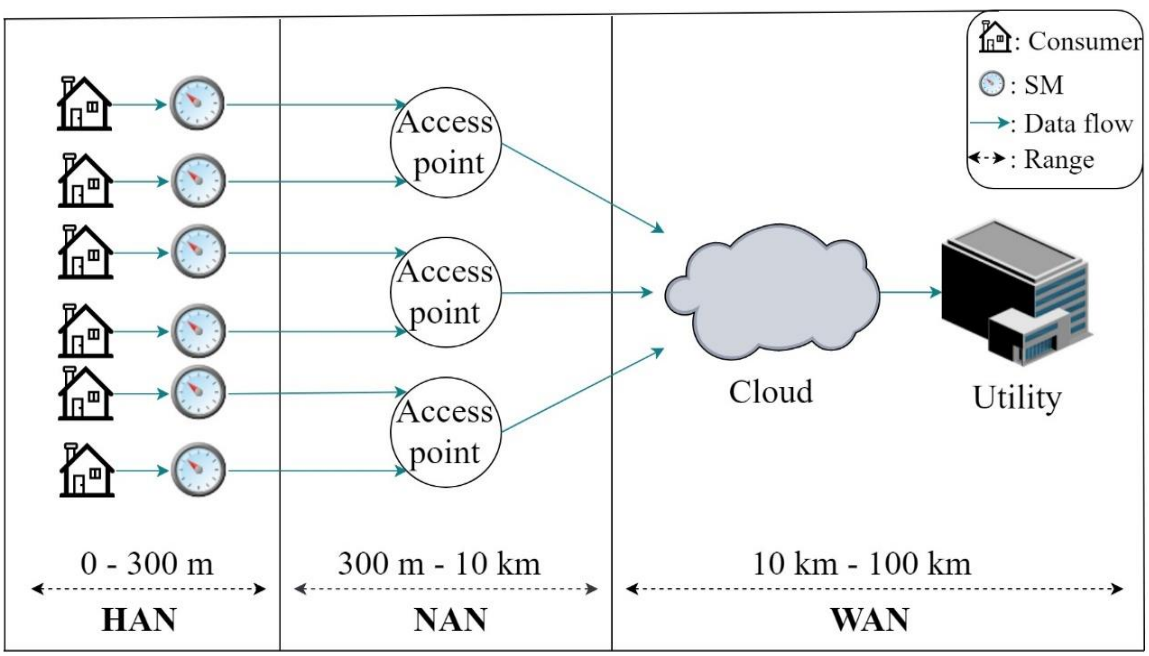

Figure 2.6. SG communication networks (HAN, NAN, and WAN) with their respective coverage requirements.

In the following subsections, the different wireless versus wired CTs that can be integrated into SG communication networks is presented. CTs can be used in SGs based on type (wired versus wireless), transmission rate, range, frequency band, network topology, and application area in SGs; NAN, HAN, and WAN. The most common wired and wireless communication technologies are classified below in Table 4 and Table 5, respectively.

Table 4. Wired communication technologies.

Name		Data rate	Range	Frequency	topology	SG Area
Coaxial cable		10 Gbps	0 – 28 km	2 GHz	Star, bus, ring	WAN
DSL	ADSL	1 – 8 Mbps	0 – 5 km	4000 Hz – 4 MHz	Point to point	HAN, NAN
	HDSL	0 – 2 Mbps	0 – 3.6 km			
	VDSL	15 – 100 Mbps	0 – 1.5 km			
Fiber optic		10 Gbps	10 – 60 km	180 – 330 THz	Point to point	NAN, WAN
PLC	HP	14 – 200 Mbps	0 – 200 m	1.8 – 250 MHz	Star, bus, ring	HAN
	NB	10 – 500 kbps	0 – 3 km	3 – 500 kHz		NAN, WAN
Ethernet		10 Mbps – 10 Gbps	0 – 100 m	100 – 500 MHz	Star, bus, ring	HAN

Table 5. Wireless communication technologies.

Name	Data rate	Range	Frequency	Topology	SG Area
Zigbee	250 kbps	0 – 100 m	2.4 GHz	Star, cluster, tree, mesh	HAN
Wi-Fi	54 Mbps	0 – 250 m	2.4 and 5 GHz	Point to hub	
Bluetooth	721 kbps	0 – 100 m	2.4 GHz	Star, bus	
Z-wave	40 kbps	0 – 30 m	900 MHz	Mesh	
NB-IoT	14.4 kbps (2G) 100 Mbps (4G)	10 – 100 km	824 MHz and 1900 MHz	Star	NAN, WAN
Wi-MAX	100 Mbps	50 km	2-11 GHz 11-66 GHz	Mesh	
Sigfox	100 bps	30 – 50 km (Rural) 3 – 10 km (Urban)	868 MHz – Europe 902 MHz – USA	Star	
LoRaWAN	50 kbps	10 – 15 km (Rural) 2 – 5 km (Urban)	900 MHz	Star	

2.3.2.1. Wired communication technologies

- *COAXIAL CABLE*

Coaxial cable CT relies on Data over Cable Service Interface Specification (DOCSIS) principle that is approved by the ITU, under ITU-T J.222 recommendation. The technology comes with six versions that were first initiated in 1997 with version 1.0. The most recent version is DOCSIS 3.1 Full Duplex, completed in 2017 that supports a transmission rate of up to 10 Gbps at a frequency range of 0 MHz to 2 GHz [69]. The network topology in this technology can vary; star, bus, or ring, based on the desired application. The technology can cover a range of approximately 28 km [70]. While earlier versions of this technology had QoS features such as capacity enhancement and channel bonding where the channel can be coupled with an adjacent channel that has same frequency band to enhance data transmission rate, DOCSIS 3.1 Full Duplex is proved with its symmetrical streaming and enhanced uploading speeds. Considering its high data rate, the technology can make a good communication medium in SG NANs and HANs where most of the data congestions occur.

- *DIGITAL SUBSCRIBER LINE (DSL)*

DSL technology is a wired communication medium that transfers data through the standard telephone lines at a frequency range of 4000 Hz to 4 MHz depending on the type. The technology is approved by ITU G.992 recommendations. Three different types of technology are commonly used [71]. Firstly, ADSL offers a data rate of 1 to 8 Mbps with maximum coverage of 5 km. On contrary, HDSL delivers data at a rate of two Mbps for a distance of 3.6 km whereas VDSL can cover a maximum of 1.5 km distance but with relatively higher data rates that range between 15 – 100 Mbps. Unlike ADSL, the key feature associated with HDSL type is the symmetricity of downstream and upstream that processes an equal amount of data packets in both directions. DSL CTs can be integrated with SG HANs and NANs. They can also provide access to rural areas and distribution and transmission substations.

- *FIBER OPTIC (FO)*

Fiber optic technology uses a glass medium where data packets are transmitted as a form of light pulses standardized by various international organizations such as ITU-T G.652 and IEC, IEC 60793. Considering the glass nature of the transmission medium in this technology, the network topology can take a point-to-point style. The technology is known for consistent transmission speeds and long-range with a frequency band of 180 – 330 THz. Using Fiber optic can deliver data up to a rate of 10 Gbps for a range of coverage 10 – 60 km [72]. In fiber-optic communication, transmission reliability is an advantage such that link failure is less likely to occur relative to copper-based wired transmission. The high data transmission rate and low costs make the technology a possible alternative to handle network requirements in NANs and WANS. However, fiber optic wires are fragile which makes it difficult to be integrated into dynamic regions or above the ground such as electric power transmission towers.

❖ *POWER LINE CARRIER (PLC)*

PLC technology makes use of electric power transmission infrastructure to accomplish bidirectional data communication. The technology comes with two types, HomePlug and Narrowband PLC [73] and standardized under IEC 61131-3. HomePlug PLC frequency band is 1.8 – 250 MHz where Narrowband PLC is 3 – 500 kHz. HomePlug PLC has a data rate between 14 – 200 Mbps whereas Narrowband PLC ranges from 10 to 500 kbps. The coverage range differs due to the difference in data rates. Unlike HomePlug that can cover a distance of 200 m, Narrowband can reach up to 3 km in coverage distance, which makes it a good alternative for NAN or WAN applications.

❖ *ETHERNET*

Ethernet communication is a conventional communication protocol that targeted connecting HAN devices. The technology is standardized under IEEE 802.3. The data rate in Ethernet can range from 10 Mbps to 10 Gbps but with a short communication distance of 0 to 100 m with a frequency band of 100 – 500 MHz. Considering this high data rate, Ethernet can be used in SG HANs.

2.3.2.2. WIRELESS COMMUNICATION TECHNOLOGIES

❖ *ZIGBEE*

This technology is mainly designed for short-range and in-door communications. As such, it is characterized by low power consumption as well as low data rates (around 250 kbps). Zigbee follows the IEEE 802.15.4 design standard and operates at a frequency band of 2.4 GHz [74]. In SG, Zigbee technology can be very useful for device communications in the infrastructure layer. The technology works very well in home automation applications at the consumer side and ensures QoS while wirelessly connecting user premises.

❖ *WI-FI*

Wi-Fi technology can also be used for device communications in the infrastructure layer of the SDN-based SG. Many user premises (such as smartphones, computers, office printers, and drones, to name a few), nowadays, are connected through Wi-Fi in an interoperable manner. In comparison with Zigbee, Wi-Fi technology is developed according to IEEE 802.11 standards. The technology is capable of transmitting data up to 54 Mbps and operates at 2.4 and 5 GHz frequency bands [75]. In addition to the data transmission rate, the communication range is also larger in this technology relative to Zigbee. Follows, the high data transmission capabilities come at the cost of increased power consumption. Thus, this technology may also be used in high data-traffic applications in the SG network. Security is another advantage of this technology since it uses provides strong authentication steps based on advanced encryption standards.

❖ *BLUETOOTH*

The technology is mainly used for data transmission, up to721 kbps, between stationary devices in short ranges (typically reaches 100 m, similar to Zigbee). It is designed according to the IEEE 802.15.1 standard and operates at a frequency band of 2.4 GHz [76]. Thus, since the technology transmits relatively low data packets per second, it is known for the low power consumption. Recently, it became widely adopted in smartphones and other devices, which can help maintain high interoperability between devices in the infrastructure layer, specifically in the SG HAN network.

❖ *Z-WAVE*

In addition to the aforementioned technologies, Z-wave is generally very useful in home automation applications. The data transmission rate in this technology is around 40 kbps. Unlike other technologies, Z-wave uses a frequency band of 900 MHz which is a significant advantage that minimizes the risk of signal interference [77]. The transmission range is approximately 30 meters, which is relatively short considering the transmission ranges of other in-door communication technologies. However, the technology performs well in terms of transmission accuracy in data delivery with minimized delays. In fact, technology is also shown to perform well in terms of scalability as well (up to 1000 customers at the same time [78]. The usefulness of this technology can greatly enhance various networking aspects in the SG communication such as signal interference and scalability, at the cost of the transmission rate.

- *NB-IoT*

Unlike the aforementioned communication technologies, NB-IoT is mainly designed for Low Power Wide Area Networks (LPWAN) with coverage that reaches up to 100 km. Therefore, the usefulness of this technology can be seen in the NAN and WAN regions of the SDN-based SG network. NB-IoT provides three types of operation (2G, 3G, and 4G) and the data transmission rate varies starting from 14.4 up to 100 Mbps, according to the operational type [79]. The advantages of high data transmission rates make the technology suitable in regions where the congestion is high. Considering the exponential growth of user numbers in the SG, the technology can assist in solving bottleneck issues around data aggregation points and base stations, which undoubtedly comes at the cost of high power consumption.

- *WIMAX*

WiMAX is designed considering the IEEE 802.16 standard in which it operates at two frequency bands (2-11 and 11-66 GHz) for data communication at a rate of 70 Mbps for a coverage area that reaches up to 50 km [80]. The WiMAX has a similar principle to Wi-Fi but differs in the distance of transmission. The technology has been updated in 2011 to enhance the data transmission rate up to one Gbps. The large communication range along with the high data transmission rate in this technology makes it a good choice when it comes to NAN and WAN networking requirements in SG networks.

- *SIGFOX*

This technology is developed in 2009 and targets long-range communications. The major function of this technology is to communicate with devices that are active for long durations of time and transmits low data packets. Therefore, the transmission rate is limited to 100 bps. The coverage in this technology varies according to the desired application (rural or urban location) [81]. Furthermore, the technology operates using two different frequency bands. One of which is 868 MHz in Europe and the other is 902 MHz in the USA.

- *LORAWAN*

This technology is also designed for WAN communications, which rely on MAC principle. The advantage of this technology is providing a robust communication link between lower-power devices considering long transmission ranges. Thus, LoRaWAN can transmit up to 50 kbps of data packets [82]. The coverage range in this technology differs from rural to urban areas with up to 15 km in urban areas. The slightly increased data transmission rate in this technology in comparison with Sigfox makes it a suitable solution for data communication in WAN SG regions, which contains a large number of devices such as smartphones, sensors, energy storage and EV charging stations, to name a few.

2.3.3. Electric Vehicles

The motivation of communities to reduce GHG emissions and raise the standards of living by offering flexible technologies that meet various requirements indorses the need to take immediate actions collaboratively among the diverse sectors in modern cities. Characterized with large amounts of air pollution caused by legacy CE-based vehicles, the transportation system is one of the sectors that require the efficient planning as well as robust infrastructure that is implemented hand-in-hand with the SG paradigm. Keeping this view in mind, the EV concept started taking place among researchers, industrial bodies, and political actors. In fact, the technology is currently adopted with an estimate of approximately 2 million EVs in stock worldwide as of 2016, with the United States and China having the largest portion in comparison with other countries [83]. The current model of operation in EVs is G2V, where energy is transported in one direction, from the SG to the EV. The EV era is expected to witness other forms of energy transportation as technology furthers such as V2G and V2V. It is believed that transferring energy from EVs to the grid would help to enhance technical parameters in the grid such as voltage and frequency stabilities. Sharing the energy between vehicles may help to minimize the charging time. The following are two of the essential key considerations for successful EV integration into the SG. The deployment of EVs is associated with both challenges and advantages to the SG [84]. In terms of challenges, the large number EVs can induce an unexpected increase in power demand in the grid, which is alerting – due to its unpredictability – especially if it coincides with peak demand hours in the electric grid. As for advantages, EV integration enables, for instance, flexibility in integrating RES and alleviate their power output variability through utilizing excess energy generated by RES when the resources are abundant. Despite the general controversy on the impacts of EVs on the SG, whether they provide benefits to the grid operational efficiency or they create weakness points that creates additional challenges, it is commonly agreed that there are adverse effects on the distribution network, where EV charging mostly occurs, due to the uncontrolled charging patterns of widespread EVs [85]. Therefore, G2V or V2G energy management protocol or control system that acts as a mediator between the EV and the SG can be developed in or efficiently manage the energy transmission process [85]. This can be achieved through approaching the grid regionally while considering the presence of EV in each certain region with specific charging schedules that are compatible with the charging schedules of other regions.

2.3.4. Energy Storage Facilities

RESs are characterized by variable power outputs that are highly dependent on weather conditions. This creates a big burden on utilities to supply reliable power during source non-availability. PV, for instance, is perceived as a sustainable solution across the globe for supplying energy. Yet, the sunlight is not available during nighttime and therefore, there is an urgent need for EESs. The ESSs (using) batteries stores the surplus generated energy during the day for later utilization during nighttime. Among the body of literature, there exist various storage methods such as electrical, chemical, and thermal energy storage [86]. There are also other hybrid methods such as electro-mechanical storage systems which can trade energy with the electric grid given the efficient power electronics [87]. In addition, although in its early stages, P2G technology is on the rise whereby it refers to the conversion of excess electric power generated by the RESs, especially wind, into a useful gas fuel [88]. Therefore, efficient planning of ESSs in the SG, along with other enabling technologies, is perceived as the promise towards 100% renewable smart cities. The idea of adopting a data-enabled grid helps to maximize the benefits of ESSs. Therefore, the SG is expected to accommodate a wide range of technologies to improve the overall efficiency of the grid. Future research and development efforts may also make use of SG facilities to improve the standby efficiency of ESSs.

2.3.5. Power Generation Facilities

The successful transition towards a fully DG-based SG may be disruptive due to the existing centralized power systems across the system. In fact, in some regions, power demand is fully met by centralized power plants (usually based on fossil fuel sources). Therefore, the gradual adoption of DGs into the current power system is seen as the ultimate solution in order to avoid disruptiveness. The power generation in this SG paradigm may take two shapes, 1. Bulk power generation plants, and 2. Distributed Generations integrated across the system, including both transmission and distribution networks. Considered the technology used in this thesis, the following chapter expands on the DG technology and discusses the essential deployment considerations.

2.4. CHAPTER SUMMARY

In this chapter, the SG technology has been discussed in detail by outlining the difference between conventional and smart grids as well as the stakeholders in the SG paradigm. The enabling technologies for the successful transition towards 100%-renewable SGs have been highlighted by outlining important considerations in their deployment. The chapter concludes that SG is expected to constitute a wide range of enabling technologies for improving the efficiency of power delivery to consumers. In fact, the definition of SG does not restrict the enabling technologies to provide solutions only to the power grid; they may also provide flexible solutions to other fields. We have learned from this chapter, for instance, that SM technology may include home automation systems that can control resources in households. Furthermore, communication networks may provide useful information on the grid status, and therefore, help to improve the quality and reliability of delivered power. The grid is expected to rely on DG sources in order to reduce the reliance on centralized fossil fuel power plants.

Chapter 3

DISTRIBUTED GENERATION TECHNOLOGY

Renewable sources based DGs play a vital role in the development of the SG structure [89]. Undoubtedly, they provide various benefits not only to the environment and consumers but also to the electrical network and enhance its operations [90]–[92]. However, in order to foster the deployment of DGs into SGs, it is essential to have a full understanding of their characteristics and integration requirements. Purposefully, this chapter firstly discusses the concept of DG technology, and then introduces the associated DG sizes and types considering the generation source; non-renewable vs. renewable sources. Finally, the chapter is summarized with a deeper understanding of the type and scale of the DG used in this thesis.

3.1. WHAT IS DISTRIBUTED GENERATION?

Back in the early stages of power generation, communities used to generate power locally and close to customer sites, in which power systems then were based on DC electricity. Later on, the advancement in technology and the introduction of AC power systems enabled electricity to be transmitted over large distances. This has contributed to massive economic growth since large amounts of power are now being transmitted to various places across the country [93]. Subsequently, the construction of interconnected large power systems, including distribution and transmission systems, has emerged. However, this dramatic expansion in large interconnected power systems has called for distributing the generation, similar to the early stages of power generation. The

International Energy Agency attributes this call for distributed generation technology to the following motives [93], [94]:

- The limitation of expanding transmission systems further.
- The need for reliable electric power supply considering the frequent power interruptions exhibited by centralized power plants.
- The increased concerns on climate change that is accelerated by fossil-fuel-based energy sources.

There are many terminologies used across the globe that refer to distributed generation such as "decentralized generation" in Europe and some Asian countries, "dispersed generation" in North America, and "embedded generation" in South American Countries [95]. However, the term "distributed generation" is suggested to be used worldwide [96], [97]. Although distributed generation technology is defined as a small-scale power generation, there still exist various definitions of the term among the rich body of literature. In the literature, the term has been defined based on different metrics such as the network or voltage level that the distributed generation is integrated into, generation type (renewables or fossil fuel-based), and size of the distributed generation. Ackermann et al. for instance in reference [97] define a DG as being "an electric power source that is directly connected to the distribution network or on the customer site of the meter". It can be said that this definition considers the voltage level of integration, in which the distributed generation cannot be installed into the transmission network. Similarly, the IEA [94] defines the technology to be a generation unit near load centers regardless of the size or type of the generation unit. Reference [93] also favors this definition since it does not include any restriction on the type or size of the distributed generation. Authors in reference [98] also define distributed generation as a generation unit that is integrated near the load centers, indirectly the distribution network. In addition, they put a restriction on the respective capacity ranging from 1 kW to 1MW at load sites, in which they see distributed generations as an alternative to centralized generation plants, ranging from 100 MW to 1 GW, placed at far locations from the customers. In addition, reference [99] specifies a restriction on the distributed generation capacity, in which it is considered to be under 200 kW. The International Council on Large Electric Systems, however, consider a capacity less than 50 – 100 as a criterion to distinguish distributed generations, as discussed by

Dondi et al in [100]. Other definitions discussed in [97], such as [101]–[103], also consider the size range as a criterion to define distributed generation technology, the ranges are specified as 25 kW to 25 MW, a few kilowatts to over 100 MW, and 500 kW to 1 MW, respectively. In comparison with the previous definitions, the Institute of Electrical and Electronics Engineers (IEEE) – also provided in reference [100] – defines the technology as generation units that are " sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system". The second portion of this definition implies that distributed generation units can also be integrated into transmission networks, in order to provide better connectivity in the grid in terms of power supply.

It can be concluded that there is no specific consensus on the exact definition of distributed generation technology. Generally, however, it can be agreed that the size of distributed generations is relatively less than centralized power plants in the range of few kilowatts to tens of MW's. As for their location in power systems, even though some definitions limit the area of integration to distribution networks, DG generations can be very beneficial to the operations in transmission networks as well. As confirmed in [97], a wind-energy based distributed generation unit with a capacity of 3.5 MW that is installed on the 11/33 kV network exported energy back to the electric grid through the transmission system during night time, since the demand during nights is low in comparison with day time. Not only this but also distributed generation units help reducing active power losses at the transmission network and help improve the voltage profile of busbars [33]. Therefore, in this thesis work, we favor the IEEE definition of distributed generation technology and it can be concluded that the integration of distributed generation must not be limited to the integration in the distribution network, as it also provides benefits to the transmission network. In fact, distributing the generation on the transmission network helps to not only reduce the reliance on centralized power generation plants and improve system technical parameters but also offers benefits to the environment, considering the integration of renewable-based distributed generation units.

3.2. POTENTIAL BENEFITS

Among the rich body of literature, there have been many research attempts to promote the benefits of using distributed generations as an alternative power-generation paradigm to make up for the shortcomings seen in centralized power generation plants. These benefits include improving the operations in transmission and distribution networks, economic savings to both utility and customers, liberalization of power systems, rural electrification, improving energy efficiency, and environmental friendliness. Figure 3.1. Summarizes the benefits and the following subsections discuss how DG systems can help to offer those benefits.

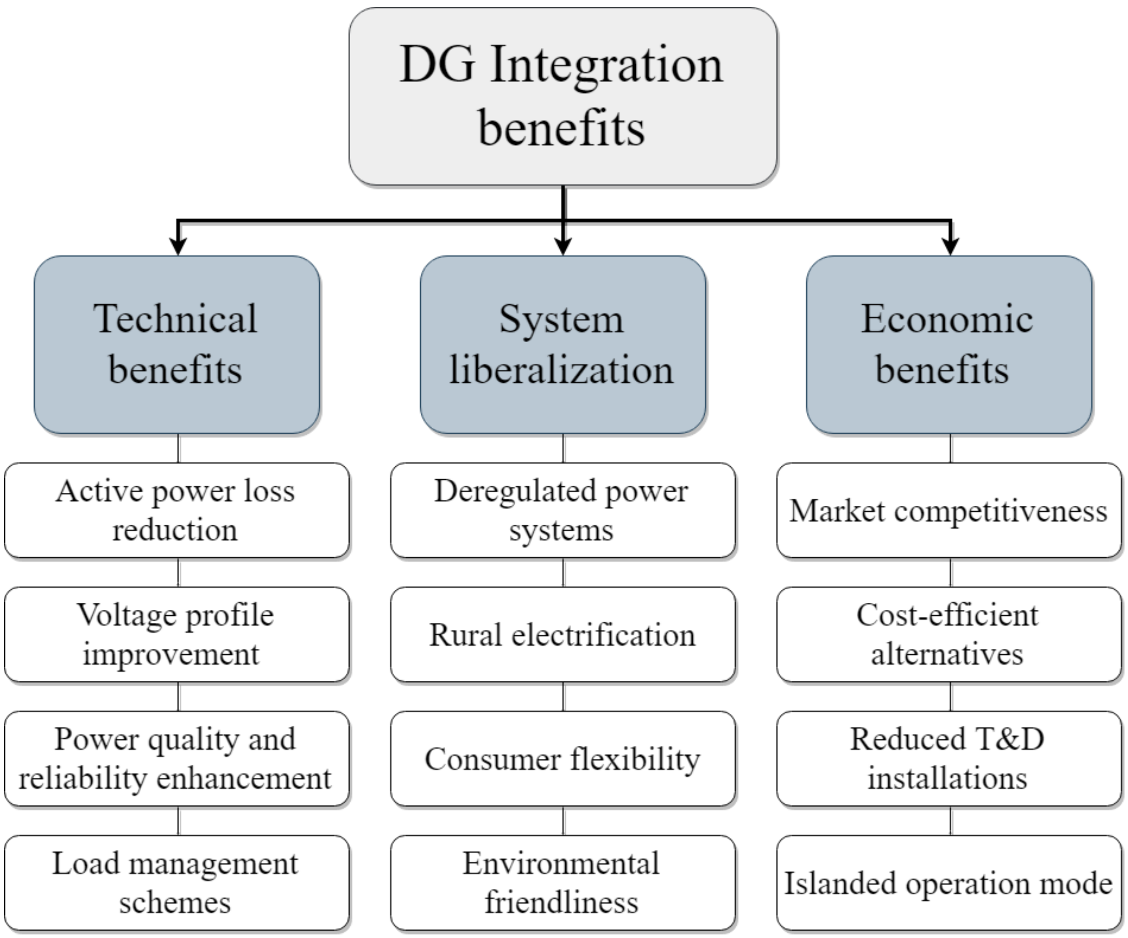

Figure 3.1 Classification of DG potential benefits

3.2.1. Technical benefits

One of the main quests for the renewed interest in integrating distributed generations is the enhancing technical parameters in power systems. The following subsections present how integrating DG systems can help to improve the efficiency of the system considering active power loss, voltage profiles, power quality, and reliability as well as providing flexible load management schemes.

3.2.1.1. Active power loss and voltage profile improvement

It is evident that distributed generation can help to minimize active power loss and improve busbar voltage profiles in the network [104]–[108]. In centralized power systems, the long-distance between generation sites and customers is considered the main factor power loss in the network, since power loss is directly proportional to the resistance of the transmission line. Therefore, the further a customer is located from the generation site, the more power loss can be exhibited.

Additionally, the infrastructure and equipment in centralized power systems are characterized by large inefficiencies that may also degrade the performance of the power transmission process to customers. For instance, low transformer and motor efficiencies, as well as poor network connections, may result in deviations of voltage magnitudes from the desired ranges at the respective busbars in the system. Distributed generation technology, on the other hand, does not only eliminate the need for transmitting electric power over large distances but also reduces the reliance on auxiliary electric equipment between power sources and destinations.

3.2.1.2. Power quality and reliability

In addition to minimizing active power loss and improving busbar voltage profiles, the integration of distributed generations can assist improving the quality as well as the reliability of supplied power. Power quality simply means delivering a smooth and steady voltage waveform to consumers; that is maintaining a pure sinusoidal voltage waveform at the customer side. Power quality issues are majorly found in variant voltage waveforms and supply frequencies. These waveform disturbances accompanied by current and voltage distortions can be caused by changeable load patterns [109]. Power quality issues may also be experienced in the case of fault and switching operations in the network. Utilities and stakeholders impose standards and certain power quality measures in order to protect the network performance from severe deterioration. Examples of such standards include the IEEE 519 – 1992 Recommended practice for harmonics control in power systems, IEC 61000-4-7 and IEC 61000-4-15 standards for power quality assessment parameters, and the EN50160 European power quality standard. Several assessment parameters of power quality are used in literature among which harmonic distortion, voltage sags, and swells, under and overvoltages, are the most widely used ones. Although the connection between distributed generations and power quality is thought to be equivocal at first [93], it is, later on, proved that the integration of distributed generations helps to minimize power quality issues. For instance, it is shown in references [110], [111] that the increased number of integrated distributed generation units in the system helps – in addition to minimizing active power loss and improving busbar voltage profiles – to reduce voltage waveform total harmonic distortions, where there has been a THD reduction from 0.4903% to 0.1487% [110].

Power reliability, in comparison with power quality, is particularly used to refer to the complete loss of voltage waveform. An ideal reliable power system suggests that the consumers will be supplied with electric power continuously without any fault, loss, or interruption of the supply. Supplying reliable power to consumers is seen as one of the main important considerations, especially in countries where engineering standards are not high and experience frequent power outages. Centralized power systems, are not efficiently structured – considering the old age of transmission and distribution infrastructure – and, consequently, there exist numerous factors that contribute to power reliability issues. Examples of such factors include faulty equipment, generator outages, and transmission line failures (in some instances cascade line failures may lead to large blackouts in power systems), to name a few. External factors such as natural disasters can also cause power reliability issues. Similar to power quality, various parameters are used to assess the reliability of the desired power system. For instance, in 2003 (revised later in 2012), the IEEE Power and Energy Society provide standardized reliability assessment indices [112]. These indices are grouped under three main categories: indices for sustained interruptions, load-based interruptions, and momentary interruptions. Improving power system reliability is bonded to the availability of distributed generations in the power system for mitigating frequent power outages [113]. In fact, power reliability indices of the system can be enhanced as shown in study [114] where authors show the potential of improving SAIFI, SAIDI, and AENS indices (sustained interruption indices) of the system with the presence of distributed generations. Not only this, but distributed generations can also help to improve system reliability in natural disaster events that disconnect distribution networks from the grid and it is evidenced that SAIFI, SAIDI, and EENS of the system can be enhanced [115]. In this regard, distributed generations can be used as back-up generation units to sustain the power supply in critical locations (such as schools, hospitals, chemical industries, etc.) during severe power outages.

3.2.1.3. Load management flexibility

DG systems are believed to offer a standby source of electric power, which does not only help the procurement of electricity but also provides flexible load management schemes. Peak shaving technique, for example, can be applied to customer load profiles for reducing the reliance on power supplied by utilities during peak times. Typically, utilities have different pricing policies, depending on the time the energy is required, at which the highest pricing rate is seen at hours of peak-demand; say, for example, at 18:00 of the day where most of the houses in a particular region are occupied. Generally, peal shaving offers economic benefits to consumers. Peak shaving at this instant can be applied in many different ways such as turning off the unnecessary house appliances or using battery storage systems to store solar energy and utilize it during peak times. However, distributed generation seems more attractive because, in addition to peak shaving, the distributed generator can also be operated during power outages, which in return enhances power reliability.

3.2.2. Power system liberalization

The ‘liberal’ power system can be best described with three distinctive features, including deregulation of the power system, electrification of rural areas, and environmental friendliness. The following subsections describe the aforementioned features.

3.2.2.1. Deregulated power systems: from hype to reality

The global community nowadays witnesses an unprecedented desire to switch to deregulated power systems. In regulated (centralized) power systems, power transactions follow a vertical top-down structure, where utilities are responsible for generating, transmitting, and delivering the power to consumers. As such, consumers do not have the flexibility of selecting the utility that meets their electricity demands. On the other hand, in addition to utility companies, deregulated power systems accommodate members that can also play a part in the electricity market and retain power generation or transmission facilities. The generated power is sold into a wholesale market and ISOs are responsible for delivering the power to consumers in a reliable manner. Thus, consumers in deregulated electricity markets can choose the 'member' or company that supplies their energy demand. This 'liberal' paradigm of electric power transactions opens up the doors for market competitiveness between power producers, which as a result, helps to diversify the generation sources in the system, as per customer preferences. In this regard, they can consider different metrics when choosing the desired power producer such as the source of produced power (renewable vs fossil fuel or nuclear) or the energy price. Distributed generation assists power producers to offer flexibility in meeting the changing requirements of customers as well as the dynamic circumstances in the market.

3.2.2.2. Rural Electrification

The term rural electrification describes the process of delivering electric power to remote areas. Although nowadays there has been a significant improvement in electrification rates in comparison with the past, accessibility to a reliable and clean source of power still forms a major challenge in the energy sector. In centralized power systems, utilities face a major challenge of delivering power to remote areas. In those areas, typically, the population is sporadically distributed and the national power system is characterized by discontinuities. Hence, to provide electricity access for those remote areas with limited electricity consumption rates, utilities would have to include high capital costs in building new transmission and distribution networks. This particular solution may not hold economically profitable or feasible, especially when adding up the cost of power loss in the processes of power transmission and distribution [95]. Therefore, distributed generation looks an attractive alternative to offer

3.2.2.3. Environmental Friendliness

Distributing the generation of power offers vital importance to the SG of reducing the reliance on centralized power generation. This also significant when the DG source is based on renewable energy sources, where they are characterized with low GHG emission factors in comparison with other power generation sources such as coal, oil, or gas DG units. The installation of efficient DGs such as CHP and RES, along with reducing power loss in the transmission system, can help mitigate the GHG emissions. In fact, it is estimated that a reduction of 1% of the power losses in the UK system helps to mitigate an equivalent amount of 2 million tons of CO_2 yearly [116].

3.2.3. Economic benefits

One of the main advantages of liberalizing the electricity market is reducing the prices of energy by enabling market competitiveness by different participants and energy providers. To this extent, DG technologies can help to provide cost-efficient alternatives that can compete with centralized power-generation projects [117]. In fact, building new centralized power plants requires the addition of T&D networks which adds up not only to the complexity of the network but also to the high installation costs, which can all be removed through investing in DG systems. In this way, minimizing the T&D networks is associated with increased system efficiency that is directly related to mitigating power outages and blackouts. The economic loss in such conditions is considerably large and utilities are generally, in some countries, are required to provide to the consumers a form of economic compensation in order to make up for the power loss. In the case of DG, on the other hand, consumers can have the flexibility of islanded operation mode, which can mitigate the economic loss.

3.3. INTEGRATION CHALLENGES

The introduction of various enabling technologies in the system (See section 2.3) requires the development of DG-enabled power systems that requires standardized coordination and planning amongst all system entities. The coordination plan may enable the technologies in the system to respond to the signals sent by market operators, and therefore, change or adjust their functionalities accordingly. This is enabled through, for example, transactive energy markets, which are in the application by several industrial initiatives such as, OpenADR, USEF, and EF-PI [118].

In addition to the development of standardized operation-frameworks, the large integration of DGs can induce new challenges to the operation in the system. Along with bidirectional communication flow, electric power is expected to flow bi-directionally as well, which may have different impacts on system stability. In this regard, the integration of DG systems will highly depend on the optimal planning considering location and size in the system in order to minimize power losses [117]. Furthermore, given the increased competitiveness among participants in the liberal electricity market, the risk of investments may increase and this may lead to economic losses.

3.4. DG CHARACTERISTICS: SIZE AND TYPE

Various technologies are developed in different relative sizes (as reported in

Table 6) to be used as a DG among which the source of energy can be renewable or non-renewable as shown in Figure 3.2 Accordingly, the performance of the DG differs from one technology to another, depending on the source of energy and relative efficiency. Figure 3.3 shows the most important performance indicators for DG technologies including environmental, technical, and economic parameters [119]. While technologies that are known for their robust technical performance, such as the efficiency of ICEs, they are characterized by high GHG emissions. Renewables, on the other hand, is environment-friendly but at the cost of power output variability. The following subsections discuss the different technologies and highlight the associated performance metrics.

Table 6. Distributed generation relative sizes [120].

No.	Class	Size
1	Micro distributed generation	1 w < 5 kW
2	Small distributed generation	5 kW < 5 MW
3	Medium distributed generation	5 MW < 50 MW
4	Large distributed generation	50 MW < 300 MW

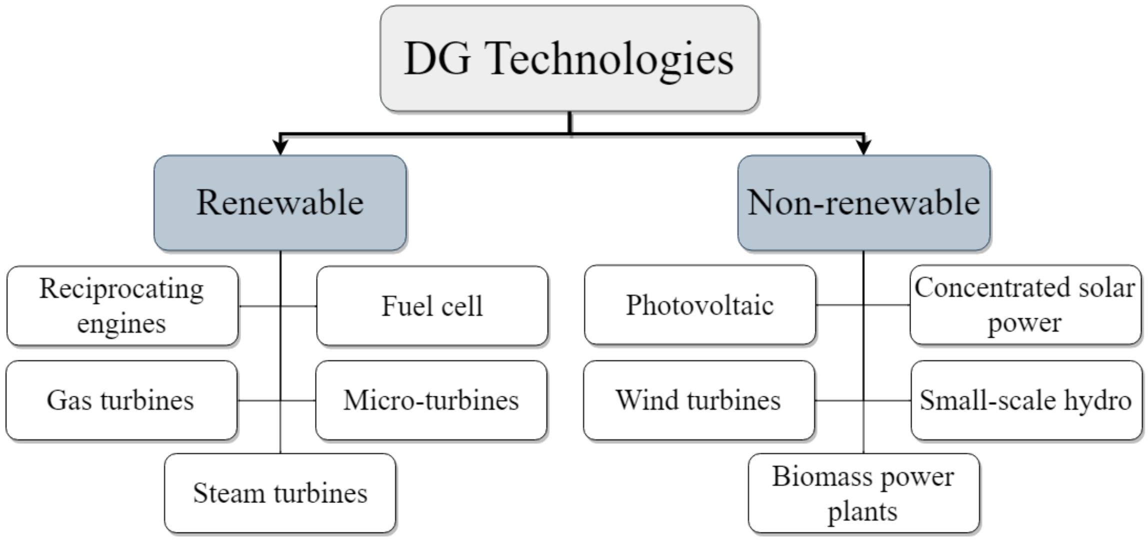

Figure 3.2. A summary of DG technologies.

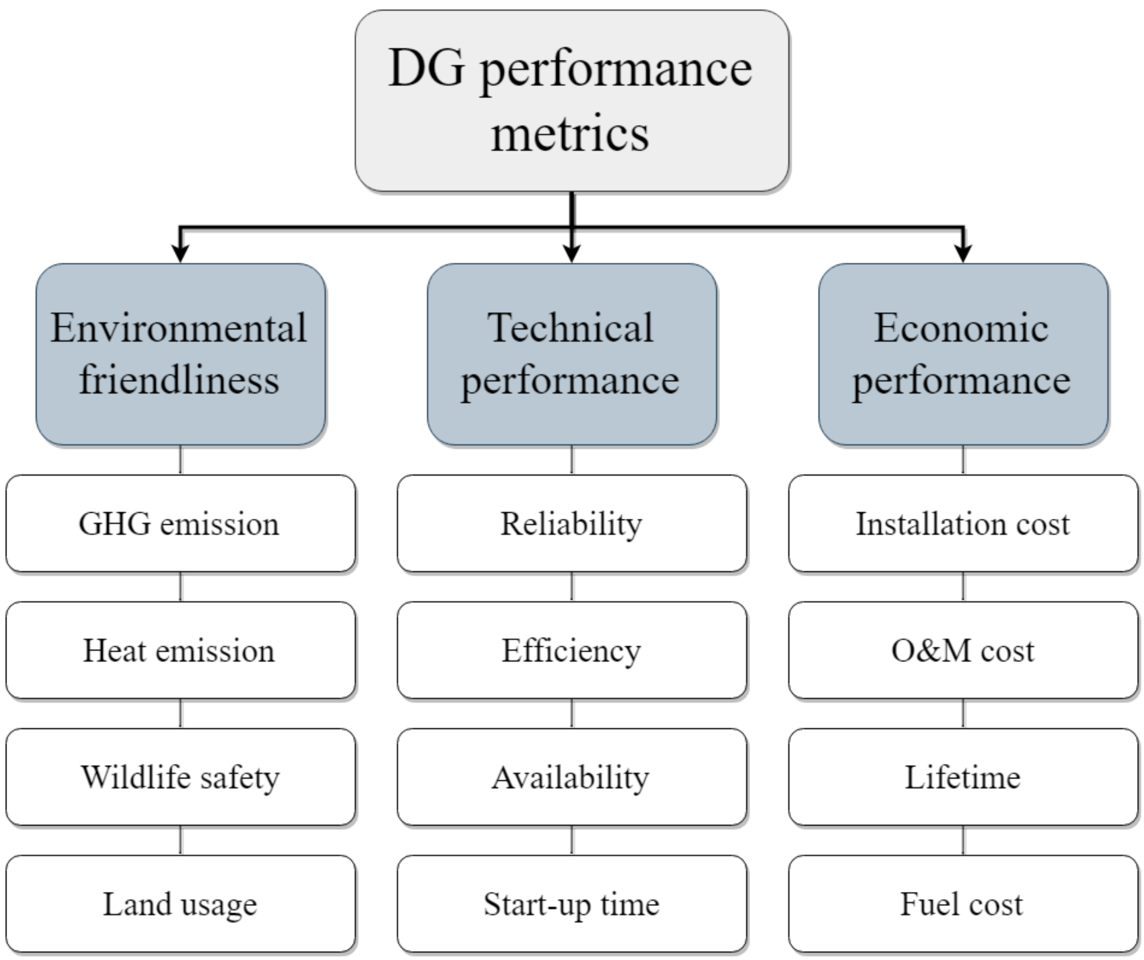

Figure 3.3. DG performance metrics.

3.4.1. Non-renewable DG technologies

3.4.1.1. Reciprocating engines

Also known as piston engines, reciprocating engines rely on one or multiple pistons for pressure-motion conversion [121]. The reciprocating engines exist in many types, among which steam engines are a famous example. The technology is widely adopted for generating power in both small and large scales; either near consumers or in centralized power plants. The usefulness of this technology is mainly seen in its reliability of supplying continuous power and the quick start-up time. The technology uses many fuel types such as diesel, gasoline, and natural gas. Therefore, this technology is known with relative GHG emissions, whereby it is estimated that a reciprocating engine emits CO_2 of around 500 to 650 g/kWh [119].

3.4.1.2. Fuel cell

Fuel cell technology converts chemical reactions into electrical power. With air assistance, the technology can provide continuous power supply provided fuel existence. The technology can use either fossil fuels or hydrogen in order to complete the conversion process. Although it is mentioned under the non-renewable DG technologies, fuel cells can also be considered renewable if the fuel source is other than fossil fuels, hydrogen. In fact, hydrogen-based fuel cells are considered as sustainable as other RESs such as PV and wind, which are all alternatives to fossil fuel sources. Despite the fact that hydrogen fuel cell application is still in its infancy, it is believed that the future is promising and, with the research and development efforts, the energy potential and environmental advantages of it can be achieved [122]. The efficiency of the technology is another attractive aspect, where it is believed that hydrogen fuel cells remove inefficiencies associated with heat loss that is typically experienced in combustion engines, in which the potential energy is initially converted into heat, and the resultant heat is converted into mechanical torque that generates electric power as shown in Figure 3.4 below.

Figure 3.4. an example of an on-site hydrogen-based fuel cell generator [123].

3.4.1.3. Gas turbines

The technology is also known as ICE or continuous combustion containing three main elements and an auxiliary element. Initially, gas turbines are comprised of a gas compressor, combustor, and a turbine. The fourth element is called a turbofan that is used for power conversion into useful electricity. The efficiency in this technology is similar to that of reciprocating engines and can be fueled with natural gas, and heavy or crude oil. The technology is known for its near 100% availability with no interruptions, which is able to sustain generating power for long durations.

3.4.1.4. Microturbines

Microturbines are characteristically similar to gas turbines, except the fact that their typical sizes are 25 to 500 kW, which categorizes them as micro-DG units. Therefore, this technology is approximately the size of a refrigerator and typically used for small energy applications such as households, restaurants, hotels, etc. It is in application worldwide as a DG alternative to other technologies (among non-renewables at least) because it is seen as a practical technology with some unique features such as small size and weight, low installation and O&M costs. The technology uses what so-called a recuperator in order to absorb the resultant heat from the compression stage. Yet, the technology is known for the low fuel-to-electricity conversation efficiency. In addition, the technology is prone to power reliability issues, especially at high heat levels, which may result in the loss of power output. It is also worthwhile mentioning that the technology is not environment-friendly when ran on fossil fuels, such as diesel. There is also the possibility of operating Microturbines on hydrogen, which is another attractive area for extended research studies.

3.4.1.5. Steam turbines

Steam turbines rely on pressurized steam, which is utilized to induce a mechanical torque that rotates a shaft as shown in Figure 3.5. The rotation of the shaft is coupled with a generator that produces electric power. Steam turbines are, to date, the most widely used for power generation since the industrial revolution to the modern world. Steam turbines typically exist in central power plants and are available in various capacities, approximately from 10 kW to 1700 MW. The 100% availability of power in this technology makes a reliable source for potential DG applications provided enough input fuels to produce the steam. The technology relies on coal, natural gas, and oil as input fuels for generating the steam. In comparison with previous technologies, the installation of steam turbines is relatively complex and therefore, the installation cost is higher. Although utilized in some industrial areas as a DG, steam turbines may be infeasible in residential areas or congested cities, at the distribution level.

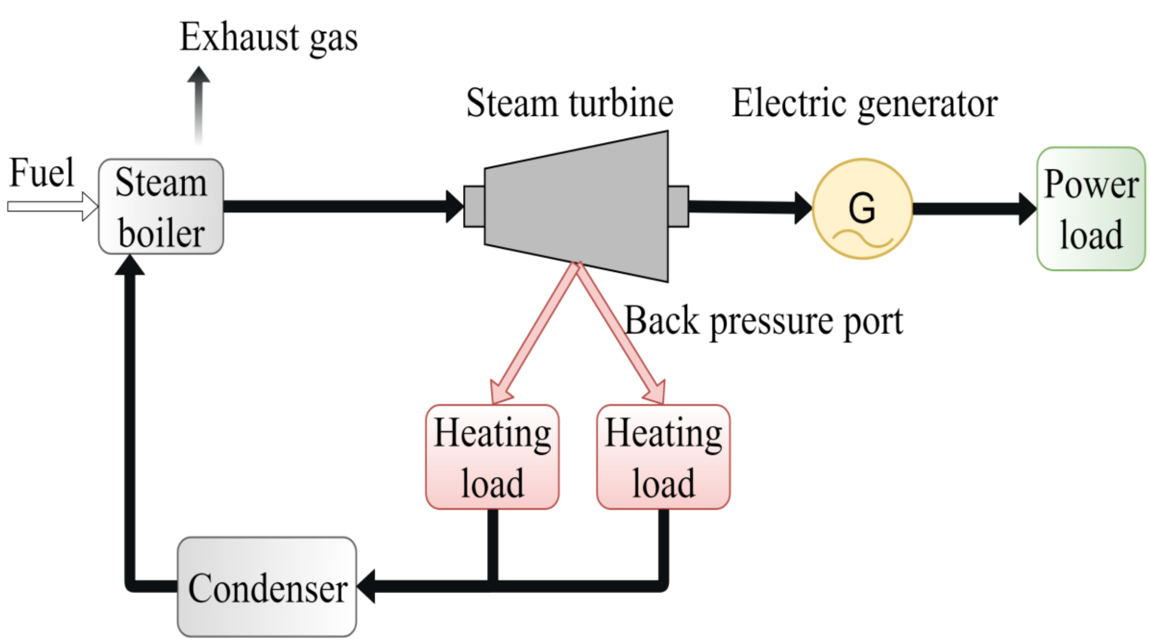

Figure 3.5. An illustration of steam turbines' working principle.

3.4.2. Renewable DG technologies

3.4.2.1. Photovoltaic (PV)

Solar Photovoltaic (PV) technology is the direct conversion of sunlight into useful electricity. A PV system consists of multiple modules that are comprised of small solar cells built with semiconducting materials that produce useful power. The main advantage of this technology is its environmental friendliness; once the system is set up, it generates power without any harmful emissions or pollutants given that the silicon – the most efficient material in solar-power conversion – is available in abundance across the globe. Additionally, the technology removes the need for auxiliary fuels to run the power conversion process, since solar irradiation is renewably available. Countries with high solar resource potential can employ this potential in generating electricity. Although at the beginning the installation price was high, nowadays the cost of PV technology has dropped dramatically. In fact, governments in some countries offer what so-called 'Green Incentives' as grants for users on installing renewables. Figure 3.6 shows a grid-connected PV model with an optional battery-storage option. Investment wise, the PV investments are becoming very attractive to investors, especially with the introduction of net metering and BSS systems in which the surplus power generated during the day can be sold back to the national grid or stored for later usage during night time when there is no sunlight.

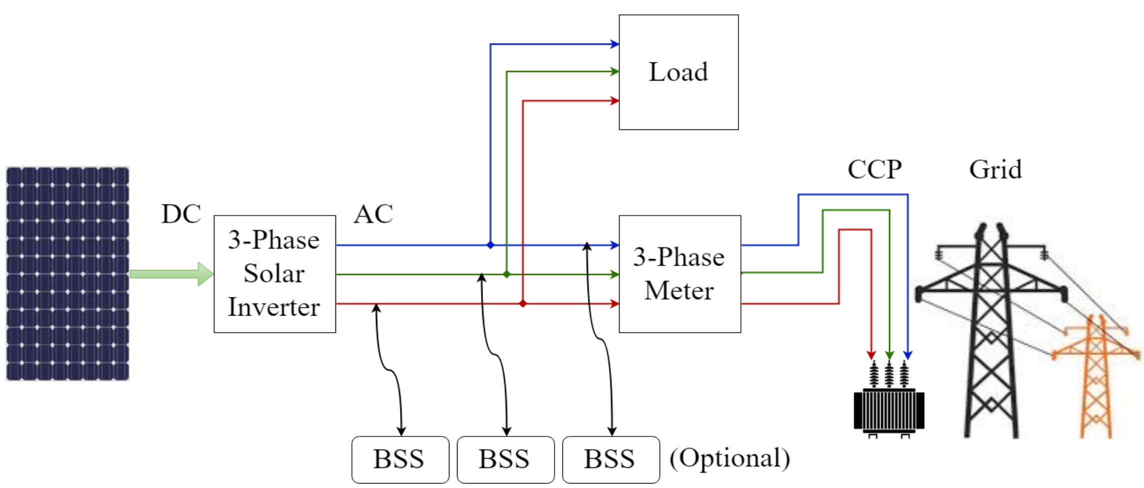

Figure 3.6. A grid-connected PV model with an optional BSS.

3.4.2.2. Concentrated solar power (CSP)

The working principle of CSP systems – sometimes referred to as Concentrated Solar Thermal systems – relies on concentrating the incoming sunlight onto a relatively small area, as the name tells. The concentrated sunlight is mainly transformed into heat that can be used to drive power generators, typically using steam turbines. CSP systems existed since the 1980s and are in practice where the installed capacity of the technology worldwide is recorded 5500 MW as of 2018. The technology is available in different sizes, ranging from hundreds to few megawatts. Therefore, the technology can be greatly used for DG applications. Although the availability of such systems can be greater than PV systems, their installation requires larger spaces and greater costs, since the technology uses generators. Prominent

3.4.2.3. Wind turbines

Wind turbines illustrated in Figure 3.7, are one of the most prominent renewable energy sources especially in countries characterized by high wind speeds. Estimates show that wind energy could supply approximately 2.600 TWh globally by 2020, which contributes to 12.3% of the global energy demand [124]. The technology generates electric power by converting kinetic energy induced by the turbine (rotor) blades into electric power through electric generators. Generators in wind turbines can be coupled directly or through a shaft that uses a gearbox in order to accelerate the rotation, and therefore, achieve higher power outputs. The technology comes with two major types: horizontal access and vertical access turbines. Additionally, the technology exists in the markets with different sizes ranging from hundred kilowatts (typically used for household, industrial, and commercial DG applications) to several megawatts.

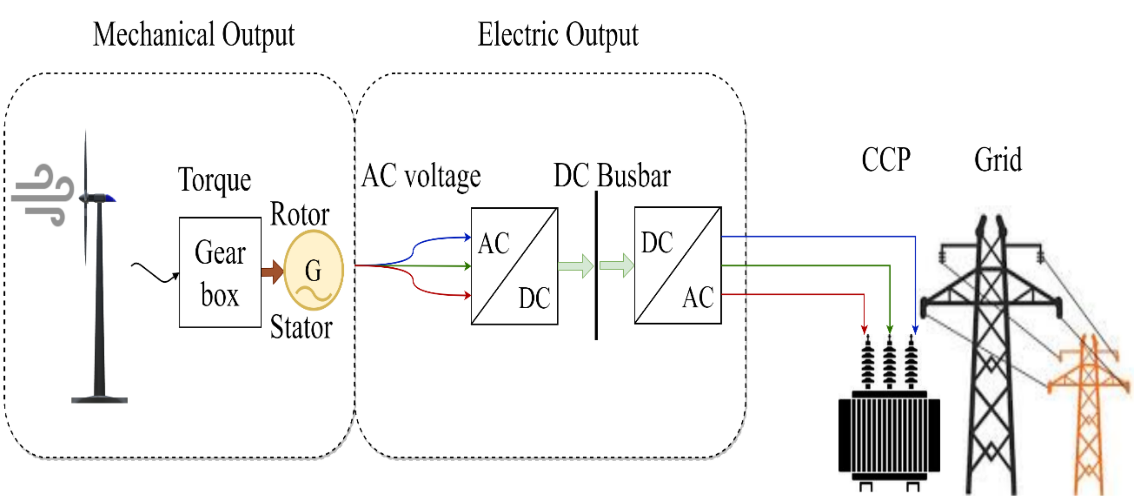

Figure 3.7. An illustration of a grid-connected wind turbine.

3.4.2.4. Small-scale hydropower

Hydropower is an essential alternative energy source that adds up to the existing generation sources. Hydropower systems can be divided according to their sizes into small-scale, medium-scale, and large-scale systems. Which varies between few kilowatts to several hundreds of megawatts. Small-scale hydropower systems can be used for generating power to households and industrial applications in remote areas ranging from 5 kW to 1 MW. The technology utilizes the water flowing through rivers, streams, and dams to create kinetic energy that is used to drive an electric generator for producing power. If the technology is designed properly, it can supply reliable power given that the water flow is continuous. Despite the idea that hydropower systems can have environmental risks such as destroying water species, if the technology is installed safely considering the protection of water species, it can be greatly used to supply power to remote areas. The area constraint is the only concern in this technology where it is only applicable around water streams.

3.4.2.5. Biomass power plants

This technology uses biomass fuels that rely on organic material to offer a sustainable and renewable energy alternative. Given a constant supply of waste material – such as municipality solid-waste, animal, forestry, and industrial wastes – the technology can supply power constantly in a reliable manner. Some initiatives in the market provide both small and large-scale biomass systems that can be used as DGs. The waste material is initially burnt to induce heat, and subsequently steam, which is used to drive a turbine for producing electricity. In fact, the heat produced by this technology can be used for heating up spaces in household and industrial areas. Although the technology is associated with some harmful emissions, it is greatly less than that of centralized fossil fuel-based power plants.

3.5. CHAPTER SUMMARY

The present chapter analyzed existing literature in order to outline important aspects associated with DG integration such as potential benefits, integration challenges, and existing technology. Purposefully, the different metrics introduced in this chapter helped to devise the DG technology used in this thesis. Considering the test case, The type of DG used in this thesis is a solar PV-based asynchronous generator simulated at a constant power factor [33]. The idea of selecting solar PV is mainly to promote renewable energy projects in the country and gradually replace centralized fossil fuel centralized power plants that currently exist in the system (See section 4.6). This type of DG is particularly favored due to the high availability of solar resources across the country in comparison with wind energy potential, which is not as significant as solar irradiation [38]. Therefore, the present thesis helps to enhance solar energy planning and integration initiatives given the expected future vast shift towards PV investments in the country.

Chapter 4

THEORETICAL FORMULATIONS AND METHODOLOGY

The present chapter provides the necessary theoretical formulations that are considered and used for driving the results. The aim of this thesis is to initially assess the solar-resource availability and then investigate the impact of PV integration on the test case. Purposefully, this chapter provides the formulas for both domains. The solar resource is assessed using economic parameters, that is, if the investments in PV projects are profitable (based on the available solar irradiation) then it is worth it to plan their integration into the power grid using system indicators such as active power loss, voltage profiles, and system overloading. Finally yet essentially, the present chapter discusses the proposed site and size selection criteria of PV units, namely the WBB and WI approaches, respectively.

4.1. SOLAR RESOURCE ASSESSMENT

The profitability of any investments in any sector- including the energy sector- is the main aim for any investor; several economic parameters can be used as measures for the economic profitability such as LCOE, NPV, PBP, and IRR. From an investor perspective, the project with higher IRR, higher NPV and lower LCOE and PBP is the most attractive. In this study, we assess the economic feasibility of PV projects in the power system using NPV, PBP, and IRR. In the following subsections, we present the theoretical formulations of the aforementioned parameters.

4.1.1. Levelized Cost of Energy (LCOE)

The Levelized cost of electricity (LCOE) is one of the economic parameters used in the energy sector to evaluate the projects where it is the cost of electricity produced by the energy system. The LCOE can be used to compare the cost of energy produced from a certain energy system with the local grid tariff and with alternative energy projects. The project with LCOE lower than the price of electricity is considered as an attractive one and the lower the LCOE the more attractive the project is. The LCOE can be calculated as:

$$\mathrm{LCOE} = \frac{\mathrm{C} + \sum_{\mathrm{t}=1}^{\mathrm{l}} \frac{\mathrm{M}}{(1+\mathrm{d})^{\mathrm{t}}}}{\sum_{\mathrm{t}=1}^{\mathrm{l}} \frac{\mathrm{E}}{(1+\mathrm{d})^{\mathrm{t}}}} \tag{1}$$

Where $LCOE$ is the Levelized Cost of Electricity [USD/kWh], M is the annual maintenance cost [USD/kWp], d is the annual discount rate [percentage] and E is the annual energy production from the PV power plant [kWh/kWp].

4.1.1.1. Net Present Value (NPV)

NPV can be calculated using Eq. (2) while IRR is equaled to the discount rate at which the NPV of the project equals zero [125].

$$\mathrm{NPV} = \sum_{\mathrm{t}=1}^{\mathrm{l}} \frac{\mathrm{R_t}}{(1+\mathrm{d})^{\mathrm{t}}} - \mathrm{C} \tag{2}$$

Where NPV is the net present value of the hybrid system, R_t represents the yearly income of the hybrid system (USD/kWh), and C is the investment cost of the hybrid system (USD/kWh).

4.1.2. Internal Rate of Return (IRR)

Internal Rate of Return (IRR) is another parameter that is widely used for project profitability assessments where it is equal to the discount rate at a NPV of all cash flows equal to zero as given in Eq. (3).

$$\mathrm{IRR} = \mathrm{NPV} = \sum_{t=1}^{l} \frac{R_t}{(1+d)^t} - C = 0 \tag{3}$$

4.1.3. Economic parameters of the PV system

Northern Cyprus started to encourage the deployment of renewable energy systems by legislating supportive laws. However, supportive laws do not support large-scale renewable energy systems and Independent Power Producers (IPPs). The government is planning in the near future to legislate laws to support IPPs and large scale renewable energy systems such as feed-in tariffs. In this thesis, it is assumed that the future feed-in tariff of grid-tied PV plants in Northern Cyprus will be equal to the feed-in tariff in Southern Cyprus [126]. All the economic parameters used in this study are listed in Table 7.

Table 7. The economic parameters of the PV systems in Northern Cyprus.

Parameter	Value	Reference
PV System Capital Cost (USD/kW)	1533	[127]
PV System Annual Maintenance Cost ($/kW)	24	[128]
Feed in Tariff (USD/kWh)	0.294	[126]
Annual Discount Rate (%)	8	[129]
System's Lifespan (years)	25	[129]

4.2. DISTRIBUTED PV INTEGRATION

The performance of the system is examined before and after injecting the distributed PV units in order to assess the proposed approaches. The focus is on assessing three different technical parameters in the test system namely, total active power loss, busbar voltage profiles, and system overloading. Overloading is examined for three system elements including transmission lines, generators, and transformers. In the following subsections, necessary theoretical formulations are provided with outlining the constraints and considerations during the analysis.

4.2.1. Power Flow Analysis

For power flow analysis in this study, the NR method will be used. The NR is controlled by active and reactive power flow equations, as follows. The complex power at busbar i can be expressed as in Eq. (4). Follows, the active and reactive power flow equations with the presence of distributed PV plants at candidate busbars for the placement can be written as shown in Eq. (5) and (6).

$$S_i = P_i + jQ_i = V_i \sum_{1}^{n} Y'_{ij} V'_j \tag{4}$$

Where:

S_i: Net complex power in MVA at busbar i.

V_i: Voltage at busbar i.

V_k: Voltage at busbar k.

V_{ik}: Voltage difference between busbars i and k.

$$P_i = P_{DG\_i} - P_{D_i} = \sum_{k=1}^{n} |V_i||V_k| \left(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}\right) \tag{5}$$

$$Q_i = Q_{DG\_i} - Q_{D_i} = \sum_{k=1}^{n} |V_i||V_k| \left(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}\right) \tag{6}$$

Where:

P_i: Real power injection at busbar i.

Q_i: Reactive power injection at busbar i.

P_{DG_i}, Q_{DG_i}: Active and reactive power supplied by DG at busbar i.

P_{D_i}, Q_{D_i}: Active and reactive power demand at bus i.

G_{ik}: Real part of admittance matrix's ikth element.

B_{ik}: Imaginary part of admittance matrix's ikth element.

θ_{ik}: Voltage angle difference between busbars i and k.

n: Total number of busbars in the system.

4.2.2. System Active Power Loss

For a given power system that contains a certain number of transmission lines, the total active power loss can be calculated as given in Eq. (7), adapted from [33]. Consider a transmission line x that carries an electrical current of I_i, the associated active power loss can be calculated as formulated in Eq. (8). R represents the resistance of the desired transmission line and the current flowing through the transmission line, I_i can be expressed as in Eq. (9).

$$P_{Total\_Loss} = \sum_{1}^{k} P_k \tag{7}$$

Where:

P_k: Active power loss in transmission line k.

k: Total number of transmission lines in the system.

$$P_k = I_i^2 \times R \tag{8}$$

R is the resistance of the transmission line and I_i can be expressed as:

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \tag{9}$$

Where:

V_i: Voltage at busbar i.

V_j: Voltage at busbar j.

y_{ij}: Admittance of the transmission line k.

4.2.3. Busbar Voltage Deviation (VDI) Index

The aim is to minimize the deviation of busbar voltages hence these limits will be considered to assess the health of voltage profiles in the system. Furthermore, Voltage Deviation Index (VDI) model is adopted from [130] to compare the effectiveness of minimizing voltage deviation using WI in comparison with the NI approach. The VDI is formulated as follows.

$$\mathrm{VDI} = \sqrt{\left[\sum (\mathrm{V_N} - \mathrm{V})^2 \div \mathrm{B}\right]} \tag{10}$$

Where:

V_N: Busbar nominal voltage.

V: Busbar actual voltage.

B: Total number of busbars in the system.

In a system, low VDI means less deviation of its busbar voltage profiles from their limits.

4.2.4. System Overloading

The assessment of system overloading before and after integrating distributed PV stations into the network is conducted for transmission lines, generators, and transformers. The overloading is considered as a percentage of the element's actual power during power flow to its rated power as formulated in Eq. (11), (12), and (13) respectively, below.

$$\mathrm{T\_Overloading} = \frac{\mathrm{P_t}}{\mathrm{P_{t\_rated}}} \times 100\% \tag{11}$$

$$\mathrm{G\_Overloading} = \frac{\mathrm{P_G}}{\mathrm{P_{G\_rated}}} \times 100\% \tag{12}$$

$$\text{Tr\_Overloading} = \frac{\mathrm{P_{Tr}}}{\mathrm{P_{Tr\_rated}}} \times 100\% \tag{13}$$

Where $T\_Overloading$, $G\_Overloading$, and $Tr\_Overloading$ represent the percentage overloading for transmission lines, generators, and transformers respectively. For the analysis, we only focus on system elements that have overloading of 80% and above. For the system under study, we identify those elements in the base case through the initial NR power flow solution without PV-DG units integrated into the system.

4.3. CONSTRAINTS

4.3.1. Busbar Voltage Profile

In order to compare the change in busbars voltage profiles before and after integrating the distributed PV plants into the system, one should refer to the grid code of transmission networks. The limits for busbar voltage magnitude change in the transmission network is set to be $\mp 5\%$ and can be defined in p.u as follows in Eq. (14) [28].

$$0.95\ p.u \leq V_i \leq 1.05\ p.u \tag{14}$$

4.3.2. DG Boundary Conditions

The operation of PV-DG units is controlled by their minimum and maximum limits according to the selected sizes. The minimum generation by the PV-DG unit is $P_{DG_{Min}}$ while the maximum is $P_{DG_{Max}}$ as given below in Eq. (15).

$$\mathrm{P_{DG_{Min}}} \leq \mathrm{P_{DG}} \leq \mathrm{P_{DG_{Max}}} \tag{15}$$

The type of DG technology used for this analysis is asynchronous generator (PV) and hence the power factor is constant during the analysis [33].

4.4. PROPOSED APPROACH

In this subsection, the proposed method for site and size selection of PV-DG units into the NCTS is discussed. Additionally, the NI integration approach is also outlined, which used for demonstrating the effectiveness of the proposed WI

4.4.1. WBB Approach for Site Selection

The WBB approach relies on the deviation of busbar voltage magnitudes from their limits for choosing the best busbars for PV DG placement. The optimal location of DG units is investigated in [131] where the voltage magnitudes of busbars are sorted in ascending order and the busbar with the least voltage magnitude is chosen as a candidate place for one DG unit. Unlike study [33] where authors choose the PQ (load) busbars for the DG units' placement. However, in the WBB approach, PV DG stations are placed on busbars having their voltage magnitude outside the limits given in (14). In this study, those busbars are called weak busbars because of their voltage deviation. By running the load flow without any PV DG stations integrated, in the base case, one can obtain the initial voltage magnitudes of busbars in the system. For the system under study, it is found that 16 busbars of which voltage magnitudes are below 0.95 p.u which are called weak busbars (See Section 5.2.1).

4.4.2. Integration Approach for Size Selection

The size of PV DG stations to be placed on weak busbars is selected as a percentage of the system total demand with weights according to busbar voltage deviations. Initially, the total size of PV DG stations is calculated as a percentage of system total load using (16) [30]**:**

$$Total\_DG_{\mathrm{Size}} = \frac{\mathrm{PL} \times \mathrm{P}_{\mathrm{Load}_{\mathrm{Total}}}}{100\%} \tag{16}$$

Where:

$Total\_DGs_{Size}$: Total DG stations' size in MW.

PL: Penetration level of DG's as a percentage of system total demand.

$P_{Load_{Total}}$: System total MW load.

4.4.2.1. Normal Integration (NI) Approach

It is examined in this study for the NI approach that $Total\_DG_{Size}$ is divided among the weak busbars in the system and hence the DG size will be same among all weak busbars and can be calculated as follows:

$$NI\_DG_{Size} = \frac{Total\_DG_{Size}}{N} \tag{17}$$

Where:

NI_DG_{Size}: Size of each DG station in MW according to NI.

N: Total number of weak busbars in the system.

4.4.2.2. Weighted Integration (WI) Approach

WI approach differs in the generation-installed capacity on weak busbars according to their voltage magnitude deviation. The more a busbar's voltage profile deviates from the limits in Eq. (14), the more installed capacity it will have relative to other busbars as formulated below.

$$WI\_DG_{Size(k)} = Total\_DG_{Size} \times \frac{D_k}{D_{Total}} \tag{18}$$

Where:

$WI\_DG_{Size(k)}$: Size of each DG station in MW according to WI.

D_k: Deviation of kth busbar's voltage magnitude.

D_{Total}: Total deviation of all weak busbars.

k: Numbers of weak busbars, in this case, study the number k ranges from one to 16.

4.5. SYSTEM GEOGRAPHICAL INFORMATION

The GHI of the selected regions and the electrical energy produced by the PV systems in different regions in Northern Cyprus were obtained from Photovoltaic Geographical Information System (PVGIS) online software [132]. The software estimates the electrical energy production taking into consideration the optimal geometry of the PV panels and all the electrical losses namely wiring, inverter and temperature losses. The economic and technical assessments of the PV projects were done for 19 regions in Northern Cyprus. Table 8 shows the geographical information and the GHI for the 19 regions in Northern Cyprus.

Table 8. The geographical information of the selected regions in Northern Cyprus as well as the average daily GHI.

Region	Altitude (m)	Latitude (degree)	Longitude (degree)	GHI ($kWh.m^{-2}$)
Alsancak	65	35.33	31.20	6.19
Bafra	12	35.35	34.05	6.30
Camlibel	277	35.30	33.05	6.41
Catalkoy	123	35.30	33.40	6.14
Dipkarpaz	172	35.62	34.40	6.16
Esentepe	172	35.33	33.57	5.97
Gazimagusa	11	35.10	33.92	6.36
Gecitkale	80	35.27	33.73	6.11
Girne	107	35.32	33.30	6.14
Guzelyurt	21	35.20	32.97	6.38
Lapta	253	35.33	33.15	6.11
Lefka	214	35.08	32.83	6.14
Nicosia	130	35.18	33.37	6.16
Sadrazamkoy	83	35.37	32.93	6.25
Tatlisu	172	35.37	33.75	5.95
Vadili	45	35.13	33.65	6.19
Yeni Erenkoy	117	35.53	34.18	6.19
Yeni Iskele	39	35.28	33.88	6.25
Yesilirmak	24	35.15	32.73	6.25

4.6. GRID INFORMATION

The Northern Cyprus power system is used to perform the analysis. The region is characterized by a high potential of solar resources where it is approximated that in a year it has 300 sunny days [133] and PV investments are economically profitable in most cities by providing a relatively lower price of energy in comparison with the national grid tariff [40]. Moreover, power supply in this particular power system relies heavily on fossil fuel resources [134] and it is essential to reduce reliance on conventional resources in order to fasten the movement towards smart power systems. Purposefully, we have chosen solar PV-DG for the analysis. PV-DG integration does not only help in mitigating climate change impacts by offering GHG emission-free power generation schemes but also can be adopted in order to enhance the operational efficiency of the system.

The system under study is composed of 2 voltage levels, transmission and sub-transmission networks with a rating of 132 and 66 kV, respectively. The total number of busbars in the system is 49 and these busbars are interconnected using 60 transmission lines as illustrated in Figure 4.1. Furthermore, the system consists of 12 two winding and a three-winding transformer. Y-connected 3-phase shunt capacitor filters are also used for waveform harmonics and active power filtering. The grid relies mostly on two operational power plants in order to supply the demand. These units are Teknecik and Kalecik having installed capacities of 290 and 142 MW, respectively as shown in Table 9. Both power plants rely on steam turbines and diesel generators. It is worth it to mention that the system already has two operational PV-DG units, which are placed on ODTU and Guneskoy Low busbars with installed capacities of 1 and 1.27 MW, respectively, and was considered during simulations. The peak power demand in the system is 264 MW distributed among 28 load busbars. System data are provided by the Northern Cyprus electricity corporation [134] and Figure 4.1 below shows the power system as modeled in DIgSILENT PowerFactory.

Table 9. Operational power plants in the Northern Cyprus power system.

Power Stations	Type	Generation (Unit x MW)	Capacity (MW)
Kalecik	Diesel Generator	8x17	136
Kalecik	Steam Turbine	6	6
Teknecik	Diesel Generator	8x17.5	140
Teknecik	Steam/Oil	2x60	120
Teknecik	Gas Turbine	1x20 + 1x10	30
Guzelyurt	PV Plant	1	1
Dikmen	Gas Turbine	1x20	20
Guneskoy	PV plant	1.27	1.27
Total installed capacity			453.3

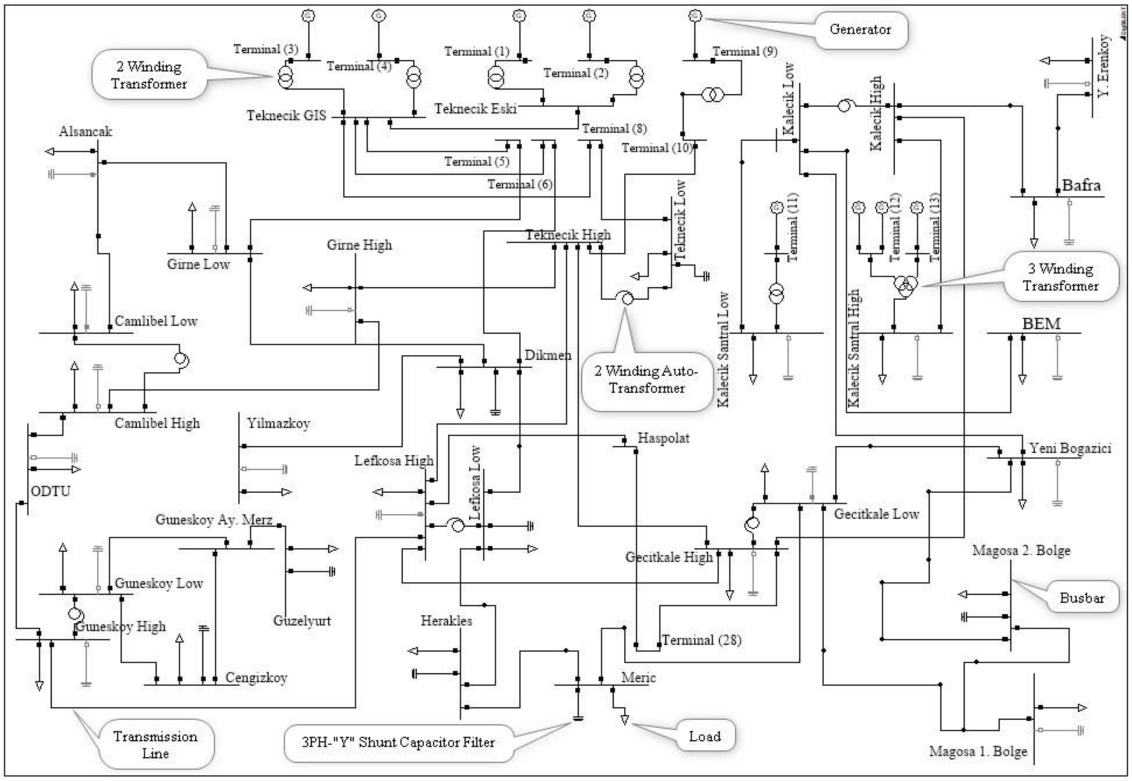

Figure 4.1. Modeling the NCTS in DIgSILENT PowerFactory.

4.7. ANALYSIS PROCEDURE

In order to analyze the benefits of integrating distributed PV units into the system, six different cases of PL are considered. The base case is firstly used as a reference point where no PV-DG units are connected to the system. Then, the WBB approach is conducted to determine the quantity and the candidate busbars for PV-DG placement. Once weak busbars are identified, PV-DG sizes are determined for the different PLs. After that, the PL of PV-DG units is increased by 10, 20, 30, 40, and 50 percent to form the other five cases. For all PL cases, the size of each PV-DG unit (to be placed on weak busbars) is determined using Eq. (18) and the simulations are conducted using their respective MW sizes for each PL. The analysis starts with loading the network data into the simulator to evaluate an initial NRPF that provides the base case information including active power loss, voltage profiles, and system overloading. Then, for each PL, PV-DG units are installed on weak busbars. Finally, load flow is conducted in each PL to extract the new parameters and compare them with the base case. Similarly, the procedure is followed for all PLs of PV units. To put the analysis on WI and NI approaches for sizing into perspective, the system under study has a total active power load of 264 MW. Considering a 10% PL of PV-DG units, according to PL in Eq. (16), the total PV-DG's size to be integrated into the network is 26.4 MW. Then, according to the NI approach in this study, 26.4 MW is divided among the 16 weak busbars using Eq. (17). Accordingly, each PV-DG unit will have a size of 1.65 MW. However, using the WI approach, the resultant PL size is distributed among weak busbars according to their voltage profile deviation from nominal values, according to Eq. (18). Figure 4.2 shows the analysis flow-chart and the following chapter presents the simulation results for the base case as well as other PLs of PV-DG.

4.8. SYSTEM CONFIGURATION

The used power flow type in this study is based on the NR power flow solution considering an AC balanced positive-sequence mode of operation. As for active power control, it is specified to be controlled as dispatched from generation sources in the system and is balanced by the slack busbar. Follows, reactive power control follows an automatic shunt adjustment scheme in order for the simulator to reach convergence at the desired control boundaries such as busbar voltages, and transmission line power flows considering reactive power limits.

4.9. CHAPTER SUMMARY

This chapter provides a detailed explanation of the theoretical formulations necessary for driving the desired results. As a part of assessing the potential of solar resources in the country, this chapter provides the associated horizontal solar resources across different regions in the country in order to assess the economic profitability of PV investments later on in the results section. Since the NR OPF method is utilized in this thesis to determine different system parameters, the present chapter explains the related formulations such as power flow, active power loss, system overloading, and VPI equations. The constraints in the system are also described in this chapter, in which the power flow in the system limited to the rated values of voltage magnitudes as well as the boundary conditions of the desired

PV DG unit. Finally and importantly, the chapter discusses the proposed criteria for siting and sizing the PV-DG units in the system considering the WBB and WI approaches, respectively. This is essential for demonstrating the effectiveness of the proposed criteria in terms of improving system technical parameters. The next chapter presents the research findings using the proposed approaches and the associated approach validation.

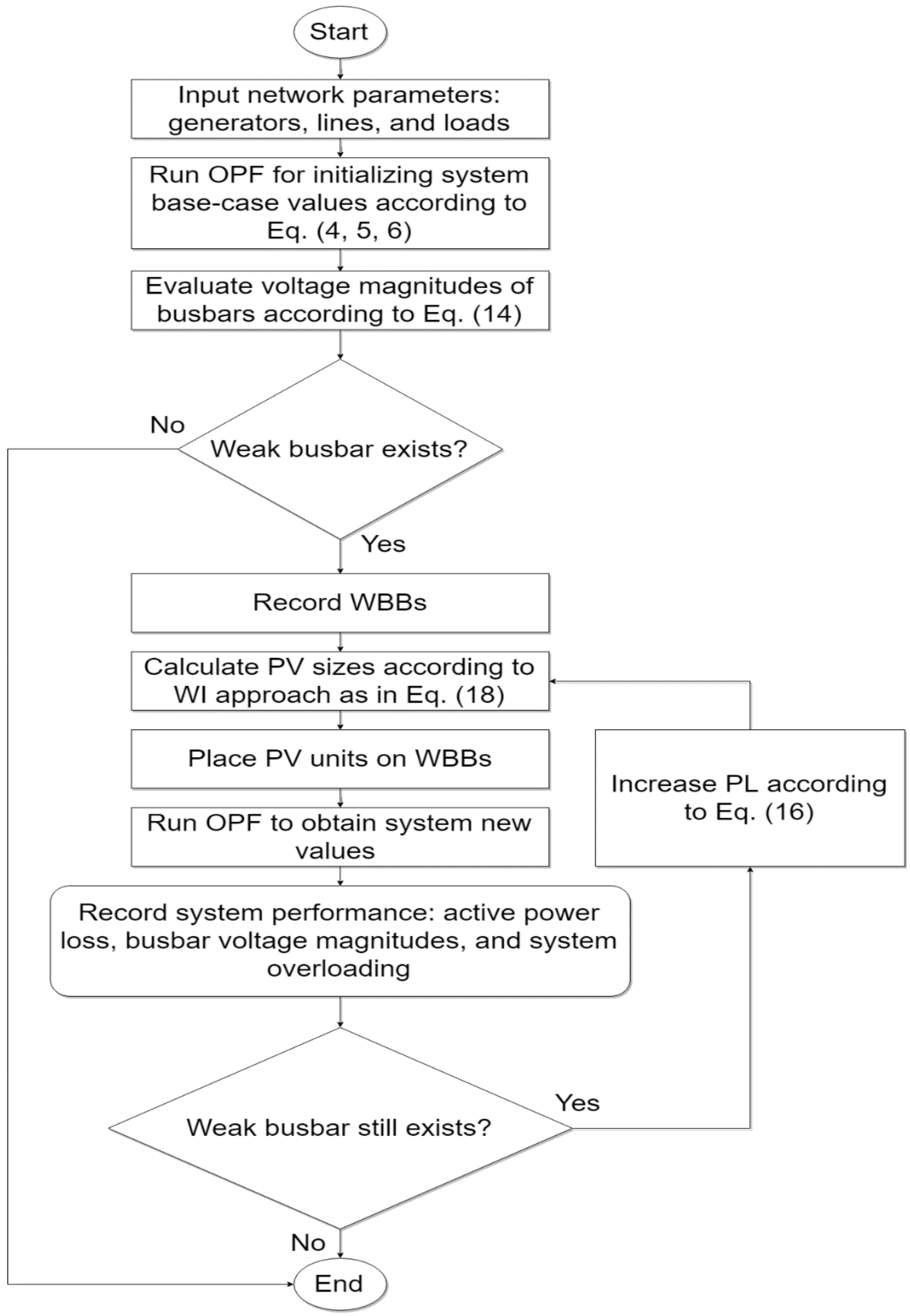

Figure 4.2. Analysis flowchart

Chapter 5

SIMULATION RESULTS AND DISCUSSION

The main goal of this chapter is to present the findings throughout this thesis work and discuss the effectiveness of the proposed criteria. This chapter is segmented into four major subchapters. Firstly, the potential of solar resources in the target test case is described by referring to the potential energy production by solar PV projects in the island and the economic feasibility of their investments. Secondly, the chapter includes a detailed analysis of the performance of NCTS with the presence of PV units on active power loss, busbar voltage profiles, system overloading, given an increased PL of PV DG units. Subsequently, the chapter discusses the potential of GHG emission reduction taking into account the location of investment as well as the PL of PV systems. Finally, yet importantly, the chapter provides an approach validation section in order to demonstrate the effectiveness of the WI approach over NI taking into account improving system technical parameters.

5.1. SOLAR RESOURCE POTENTIAL

The geographical location of the PV projects affects significantly the profitability of it due to the variation in solar radiation and the ambient temperature since they affect energy production. Obviously, projects with the highest profitability are more attractive to investors. Therefore, the technical performance and the economics of PV projects in different regions in Northern Cyprus are analyzed in order to specify the best regions for such investment. Table 10 shows the economic parameters of the PV investments in 19 regions in Northern Cyprus in addition to their annual capacity factor. It can be clearly seen from Table 3 that Guzelyurt is the best place for PV investments in Northern Cyprus followed by Gazimagusa with LCOE of 0.1035 and 0.1047 USD/kWh respectively and NPV of 3256.1 and 3198.3 USD/kWp respectively. Moreover, all the PV investments in Northern Cyprus can be profitable and attractive since their LCOE lower than the local grid tariff and their NPV higher than zero.

Table 10. The economic and technical parameters of the PV power plant in different regions in Northern Cyprus in addition to the annual electricity production from the PV DG units.

Region	$\boldsymbol{E}$ (kWh/kWp)	LCOE (USD/kWh)	NPV (USD/kW)	PBP (years)	IRR (%)	$\boldsymbol{CF}$ (%)
Alsancak	1670	0.1078	3053.9	6.4	30.42	19.06
Bafra	1700	0.1059	3140.6	6.3	31.00	19.41
Camlibel	1710	0.1053	3169.5	6.3	31.19	19.52
Catalkoy	1650	0.1091	2996.2	6.5	30.04	18.84
Dipkarpaz	1660	0.1085	3025.1	6.5	30.23	18.95
Esentepe	1580	0.1140	2794	6.8	28.68	18.04
Gazimagusa	1720	0.1047	3198.3	6.2	31.39	19.63
Gecitkale	1630	0.1105	2938.4	6.6	29.65	18.61
Girne	1640	0.1098	2967.3	6.6	29.84	18.72
Guzelyurt	1740	0.1035	3256.1	6.1	31.77	19.86
Lapta	1620	0.1112	2909.6	6.6	29.46	18.49
Lefka	1660	0.1085	3025.1	6.5	30.23	18.95
Nicosia	1660	0.1085	3025.1	6.5	30.23	18.95
Sadrazamkoy	1670	0.1078	3053.9	6.4	30.42	19.06
Tatlisu	1570	0.1147	2765.2	6.9	28.49	17.92
Vadili	1660	0.1085	3025.1	6.5	30.23	18.95
Yeni Erenkoy	1670	0.1078	3053.9	6.4	30.42	19.06
Yeni Iskele	1670	0.1078	3053.9	6.4	30.42	19.06
Yesilirmak	1690	0.1065	3111.7	6.3	30.81	19.29

5.2. PLACEMENT OF PV STATIONS ON NORTHERN CYPRUS POWER SYSTEM

This subsection presents the findings associated with the impact of increased PV PLs on system parameters. First, the base case and initial system conditions are presented and then, the system performance, in terms of active power loss, voltage profiles, and overloading is discussed with the presence of PV-DG units.

5.2.1. Base Case

The base case is chosen as the reference to assess the impact of increased PV PLs on the NCTS. The base case is obtained by running the load flow analysis without integrating PV-DG units. However, the already-existing solar PV plants at ODTU and Guneskoy Low are considered in the base case analysis, as mentioned previously. Active power loss, voltage magnitudes, and system overloading are the target parameters for results comparison. The initial NR power flow analysis shows that the total active power loss in the system is 5.42 MW, which is the reference point for comparing active power loss. Secondly, for the system under study, it is found that 16 busbars of which voltage magnitudes are below 0.95 p.u (weak busbars) as illustrated in Figure 5.1 with the weakest busbar being Girne-low. Whereas the closest busbars to the lower voltage limit (0.95 p.u) are ODTU, Guneskoy high, and Camlibel high. Hence, considering a 10% PL of total demand, Using WI approach using Eq. (16), Girne low busbar will have a size of 3.392 MW. Whereas ODTU busbar will have a size of 0.1474 MW. Subsequently, B in Eq. (10) is chosen to be 16 because the system under study consists of 16 weak busbars in the base case. Therefore, the higher the bus voltage deviation, the more share of the desired PL it will have. PV-DG sizes for each busbar are calculated according to Eq. (18) and reported in Table 11. Finally, overloading is assessed by examining the elements in the network that have overloading in the base case higher than 80% according to Eq. (11), (12), and (13). The system contains 5, 3, and 1 overloaded transmission lines, generators, and transformers respectively as shown in Table 12 with their names.

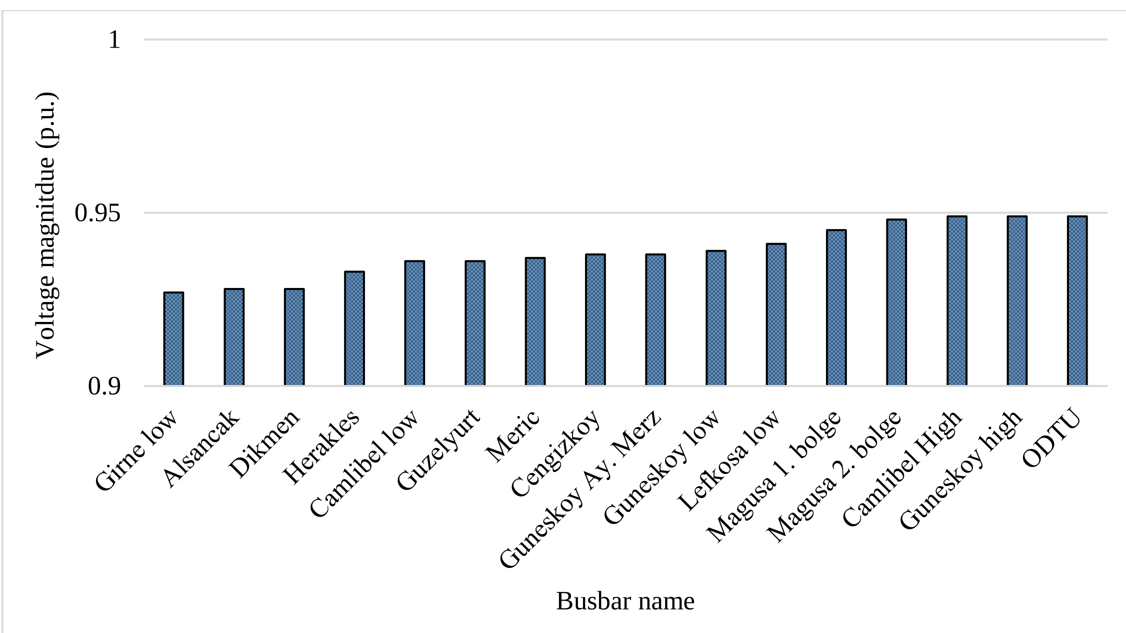

Figure 5.1. Base case weak-busbar voltage magnitudes.

Table 11. Pv DG sizes to be placed on weak busbars according to the different PLS.

Busbar Name	10 %	20%	30%	40%	50%
Girne low	3.392	6.784	10.177	13.569	16.961
Alsancak	3.245	6.489	9.734	12.979	16.223
Dikmen	3.245	6.489	9.734	12.979	16.223
Herakles	2.507	5.015	7.522	10.029	12.536
Camlibel low	2.065	4.130	6.194	8.259	10.324
Guzelyurt	2.065	4.130	6.194	8.259	10.324
Meric	1.917	3.835	5.752	7.669	9.587
Cengizkoy	1.770	3.540	5.309	7.079	8.849
Guneskoy Ay.	1.770	3.540	5.309	7.079	8.849
Guneskoy low	1.622	3.245	4.867	6.489	8.112
Lefkosa low	1.327	2.655	3.982	5.309	6.637
Magusa 1. bolge	0.737	1.475	2.212	2.950	3.687
Magusa 2. bolge	0.295	0.590	0.885	1.180	1.475
Camlibel High	0.147	0.295	0.442	0.590	0.737
Guneskoy high	0.147	0.295	0.442	0.590	0.737
ODTU	0.147	0.295	0.442	0.590	0.737

Table 12. Base case overloading.

Element	Name	Base case Overloading (%)
Transformer	Kalecik Santral - Terminal 11	87.23
Generator	Synchronous Machine 5	86.73
	Synchronous Machine 7	84.54
	Synchronous Machine 8	81.86
Transmission Line	ND1 - Magusa	105.94
	ND29	105.8
	Kal Santral - Kal junk2	92.76
	Nd12 - ND9	81.56
	Junk1 - BEM	80.51

5.2.2. Active Power Loss Reduction

The system's total active power loss is assessed for the different analysis cases. After each PL of PV-DG with their respective MW sizes, the NR power flow is conducted to observe the system's total active power losses. The analysis shows that active power loss in the network is minimized after integrating distributed PV units. Figure 5.2 below illustrates the active power loss in the network for different PLs. The highest active power loss occurs in the base case by 5.42 MW where no PV-DG units are integrated into the network. As the PL increases, the active power is further reduced. The lowest active power loss in the network is seen at 50% PL.

5.2.3. Busbar Voltage Profile Improvement

The second objective is to improve voltage profiles of weak busbars. Similar to the base case, the voltage profiles of weak busbars are examined for other PV PLs. It is found that weak voltages are improved relative to the base case when integrating PV-DG units into the network. **Figure 5.3** – Figure 5.7 shows voltage profiles of busbars in the system considering the respective PL compared with the base case. All voltage profiles of weak busbars in the base case (Figure 5.1) deviate from their limits according to Eq. (14). Therefore, it is worthwhile to mention that voltage magnitudes at weak busbars gradually increase and approach 0.95 p.u as the PL increases. At 50% level of PV-DG penetration in Figure 5.7, all voltage magnitudes are improved to 0.95 p.u and above. Since PV-DG stations are placed on weak busbars, electric power does not have to travel from far distances (other system busbars) to meet their demand, which is advantageous for enhancing the system's overall efficiency. The most voltage-profile enhancement is seen in Meric busbar where its voltage magnitude improves from 0.937 to 0.967 p.u.

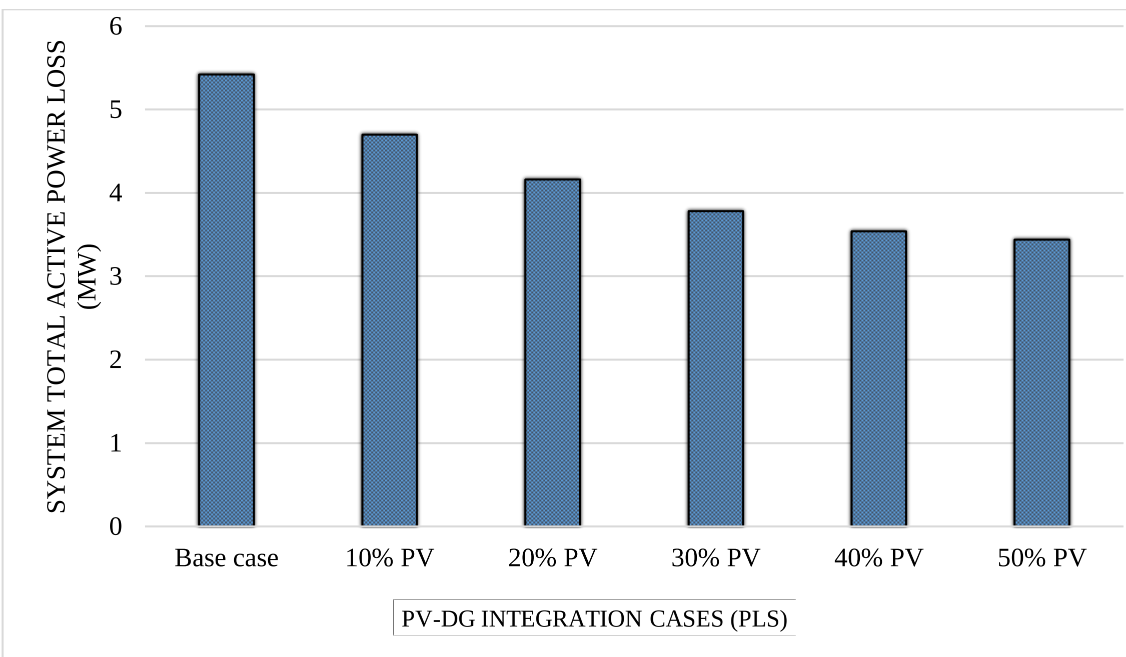

Figure 5.2. System total active power losses reduction for different PL cases using the WI approach.

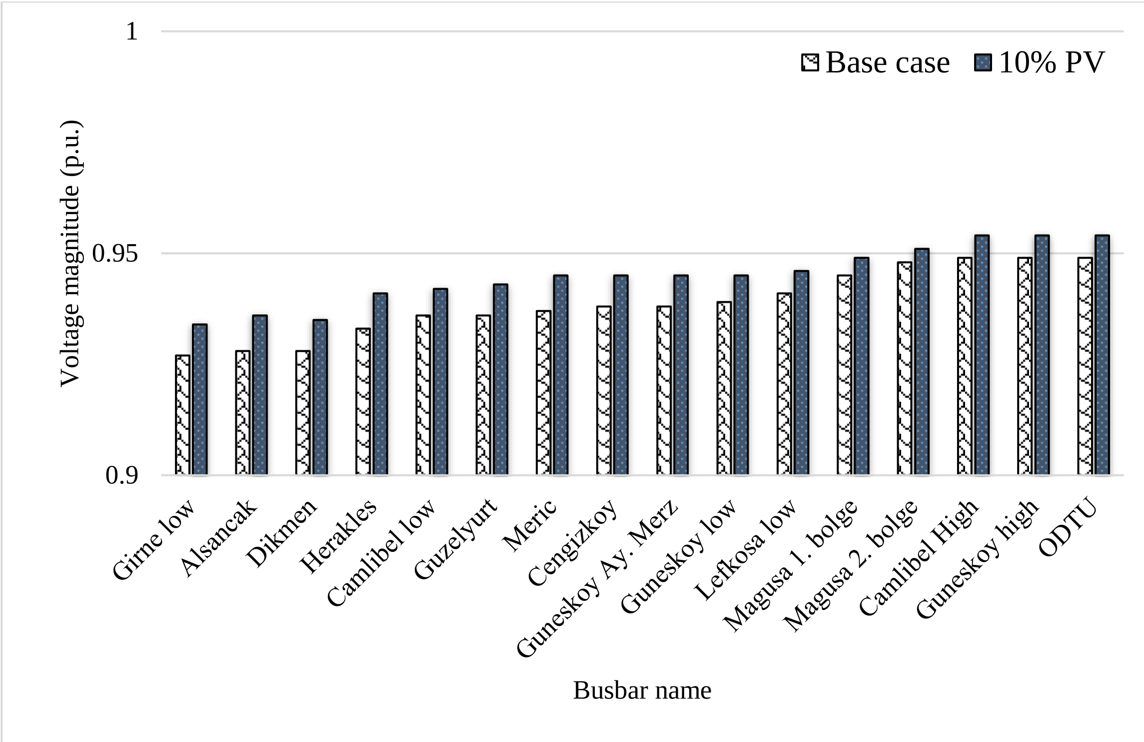

Figure 5.3. Voltage profiles of WBBs at 10% PV PL.

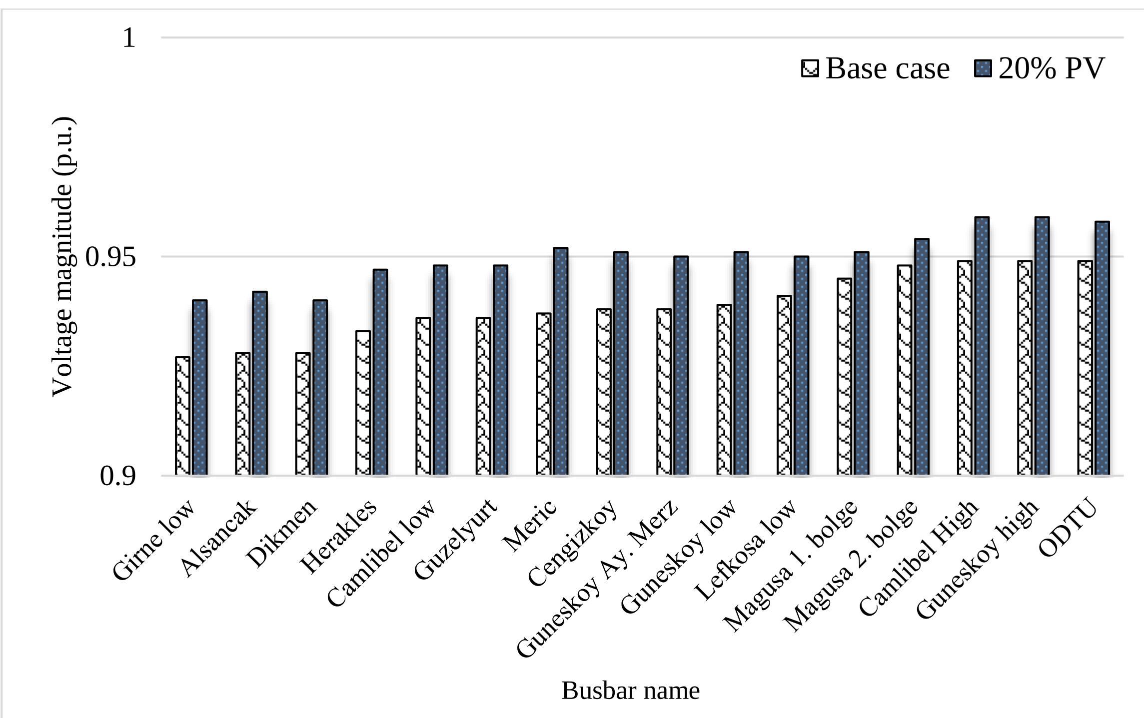

Figure 5.4. Voltage profiles of WBBs at 20% PV PL.

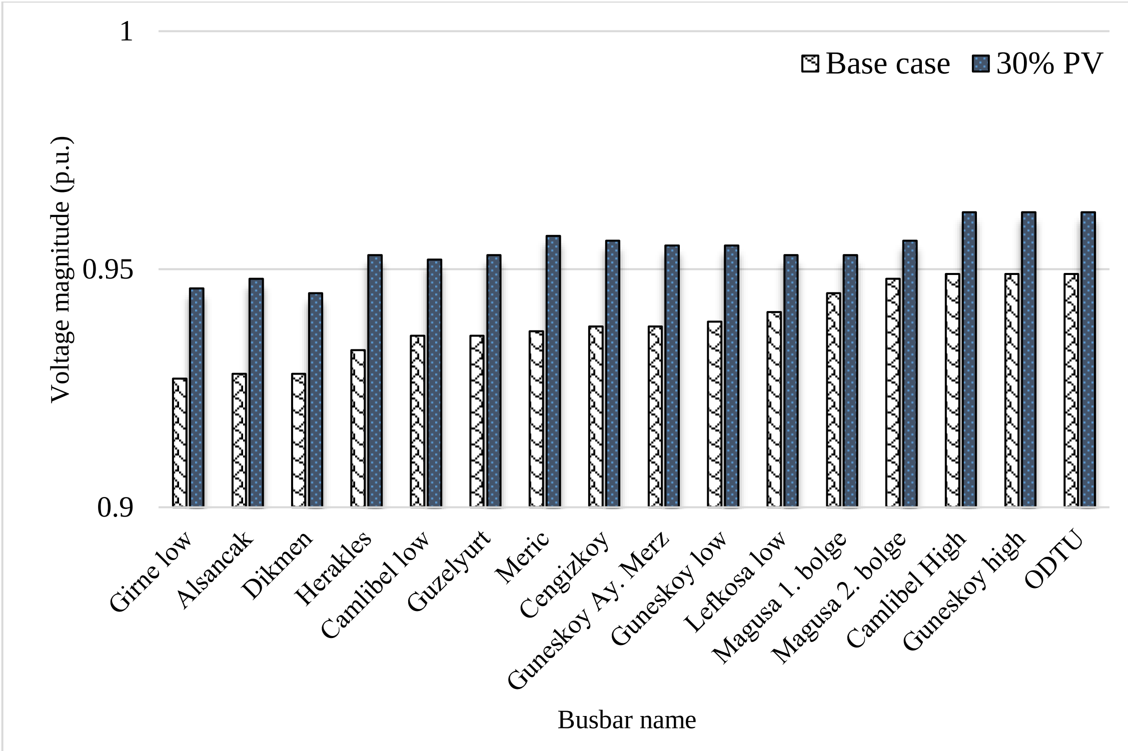

Figure 5.5. Voltage profiles of WBBs at 30% PV PL.

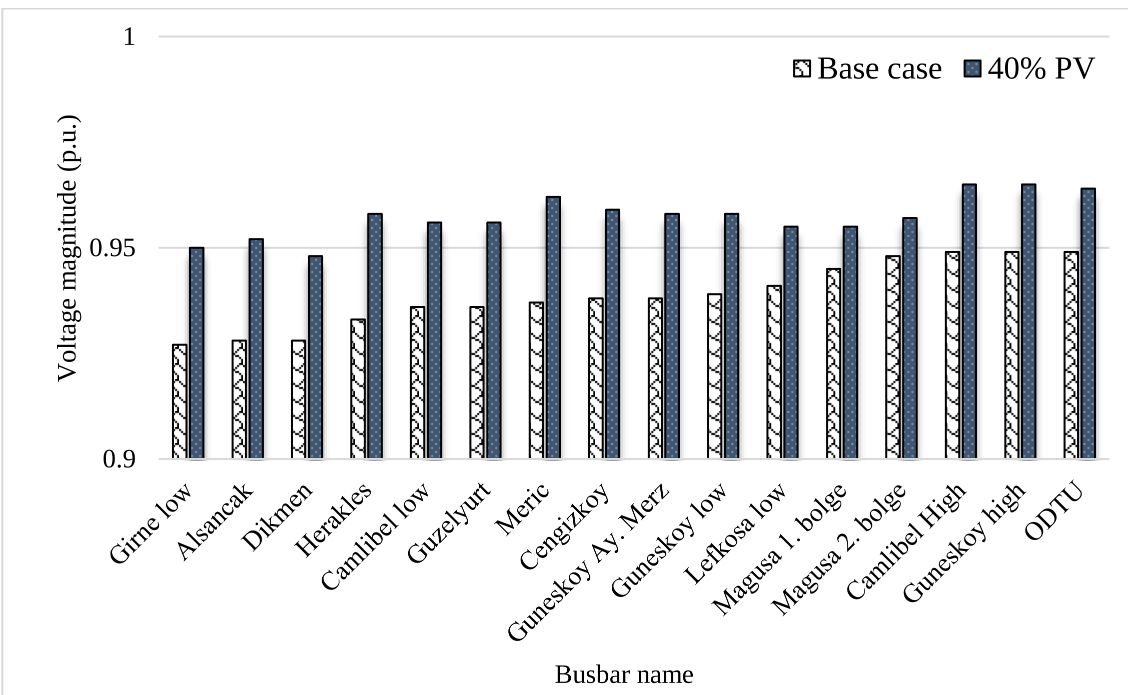

Figure 5.6. Voltage profiles of WBBs at 40% PV PL.

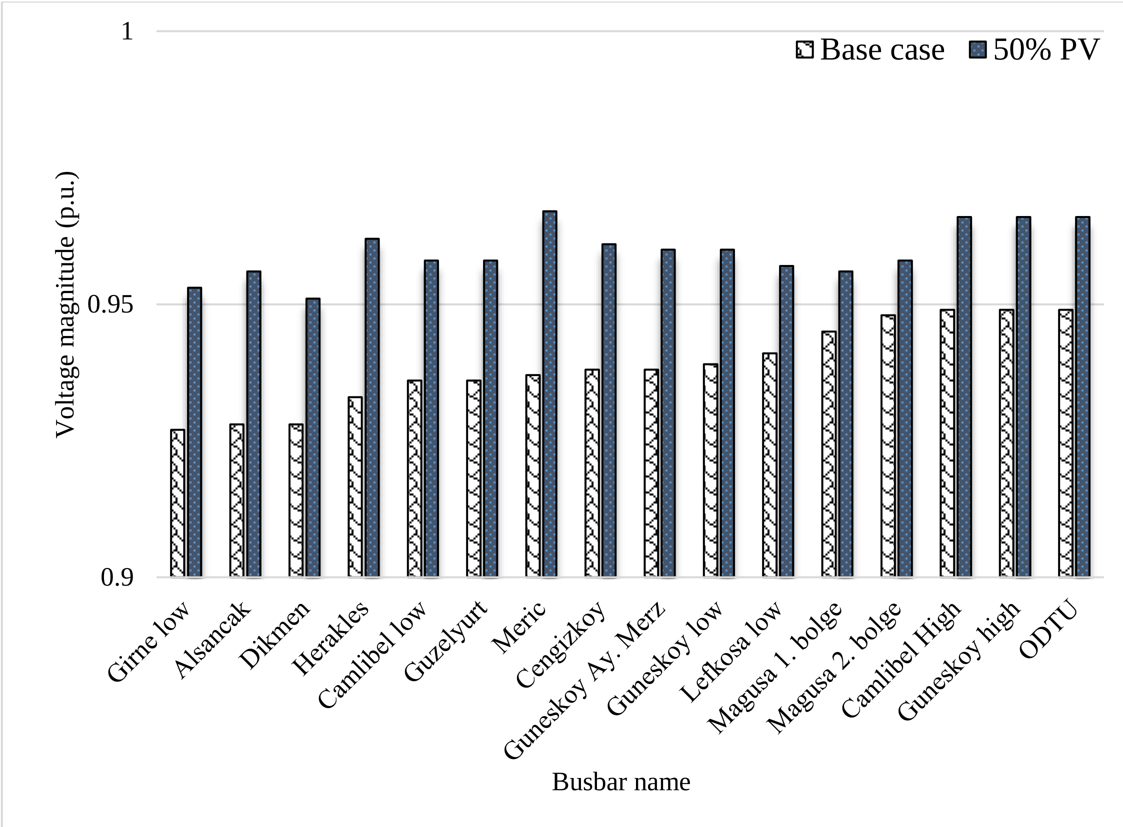

Figure 5.7. Voltage profiles of WBBs at 50% PV PL.

5.2.4. System Overloading Reduction

The overloading is assessed for three different network elements, namely, transmission lines, generators, and transformers. Parameters with overloading higher than 80% are considered. The analysis shows that the overloading of those parameters decreases as the PV-DG PLs. Five transmission lines in the base case have overloading above 80%. ND1-Magusa and ND29 transmission lines have the highest overloading among other transmission lines of around 105%. When the PL of PV-DG units into the system increases, their overloading is minimized down to around 90%. The overloading reduction is also observed in other overloaded transmission lines in the system, Kal Santral-Kal junk2, ND12 – ND9, and Junk1-BEM that are reduced around 10% of their original overloading in the base case. Figure 5.8 illustrates the reduction in transmission-line overloading in comparison to the base case. Similarly, the overloading is minimized for generators that have an overload above 80% in the base case as shown in **Figure 5.9**. As for transformers, Kalecik-Santral-Terminal11 transformer is the only one in the base case with overloading above 80%. Results show that the increase in PV-DG integration reduces its overloading as can be seen in Figure 5.10.

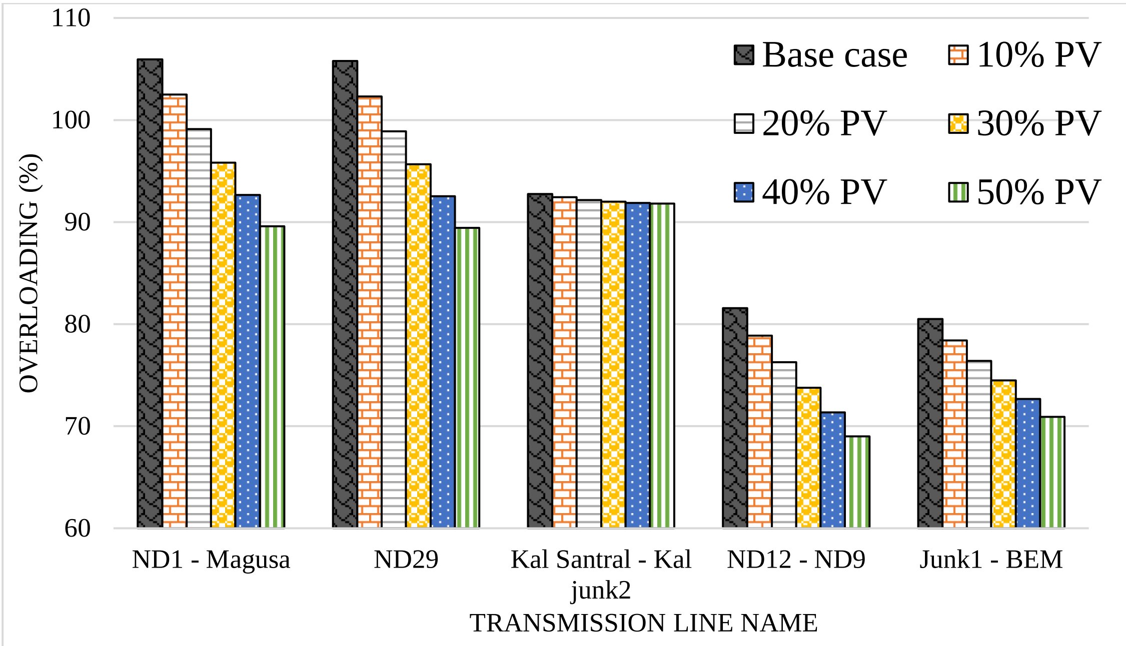

Figure 5.8. Transmission lines overloading reduction.

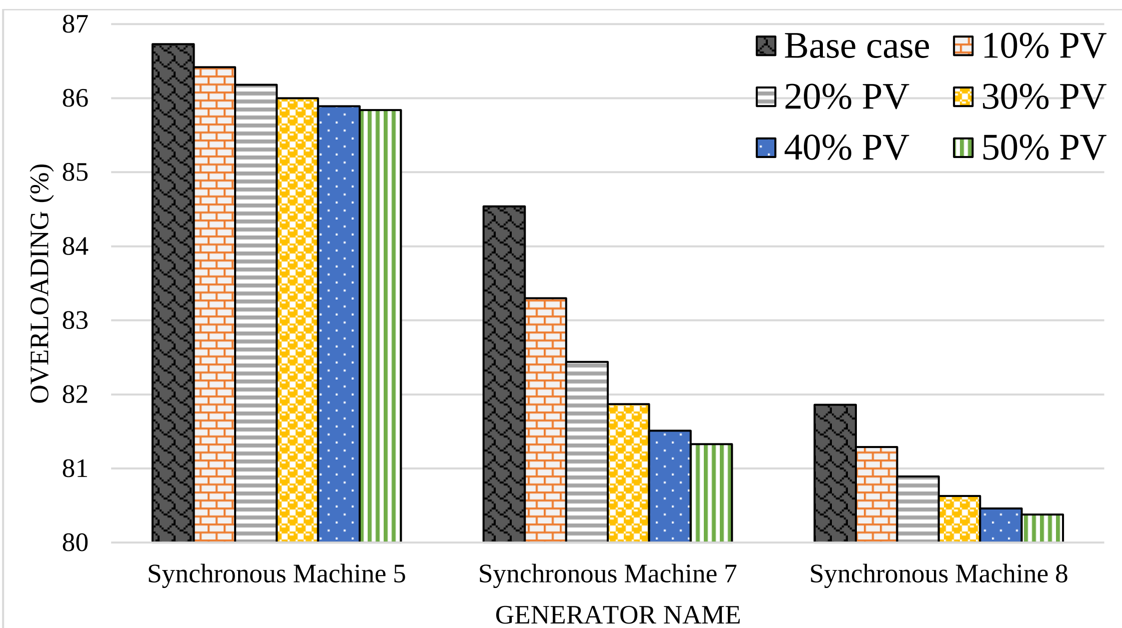

Figure 5.9. Generators overloading reduction.

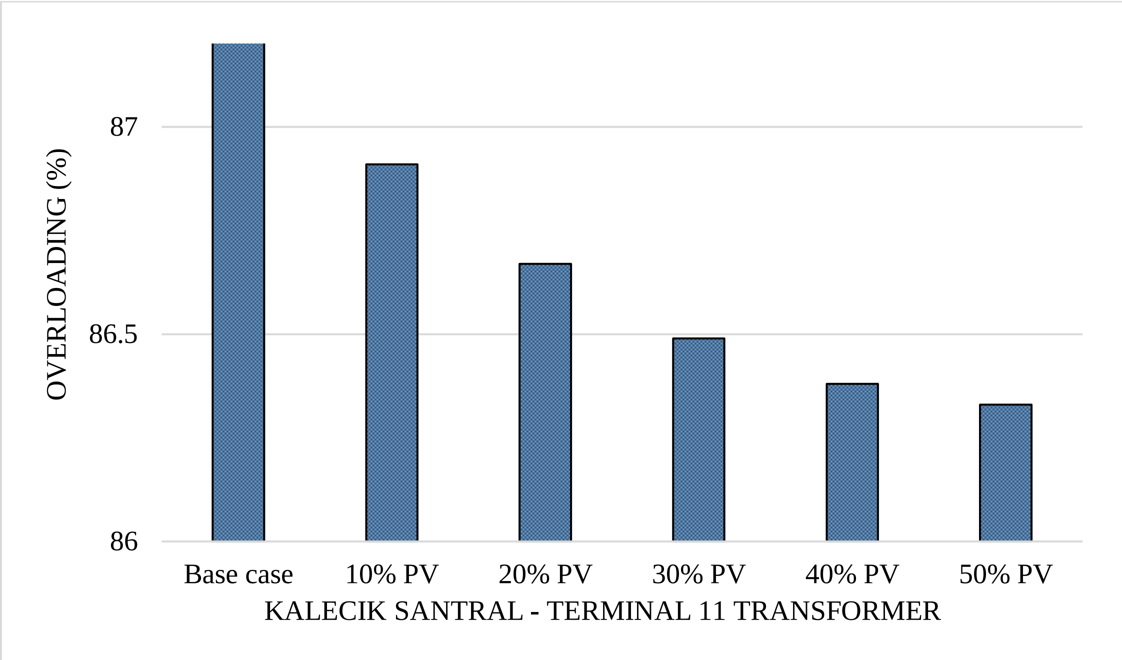

Figure 5.10. Transformer overloading reduction.

5.2.5. Maximum Allowable PL

Although might seem too optimistic, the PL of PV systems is further increased up to 100% of the system demand in order to determine whether the system performance can degrade subject to the high PL of PV. Accordingly, it can be judged that the system requires upgrade initiatives in order to be able to accommodate higher levels of PV systems.

Considering system losses, until 50% PL, the active power loss is reduced to 3.44 MW in comparison with the base case. As the PV PL exceeds 50%, active power loss starts increasing as shown in **Figure 5.11** At 60%, for instance, the active power loss is recorded to be 3.48 MW and similarly increases with increasing the PV PL until 100% PL where it reaches up to 5 MW. Therefore, considering this response from the system active power loss against increasing PV PL, it can be said that the maximum allowable penetration level of PV capacity is 50% for this particular power system.

As for busbar voltage profiles, the VPI is reduced with increasing the PV PL relative to the base case. However, it can be seen from Figure 5.12 that there is a slight increment of the VPI at PLs of 90% and 100%. Although the increment in the VPI is not very significant, it can be said that at higher levels of PV integration the system requires upgrades.

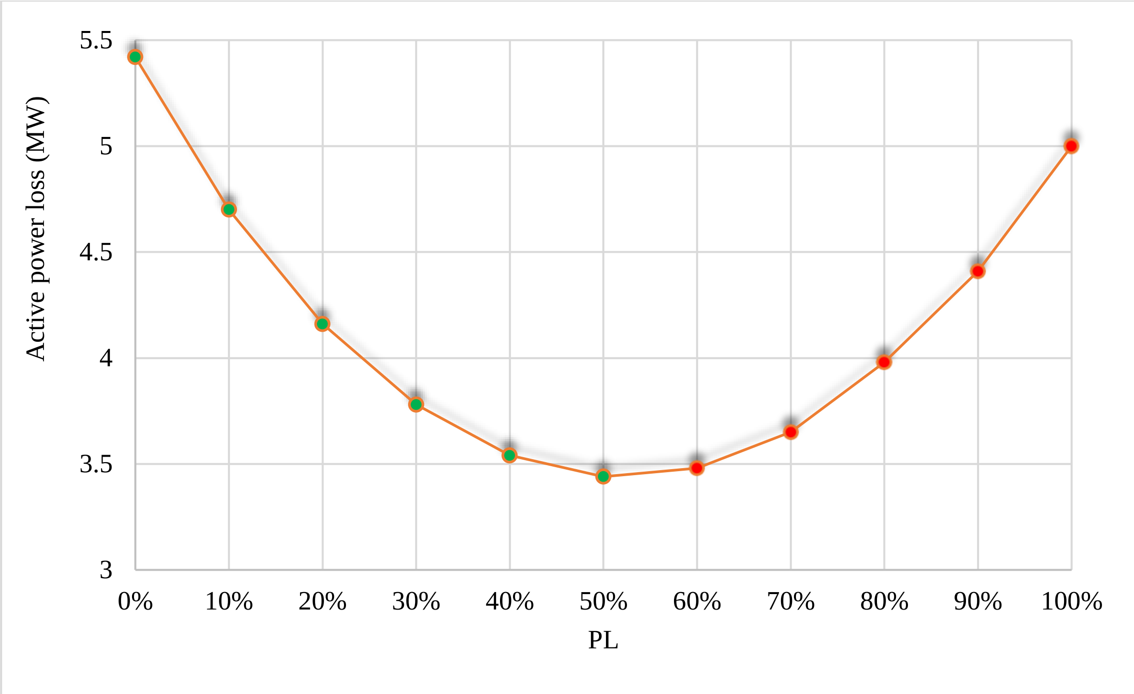

Figure 5.11. System active power loss until 100% PL.

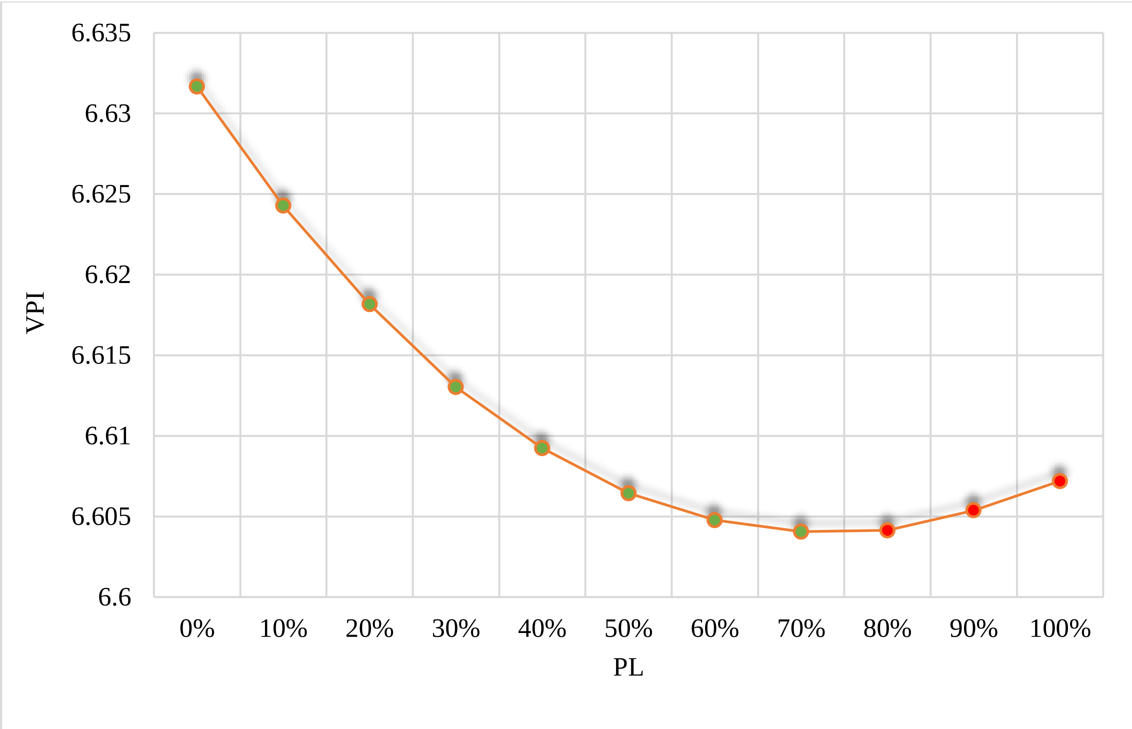

Figure 5.12. VPI of busbars until 100% PL.

5.3. GREENHOUSE GAS REDUCTION

Northern Cyprus is characterized by a high dependence on imported fossil fuels for meeting their energy demand. Therefore, it is essential to show the benefits of integrating PV plants into the system in terms of GHG reductions.

In the following subsections, the potential of reducing GHG emissions by integrating distributed PV plants in the NCTS is discussed. The GHG reduction is, initially, quantified per kWh for distributed PV investments in major locations in the system and then presented as reduction equivalency in terms cars not used, barrels of crude oil not consumed, and hectares of forest absorbing carbon for the different PV PLs.

5.3.1. Reduction per kWh

Figure 1 shows the annual reduction rate in the CO_2 emissions by the PV projects in the selected regions in Northern Cyprus. As can be seen from Figure 5.13, that Guzelyurt has the highest environmental benefits- represented by the CO_2 reduction rate- followed by Gazimagusa with 1016 and 1004 ton/kWp respectively, which mean that these regions ensure the highest environmental benefits.

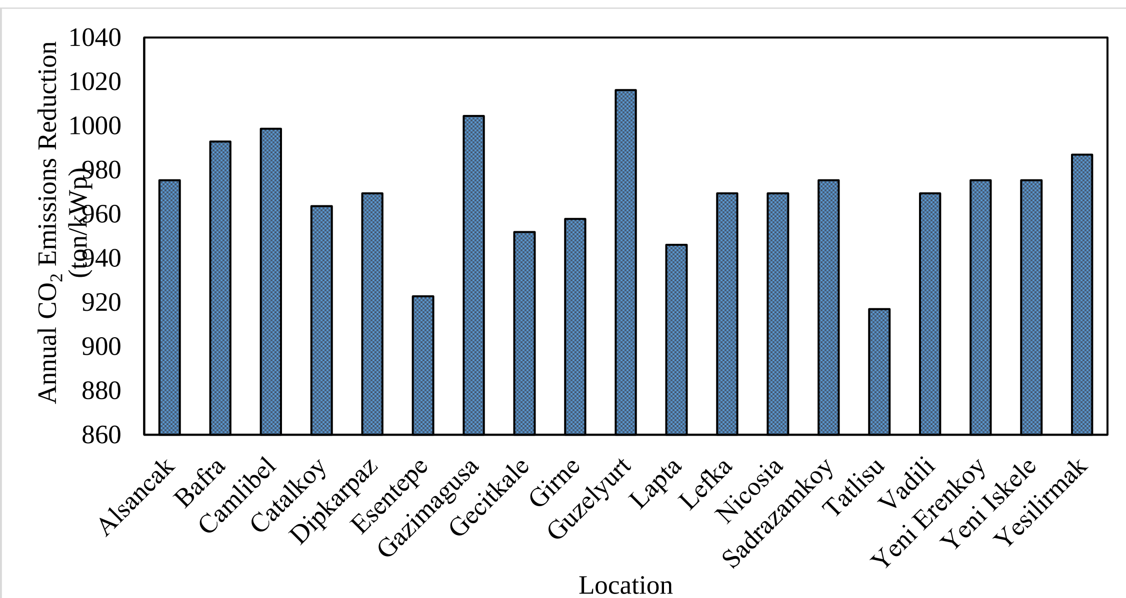

Figure 5.13. The annual reduction rate in the CO_2 emission in different regions in Northern Cyprus by the PV projects.

5.3.2. GHG Reduction Equivalency

The country has a GHG emission factor of 0.732 tCO_2/MWh, which can be used to calculate the expected amount of GHG reduction when integrating renewable energy. Therefore, Table 13 presents the possible amount of CO_2 reduction for each of the PL's, 10 – 50% as well as the reduction equivalency in terms of cars not used, barrels of crude oil not consumed, and hectares of forest absorbing carbon. Apart from active power loss reduction, it is possible to reduce carbon emissions. The purpose is to show the significance of increasing the PL of renewable generation on the island, especially solar power. For instance, increasing the PL level of PV generation to meet 10% of the aggregated demand in the system can result in 35,090 Annual tCO_2 reductions. This amount of carbon reduction is equivalent to 6,426 cars not used annually, 81,605 barrels of crude oil not consumed, or 3,227 hectares of forest absorbing carbon.

Table 13. GHG reduction potential and its equivalency.

Case	Annual tCO_2 reduction	Annual tCO2 reduction equivalency		
		Cars not used	Barrels of crude oil not consumed	Hectares of forest absorbing carbon
10%	35,090	6,426	81,605	3,227
20%	70,181	12,853	163,210	6,454
30%	105,271	19,280	244,816	9,682
40%	140,361	25,707	326,421	12,909
50%	175,452	32,134	408,027	16,137

5.4. APPROACH VALIDATION: WI VS. NI APPROACH

In this subsection, it is demonstrated that the WI approach is more effective relative to the NI approach in terms of reducing active power loss and improving busbar voltage profiles.

5.4.1. Active Power Loss Reduction

The idea of the WI approach in Eq. (18) is to place relatively larger PV-DG units on the weakest busbars; electric power at those busbars is withdrawn from close generation (i.e. PV-DG generators) rather than being supplied from farther sources in the network. This is because long-distance power transmission may result in weakening busbar voltage profiles as well as increasing active power loss in the network. In comparison with the NI approach, active power loss in the system is reduced greater using WI approach, as reported in Figure 5.14. Initially, it can be observed that both approaches help reducing active power loss. However, as the PL of PV-DG increases, WI approach is able to reduce active power loss to 3.44 MW for 50% PL where NI approach records 3.65 MW.

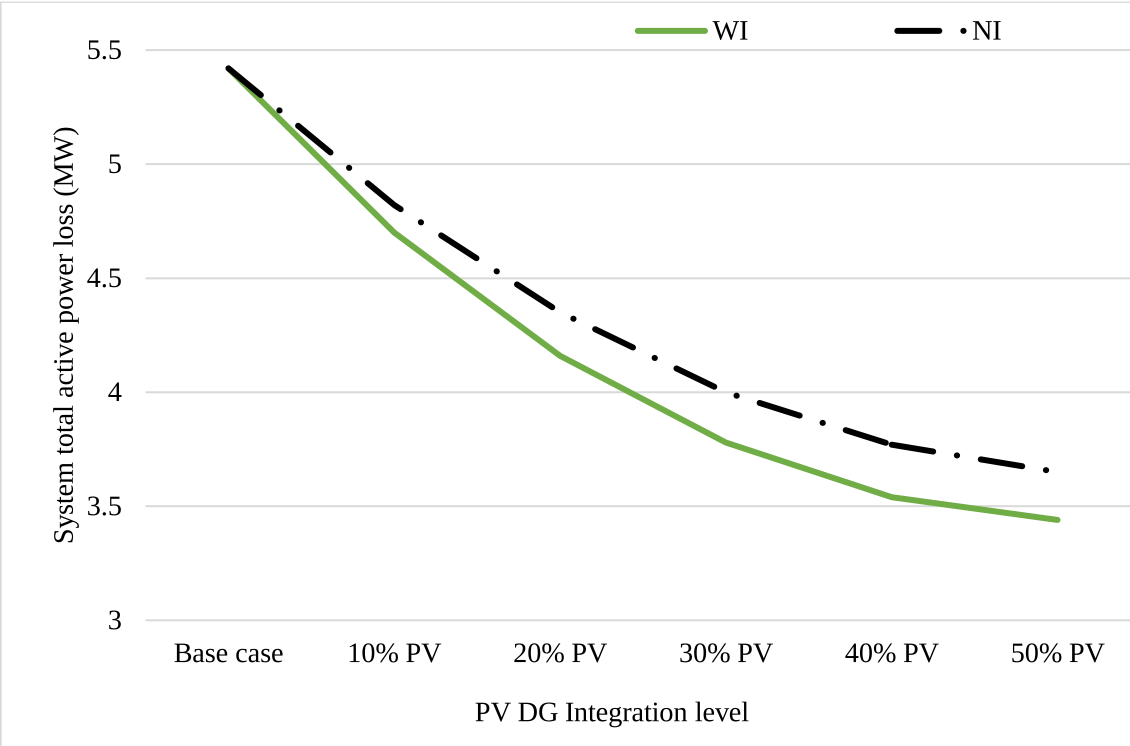

Figure 5.14. Comparison between WI and NI approaches in terms of system total active power loss reduction for different PL's.

5.4.2. Busbar Voltage Profile Improvement

Similarly, the WI approach significantly helps improving voltage profiles towards the rated value relative to NI approach. Figure 5.15-Figure 5.19 below illustrates a comparison between WI and NI approaches at different PLs. It can be seen that both approaches enhance voltage profiles as the PV-DG PL increases. However, WI approach shows a better performance, especially at higher PLs such as 40% and 50% in Figure 5.18 and Figure 5.19, respectively. It is worth noting that at 50% PL, voltage profiles of Guzelyurt, Camlibel low, Herakles, Dikmen, Alsancak, and Girne low busbars are below 0.95 p.u. whereas using WI approach, at 50% of PL, all busbar voltages are improved to 0.95 and higher. Furthermore, unlike WI approach, NI approach shows a decrement of ODTU busbar voltage profile from 0.964 to 0.958 p.u. Accordingly, VPI is examined for both approaches. As shown in Figure 5.15-Figure 5.19, for the different PLs, WI shows lower VPI compared to NI approach. It is also noticed that at 50% of PL, the VPI of NI approach is higher than that of the 40%, which is expected since ODTU busbar voltage magnitude decreases from 0.964 to 0.958 p.u when using NI approach for 40% and 50% PLs as mentioned previously. Whereas for the WI, the VPI is further increased compared with that of the same approach at 40%.

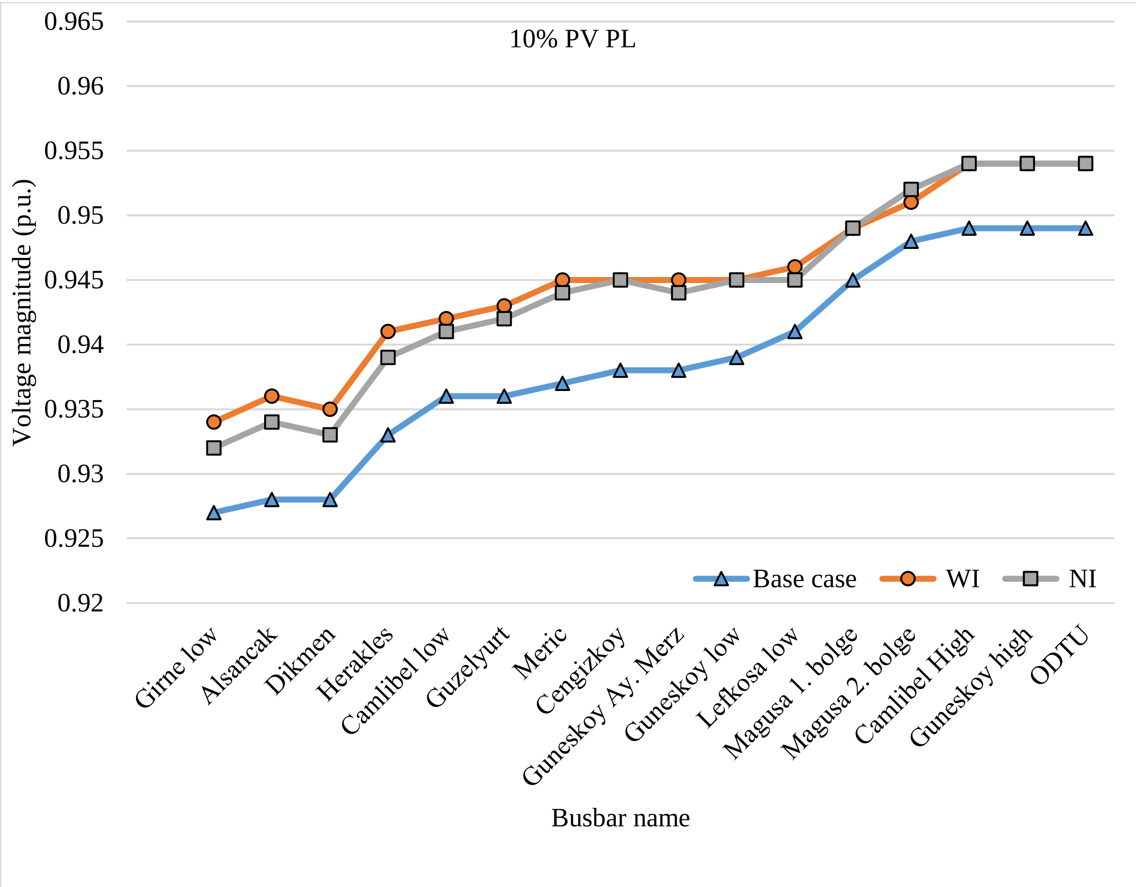

Figure 5.15. Comparison between WI and NI approaches in terms of voltage profile improvement at 10% PV PL.

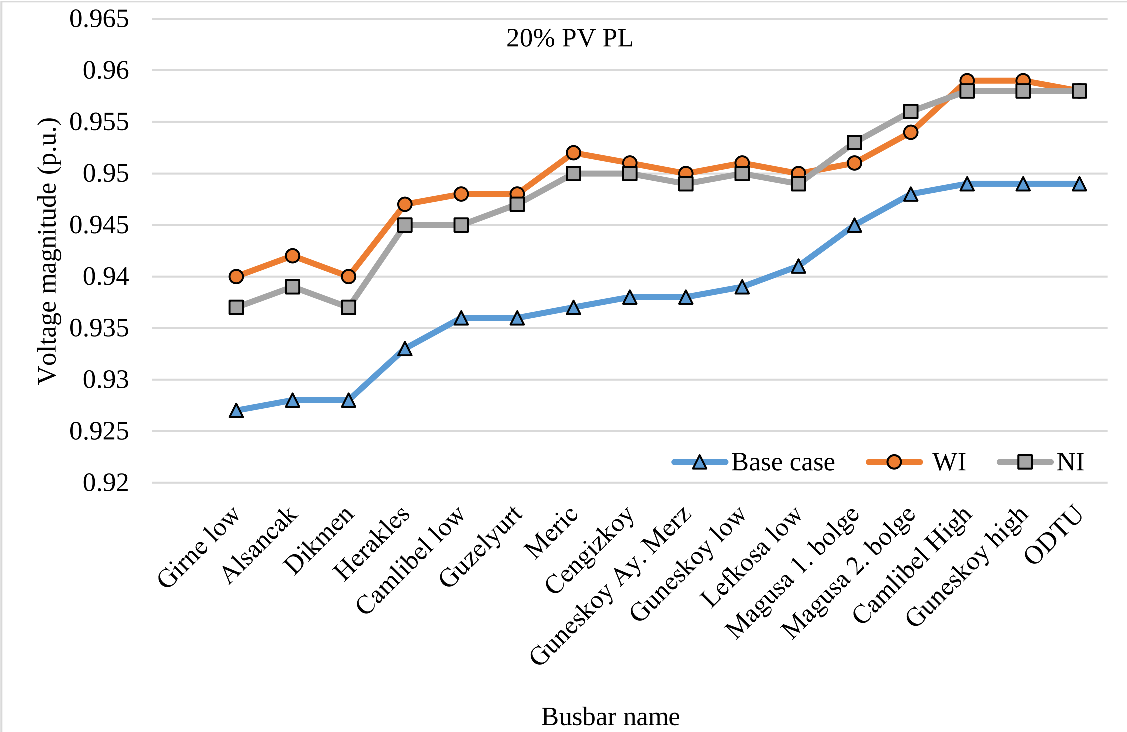

Figure 5.16. Comparison between WI and NI approaches in terms of voltage profile improvement at 20% PV PL.

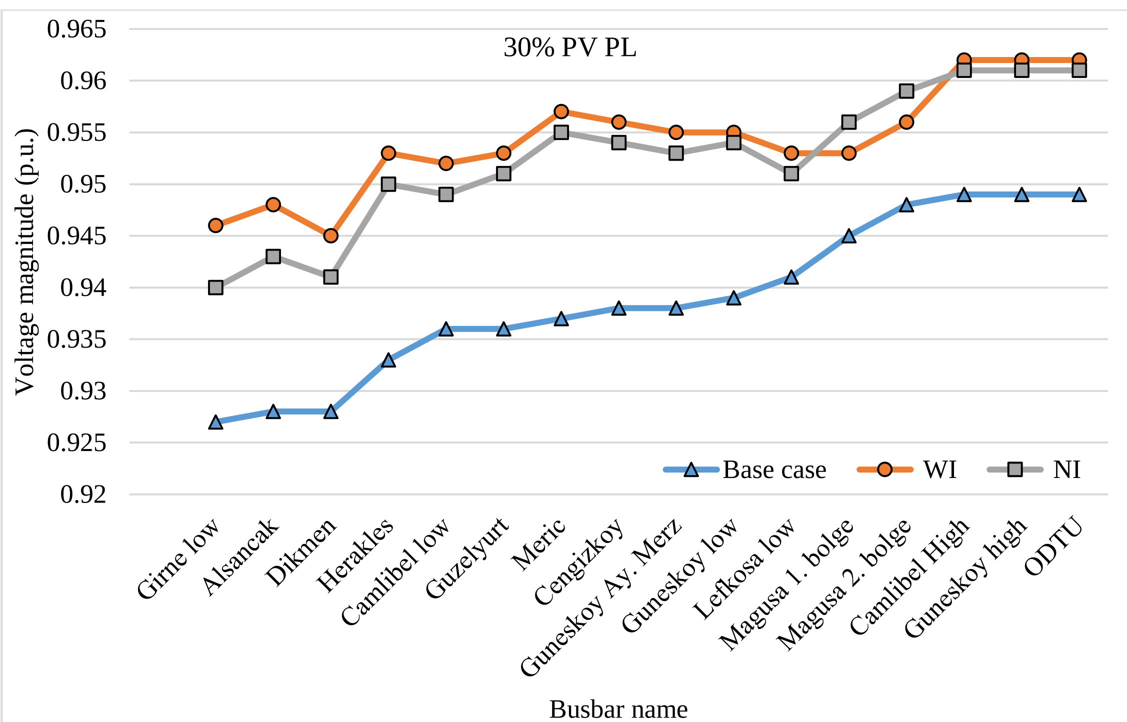

Figure 5.17. Comparison between WI and NI approaches in terms of voltage profile improvement at 30% PV PL.

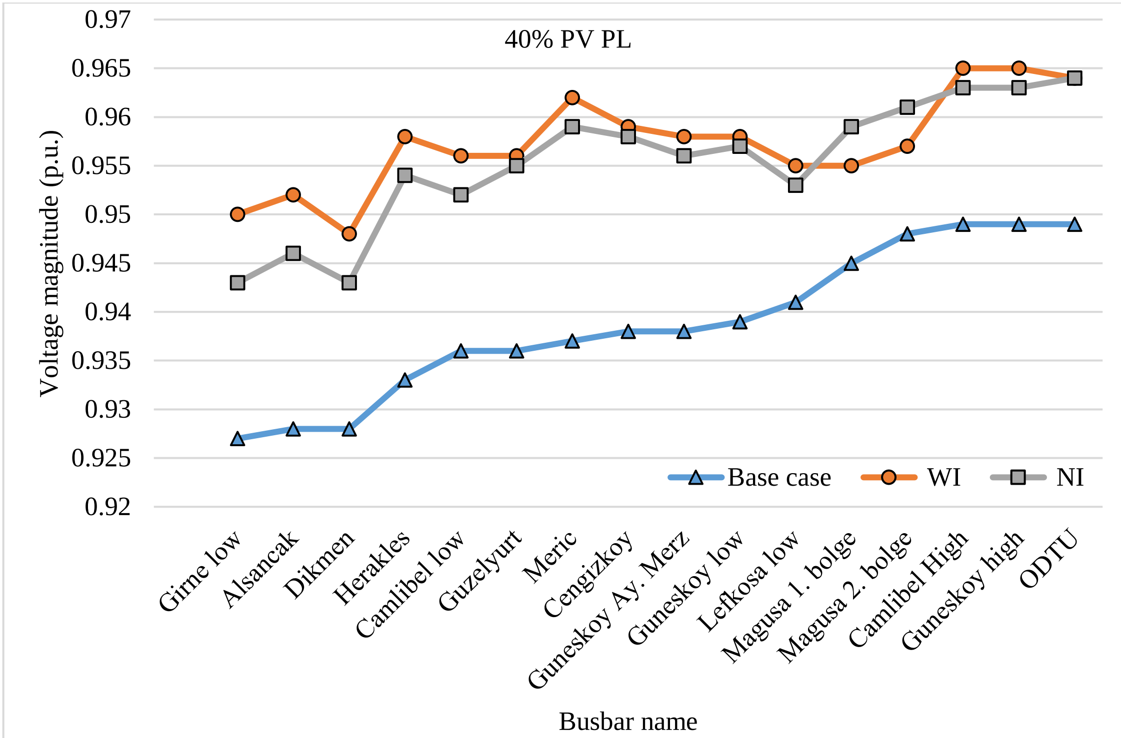

Figure 5.18. Comparison between WI and NI approaches in terms of voltage profile improvement at 40% PV PL

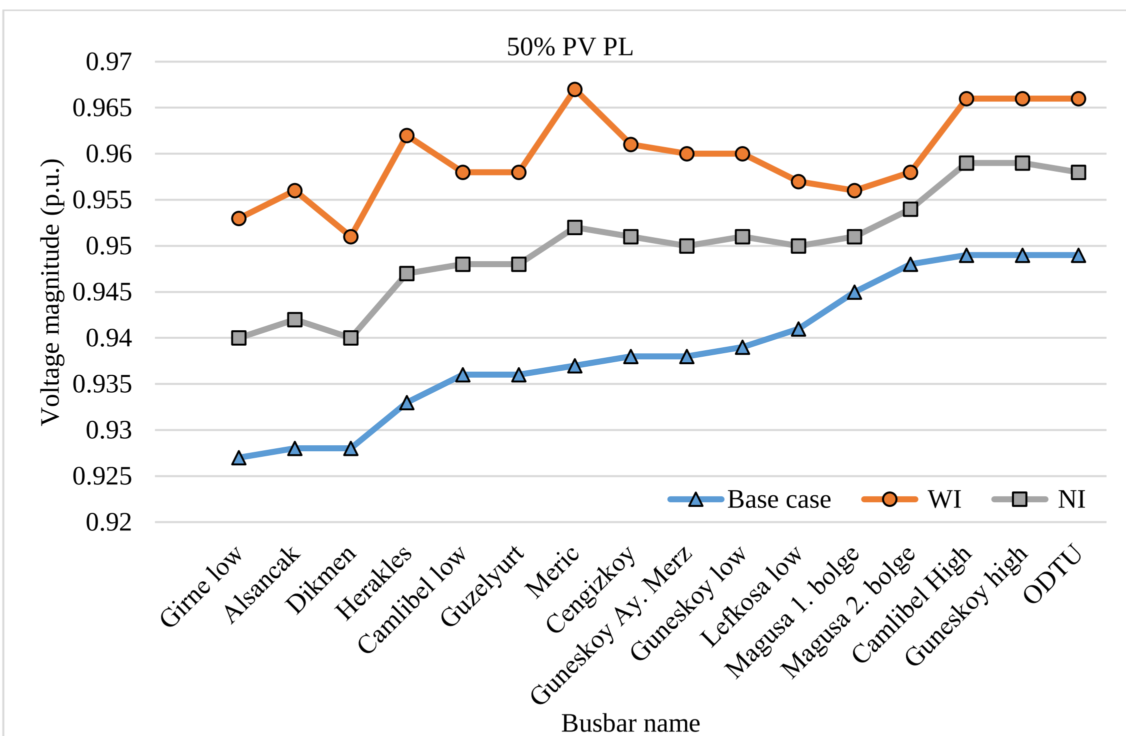

Figure 5.19. Comparison between WI and NI approaches in terms of voltage profile improvement at 50% PV PL.

Figure 5.20 below supports the findings in Figure 5.15-Figure 5.19 where WI provides better VPIs at all PLs compared to NI approach. It can be seen from Figure 5.20 that both approaches can help to minimize VDI. However, the effectiveness of VDI reduction is more significant using WI relative to NI. It can also be noticed that at 50% of PL, the VDI of the NI approach is higher than that of the 40%. This is expected since ODTU busbar voltage magnitude decreases from 0.964 to 0.958 p.u when using NI approach as shown previously. As for the WI, the VDI is further decreased compared with that of the same approach at 40%. Thus, it can be concluded that the WI provides better performance in comparison with NI in terms of voltage profile improvement.

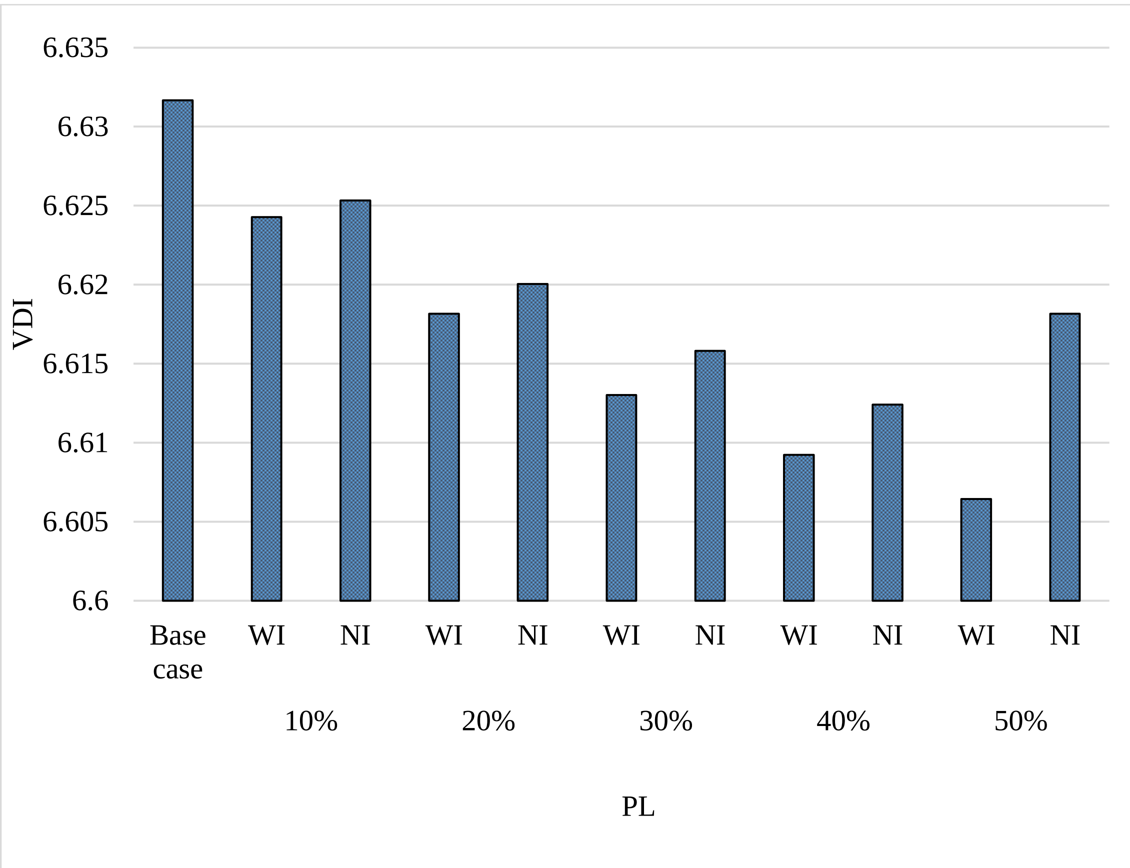

Figure 5.20. Comparison between WI and NI approaches in terms of voltage profile improvement at different PV PLs.

5.5. CHAPTER SUMMARY

In this chapter, the detailed analysis setup and thesis findings have been presented. Taking into account the climatic conditions of the present test case, this chapter initially discussed the high potential of solar resources in the region, which can be greatly useful for distributed PV projects. Subsequently, the chapter takes into account PV integration and investigates the impacts of distributed PV systems on different technical parameters (active power loss, voltage profiles, and system overloading), and outlines the associated GHG reduction potential. Finally, the chapter includes an approach validation section that demonstrates the effectiveness of the proposed approaches in terms of active power loss reduction and voltage profile improvement.

Chapter 6

CONCLUSIONS AND FUTURE WORK

This chapter serves to conclude the Thesis work by summarizing the most significant findings. In addition, this chapter details how the present Thesis addressed the objectives proposed in Chapter 1. The future research directions and plans as a continuation of this Thesis are also outlined at the end of this chapter.

The current structure in power systems is gradually changing in response to the changing requirements of modern societies. Conventionally, power systems have been planned to rely on a radial topology, in which the generation is centralized with unidirectional power flow from generation sites to consumers. In comparison with the past, communities nowadays including users, investors, and non-governmental organizations are motivated to collaborate with governments to modernize the operations in power systems and implement the measures of a SG. The main driving force to the SG paradigm is the need for an inclusive framework that satisfies the requirements of all involved stakeholders such as mitigating climate change impacts, improving system efficiency through communication technologies, and providing flexible services to consumers while meeting the standards of power-delivery process. In line with technological advancements, RESs and DG systems are perceived as promising solutions that, if applied into SGs, can offer tremendous benefits such as reducing the reliance on centralized generation, hindering the advancement in climate change (especially in countries with abundant RESs), and modernizing the system where consumers can choose the source of power. However, the implementation of these technologies is generally associated with a series of challenges that form a big burden for utilities to cope with. Some of these challenges are closely related to resource availability – for RESs – and system efficiency – for DGs – where it is known for a fact that non-optimal planning of RES-based DGs may lead to excessive system losses and voltage imbalances. Therefore, the integration of RES-based DG units into the SG requires careful planning in order to achieve their maximum benefits. [135]

6.1. SUMMARY OF THE RESEARCH FINDINGS

The present thesis attempts to, initially, provide a comprehensive review of SG and the role of DG technology in system liberalization. Foremost, the thesis targets planning the integration of PV-DG units into the NCTS considering two stages. First, the solar resources are assessed for the target test case considering the available solar resources and the economic profitability of the investments. For the lateral stage, the location and size of PV-DG units are selected considering system conditions such as active power loss, busbar voltage profiles, and system overloading. This stage employs a novel method for the site and size selection of PV-DG units into the system, WBB and WI approach, respectively. The OPF analysis is conducted for base case results in order to record the initial conditions in the system. Subsequently, the WBB approach takes into account the deviation of busbar voltage-magnitudes from the rated values, which are called Weak Busbars (WBBs). To this end, the WI approach is implemented in order to quantify the sizes of the candidate busbars for PV-DG placement. WI considers the significance of busbar voltage-deviation into the size of PV-DG unit. With additional OPF analysis, considering different PLs of PV-DG units, the findings are promising and are validated against the NI approach, which does not take into account the significance of the deviation of busbar voltage-magnitudes. The following bullet points outline the major findings in this thesis:

- Power systems across the globe are characterized by shortcomings such as old infrastructure, lack of information on system operations, and essentially the high reliance of centralized and fossil fuel power plants.
- The necessity of developing the SG paradigm is inevitably essential for solving the challenges in centralized power systems where the power flow follows a top-down hierarchy.
- Renewable energy-based DG technology is perceived as pivotal for modernizing the current grids and their successful adaptation into SG paradigm helps to 'liberalize'

the system in which consumers can both have information on the status of power delivered and select the generation source while ensuring the quality of services.

- The present test case (the NCTS) enjoys the high availability of solar resources that can be exploited for PV investments. The average GHI in major locations of the NCTS is approximately 6.20 kWh/m^2, which is considered significant in comparison with global figures.
- Follows, the profitability of PV investments in any region highly depends on the GHI factors. As for the NCTS, it is found that PV investments are profitable where the installation of any PV system in any location of the NCTS provides LCOE prices lower than the available grid tariff with attractive NPV and PBP values.
- The NCTS contains 49 busbars in total, among which 16 busbars are considered 'weak' and selected as candidate locations for PV-DG placements in the system. The voltage profile of these busbars deviates from the rated p.u vales (See Eq. 14).
- Using WI, The Integration of PV-DG units into the NCTS helps to reduce active power losses at different PLs, where it is observed that the integration helps to reduce active power losses from 5.42 MW in the base case to 3.44 MW.
- In addition to power loss reduction, the integration of PV DG units helps to improve busbar voltage profiles. The voltage magnitudes of 'weak' busbars are within the rated limits of 0.95 and 1.05 p.u (according to Eq. 14). The VDI is also reduced from 6.63 to 6.60, which means that less voltage magnitude deviations are achieved with higher PLs.
- System overloading, as a secondary objective, is also among the parameters that are improved with the WI integration approach. System overloading is assessed through the generator, transmission-line, and transformer loading among which their overloading is reduced further with the different PLs.
- The maximum allowable PV PL is quantified using WI and found to be 50% and 70% when considering active power loss and VPI, respectively. This implies that the current grid requires further upgrade schemes in order to accommodate higher PV levels.

- As a part of promoting renewable energy investments, the integration of PV-DG units can assist in reducing GHG emissions. The highest potential of GHG reduction is seen in Guzelyurt because it is characterized by relatively higher GHI measures.
- Finally, the proposed methodology for site and size selection of PV-DG units in the NCPS is validated against the NI approach. The results show that the WI approach provides better performance in both active power loss reduction and voltage profile improvements.

6.2. SCOPE FOR FUTURE RESEARCH DIRECTION

The present work investigates the potential of improving grid technical parameters using a renewable-energy based DG technology. The analysis considers PV-DG systems for the particular test case due to the reasons presented in sections 1.2 and 3.2. The following ideas can be undertaken by extended research studies as a continuation of the present work:

- This research has considered one type of DG technologies. Future analysis, however, may incorporate different types of renewable-energy based DG technologies – although they are not as abundant as solar resources – and assess their impact on the system. Wind turbines can be a good start in this aspect. Further, the impact of PV-DG integration can also be analyzed with the presence of BSSs.
- The performance of the system in terms of power quality such as harmonics, voltage sags, and flickers can be examined with the insertion of DG systems with various power electronic devices including DC/AC converters.
- Future work may also consider the transient stability of the system. In fact, transient stability forms a large obstacle for the successful implementation of SG measures. Therefore, it can be investigated with the presence of DG systems.
- The current work considers a regional test case. However, future research plans may include validating the proposed approaches to standardized IEEE test systems. In fact, the approaches can also be implemented on distribution networks considering reasonable DG sizes that can serve supply energy to small applications such as households and commercial setups.

- With the ‘aggressive’ integration of different SG technologies, the development of a Multi-objective Optimization Index can serve well to include different aspects of the problem. For instance, EVs, BSSs, economic benefits to consumers, energy arbitrage and DSM, can all be considered simultaneously in the problem of DG site and size selection.

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