PLANNING THE GRID INTEGRATION OF MINIGRIDS IN DEVELOPING COUNTRIES

Madalitso Chikumbanje

Institute for Energy and Environment

Department of Electronic and Electrical Engineering

University of Strathclyde

Glasgow, Scotland, UK

This dissertation is submitted for the degree of Doctor of Philosophy in Electrical Engineering

July 2022

In loving memory of Andrew Wilson Chikumbanje.

I am sure he would have loved to see this day.

...let there be light…

DECLARATION

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date: July 2022

Madalitso Chikumbanje

University of Strathclyde

ABSTRACT

In the two decades since 2000, the world electricity access rate has improved from 73% to 90%, through grid extension and off-grid solutions, like minigrids and solar home systems. Beyond electricity access, the integration of main grids and minigrids, is a prospect for addressing some challenges associated with current electricity access initiatives, such as network losses and poor supply voltages. The grid integration of minigrids is comparable to the integration of low carbon distributed energy resources (DERs) in the global north grids, whose success has been ensured by developing appropriate planning methods for maximising benefits. However, no suitable planning methodology is available to maximise the benefits of grid integration of formerly autonomous minigrids in developing countries.

This thesis proposes a minigrid integration planning (MGIP) method that minimises active and reactive power losses and improves voltage profile. It builds on the available academic work on distribution network planning and DER integration by including a significantly 'better' articulation of the performance of downstream minigrids within the associated optimisation problem.

The thesis also proposes a pre-assessment procedure for characterising the application of MGIP to a specific set of minigrid integrations. The procedure pre-qualifies minigrids and classifies the expected 'value' of MGIP to improve system parameters (e.g., losses, voltage profile). Minigrids with limited benefits are removed from the global optimisation problem to provide a resultant saving in computational effort.

Case studies akin to sub-Saharan Africa grid applications are developed and considered. Results show that applying the MGIP can reduce losses by up to 76% and significantly improve voltage profiles. Additionally, the pre-assessment procedure offers regular computational savings and improves decision-making when applying the MGIP. The work presented in this thesis contributes to the technical aspects of planning the grid integration of formerly autonomous minigrids initially deployed to widen electricity access in developing countries.

ACKNOWLEDGEMENTS

Firstly, I thank God for an overflowing, abundant life.

Secondly, I thank the research community, colleagues and friends at Strathclyde for a fulfilling journey in my doctoral studies. My supervisors, Professor Stuart Galloway and Damien Frame, secured funding for this project, tirelessly supervised it, and supported me in countless ways, even amidst a global pandemic and related restrictions. My colleagues within the research group, led by Prof Galloway, were supportive and gave me valuable feedback to improve the work. Friendship with people like Dr Asif Khan filled my lunch breaks with refreshing conversations.

Lastly, I thank my family for the support and encouragement they have given me throughout my life. Mirriam and Andrew are a constant source of motivation and were particularly understanding when I had to spend extra hours stitching this thesis together. Jeff and Jean gave me the confidence to spread my wings and get an education and experience outside my native country. Alinafe, Mtisunge, Singatiya and Edward are the never-tiring cheerleaders I have been privileged to have in this life.

Madalitso Chikumbanje

Glasgow, 2022

CONTENTS

LIST OF TABLES

List of Figures

LIST OF ABBREVIATIONS AND ACRONYMS

ACRONYM	MEANING
AC	Alternating Current
DC	Direct Current
DERs	Distributed Energy Resources
DNEP	Distribution Network Expansion Planning
DNP	Distribution Network Planning
FiT	Feed in Tariff
GA	Genetic Algorithm
GDP	Gross Domestic Product
HDI	Human Development Index
HG	High Demand Load Profile
LV	Low Voltage
LVDC	Low Voltage Direct Current
LW	Low Demand Load Profile
MD	Medium Demand Load Profile
MGIP	Minigrid Integration Planning
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MMLI	Multi-feeder Minigrid Loading Index
MO-MGIP	Multi-objective Minigrid Integration Planning
MP	Microgrid Planning
MST	Minimum Spanning Tree
MV	Medium Voltage

NP	Network Planner
OnSSET	Open Source Spatial Electrification Toolkit
PPA	Power Purchase Agreement
PS	Particle Swarm
PV	Photovoltaic
REM/RNM	Reference Electrification Model/Reference Network Model
SDG7	Sustainable Development Goal 7
SEforALL	Sustainable Energy for All
SPD	Small Power Distributor
SPP	Small Power Producer
SPP&D	Small Power Producer & Distributor
SSA	Sub-Saharan Africa
SSO	Side-by-Side Operation
TS	Tabu Search
UN	United Nations

LIST OF SYMBOLS

SYMBOL	MEANING
$\boldsymbol{B}$	Set of all network branches
$\boldsymbol{B}_{mg}$	Set of Low Voltage (LV) network branches in a minigrid, mg
$\boldsymbol{B}_{mv}$	Set of Medium Voltage (MV) network branches
$\boldsymbol{G}$	Set of generators connected to the minigrid networks
$\boldsymbol{ST}$	Set of storage devices
MG	Set of minigrid networks
N	Set of all network nodes
N_{mg}	Set of all nodes within a minigrid, mg
N_{mv}	Set of MV network nodes
TFR	Set of transformers connecting MV and minigrid networks
$\psi_{mg,z_{mg}}$	Set of minigrid branches whose power flow is affected by output of the local generation due to placement of a grid infeed point
Z	Set of grid infeed points for a cluster of minigrids
h	Index for the hour of the day
km, mn	Indices for network branches
k, m, n	Indices for network nodes
z_{mg}	Index for the point of grid infeed into a minigrid, mg
mg	Index for a minigrid
C_{energy}	Cost of energy [c$/kWh]
C_{mv}	Cost of MV network expansion [$/km]
$C_{z_{mg}}^{tfr}$	Cost of MV/LV transformer placed at grid infeed point, z_{mg}

L_{mn}	Length of network branch mn [km]
R_{mn}	Resistance of network branch mn [**Ω**]
X_{mn}	Reactance of network branch mn [**Ω**]
d	Discount rate [%]
y	Project evaluation period [years]

C_{ann}^{inv}	Total annual investment cost [$]
C_{ann}^{loss}	Total annual cost of losses [$]
CRF	Investment cost recovery factor
I_{mn}	Current through network branch mn
P_n^g, P_n^{st}, P_n^d	Active generator, storage and demand power at node n
P_{mn}	Active power through network branch, mn
$P_{loss,h}^{mg,z_{mg}}$	Hourly power loss within a minigrid with node z_{mg} as point of grid infeed
Q_n^g, Q_n^{st}, Q_n^d	Reactive generator, storage and demand power at node n
Q_{mn}	Reactive power through network branch, mn

List of Appendices

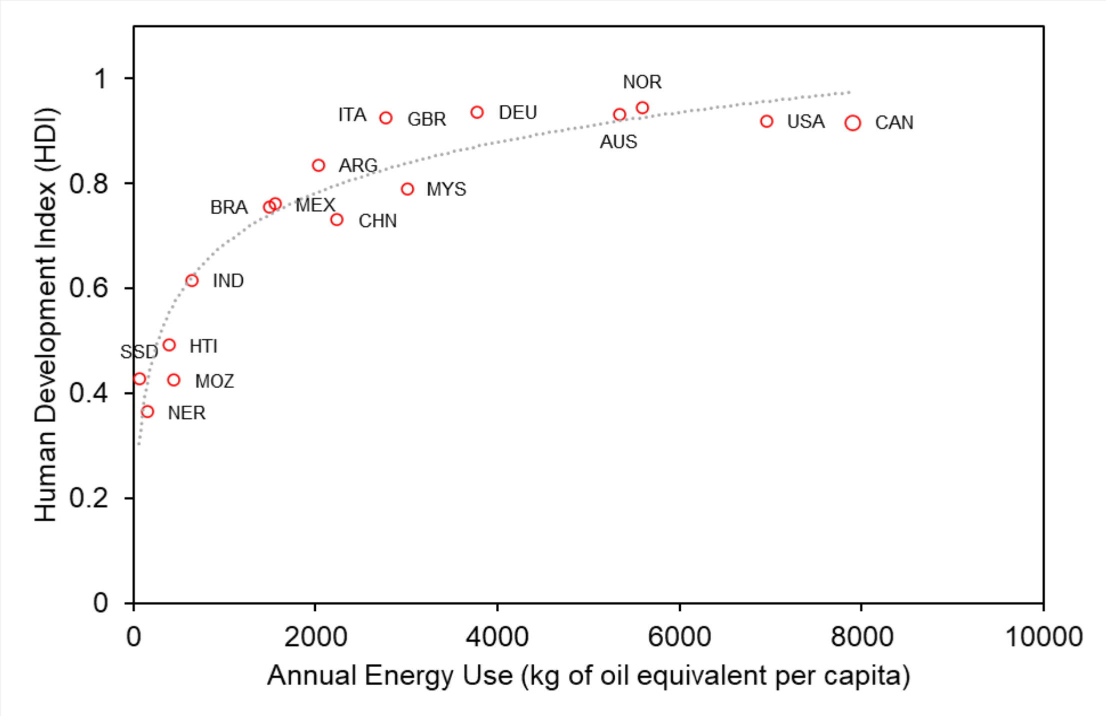
1 INTRODUCTION

1.1 Thesis background and context

1.1.1 Energy and development

From the discovery of fire to harnessing renewable energies, such as wind or solar, into electricity, energy has been and remains critical to human development [1]. This assertion is evidenced in the literature where energy use shows strong correlation with various economic development indicators. For example, [2] and [3] correlates energy use with Gross Domestic Product (GDP) and [4] with Human Development Index (HDI). According to the United Nations (UN) [5], "HDI is a composite index measuring average achievement in three basic dimensions of human development – a long and healthy life, knowledge and a decent standard of living." Due to its inclusiveness of several indices, HDI is considered a better development metric than GDP. Using empirical data from [5], [6], Figure 1 captures the relationship between primary energy use and HDI score for certain countries.

Two main things can be observed from Figure 1. Firstly, it shows that high energy use is associated with a high HDI score, and this is synonymous with developed countries such as Canada, United States and Norway. Conversely, low energy use is associated with low score of HDI, and that trend is synonymous to developing countries such as Niger, Mozambique, and Haiti. Secondly, that beyond a certain level of energy use, approximately 2,000 kgoe per capita, there is an apparent saturation in the associated increase in HDI score [7]. This suggests that for the same absolute increase in energy use, there is high significant human development impacts in a developing country, like Mozambique, than in an already developed country, like Canada [3].



[1]

Figure 1: Human Development Index and energy use (Data from [5], [6])

The correlation between energy use and HDI, as illustrated in Figure 1, leads to a strong argument that energy access is a critical enabler in the fight against poverty [8]. Aware of the negative environmental impacts of energy usage in the previous century, as reported by the Intergovernmental Panel on Climate Change (IPCC) in [9], efforts towards addressing energy access in developing countries [10] or the decarbonisation of other energy intensive sectors such as heat and transport [11] are expected to be sustainable and environmentally friendly. Consequently, there has been an emergence of several global efforts towards advancing access to modern and sustainable energy resources, such as Sustainable Energy for All (SEforALL), which was established in 2011 under the UN but now is an independent organisation that retains close links with the UN [12]. Presently, the core mandate of SEforALL is to drive the achievement of Sustainable

[1] 1 kg of oil equivalent = 11.63kwh

Development Goal 7 (SDG7) in partnership with various stakeholders such as the UN, governments, financial institutions, philanthropic organisation, and charities. [12].

SDG7 is one of the seventeen Sustainable Development Goals (SDGs), adopted by the UN and its member states in 2015, that encapsulate the blueprint of present and future peace and prosperity for people and the planet [13], [14]. Specifically, SDG7 aims to achieve universal access to affordable, reliable, sustainable and modern energy for all by 2030 [13][15]. Emphasising the previously demonstrated correlation between energy and development, SDG7 is known as the "golden thread" that links all SDGs [16]. While access to energy is a much broader topic [17], this thesis focuses on issues associated with access to electricity, which is a vital form of energy.

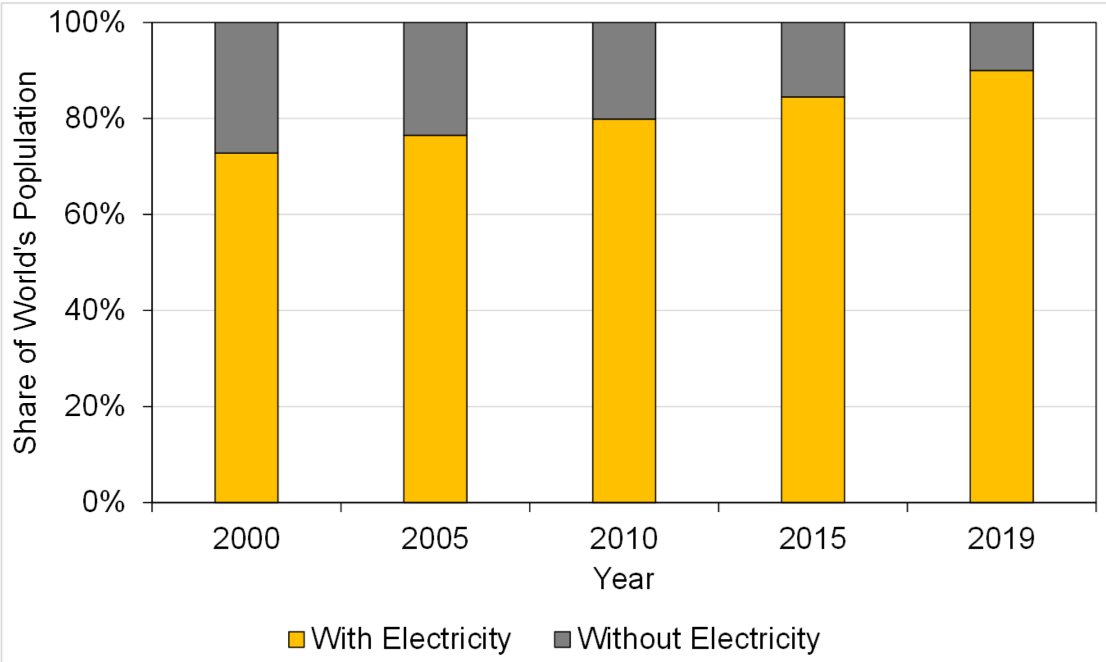
1.1.2 Electricity access in developing countries

According to [17], electricity access entails "*a household having reliable and affordable access to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average*". The electricity access planning problem involves deciding on the least cost pathway, among main grid extension, minigrids or fragmented energy services, for a household or group of households to realise electricity access [15], [43]. The latest SDG7 tracking report [18] suggests that over the past two decades, there has been substantial progress towards achieving universal access to electricity. Specifically, the number of people without access to electricity has dropped from 1.3 billion in 2000, representing 27% of the World's population, to 759 million in 2019, representing 10% of the World's population. Figure 2 (a) shows the progress made in electricity access over the past decade, and Figure 2 (b) presents a regional breakdown of the population that remains without access to electricity.

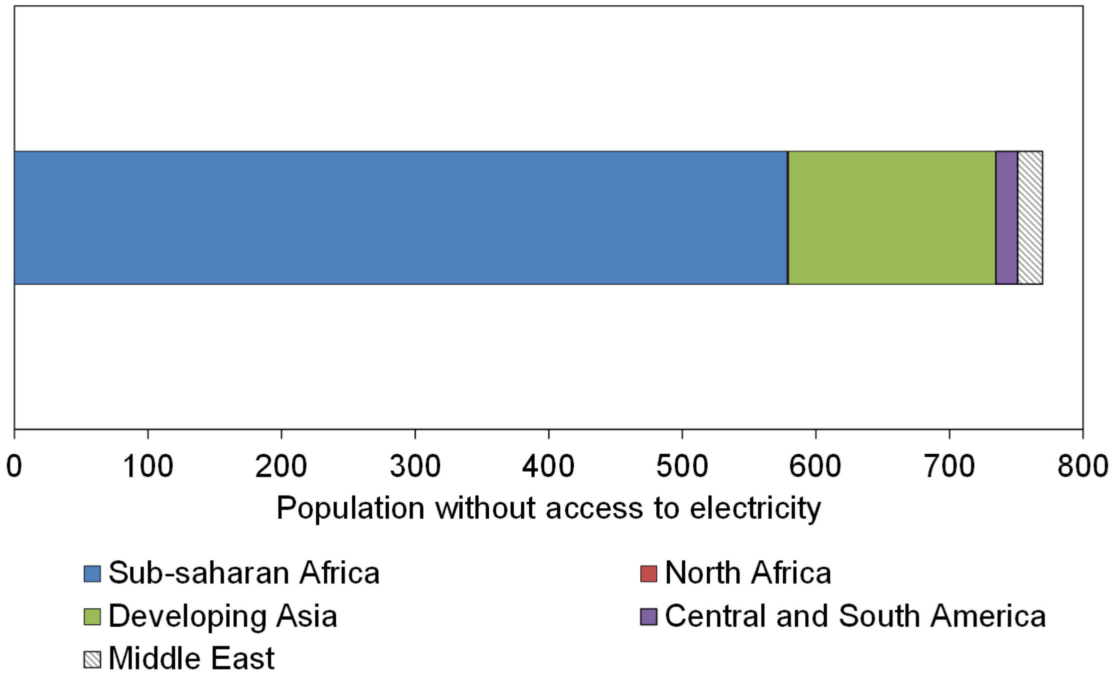
The progress in electricity access, shown in Figure 2 (a), is attributable to three main pathways to electricity access [19],[20], namely; main grid expansion, community level offgrid[2] systems called minigrids, and various fragmented energy services such Solar Home Systems (SHS) and solar lanterns. While these pathways have their advantages and disadvantages (see [20] for a thorough discussion), each is expected to play a role in

[2] Offgrid means not being connected to the main grid

further reducing the number of people without access to electricity, most of which are in developing countries, particularly in SSA as shown in Figure 2 (b).



(a) World electricity access trend



(b) Distribution of population without electricity in 2019

Figure 2: Electricity access trend and geographical distribution of population without electricity in 2019 [18]

As a pathway to electricity access, main grid expansion entails achieving electrification through a local electricity network that is connected to a nation or regional wide transmission network with centralised large capacity power generators [20]. On the other hand, electrification achieved through minigrids involves getting supply from "*localised power networks powered by modular generation technologies like solar photovoltaics, usually without infrastructure to transmit electricity beyond their service area [17].*" Lastly, the most dominant technology is electrification through isolated energy services are SHSs which are standalone photovoltaic systems that provide a relatively, compared to the main grid or minigrids, low power supply to a single household [7].

The electricity access definition presented earlier in this section suggests that electricity access is a binary issue – either a household has access or not. While that assertion is true, the service level of electricity access varies significantly depending on the electrification pathway and associated capacity, duration of supply, reliability, affordability, and quality of supply. Consequently, [8] proposed a six level Multi-Tier Framework (MTF) for classifying electrification with Tier 0 being without electricity access and Tier 5 means having a full electricity service. The MTF is illustrated in Figure 3 using the duration of the electricity services and the devices they can support. Fragmentated energy services like SHSs and solar lanterns can achieve up to Tier 2 service level while the main grids and minigrids have the potential to achieve up to Tier 5.

Figure 3: Electricity access tiers and associated service level [8]

In the lead up to 2030, minigrids will play a crucial role in closing the energy access gap, with the World Bank suggesting that minigrids can supply electricity to half a billion people [21]. Although [18] recognises that the prospect of fully achieving SDG7 by the year 2030 remains ambitious, the reported progress in the previous two decades, shown in Figure 2 (a), and the impetus towards deployment of offgrid systems like minigrids [21] suggests that sooner or later, access to electricity will cease to be a primary challenge in most developing countries. The likelihood of achieving universal access to electricity using both grid extension and off grid energy services is enough of a prompt to ask the question, “What will happen beyond achieving electricity access?” and in response some of this is discussed in [22], [23].

1.2 Beyond energy access in developing countries

Beyond achieving SDG7 using the current pathways of grid expansion, community level minigrids and isolated offgrid systems, the focus of electricity research in developing countries will, given time, shift from energy access to that synonymous to mature electricity and energy systems in the global north [24]. During this transitional period, developing countries will need to deal with issues such as the convergence of the main grid and offgrid electricity systems [25], [26]; the high network losses [27], [28]; and the low quality of electricity supply [29] [30].

1.2.1 Convergence of the main grid and off-grid systems

The delivery of electricity access to developing countries involves choosing the least cost option between grid expansion and one of the several offgrid alternatives to supply electricity to a particular population [31], [32]. For this reason, beyond SDG7, some populations will be serviced with the grid while others will be getting their electricity supply from offgrid systems such as minigrids. However, it is unlikely for the situation in these countries to remain like that for a long time, as evidenced in [10], [22], [33]. Authors in [22] and [33] report that after achieving substantial electricity access through grid expansion and offgrid methods, the grid in India, Cambodia, Sri Lanka and Indonesia continued to expand and started converging with various offgrid minigrids.

According to [33], upon the arrival of the main grid in Cambodia, Sri Lanka, and Indonesia, some minigrids were integrated with the main grid, others continued to operate independently from the grid (side by side operation with the main grid), while others were completely abandoned in favour of the incoming grid, see Figure 4. The fate of minigrids upon the arrival of the main grid is highly influenced by among other things the Tier of access that any of those converging technologies guarantee. Unlike the electrical service provided by SHSs and Solar Lanterns, which are significantly poor compared to a stable grid supply, certain minigrids guarantee access tiers that are comparable and at times better than the main grid in developing countries [8], [34]. Therefore, it is not a surprise for Figure 3 to show that minigrids have a role to play beyond the arrival of the main grid whether continuing as standalone minigrids (side by side operation) or integrated to the main grid. Some of the benefits of such integration would include loss reduction and voltage profile improvement [27]

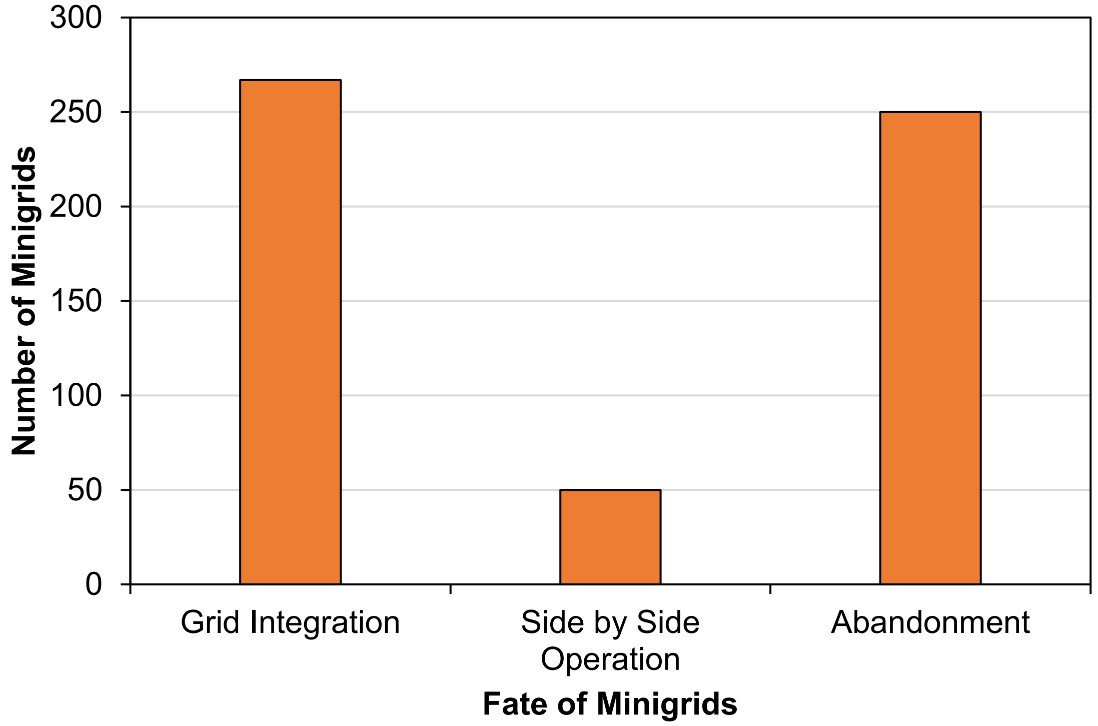


Figure 4: The fate of minigrids upon grid arrival in Cambodia, Sri Lanka and Indonesia [33]

Despite the potential for technical benefits to the grid integration of minigrids, little attention has been given to investigating how they can be realised. Critical articles on the convergence and integration of the grid and minigrids, [25], [26], [35], have focused mainly on policy, regulation and business aspects of the integration. The limited academic work on the technical aspects of the convergence of the grid and autonomous minigrids [36]–[38] focuses on individual minigrid connections or a technological solution.

For example, the authors in [37] analyse the techno-economic impacts of connecting a photovoltaic-diesel hybrid minigrid to the main-grid in Tanzania. While insightful, the analysis lacks technical depth as it was conducted using Homer Software [39] which does not model the electrical behaviour of either the minigrid or the main grid. In [36], [38], the authors focus on enabling the compatibility of minigrids and main grid control and protection systems to allow both grid-connected and islanded operation of the formerly autonomous minigrids. Authors in [36] propose the change of setting to achieve compatibility of the two grids, while in [38] a back-to-back converter as an interface between the grids is proposed to achieve the same goal.

Although it is necessary to investigate the techno-economic impacts of grid integration of a minigrid or enable compatibility between the arriving grid and minigrids, the work in [36]–[38] assumes that the grid will just appear and integrate with the minigrids without the need to plan such integration. Despite a well-established body of literature suggesting the need to plan and optimise various forms of grid integrations [40]–[42], the authors in [36]–[38] did not make any commentary on whether planning and optimisation would be required in the grid integration of minigrids. The work in this thesis establishes and addresses this gap in knowledge.

1.2.2 Planning the grid integration of minigrids

The primary objective of electricity access planning is to supply the least-cost electricity to as many people as possible [15], [43]. However, that has consequently meant that other imperatives, such as loss reduction and supply quality, are compromised. For example, the International Energy Agency (IEA) [28] reports that the average electricity technical losses in Africa, where achieving electricity access remains a priority, are 16% compared to 9% in other developing countries (excluding Africa). Similarly, works in [23], [30] and [29] are evidence that most electricity access interventions in developing countries are synonymous with poor supply voltage and reliability. Therefore, beyond electricity access in developing countries, electricity network efficiency and quality of supply issues will need addressing in tandem with the convergence of the main grid and minigrids.

Despite the need to ensure that grid integration of minigrids beyond achieving electricity access does not worsen the network efficiency and power quality issues in developing countries, there is a lack of appropriate methodology to realise that. For example, reported cases [22], [33], where minigrids and the main grid have converged and integrated, are silent on the methods used to ensure the realisation of maximum technical benefits from such integrations. Alternatively, [36] recommends a non-systematic approach to minigrid integration planning where the grid incomer[3] is always connected to the minigrid node

[3] The portion of the main grid network extending from the main grid to a formerly autonomous minigrid

hosting the minigrid generator. However, there is no evidence relating to the technical performance of the integrated network that supports the approach in [36].

Therefore, power utilities and practitioners in developing countries lack a suitable systematic planning approach to ensure that grid integration of minigrids alleviates electricity network inefficiencies and power quality issues. Planning methodologies such as those in electricity access planning [44], distribution network expansion planning (DNEP) [45], and optimal distributed energy resources planning (ODERP) [46] could be related to minigrid integration planning. Still, none of them is suitable for planning the grid integration of minigrids for various reasons.

Firstly, Electricity access planning tools such as Homer [39], Open Source Spatial Electrification Tool (OnSSET) [47], Reference Electrification/Reference Network Model (REM/RNM) [43] and Network Planner (NP) [48] have got unique capabilities for assessing and recommending the best way to electrify a population. However, most of these tools and their associated methodologies have significant limitations. For example, these tools are used to decide between grid expansion and offgrid electrification [49]. Hence, they cannot plan both electrification pathways' subsequent convergence and integration [50]. Another limitation of electricity access planning tools is that they do not have an underlying power flow analysis capability which is key in assessing the loss reduction and voltage profile improvement associated with the grid integration of minigrids. Unlike electricity access planning tools, DNEP [11] and ODERP [12] involve some power flow analysis but are also not suitable for planning the grid integration of minigrids.

Secondly, traditional DNEP involves solving a top-down grid expansion problem to a greenfield site or improving the existing network's capacity [51]. However, in grid integration of minigrids, the grid will be expanding to existing minigrid networks with incumbent loads and DERs. These downstream assets will require a better articulation and consideration than in a typical DNEP problem.

Thirdly, ODERP involves optimising the size, location and type of DERs to integrate into an existing network [52], [53]. Although minigrids have incumbent DERs, their sizes, location and types are already decided long before the grid integration becomes a possibility [54]. Also, the grid integration of minigrids cannot be considered a typical ODERP problem because a minigrid is a unit with loads, network and DERs while ODERP only focuses on the DERs integration into an existing distribution network.

Beyond electricity access, the planning tools and approaches highlighted above are unsuitable for planning the grid integration of minigrids while addressing network losses and poor electricity supply quality issues reported in developing countries. Without a suitable planning method, utilities and practitioners in developing countries will not be able to maximise the technical benefits of grid integration of minigrids. This thesis presents outcomes of a research that addresses this gap in knowledge.

1.3 Research objectives, significance, and contributions

1.3.1 Research objective and significance

Based on the issues and gaps that have been identified concerning grid access, operation and planning the main objective of this research was to establish how the integration of the main grid and autonomous minigrids can be systematically planned to address some of the post energy access challenges in developing countries. To meet this objective, the following specific research questions are addressed in the work of this thesis:

- What does optimal grid integration of minigrids entail?
- Are existing energy access or distribution network planning frameworks/tools/methodologies suitable for optimal grid integration of minigrids in developing countries?
- To what extent can differences and similarities between grid integration of minigrids and integration of distributed energy resources in developed countries be positively exploited?
- How do residual minigrid DERs, demand profiles, and topologies affect the optimal grid integration of minigrids?

Therefore, the specific objectives of the thesis are:

- To explicitly define optimal grid integration of minigrids.
- To assess the suitability of existing grid energy access or distribution network planning frameworks or tools to achieve optimal grid integration of minigrids.
- To develop and test a methodology for undertaking grid integration planning of minigrids based on the differences and similarities between grid integration of minigrids and integration of distributed energy resources in developed countries.

- To assess the effect of residual minigrid assets and minigrid topology on the optimal minigrid integration plan.

This research is significant because:

- There is a need to improve the efficiency of network and quality of electricity supply in developing countries as energy access initiatives consider these issues secondary.
- Utilities, minigrid operators, and regulators in developing countries need guidance on dealing with the imminent convergence of the main grid and minigrids as their current focus is primarily on bridging the energy access gap.
- There is a need for relevant tools/frameworks/methodologies for planning the grid integration of minigrids in developing countries as existing grid integration tools are biased towards integrating distributed energy resources in mature networks.

1.3.2 Contribution to knowledge

The main areas of novelty in this research relate to the extension of distribution planning principles to optimise the grid integration of autonomous minigrids in developing countries. Currently, there is a lack of a suitable systematic approach to planning the grid integration of minigrids. The reported cases of grid integration of minigrids are silent on the planning methodology used [22], [33] or always connect the grid incomer to the minigrid generation hub [36]. The research in this thesis makes the following contributions to knowledge:

- Presents a novel power system-based formulation and methodology for the optimal planning of the grid integration of minigrids with a better articulation of the performance of a single or multiple downstream minigrid networks.
- Present a framework for evaluating minigrid integration planning problem that can be used by academics, to advance the presented work, and industry, to facilitate the optimal planning of the grid integration of minigrids in developing countries.
- Presents guidelines to utility planners for screening the suitability and application of the proposed minigrid integration planning approach to minigrids with various topologies.

In summary, this work contributes to the knowledge of grid integration of formerly autonomous minigrids by presenting a novel approach for optimising the grid integration of previously autonomous minigrids in developing countries. The presented approach can be useful to academics, developers of power system analysis tools and utility network integration planners. The following section presents publications associated with this work and an outline of the thesis.

1.4 Publications and thesis outline

1.4.1 Associated publications

The following articles have been published while preparing this thesis:

Journal Publication

- M. Chikumbanje, D. Frame, and S. Galloway, "Future grid integration of autonomous minigrids for loss reduction and voltage profile improvement in sub-Saharan countries," *Sustain. Energy, Grids Networks*, 2022 (In Review).

Conference Proceedings

- M. Chikumbanje, D. Frame, and S. Galloway, "Minigrid integration in sub-Saharan Africa identifying the 'optimal' point of connection," in *2020 6th IEEE International Energy Conference (ENERGYCon)*, Sep. 2020, pp. 625–630.
- M. Chikumbanje, D. Frame, and S. Galloway, "Enhancing Electricity Network Efficiency in sub-Saharan Africa through Optimal Integration of Minigrids and the Main Grid," in *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020*, Aug. 2020, pp. 1–5.
- M. Chikumbanje, D. Frame, and S. Galloway, "Multi-feeder minigrid loading index – a prequalifier to rigorous grid integration planning of minigrids," in *2022 IEEE PES/IAS PowerAfrica, PowerAfrica 2022*, Aug. 2022, pp. 1–5 (Accepted for presentation)

Poster Presentations

- M. Chikumbanje, D. Frame, S. Galloway, "Using Solar-hybrid Mini-grids to Enable Decentralised Grid Operation in Developing Countries," *Poster presented at LCEDN-University of Strathclyde 8th Annual Conference,* Glasgow, 2019
- M. Chikumbanje, D. Frame, S. Galloway, "A Case for Technical Optimality when Integrating Minigrids and the Main Grid in sub-Saharan Africa" *Poster presented at Manchester Energy and Electrical Power Systems (MEEPS) Workshop*, Manchester, 2019.

Magazine Article

- D. Frame, M. Chikumbanje, and S. Galloway. (2019) Unlocking the potential of self-generation. ESI Africa. Available: https://www.esi-africa.com/industry-sectors/future-energy/unlocking-the-potential-of-self-generation/

1.4.2 Thesis organisation

Including this chapter (Introduction), the thesis is presented in six chapters as follows:

Chapter 2 presents a critical review of the extent to which issues beyond electricity access in developing countries have been addressed and identifies a gap in literature that this thesis addresses. Firstly, it reviews articles on future power systems and comments on the likelihood of achieving the identified futures and pathways to the most likely future. Then a review of developing countries' readiness to achieve the most likely future from a policy, regulatory and technological perspective is presented. Generally, Chapter 2 provides the academic and professional basis for the need to design a planning methodology for future integration of grids and minigrids in developing countries, presented in this thesis.

Chapter 3 builds on Chapter 2 and presents a brief overview of optimisation principles and their application in distribution network planning. Then, what happens to minigrids upon grid arrival is presented before the conceptual definition of the minigrid integration planning (MGIP) problem. The optimisation principles presented in the earlier sections of this chapter are used to define and present a mathematical formalisation of the MGIP. Then, a framework for evaluating MGIP is presented. In summary, Chapter 3 presents the methodology that is developed, applied, and tested in the thesis and a framework for applying it.

Chapter 4 presents the application of MGIP on different case studies. Firstly, the parameters/data used in the case studies are discussed. Then, the MGIP is applied on a single minigrid and a cluster of minigrids with different compositions of residual DERs. The main objective of this chapter is to demonstrate the application of MGIP and quantify the loss reduction benefits of applying the proposed MGIP methodology when the grid arrives within the vicinity of a single or a cluster of minigrids.

Chapter 5 presents two key things. Firstly, it builds on Chapter 3 and 4 to present other benefits of using MGIP grid integration planning of minigrids. This is achieved by recasting the MGIP problem as a multi-objective optimisation problem to assess how the benefits relate to each other. Secondly, this chapter also presents a pre-assessment tool for assessing whether a planner should use the full MGIP methodology in planning the grid integration of minigrids with multiple feeders. The developed pre-assessment tool helps to identify and qualify circumstances where it is more beneficial to use the MGIP methodology or otherwise.

Chapter 6 presents conclusions to the research work reported in this thesis and potential future work. It restates and summarises the main findings and results of the thesis. Finally, possible areas for advancing knowledge in the grid integration of minigrids in SSA that build on the work of this thesis are discussed. .

1.5 Chapter summary

This chapter has presented the context, background, motivation, and contributions of this thesis. In the aftermath of the reported convergence of the main grid and minigrids in South-East Asia, there is a growing need to address knowledge gaps associated with possible grid integration of autonomous minigrids beyond helping to achieve universal electricity access. While several authors address the policy, regulatory and business aspects, this thesis contributes to optimal planning of the grid integration of autonomous minigrids, a subject which has not received significant attention.

In the next chapter, a detailed literature review is presented to establish the academic and professional basis of this thesis.

2 Electricity Access and Network Planning

2.1 Introduction

The latest electricity access tracking report [18] shows substantial progress toward achieving SDG7 in the past two decades. Specifically, the number of people without access to electricity has dropped from 1.3 billion in 2000 to 759 million in 2019. This statistic represents an improvement in electricity access from 73% to 90% of the world's population in 2000 and 2019, respectively. The report also recounts that most of those without access to electricity remain in developing countries. However, electricity access gaps in those countries continue to narrow through expansion of the main grids and deployment of mini-grids and various fragmented energy services such as Solar Home System (SHS) and solar lanterns [19],[20]. Although [18] recognises that the prospect of fully achieving SDG7 by the year 2030 remains ambitious, the reported progress and continued efforts to close the electricity access gap demonstrates that, sooner or later, access to electricity will cease to be a challenge for many people in the global south.

The previous chapter identified that beyond achieving SDG7 using the current pathways, energy (or electricity) research objectives in developing countries would shift from energy access to that synonymous with mature electricity and energy systems in the global north [24]. In contrast to the current narrative where achieving electricity access is the main focus, there will be more emphasis on improving efficiency [27], quality [29] and reliability [23],[30], of supply as most developing countries are currently lagging in these aspects. As populations in these countries move from the lowest tiers of electricity access to higher tiers [8], there will be a demand for higher levels of efficiency and quality of supply, hence the change in emphasis.

This chapter reviews the extent to which literature has covered issues beyond electricity access in developing countries. Then, it examines the usefulness of electricity access and distribution network planning methodologies to achieve critical planning objectives beyond attaining universal electricity access in developing countries.

2.2 Future of power systems in developing countries

The electricity supply industry is undergoing significant evolution due to global policies towards decarbonisation, decentralisation, and digitalisation of the power system [55]. This evolution has prompted many researchers, for example, [55]–[62], to contemplate the future of the electricity supply industry from different perspectives. Such perspectives include strategies and initiatives for utilities to adapt to the rise of semi-autonomous customers [55], [60]; innovative approaches to governance, regulation, and policies that facilitate the transition [58], [59]; or future topologies and architectures of the power system (or grid) [56], [61], [62].

According to [58], articles on utilities, regulation, and future policies are context-specific and have limited applications across differing environments. For example, authors in [59] take a governance perspective and propose a framework for proactive regulation, policies, and markets to facilitate the transition to a future power supply industry. However, the underlying assumptions of the framework in [59] assume a mature power supply industry in Europe; hence its conclusions may not be directly applicable in a developing country. This shortfall is also attributable to [55] and [60], where readiness of power utilities to the changing environment is presented from a Global North point of view.

Unlike articles which focus on utilities, regulation and policies of the future, those on the future topologies and architecture of the power system are often less context-specific [56], [61]. Authors in [62] and [63] present three groups of topologies and architecture of future power systems based on the interconnectedness and distribution of grids. There are less distributed and less interconnected grids called "super grids", highly distributed and highly interconnected grids called "smart grids", and highly distributed and unconnected grids called "off-grids". Although the term "smart grids" assumes several meanings in the literature, as noted in [64], the meaning in [62], stating that smart grids are highly distributed and highly interconnected grids, will be used in this thesis.

Among the three classifications reported in [62], the super-grid resembles developments at the transmission level because it covers vast geographical areas [65]. At the same time, the smart-grid and off-grid futures are reminiscent of the transition at the distribution level [64], where the majority of electricity access initiatives occur [7]. Despite the synergies between transmission and distribution levels of electricity supply, their respective futures cannot be considered competing visions of the future power system because they ae both needed for different reasons and one cannot replace the other. Therefore, the rest of this section reviews the relevant articles that consider the possibility of smart grid and off-grid futures in developing countries.

2.2.1 Smart- or off-grid future in developing countries

According to [56], reducing solar photovoltaic (PV) and energy storage prices could lead to a future of highly distributed off-grid small-sized power systems. Other proponents of the off-grid future, e.g. [66], [67], also argue that once energy cost from consumer-owned PV and storage reaches grid parity or becomes cheaper, there will be a mass defection of customers from the main grid. It has been hypothesised that such defections from the main grid could result in utility companies' "death spiral" as shown in Figure 5 [68]. In [68], the authors consider that the defection of some grid customers will increase the cost burden of maintaining the network on the remaining customers. The increased cost burden on the remaining grid customers is expected to trigger further exodus. In the extreme this would require government intervention to protect the cost recovery for network operation and maintenance.

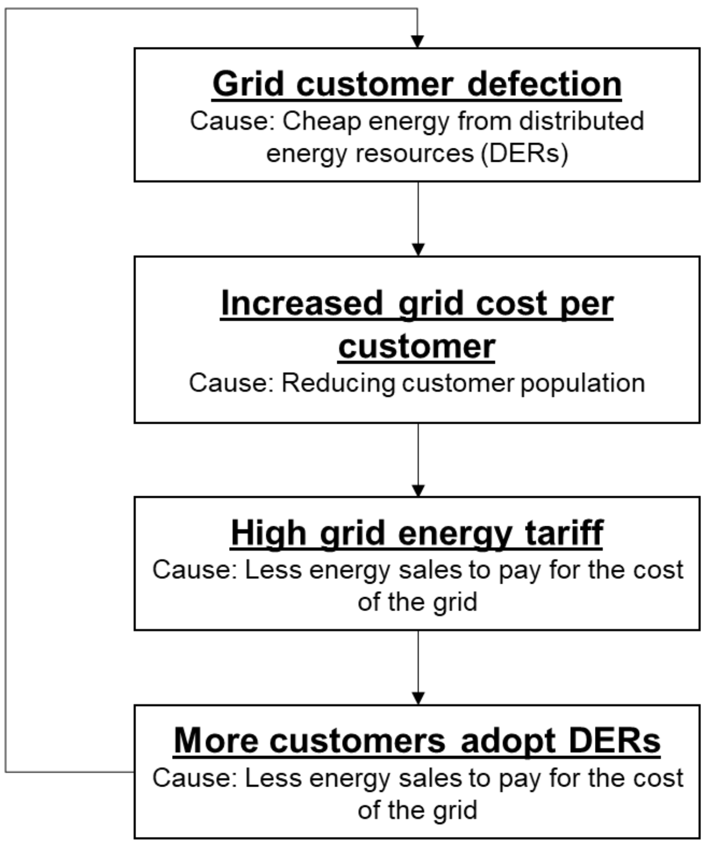


Figure 5: A possible consequence of off-grid future – utility death spiral [68]

The arguments for a possible off-grid future are limited from two main perspectives. Firstly, without considering the context and region of deployment, [69] argue that off-grid future through grid defection and subsequent "death spiral" of utilities may not be a realistic view of the future as such defections forfeits reliability benefits associated with being grid-connected. This argument is further supported by [70] who argue that utility death spiral would have been possible if energy were the only value of being connected to the power grid.

Secondly, from a developing country perspective, proposals of the off-grid future by grid defection ignore these countries' specific issues and evidence. For example, [15] reveals that not everyone has a grid connection in developing countries as others are already accessing offgrid technologies. Also, there is a lack of evidence that those already connected to the grid may be contemplating grid defection. On the contrary, the evidence from Southeast Asia suggests that those who already have an off-grid electricity supply would prefer an interconnection with the main grid compared to continuing with off-grid operation [33]. Due to their association with inferior services at a higher cost, as highlighted in [25] and [71], most customers to off-grid energy services in developing countries demand a grid connection whenever it becomes available [25]. If such off-grid energy services are grid compatible [72], their interconnection with the main grid will spur a network of highly connected and distributed systems in developing countries.

Where the grid is not readily available, the authors in [56] suggest the bundling of off-grid energy services, such as Solar Home Systems (SHS), to form a community-scale energy network from the bottom up. Other advocates of this paradigm argue that it allows for sharing of the generation and storage resources, improves reliability and creates an opportunity for local energy trading [73]. One of the recent advancements towards such bottom-up minigrids is reported in [74], where an enabling interconnection technology was developed and successfully trialled in Rwanda.

The momentum toward interconnection of isolated energy resources in developing countries, as proposed in [56], [73], [74] confirms that the development of power systems in developing countries, led by national utility companies, is not towards a highly distributed and less interconnected off-grid paradigm. Instead, they indicate organic growth towards a highly distributed and interconnected smart grid.

Therefore, beyond meeting energy access in developing countries, the power system is likely to transition into a smartgrid to attain a level of maturity associated with grids in developed countries. Recognising that electricity access pathways will leave an expanding grid and a myriad of off-grid electricity infrastructure [20], the next subsection reviews how remnants of the grid and off-grid electrification pathways can be transitioned or combined into smart grids in developing countries.

2.2.2 Pathways to smart grids in developing countries

From [43] and [10], it is evident that energy access initiatives will leave most developing countries with an expanding grid and several off-grid electricity networks and services, such as minigrids and SHSs. In principle, all post SDG7 infrastructure and possible interactions will provide the majority of the backbone of the future power system beyond energy access in developing countries [56]. This sub-section reviews how each electricity access solution contributes to a future smartgrid in developing countries. The authors in [24] noted that reliable and secure systems are preferred beyond electricity access. This review focuses on two main pathways for delivering highly distributed and interconnected power systems in developing countries. These are retrofitting the main grids and convergence pathways [56], as shown in Figure 6.

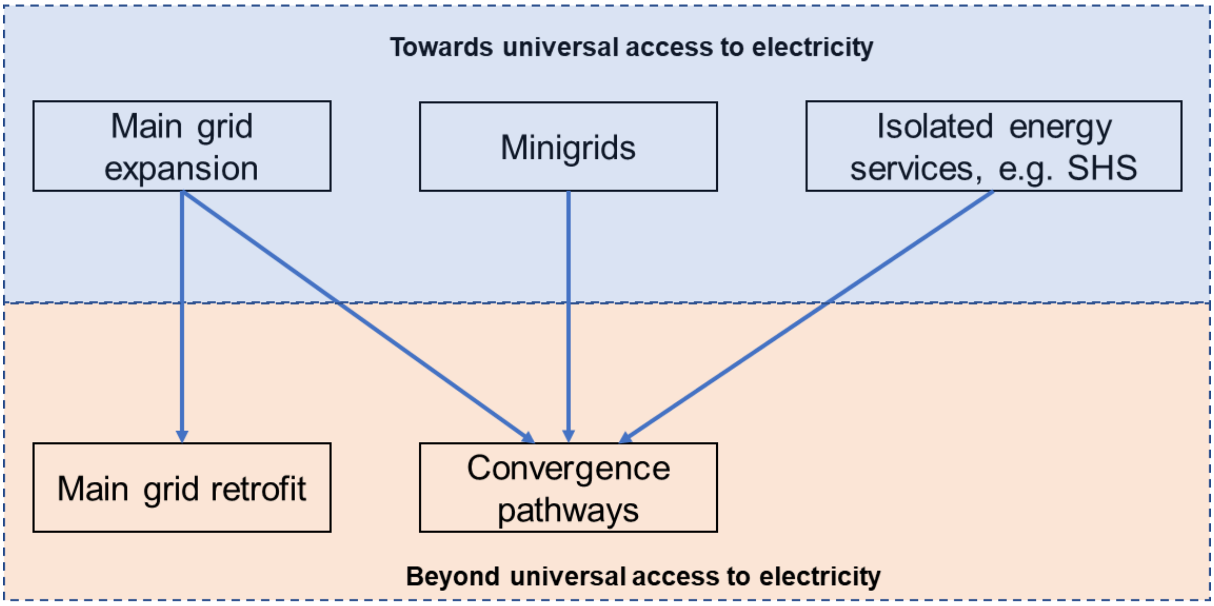


Figure 6: Electricity infrastructure in developing countries

A description of main elements identified in in Figure 6 is provided in the following sub-sections.

2.2.2.1 Retrofitting the main grid

Until recently, the power system has traditionally been characterised by unidirectional power flow – from centralised generators through the transmission and distribution network to loads [75]. This characteristic is the initial basis for designing and operating the centralised legacy power systems in developed countries [76] and electricity access initiatives through grid expansion in developing countries [10], [32]. However, the increasing prominence of renewable and distributed energy resources, such as wind, solar, storage, etc., and various communication technologies applications have introduced novel ways of designing and operating modern power systems [77], [78]. These could be adopted in main grids within developing countries to improve the reliability and quality of electricity supply beyond achieving energy access [27].

In most developed countries, everyone has had access to the electricity grid for a long time [28]. However, the grid in the developed countries is increasingly becoming smart by being repurposed and retrofitted to accommodate the embedment of various DERs and communication technologies [64]. Amongst other things, optimal integration of DERs has improved network efficiency, enhanced supply quality, and optimised the utilisation of assert [64]. In contrast, the greatest impact of DERs and the latest communication technologies in developing countries have not been on the main grid but on off-grid electrification solutions [19].

Therefore, beyond SDG7, the main grid in developing countries may also be retrofitted to accommodate DERs similar to networks in developed countries and meet objectives like loss reduction and voltage profile improvement [56], [79]. Retrofitting the main grid in developing countries should happen reasonably quickly than in developed countries because significant evidence on the best ways to achieve that has been gathered in this area from the experiences in developed countries [76]. As soon as the necessary operating environment, in the form of regulation and mechanisms that facilitate these transitions are in place, no significant context-specific issues may hinder this transition [62], [63]. The developing countries will benefit significantly from a rich body of knowledge on the methods, techniques, and strategies for integrating DERs and other technologies in already existing passive networks [40], [80], [81].

2.2.2.2 Convergence – primary grid and fragmented energy solutions

Another pathway to a smart grid in developing countries is through the grid convergence and integration of the fragmented energy services (or their clusters) [56]. Authors [73], [74] consider the grid integration of clusters of interconnected SHSs as the final step in stepwise ‘swarm electrification’[4] that begins with isolated SHSs. Considering the smart technologies employed in most SHSs [82], their integration with the main grid would indeed transform the grid in developing countries. Nevertheless, such interconnection is not without its own challenges such as the disparity of electrical technologies employed, the capacity of the clustered SHSs, and the cost of the energy service supplied from SHSs and their clusters.

The first challenge to the grid integration of SHSs is the disparity of electrical technology between the main grid and SHSs. Like in many parts of the world, the main grid in developing countries is predominantly operated using alternating current (AC) technology [63]. However, individual and clusters of SHSs use direct current technology (DC) [74]. Despite the recent arguments for the use of DC technology at the distribution level [83], [84] and advancement in power electronic equipment for interfacing the two technologies [85], the integration of DC operated SHSs clusters, and an AC operated grid remains a challenge in many ways. These challenges include utilities' inexperience in operating DC grids, the limited number of appliances that can directly connect to a DC supply (and those that can, are often expensive as noted by [74]), and the industry standards for DC grids have not reached the maturity of their AC counterparts [7].

The second challenge to the grid integration of SHSs is the capacity disparity between the main grid and SHSs. SHSs, unlike the main grid, are typically designed for low power and low capacity usage [20]. For example, [74] reveals that most SHSs operate at 12VDC, and they are connected in a cluster to a common bus of 48VDC. Despite the benefits asociated with interconnecting SHSs into a cluster and the higher DC interconnection voltage level, the capacity of such installations remain low and cannot support high power devices such as kettles and pressing irons or heavy motors for productive use of electricity [20]. Therefore, even after integrating the DC SHSs (or their clusters) to the main grid, as suggested in [73], the SHSs are less likely to realise the full benefit of being grid-connected unless there is a significant upgrade as the inherent capacity of the clustered SHSs.

The third challenge to the grid integration of SHSs is the cost of energy supplied from SHSs. In a ranking of electricity access technologies, authors in [71] conclude that SHSs

---

4 https://energypedia.info/wiki/Swarm_Electrification_-_A_Paradigm_Change:_Building_a_Micro-Grid_from_the_Bottom-up

are an expensive technology compared to AC minigrids and the main grid despite providing low-quality energy service than the other two. Clustering SHSs into a DC minigrid has advantages, such as improving the reliability of supply [30], [31], but reducing the energy cost is not one of them. Coupling this challenge with the other disadvantages associated with grid integration of SHSs (or their clusters), it is evident that the convergence of the main grid and SHSs is an unlikely route for the post SGD7 delivery of a smartgrid in developing countries.

Therefore, although [74], [86] identify that individual or clusters of SHSs can integrate with the main grid and deliver a post-SDG7 smart grid in developing countries, the evidence presented in this section suggests otherwise. Issues such as network incompatibility, high cost of energy from SHSs, limited capacity of SHSs and quality of supply from SHSs present real barriers for integrating SHSs with the main grid as a critical pathway for the delivery of smart grids in developing countries.

2.2.2.3 Convergence – primary grid and minigrids

Authors in [56] also identify that another pathway to future power systems in developing countries will be forged by the convergence of the main grid and minigrids (or their clusters). Since most minigrids are equipped with smart functionalities such as remote monitoring and smart metering [87], integrating with the main grid would be another pathway to a post SDG7 smart grid in developing countries. This pathway has already been observed in Southeast Asia, as reported in [33]. It is expected to become prominent as energy access gaps narrow in developing countries while the main grid is still expanding [21].

Unlike in the convergence with fragmented energy services (or their clusters), which are usually DC [86], most minigrids use AC technology and have a capacity that is akin to the distribution systems of the main grids in developing countries [7]. Therefore, issues of AC and DC technology disparity and network capacity would not hinder the grid integration of minigrids. Also, work reported in [71] shows that although energy from minigrids is slightly expensive compared to the main grid, it is not as expensive as that from SHSs. While this evidence suggests that the grid convergence of AC minigrids has potential for the delivery of smart grids in developing countries, this pathway is not without challenges that need addressing.

Work reported in [36] suggests that upon arrival of the main grid, minigrids can be abandoned, interconnected to the main grid in various operational modes or operate side by side with the main grid. Although this classification has been seminal in recent articles, such as [25], [33], [88], there is a lack of a comprehensive framework to guide practitioners on which option is suitable for a given circumstance of grid and minigrid convergence. Authors in [21] attempt to provide such a guide, by presenting a decision tree for what happens when the grid converges with a minigrid. However, the presented framework is mainly qualitative; hence its outputs would be subjective. For example, one of the steps in the decision tree involves determining whether grid connection is essential or not but there is no suggestion of how such necessity can be established robustly.

Another perspective on integrating the main grid and minigrids in developing countries is reported in [26]. Here, the authors present several technical, regulatory and market-related questions that need addressing to integrate the main grid and minigrids in developing countries successfully. Those questions include: (1) What market designs can enhance minigrids to support the main grid in developing countries? (2) Which technical solutions will foster the adoption of grid integration of minigrids? (3) Do minigrids in developing countries need regulatory reform to give the best support to the main grid? These questions are necessary because the grid integration of minigrids involve joining infrastructure and markets currently planned and regulated separately in developing countries [89]. Nevertheless, [26] only presents the open questions, some of which are presented above, and does not attempt to address any of them.

The need to further investigate the technical and regulatory aspects of the grid integration of minigrids is reinforced by the case studies in Southeast Asia reported in [33]. The report revealed that, upon grid convergence, some minigrids were integrated with the main grid, and some were abandoned. Such abandonments meant losing out on the possible benefits of grid integration of minigrids suggested in [27]. The report [33] further suggests that addressing related regulatory and technical issues could improve outcomes of the convergence of the main grid and minigrids. While the reported case studies in [33] are from South Asia, similar trends can also be expected in sub-Saharan Africa (SSA), currently the least electrified region in the world [28]. With [21] suggesting that minigrids shall supply initial energy access to half a billion people who currently lack access to electricity, practitioners and stakeholders in developing countries should be ready for the future grid integrations of minigrids.

2.3 Policy and regulation readiness of grid and minigrid convergence

While earlier energy policy and regulatory frameworks in developing countries were grid centric, recent ones include off-grid systems to varying degrees [89]. For example, the latest energy policies in India [90] and Rwanda [91] acknowledge the role of off-grid systems in addressing energy access challenges. The publication of various off-grid policies and regulations has brought clarity and ease of access into the minigrid sector, which is key to achieving the ambitious targets of deploying minigrids to supply electricity to over half a billion people who are currently unelectrified [21].

However, most of the current understanding of minigrid regulation assumes that the grid and off-grid systems are deployed in separate territories to ramp up access to electricity [92]. Recent evidence in Southeast Asia [33] has led to significant suggestions that minigrid regulation should consider what happens if the grid and minigrids converge beyond achieving electricity access [21], [35]. This section reviews energy policy and regulation readiness in developing countries for the grid integration of off-grid minigrids from two main perspectives of institutional structure and governance, and technical standards [93].

2.3.1 Institutional structure and governance

Key institutions in the minigrid market are governments and their agencies, minigrid developers and financiers [94]. Relating the arrival of the main grid, minigrid developers and their financiers seek the presence of associated regulation and some clarity on the institutional structure and governance for implementing such regulations as a way of de-risking investments in off-grid electrification [95]. In many cases, these rules define procedures for grid integration and/or compensations for minigrids [35]. Despite the importance of these rules, [95] reports that as of 2018, only nine out of the forty-six countries in the SSA region had clear rules on what would happen if the main grid converged with minigrids. The availability of these rules in only 20% of the states in the SSA region indicates that national governments and regulators need to expedite the publication of these rules to minimise long-term uncertainties in the minigrid industry and achieve their policy goals of achieving universal electricity access.

While the presence of rules regulating the convergence of minigrids and the main grid is important, the comprehensiveness of the stipulations in the rules also matter [36]. Two critical but related features that define the comprehensiveness of such regulations are provisions on technical and financial issues [93]. The next part of this review focuses on technical provisions associated with the convergence of the grid and minigrids.

2.3.2 Technical Standards

The importance of specifying technical standards concerning the convergence of the main grid and minigrids is highlighted in [21], where grid compatibility of minigrids is a critical factor for determining the fate of minigrids. If it is compatible, grid integration would be considered; else, it would not be considered. Since verifying the grid compatibility of minigrid is such an essential issue for future grid integration, it is important for in-country regulations to have minigrids technical standards and grid interconnection procedures that can be made available to minigrid developers in view of a potential grid integration in future. According to [27], these may include recommended designs for grid-ready minigrids as well as provisions for possible retro filling to enhance the grid readiness of a particular minigrid.

Regarding the development of grid-ready minigrids, [72] assessed the feasibility of developing grid compatible minigrids to enhance long-term societal benefits. This work noted that grid-ready minigrids demand a high upfront cost, which eventually affects its operations' financial viability and sustainability in the off-grid state. The authors concluded that long-term value of grid-ready minigrids depends on the availability of incentives to the minigrid operator and the assumed cost of unserved energy. As such, when regulators and other government authorities demand grid-ready minigrids, the regulation/procedures should clearly state available support and assumed cost of unserved energy to level the playing field among developers. Despite the conclusion in [72] and prospective benefits for the grid integration of minigrids in SSA [26], some existing minigrid regulations, such as [96] in Malawi lack clarity on some aspects of grid readiness.

The minigrid regulation in Malawi [96] agrees with the decision tree in [21] that grid-ready minigrids will be integrated on grid arrival and non-grid-ready minigrids will not be integrated. Although the regulation refers to the national grid code, it does not suggest any pre-emptive design options for grid readiness of minigrids. Also, the regulation does not include possible solutions to partially grid compatible minigrids, for example, if only the network or minigrid generator is compatible. Other rules in the region have similar shortcomings as reported in [95], although [35] state that Nigeria and Tanzania are among the few countries that have advanced regulations to ensure grid readiness.

Regarding the procedure for interconnecting minigrids upon grid arrival, work reported in [36] remains the most comprehensive in articulating guidelines for the technical aspects of the integration and associated process. The authors suggest that the interconnection procedure should state the application process, who is responsible for analysing and approving the connection, who pays for the interconnection, tests and commissioning procedures and communication and data exchanges between the minigrid operator and the electric utility company. However, except for Tanzania [97], these procedures have not been adequately adopted in some countries, such as Malawi [96] and Nigeria [98]. For example, the regulation in Malawi [96] does not include any procedure for grid integration of formerly autonomous minigrids. Instead, it refers to standard procedures for the grid integration of utility-scale power plants, which may be overly demanding and unsuitable for small generators and networks like those associated with minigrids.

2.4 Technological readiness of grid and minigrid convergence

Due to the different circumstances in the initial deployment of minigrids and the main grid, technological differences between the infrastructure can be expected [33]. In readiness for their convergence and integration, technology should be necessary to facilitate and maximise the benefits of such interactions [99]. This sub-section reviews the technological readiness of developing countries for the convergence of minigrids and the main grid from two different perspectives of control, protection and operation, and planning [87].

In assessing the control, protection, and operation readiness of grid integration of minigrids, the ability of the state of the art to facilitate or hinder successful integration is presented. The planning readiness is achieved by assessing the capability of existing planning tools to achieve the post-SDG7 objectives such as minimising losses [27], [28]; and improving quality of electricity supply [29] [30] in developing countries . Therefore, the requirements for an appropriate planning tool for grid integration of minigrids are that it should be able:

- To evaluate losses and voltage profiles of the integrated network from power flow analyses.
- To economically design and size electricity network between the grid terminal point and candidate minigrids for integration.
- To identify the best planning option while considering the capacity, type, and location of residual minigrid DERs as fixed variables.

2.4.1 Control, protection, and operation readiness

The prospect of integrating an autonomous minigrid with the main grid entails the need to reconcile the control, protection and operation systems of the two formerly independent systems [36]. Depending on local regulation, such reconciliation may mean enabling the minigrid to operate in dual-mode – grid-connected, when the grid is available and islanded, when the grid is unavailable [38], [100]. The readiness of state of the art in control, protection and operation for grid integration of autonomous minigrids in developing countries is favourable for three reasons [76].

Firstly, there is worldwide research interest in microgrids' [75], [101], which are not different from grid-connected minigrids in control, protection, and operation [25], [36]. Secondly, there is a growing prominence of low-voltage direct current (LVDC) which would support the grid integration of DC minigrids that would otherwise be considered grid incompatible [83], [84]. Although the advances in LVDC systems and their integration with the main grid are still in their infancy, the grid integration of DC minigrids in developing countries is likely to benefit from advances in this area of research. Lastly, available guidelines in [47] address issues such as frequency and voltage control, intentional islanding, and protection coordination for the grid integration of minigrids. This guideline presents a significant technical reference for utilities, minigrid operators and regulators in SSA to ensure the safe operation of minigrids upon grid integration.

Therefore, the published literature significantly covers the control, protection, and operation of formerly autonomous minigrids upon grid integration. The focus on these technical issues is important from an operation, maintenance and safety perspective and because a grid-connected minigrid has a similar set of operational problems as those of microgrids which are equally well cover in the academic literature, for example in [75], [85].

2.4.2 Electricity access planning and grid integration of minigrids

The need to achieve universal access to electricity in developing countries has led to the increase in associated planning and design tools [44], such as Hybrid Optimisation of Multiple Energy Resources (HOMER) [39] and Network Planner [48]. The capabilities of such tools and their suitability to achieve electricity access planning are reviewed in [43], [50], [102]. However, such reviews seldomly comment on the appropriateness of the electricity access planning tools in planning the convergence and subsequent integration of minigrids and the main grid, and this gap is addressed in this section of the thesis. From the comprehensive collection of electricity access planning tools reviewed in [43], [50], [102], the review presented here focus on mostly used electrification tools in making decisions involving both the grid and minigrids [103]. These are HOMER [39], Open Source Spatial Electrification Tool (OnSSET) [47], Reference Electrification Model/Reference Network Model (REM/RNM) [43], and Network Planner [48].

HOMER is a project specific techno-economic analysis tool for identifying the least-cost mix of various energy resources to supply electrical demand through a standalone or networked system like minigrid [39]. In [104], HOMER is used to assess the techno-economic feasibility of an offgrid solar-biomass system to electrify some areas in rural Pakistan. The authors recommended the optimised solar-biomas system as it was found to supply energy that was 46% cheaper compared to grid supplied electricity. Another application of HOMER is reported in [105] where, using a case study, it was concluded that a standalone minigrid was viable if it was 98km away from the primary grid. Generally, HOMER is useful in choosing and sizing DERs (e.g., generation technologies and storage) that minimise the net present cost and cost of energy from a hybrid power systems. In some case studies, the established costs are compared to similar costs associated with grid extension to establish the most economical way of supplying electricity to a given case study.

Despite being widely applied in electricity access planning studies and playing a key role in comparing grid extension and offgrid electricity access [104], [105], HOMER has a number of limitations. Firstly, [106] argues that HOMER does not consider the geospatial aspects of the hybrid energy system that it optimises, hence its analysis does not consider the effect of how customers and DERs are connected to each other, a parameter which may affect the operational outcomes of the hybrid system designed. Secondly, [107] notes that HOMER does not include any form of power flow analysis to quantify network losses and voltage profile of the planned power system. Instead, all such parameters are assumed and not based on robust calculation.

Therefore, HOMER would not be suitable for planning the grid integration of minigrids and the main grid. Firstly, HOMER does not have the capability to account for the network layout in the existing minigrid and cannot give a detailed account of the network required between the existing grid terminal and the minigrid requiring grid integration. Secondly, since reducing losses and improving voltage profile would be a critical objective beyond SDG7 [23], HOMER’s inability to apply power flow in a robust calculations of losses and voltages makes it unsuitable for loss reduction and voltage profile improvement studies.

OnSSET [47] is a geo-spatial based electricity access planning tool that conducts preliminary assessment of an unelectrified area and applies least cost methods to recommend electrification strategies i.e. grid extension, minigrids or isolated system. Case use of OnSSET include [108] where it was established that in Malawi, the optimal electrification strategy would be grid connection for 32.6% of the population and offgrid supply for 67.4% of the population. A similar study was done for Madagascar [109], and it was reported that grid extension makes sense for 25% of the population and the rest of the population should get access through offgrid means of minigrids and isolated systems like SHS. Generally, OnSSET is not a project specific tool, rather, it uses least cost planning to demarcate unelectrified regions into zones for grid expansion and off-grid electrification.

Beyond SDG7, the application of OnSSET in planning the grid integration planning of minigrids is limited for several reasons. Firstly, the existing capability of OnSSET only enables the demarcation of an area into grid electrification or offgrid systems and does not consider a possibility of any overlaps in future [47]. Secondly, OnSSET does not include network design and analysis [50] of either the main grid or minigrid networks. Therefore, it cannot be the right tool to optimise parameters such as voltage profile improvement and loss reduction which will be vital in developing countries beyond meeting SDG7 goals.

REM/RNM [43] is a geospatial electricity access planning tool that is similar to OnSSET in that, using the REM module of the tool, it considers every load point of an unelectrified area and recommends the least cost strategy for electrifying it. However, RNM component of this tool distinguishes it from OnSSET by providing detailed designs of the grid and minigrid networks recommended by REM. REM/RNM has been applied to model Rwanda's national electrification plan [110] and a county in Kenya [111].

Although REM/RNM includes the detailed design of networks, it has limited applications in planning the grid integration of minigrids. Firstly, similar to OnSSET [47], REM/RNM does not consider the overlap of grid and offgrid infrastructure planning. Since convergence of minigrids and the main grid involves overlapping the two electrification pathways [33], REM/RNM would not be a suitable tool. Secondly, despite the capability to design networks within the RNM module, REM/RNM does not run any power flow analysis to establish the electrically optimal designs and minigrid network designs in REM/RNM are independent of primary grid expansion design [50]. Therefore, REM/RNM would require significant modifications to plan the grid integration of minigrids beyond meeting SDG7 in developing countries.

Network Planner (NP) [48] is another geospatial electricity access planning tool that uses costs to compare grid extension with offgrid electrification options. The capabilities of NP include proposing a minigrid network layout and sizing of solar and diesel-powered generators. NP is used in many electricity access planning studies in developing countries, including [112] in Ghana and [113] in Nigeria. Despite its wide application in electricity access planning, NP does not include a power flow analysis functionality [10]; hence it can not be used to optimise losses and voltage profile in the grid integration of minigrids.

Table 1 summarises the capabilities of the key electricity access planning tools, including their ability to plan the expected convergence of minigrids [33][25].

Table 1: Capabilities of key electricity access planning tools

Capability	Electricity access planning tool			
	Homer	ONSSeT	REM/RNM	NP
Assessing grid vs offgrid choice	✓	✓	✓	✓
Includes geospatial planning element	×	✓	✓	✓
Grid expansion network design	×	×	✓	×
Minigrid DER sizing and selection	✓	✓	✓	✓
Minigrid network layout design	×	×	✓	✓
Includes power flow analysis	×	×	×	×
Considers overlap of primary grid and offgrid	×	×	×	×

Table 1 shows that existing electricity access planning tools are focused on splitting unelectrified areas into zones that will be better electrified through grid expansion and offgrid technologies. However, these tools do not provide any insight into planning the convergence and subsequent integration of the main grid and minigrids, a post electricity access scenario observed in [33]. This convergence is expected to happen in many countries beyond achieving universal energy access using current pathways of grid expansion and significant deployment of minigrids [21], [100]. Table 1 also indicates that the reviewed electricity access planning tools do not include the suggested plan's electrical feasibility [50]. For this reason, they are not suitable for planning the grid integration of minigrids as some of the likely post-SDG7 objectives, such as loss reduction [27] and voltage profile improvement [29], cannot be achieved without using a form of power flow analysis [114], [115].

Therefore, beyond achieving universal access to electricity, planning the integration of grids and minigrids in developing countries will require unique planning tools than those developed to achieve electricity access. Since grid integration of minigrids is expected to be done at distribution level [33], [36], the subsequent section reviews how different aspects of distribution network planning can influence planning the grid integration of minigrids beyond achieving universal electricity access in developing countries.

2.4.3 Distribution network planning and grid integration of minigrids

Reports on the convergence of minigrids and the main grid in Southeast Asia [22], [33], [36] indicate that their integration is happening at the distribution level. This should be expected because minigrid networks seldomly cover a vast geographical area to require high voltage (greater than 33kV) power lines associated with the transmission system [7]. Therefore, planning the grid integration of minigrids should be considered a sub-problem within a broad area of distribution network planning (DNP) [116].

Traditionally, DNP has involved the optimal placement and design of passive electric distribution network assets, namely feeders and transformers, to supply specific electrical demand [116], [42]. The growing prominence of DERs, such as renewable power generators and storage, in the distribution network, has led to a significant rethink of traditional DNP problems to include the presence of DERs [75], [78], [80]. Since grid integration of minigrids involves grid expansion to autonomous minigrids that have inherent DERs [21], [33], it has aspects of other DNP sub-problems. For example, the grid expansion part compares with distribution network expansion planning (DNEP) [117], and the minigrid component and its DERs compare with optimal distributed energy resources planning (ODERP) [40], and microgrid planning (MP) [118]. This section reviews how DNEP, ODERP and MP, and their suitability for planning the grid integration of minigrids.

2.4.3.1 DNEP and minigrid integration planning

DNEP is a techno-economic analysis to determine an optimal plan for installing new or reinforcing existing electric distribution network assets, such as feeders, substations, and transformers [45]. Typically, DNEP problems are cast as optimisation problems with either a single objective [119] or multiple objectives [120], and they are constrained to technical parameters such as power flow equations and voltage limits [121]. Common objectives in DNEP include minimising investment costs on the assets, minimising losses in the network, and minimising voltage drops [45].

Unlike electricity access planning techniques, such as REM/RNP [43], aspects of detailed DNEP would be instrumental in establishing an optimal minigrid integration plan for two main reasons. Firstly, DNEP involves using power flow analysis, which is critical in establishing electrically feasible integration plans. Secondly, the objective functions in DNEP, such as loss reduction and minimising voltage drops, would be required in the post-SDG7 developing countries because the push for electrical access is leading to systems with poor voltage profiles [29] and high power losses [27], [28].

Despite its promise in minigrid integration planning, the direct application of DNEP in minigrid integration planning is hindered by two main reasons. Firstly, due to its combinatorial nature, most DNEP problems involve the independent consideration of expanding either the primary [119], [122] or secondary [123], [124]. When the emphasis is on the primary network, like in [122], the secondary networks are not well articulated and usually presented as a point load. Although minigrid integration planning will involve expansion of the primary distribution network to an existing minigrid, the electrical characteristics of the minigrid should be expected to influence the planning decision and the associated expansion plan should take account of that.

Secondly, DNEP problems that simultaneously consider primary and secondary distribution networks, e.g. [125], [126] and [127], focus on expanding the network to a greenfield site where there is no prior grid-like infrastructure. For example, [125] proposes a framework for coordinating MV and LV network planning in a greenfield site. Also, [126] presents a bi-level method for solving a distribution network expansion problem that considers both MV and LV network expansion. Though these works present a detailed articulation of primary and secondary distribution networks, they can not be directly applied in the grid integration of minigrids. Unlike in [125], [126] and [127] where the secondary network is planned concurrently with the primary network, grid integration planning of a minigrid will involve expanding the primary grid to an existing minigrid network with inherent DERs. Hence this thesis considers a unique set of circumstances where a greenfield primary network is deployed to integrate an already existing secondary network, in form of a minigrid.

Therefore, DNEP can form a crucial part of planning the grid integration of minigrids, especially on the grid expansion component – from a known grid terminal point to the minigrid requiring integration [100]. However, to be applicable in minigrid integration planning, DNEP requires significant adaptation to account for the already existing minigrids that the grid will be expanded to in developing countries.

2.4.3.2 ODERP (or MP) and minigrid integration planning

Another extensively studied DNP sub-problem related to minigrid integration planning is optimal DER planning [36]. ODERP is a relatively new DNP sub-problem that involves the optimal selection, sizing and placement of DERs in the distribution network for loss reduction, investment deferment and voltage profile improvement [46], [53], among other objectives. This subproblem is relatively new because, until recently, distribution networks have been considered passive networks that receive power from the transmission system to supply loads [64]. However, renewable energy technologies have led to increasing integration of small generation and storage resources within the distribution networks to make them active [78].

To some extent, ODERP is considered similar to planning the grid integration of minigrids because many minigrids will have incumbent DERs during their integration with the grid [36]. Therefore, the grid integration of such minigrids is expected to have similar impacts to grid integration of DERs such as loss reduction [46], voltage profile improvement [52], investment deferment [128], etc. In [54], it was demonstrated that grid integration of minigrids can indeed have similar effects like grid integration of DERs. However, planning the grid integration of minigrids is significantly different from planning the grid integration of DERs.

In DER integration, the optimal sizing, siting and selection of DERs are the significant parameters that affect the ODERP, for example, see the reviews in [40], [80] and [129]. However, minigrid DERs that will be integrated with the main grid will have already been placed, sized and selected before the arrival of the grid [107]. Typically, the DERs of autonomous minigrids in developing countries are sized, selected and placed to meet demand [22], [130] and not to address any issues related to loss reduction, voltage profile improvement, or other electrical features.

Related to ODERP is microgrid planning in distribution systems [118], [125], [131]. Microgrids are small clusters of controllable distributed energy resources (DERs), loads and assets with the capability to operate in islanded and grid-connected mode called “microgrids” [132]. Since DERs are a crucial part of microgrids, MP also involve selection, sizing and siting of DERs, like in ODERP. However, to achieve autonomy in islanded mode, MP also involves scheduling of the microgrid DERs [131], [133].

MP is considered similar to planning the grid integration of minigrids because microgrid in developed countries are, in many ways, comparable to autonomous minigrids[5] in developing countries [76]. However, contrary to that argument, [33] recognises that there are significant differences between minigrids and microgrids that would make grid integration planning a unique problem from MP. Some of those differences are their ability to connect with the main grid, customer profile, motivations for deployment, design philosophy, fuel for energy sources, and presence of communication systems, as summarised in Table 2

Therefore, planning the grid integration of minigrids differs from ODERP (or MP) because grid integration of minigrids will include the integration of minigrid DERs that were not selected, sized and placed with the grid in mind. This is unlike in ODERP or MP where everything is done with the grid in mind from the first instance. Due to this, the arrival of the grid within a formerly autonomous minigrid may necessitate decommissioning, derating or reallocation of such DERs to achieve grid compatibility or ensure ODERP (or MP) like optimality [26], [33]. However, such approaches may be challenging to implement because decommissioning or derating an already operating DER would not reflect well on the economics of the minigrid project [25], [35]. Hence, there is a need to develop new methods for planning the grid integration of formerly autonomous minigrids in developing countries. Such methods should ensure optimal

[5] Scholars are yet to agree on the distinction and usage of the terms “minigrids” and “microgrids” [94]. This thesis assumes the position in [33] where microgrids refer to clusters of DERs, loads and distribution network assets within a mature distribution network of a developed country and can operate in both islanded and grid connected mode. On the other hand, minigrids refer to similar infrastructure deployed in offgrid environments to operate autonomously for the enhancement of electricity access in developing countries.

integration of the minigrids even when the incumbent DERs were not initially sized, selected or sited with the grid in mind.

Table 2: Key differences between minigrids and microgrids [33]

Characteristic	Minigrids (in developing countries)	Microgrids (in developed countries)
Grid connection	Developed off-grid and their planning and designing have little to no consideration of grid parameters.	Most of them are grid-connected from day one. Those that are not grid-connected are for off-grid uses like military use.
Purpose of deployment	Mainly to increase electrification	It may be for electricity supply security when the grid goes off or to increase uptake of distributed energy resources in a certain portion of the network.
Design	Most of them have trunk-and-branches, and hub-and-spoke topologies and the power sources and storage are modular with possibilities to expand.	“One-off” designs with no distinctive topology – every project is different
Energy source	They are dominated by diesel and hydro with the increasing significance of solar and solar hybrid.	They comprise all sorts of energy sources, including wind, natural gas, co-generation facilities, etc.
Communication	Usually, no need for communication as they are isolated. Whenever the need to communicate is there, the internet is used.	They have sophisticated real-time communication with the main-grid system operator.

2.5 Chapter summary

This chapter has presented a review of the issues beyond achieving energy access in developing countries and the usefulness of existing knowledge to address those issues. This objective has been achieved by reviewing the literature on future power systems in developing countries and the policy and technological readiness to effectively realise that future.

The literature reviewed in this chapter reveals two main schools of thought on future power systems, especially at the distribution level. These are a possible off-grid future that will trigger a utility death spiral and a smart-grid future that will see the increased adoption of a highly distributed and interconnected power system. The reviewed evidence from developing countries suggests that an off-grid future is improbable beyond universal electricity access. Many of those who get initial access to electricity through off-grid still seek a grid connection. Therefore, the smart-grid future is found to be highly likely in developing countries.

The review also confirms that there are three main pathways for the realisation of smart-grids in post energy access developing countries. These are retrofitting the primary grid with DERs, the convergence of the main grid with minigrids and convergence of the main grid with fragmented energy solutions like SHSs. Of the three pathways, the convergence of the main grid with minigrids has been identified as a more realistic pathway, peculiar to post universal energy access developing countries. Otherwise, retrofitting the main grid with DERs is already happening in developed countries, hence it can be achieved using lessons from those countries. On the other hand, the convergence of the main grid and fragmented energy solutions is unlikely to amount to something because most fragmented energy services are low-power, low capacity and incompatible with an AC grid.

Then, the present review considers the policy and technological readiness to facilitate the convergence and the subsequent grid integration of formerly autonomous minigrids in developing countries. That analysis reveals the need for significant work to update policies and regulations to create a suitable environment for such integration. The research has also shown that there remains a significant technology gap in planning such grid integration.

Specifically, the review has revealed that energy access planning methods are focused on splitting an area into either grid or off-grid electrification. Besides that, most energy access planning tools do not have a power flow analysis capability to ensure improved power quality and network efficiency, which are ignored in electricity access projects. On the other hand, although various aspects of DNP, such as DNEP, ODERP, and MP, have power flow analysis capability, they are not an exact fit to plan the grid integration of minigrids. This is mainly because DNEP is applied on greenfield networks or reinforcing an existing network which is not the case in grid integration planning of minigrids. Alternatively, ODERP and MP are based on planning DERs with the grid in mind, while in grid integration of minigrids, residual minigrid DER capacities, location, and types are fixed parameters, as the grid connection comes later than when these assets were installed.

Therefore, this review demonstrates that both electricity access and established distribution planning methods are not suited to planning the grid integration of minigrids in developing countries. New methods and frameworks are required to ensure optimal grid integration of formerly autonomous minigrids, and this thesis proposes and examines some of those. The next chapter presents a background of what happens when the grid converges with a minigrid, a general approach to specifying a planning problem and specifies a minigrid integration planning problem, the critical methodological approach proposed in this thesis.

3 MINIGRID INTEGRATION PLANNING PROBLEM

3.1 Introduction

The grid integration of previously autonomous minigrids in developing countries is as much a technical issue as it is a policy and regulatory challenge [88]. Particularly, the previous chapter has highlighted that the main regulatory and policy challenge is due to the lack of comprehensive mechanisms for facilitating the integration. Technically, the previous chapter has highlighted that lack of suitable planning methodology hinder the possibility of taking advantage of the benefits associated with grid integration of formerly autonomous minigrids.

Significant efforts to address the policy and regulatory challenges are reported in [22], [35], [95], which have recently led to a publication of template regulatory frameworks that developing countries can adopt [134]. However, the associated technical challenges have received little attention in the literature. Notable articles addressing the technical aspects of the grid integration of minigrids are [36] and [37]. Both articles focus on operational aspects of the grid integration of minigrids beyond achieving access to electricity. Yet, they do not consider any planning approaches that could take advantage of grid integration of minigrids to improve the poor quality of supply [29] and high losses [27] related to current electricity access projects in developing countries.

This chapter presents a novel methodological approach for planning the grid integration of minigrids. Initially, it builds on the previous work presented in [25], [33], [36] by offering the advantages and disadvantages of various options available to minigrids upon grid arrival and their implications for planning. Then, a review of general approach to specifying a power system planning problem is presented, which informs the definition of a power system analysis-based optimisation approach for minigrid integration planning (MGIP) developed as part of the work of this thesis. Finally, a structure for evaluating MGIP, including input, optimisation, and output blocks, is presented.

3.2 What happens when the grid converges with minigrids?

When the grid arrives within an area whose electricity needs are served by an autonomous minigrid, three main things can happen to the minigrid, according to [25], [33], [36], namely: abandonment, grid integration and side-by-side operation, as illustrated in Figure 7.

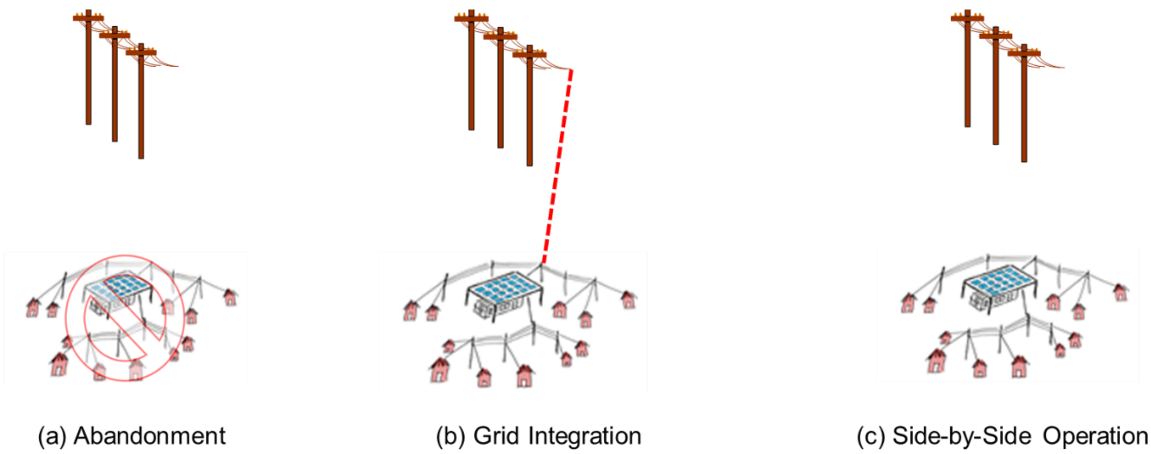


Figure 7: The fate of minigrids upon arrival of the main grid [6]

Determining the fate of minigrids depends on several factors [21]such as the minigrid's compatibility with the main grid, minigrid's reliability of supply compared to the main grid, and stipulations in the local regulation. These preconditions are discussed in detail in [21] and in the following sections, a brief description of the three options presented in Figure 7 is given. In each case, the respective advantages, challenges, and planning requirements are considered.

3.2.1 Minigrid abandonment

An autonomous minigrid can be abandoned when the grid arrives, as shown in Figure 7(a), and the customers to such minigrid are connected to the arriving grid through a newly built network infrastructure. According to most regulatory frameworks on the convergence of minigrids and the main grid, if a minigrid is abandoned, the minigrid operator is compensated or allowed to relocate the minigrid [35], [134]. In [10], the World Bank reports that abandonment was the fate of 44% of the minigrids in Cambodia, Indonesia and Sri Lanka upon the arrival of the main grid. Such abandonment can be due

[6] Artwork adapted from: https://www.energyfordevelopment.net/wp-content/uploads/2019/06/e4D_2019_leaflet_web.pdf

to several reasons such as grid incompatibility, policy environments that protect the main grid from any competition, or the high cost of operating the minigrid compared to the main grid[21].

While the other two reasons for minigrid abandonment are straightforward, grid compatibility of minigrid can be defined as its ability to seamlessly integrate with the main grid when it arrives [72]. Since most power grids use AC technology, DC minigrids are considered grid incompatible as DC technology in last-mile electrification is yet to become mainstream [135], [136]. Besides DC minigrids, some alternating current (AC) minigrids that were not built according to the local grid code standards would also be considered grid incompatible hence candidates for abandonment [36].

Advantages and challenges of minigrid abandonment

One of the significant advantages of minigrid abandonment is that it saves the utility company from the pressure and cost of transacting with numerous but small minigrid operators. Another advantage is that traditional methods of grid expansion remain applicable in planning the electricity supply to customers who previously belonged to the abandoned minigrid [21].

However, minigrid abandonment has three significant disadvantages. Firstly, it leads to an overall high cost of electrification as the utility company reinvests significantly in re-electrifying communities previously electrified by the abandoned minigrid. Secondly, where the regulation is unclear, the prospect of uncompensated abandonment increases the uncertainty associated with minigrid deployment, reducing the appetite of private investors to invest in minigrids [95]. Thirdly, abandonment can often be attractive to consumers who think the main grid will be more reliable, but this is not always the case, especially in many developing countries [23], [30]

Implications of minigrid abandonment on planning

If a minigrid is abandoned, planning the grid connection of former minigrid customers is not different from typical electrification through national grid expansion to new customers [7]. The only difference will be that knowledge of load data from the previous minigrid that served the community may better estimate the initial demand in the area. Such estimation will be a significant input in the sizing of power system equipment such as transformers.

3.2.2 Side-by-Side Operation (SSO) of the main grid and the minigrid

Despite the convergence of the grid and minigrids, under SSO, they continue to operate independently of each other, as shown in Figure 7(c). This operational model has been reported in instances in some parts of India where the grid is significantly unreliable, and minigrid customers prefer to remain supplied with energy from the minigrid than the unreliable grid [22]. Table 3 summarises the advantages and challenges associated with SSO.

Table 3: Advantages and challenges of SSO option

Advantages	Challenges
• No transaction/intergration costs incurred by either minigrid operator or utility. • Ideal only when the minigrid is much reliable than the main grid. • No planning is required as the minigrids do not integrate with the grid.	• Lack of symbiotic relationship between the minigrid and the main grid.

Since minigrids and the main grids operate independently, the SSO model does not require any planning exercise.

3.2.3 Grid integration of the minigrid

Upon the arrival of the main grid within premises of autonomous minigrids, the two grids can be integrated, as shown in Figure 7(b). This option entails extending and connecting the main grid to the minigrid with little to no modification to the incumbent minigrid network and assets. Some of the necessary modifications may include aligning the control and protection systems/philosophies of the minigrid to the main grid [36]. Grid integration is the likely fate of most grid compatible minigrids upon the arrival of the main grid [72]. In [33], the World Bank reports that 47% of the minigrids in Cambodia, Indonesia and Sri Lanka were integrated into the main grid.

Within the grid integration option, there are four different operation or business models, namely: Compensation (or asset buy out), Small Power Producer and Distributor (SPP&D), Small Power Producer (SPP) and Small Power Distributor (SPD) [22], [25],

[33]. These operational options are illustrated in Figure 8, where the green shading indicates the presence of a minigrid operator beyond grid integration.

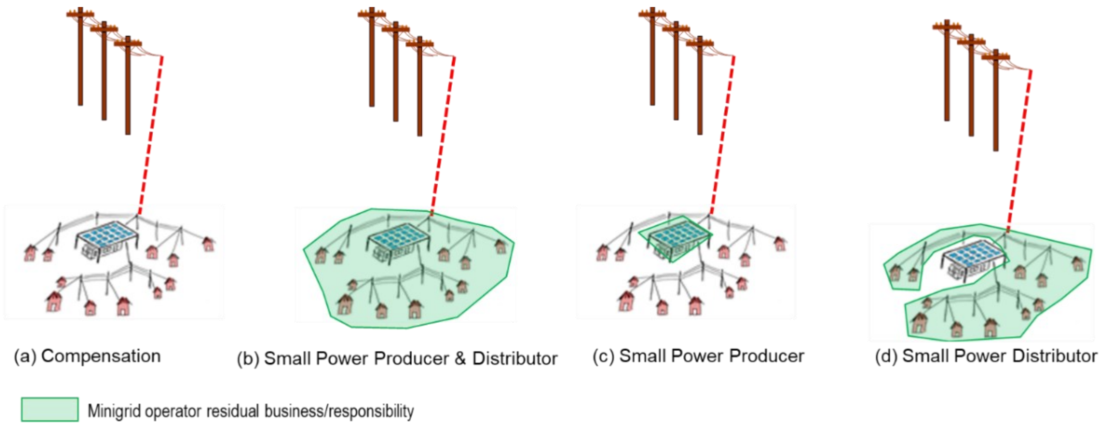


Figure 8: Illustrating minigrid operational models after grid integration

The choice of the grid integration operational models in Figure 8 largely depends on the post-integration role of minigrid operators and utility companies as defined in the local governing policy [35] and the grid compatibility of the residual assets in the minigrid [72]. For example, suppose a minigrid's generation assets are grid incompatible while the network is grid compatible. In that case, the generation assets are decommissioned (or abandoned), hence SPP and SPP&D are unlikely operational options as what remains for grid integration is the minigrid's network.

Here are brief descriptions of the post grid integration minigrid models, their advantages and disadvantages, and implications on planning.

3.2.3.1 Compensation (or Asset buyout)

In this operational model, the minigrid fully integrates with the main grid, and the minigrid operator transfers its operation and management responsibilities to the main grid operator [25], as shown in Figure 8 (a) – where the minigrid operator is absent compared to the other illustrations in the exact figure. For this to happen, the minigrid operator is compensated for the residual value of the minigrid or any other form of compensation that may be stated in the regulations. For example, the regulation in Nigeria [98] states that the minigrid operator's compensation consists of the residual depreciable value of the minigrid assets and a sum equivalent to 12 months revenue before the grid connection. Table 4 shows the potential advantages and challenges of this option.

Table 4: Advantages and challenges of compensation model

Advantage	Challenge
• Ideal when there are no minigrid operational incentives that are required for the economic viability of most grid-connected minigrids.	• Potential poor quality of supply in the previously autonomous minigrid as the utility company may marginalise the newly acquired and grid integrated minigrid assets due to their small size and remote location. • Lack of established planning approach to maximise benefits from grid integration of minigrids.

3.2.3.2 Small Power Producer (SPP)

In this grid integration operational model, the minigrid operator retains ownership and operation of the generation facilities but hands over the network assets to the utility company at an agreed fee. As shown by the green shading in Figure 8(c), the responsibility of the minigrid operator is restricted to the power generation facilities of the minigrid. The SPP sells energy to the grid operator at a price decided through either a negotiated Power Purchase Agreement (PPA) or a Feed-in-Tariff (FiT) arrangement [25]. Table 5 summarises the advantages and challenges associated with the SPP model.

Table 5: Advantages and challenges of the SPP model

Advantages	Challenges
• It keeps the minigrid operator in business as a small power generator. • Reduced transaction burden to the minigrid operator as it will only have one customer - the utility company. • The presence of embedded generators may help utility companies to reduce distribution losses and improve voltage profiles.	• The process of signing transaction contracts between the utility company and the minigrid operator (as an SPP) may be expensive for both parties, especially where there are strict regulations. • May lead to significant investment to retrofit the minigrid generating facility for grid connection. • The SPP may experience a frequent loss of energy sales when the grid is unreliable. If the SPP claims this loss of energy sale as deemed energy, such claims may strain the utility financially. • Lack of established planning approach to maximise benefits from grid integration of minigrids.

3.2.3.3 Small Power Distributor (SPD)

In this model, the minigrid generation facilities are decommissioned upon integration with the main grid while the network is retained, as shown in Figure 8(d). The minigrid operator has the trading rights within the residual minigrid network, buys electricity from the main grid at an agreed price and uses the minigrid network to supply energy to its customers at a profit. This operational model was implemented in Cambodia [33], where the source of minigrid generation was predominantly diesel which is very expensive and polluting. In such and similar circumstances, decommissioning of the generation facilities make both economic and environmental sense. The advantages and challenges associated with SPD are in Table 6.

Table 6: Advantages and challenges of SPD operational model

Advantages	Challenges
• It keeps the minigrid operator in the business as a small energy distributor. • There is no significant change in the minigrid operator's business model – instead of selling energy from minigrid generators, the minigrid operator sells energy purchased from the grid. • Efficient and effective maintenance and operations of the network as the minigrid operator may have a local presence.	• It requires regulatory incentives where the main grid electricity tariff is uniform to keep the minigrid operator profitable. • In case of an outage of the main grid, the minigrid is also equally affected as it is void of generation generation facilities. • Lack of established planning approach to maximise benefits from grid integration of minigrids.

3.2.3.4 Small Power Producer and Distributor (SPP&D)

In this model, as in Figure 8(b), the mini-grid operator continues operating the minigrid in the same way as before grid integration. The only change is a connection to the main grid network. This connection gives the minigrid operator an option to export excess power into or import deficit power from the grid. In other cases, the grid connection is set up to allow for a dual mode of operation (islanded and parallel to the main grid) for the minigrid [36]. The benefits of dual-mode operation are significant where the main grid has insufficient generation capacity, which causes regular brownout (or blackouts) [137]. Table 7 shows the potential advantages and challenges of the SPP&D.

Table 7: Advantages and challenges of the SPP&D model

Advantages	Challenges
• It helps to compensate for an unreliable grid as the minigrid customers can potentially be served with power from the minigrid generator when the main grid is off. • Combines the advantages of SPD and SPP (see Table 5 and Table 6).	• May need regulatory incentives when the minigrid tariff is not at parity with the national grid tariff. • Lack of established planning approach to maximise benefits from grid integration of minigrids.

Implications of grid integration to planning

Regardless of the final asset ownership, business, or operational model between the utility company and the minigrid operator, grid integration will involve the electrical connection of the main grid and the minigrid assets. From a technical perspective, the resulting business model is not a key component of the decision making compared to the residual assets within the minigrid, their size, and location [101]. For example, suppose a situation where the network, storage, and generation assets of a minigrid are grid compatible. In that case, an SPP&D or Compensation model of operation can be adopted upon grid integration. However, whether SPP&D or Compensation, from a grid integration point of view, operationally, these models will be the same as they will all involve the grid integration of a minigrid with a network, generation and storage assets.

Therefore, grid integration of minigrids requires systematic planning regardless of the resulting business/ownership model. Such planning should, among other things, maximise the use of the residual assets in the minigrid, namely, the minigrid network, power generation sources, and storage. Before specifying the minigrid integration planning (MGIP) problem, it is crucial to outline the general approach in setting similar DNP problems [121], [138].

3.3 General approach to specifying DNP problems

DNP problems are often presented as formal optimisation problems with objectives, constraints and applied solution methods [117],[45]. For example, the main objective in [139] is to minimise investment costs in integrating storage to an LV network. In this paper, the DNP problem is solved using a combination of two modern optimisation techniques namely, Simulated Annealing and Genetic Algorithm. It is constrained to power flow equations, the thermal capacity of network assets, and voltage limits. Similarly, the DNP problem in [119] involves minimising investment, losses and maintenance costs when expanding a distribution network amidst distributed generators. The problem is again constrained to parameters such as power flow equations, thermal limits, and radiality of the distribution network, and in this case it is solved using mixed-integer linear programming methods to find the global optimum.

Since DNP problems are specified using optimisation concepts and principles, this section provides background information to the optimisation principles concerning problem definition, modelling, and solutions.

3.3.1 Problem definition

The definition of an optimisation problem involves specifying variables, the objective function(s), and constraints functions (if any) [140]. A problem that does not have any constraint function is called the *unconstrained optimisation problem*. However, most operational problems, including DNP problems [139],[119], are constrained problems as there are always limitations associated with decisions that people make.

3.3.1.1 Types of variables

Like any optimisation problem, DNP problems consist of two types of variables: dependent and independent variables [138]. A decision-maker will always aim to determine the optimum value(s) of the independent variable(s), and the dependent variable is evaluated based on the determined value(s) of the independent variable(s). For this reason, independent variables are also called decision variables of the problem. For example, in generator placement problems within electric distribution networks, such as those reviewed in [40], the decision variables are the size, number, location and type (or technology) of generators, while the dependent variables are the power flows in the network elements, network losses, bus voltage, etc.

The nature of decision variables is one of the critical factors for characterising an optimisation problem. An optimisation problem is *discrete* if at least one of the variables is discrete (integer), *continuous* if all variables are continuous, and *mixed* if it has both discrete and continuous variables [141].

3.3.1.2 Objective function(s)

The objective function of any optimisation problem, including DNP problems, is a function that is implicitly (or explicitly expressed) in terms of the decision variables, and it helps the decision-maker establish a desirable solution [45]. Like variables (in Section 3.3.1.1), objective functions also inform the characteristics of an optimisation problem. For example, a DNP problem is *single-objective* if it has one objective function, such as minimising losses in allocating distributed energy resources [46]. A DNP problem is *multiobjective* if it has more than one objective function like minimising the cost of network upgrade, purchase energy, cost of energy losses, and energy not supplied in [142].

3.3.1.3 Constraint function(s)

As stated previously, most real-life optimisation problems, including DNP problems, have limitations, and constraint functions in the optimisation formulation represent these. In planning problems, these constraints may be technical, like power flow equations in [46] or economic, like economic distance limit in optimising the choice between grid extension and off-grid electrification [7]. Every set of constraints splits or partitions the solution space into *feasible* and *non-feasible regions*. If $\mathbf{\Omega}$ denotes a feasible region within the solution space, a vector of decision variables, $\mathbf{x}$, in the feasible region will be presented as $\mathbf{x} \in \mathbf{\Omega}$.

The objective function and constraint functions inform two characteristics of the optimisation problem: *linearity* and *convexity*. In mathematical programming [143], if both objective and constraint functions are linear, a problem is said to be a *Linear Program* (LP), else it is a *Nonlinear Program* (NLP). Linearity is one of the vital characteristics that inform the difficulty of an optimisation problem – linear problems are less demanding than their nonlinear counterparts and can typically be solved using analytical methods.

According to [144], unlike *linearity, convexity* (or *concavity*) is a better indicator for ascertaining the difficulty of an optimisation problem. To understand convexity a bit better, geometrically, a function $f(\mathbf{x})$ is convex if a line connecting any two points, (x_1, $f(x_1)$) and (x_1, $f(x_1)$), on the graph of $f(\mathbf{x})$ lies above the graph of $f(\mathbf{x})$ between x_1 and x_2. On the other hand, f(x) is concave if $-f(\mathbf{x})$ is convex. Figure 9 illustrates the concept of convexity and concavity of functions in the two-dimensional case.

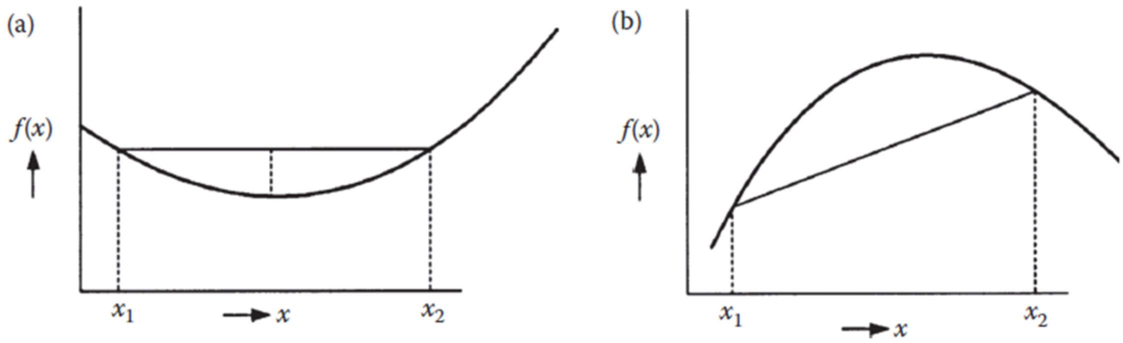


Figure 9: (a) Graph of a convex function, (b) Graph of a concave function [144]

For an optimisation problem with convex objective and constraints function(s), any local extrema (minima or maxima) is also the global extrema of that problem [144]. On the other hand, non-convex problems have multiple extrema and are more challenging to solve than their convex counterparts. As such, convexity (or lack of it) is a better indicator of the difficulty of finding a solution to an optimisation problem than linearity. Most power system optimisation problems are non-convex unless they are relaxed or approximated, like in [35] where the joint generation and distribution network planning problem is approximated as a convex problem.

3.3.2 Problem formulation

In general terms, an optimisation problem can be written as follows:

$$\mathbf{F(x)} = \boldsymbol{min}([f_1(x), f_2(x), \dots, f_m(x)]) \tag{3.1}$$

Subject to:

$$\boldsymbol{A}_j(x) = 0, \qquad \forall j \tag{3.2}$$

$$\boldsymbol{D}_k(x) \ \leq 0, \quad \forall k \tag{3.3}$$

$$x \in \Omega \tag{3.4}$$

Where $\boldsymbol{F}(\boldsymbol{x})$is a vector of objective functions with dimension m. For a single-objective problem, m=1; otherwise, m>1 for multi-objective problems. If the objective maximises a specific function, the problem is modelled as minimising the negative of the objective function, i.e., $\max f(x) = -\min f(x)$. $\boldsymbol{x}$ is a set of decision variables that are members of the decision domain $\boldsymbol{\Omega}$. The extent of the decision domain is defined by equality and non-equality constraints represented (3.2) and (3.3) with dimensions of j and *k,* respectively.

3.3.2.1 Model characterisation

Once an optimisation problem is formulated, the mathematical nature of decision variables (discrete or continuous), number of objective functions (single or multi-objective), presence of constraints (constrained or unconstrained), linearity, and convexity of the objective or constraint functions inform the characteristics of the problem. Together with desired speed and accuracy of decisions, these characteristics are crucial in informing the difficulty of the optimisation problem and the choice of algorithms for solving it. Broadly, [141] states that optimisation problems may fall into any categories shown in Table 8.

Table 8: Categories of Optimisation Problems [141]

Category	Decision Variable(s)	Objective Func (s)	Constraint Func(s)
Linear Programming (LP)	• Continuous Scalar	• Linear	• Linear
Nonlinear Programming	• Continuous Scalar	• At least one of them is nonlinear	
Integer Programming (IP)	• Integer scalar	• Linear/nonlinear	• Linear/nonlinear
Mixed Integer Linear Programming (MILP)	• Integer scalars • Continuous scalars	• Linear	• Linear
Mixed Integer Nonlinear Programming (MINLP)	• Integer scalars • Continuous scalars	• At least one is nonlinear	
Discrete Optimisation (includes IP, MILP and MINLPs)	• Continuous scalars	• Linear/nonlinear	• Linear/nonlinear
Optimal Control	• Vectors	• Linear/nonlinear	• Linear/nonlinear
Stochastic Programming	• Any of the above	• Any of the above with uncertain (random) variables	
Multiobjective Optimisation	• Any of the above	• More than one objective	• Any of the above

In each case, the planning problem characteristics (the features of the DNP problem in terms of the work of this thesis) can guide the choice of solution technique or tool. For example, authors in [145] present a MILP model for optimising the design of autonomous regional and local microgrids and a mathematical tool called CPLEX [146] was used to solve it. The same tool is also used to solve a multi-objective distribution planning problem which was also converted into a MILP presented in [120]. Also, [147] presents another multi-objective planning problem that considers reliability, operational and expansion cost and is solved using a multi-objective reactive Tabu search algorithm. Due to the influence of problem characterisation on guiding a solution technique, the following section presents the solution techniques available to planning/optimisation problems, and from this, the approach for the planning problem of this thesis will be developed.

3.3.3 Problem Solution

Optimisation/planning problems are solved iteratively using either mathematical or heuristic algorithms/optimisers [148]. The process of solving an optimisation problem can be summarised in Figure 10. The optimiser is initialised and generates a set of values of the decision variables. These initial values are inputted into the model to evaluate the objective and constraints functions. The optimiser uses the output values from the model to generate a new set of solutions. This iterative process continues until the criteria specified in the algorithm is satisfied. Such criteria may be based on changes in the objective function, number of iterations, or other similar stopping criteria [138].

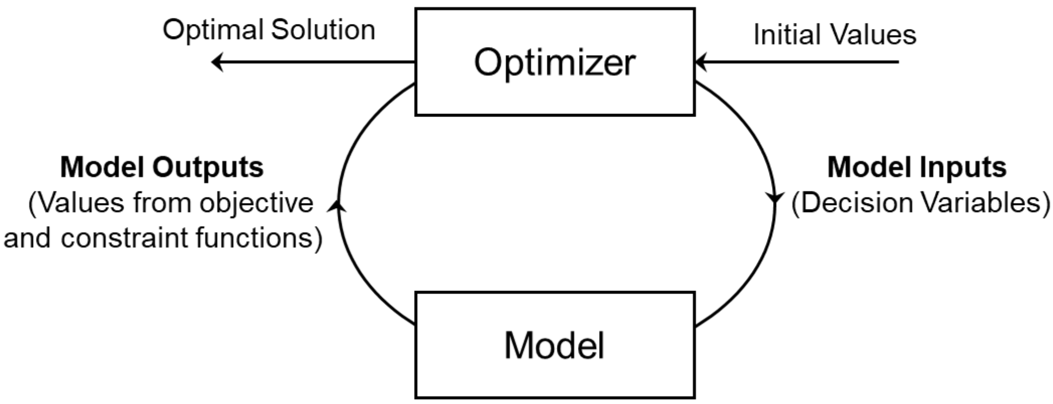


Figure 10: Generic optimisation framework [141]

The representative problem (3.1) to (3.4) can be solved using various optimisation techniques or algorithms. The selection of these algorithms depends on the problem's mathematical characteristics, speed or relative accuracy required by the decision-maker [148]. A discussion on the *mathematical* and *heuristic* methods for solving optimisation problems is presented next.

3.3.3.1 Mathematical Methods

The application of optimisation methods is dependent on the mathematical characteristics of the problem. For example, mathematical methods used to evaluate an integer problem, like branch and bound method, cannot be applied to a linear problem with continuous variables [144].

Therefore, identifying an appropriate mathematical algorithm to solve an optimisation problem requires a deeper mathematical understanding of the problem. This need for a deep mathematical understanding of the problem is one of the main disadvantages of applying mathematical methods as they may tend to involve complex mathematical implementation. However, one of the key strengths of mathematical methods is that they guarantee convergence, although global optimality may only be guaranteed in some (and not all) problems [138].

3.3.3.2 Heuristic Methods

Practical power systems related optimisation problems are nondifferentiable, non-convex, and nonlinear [144]. These characteristics significantly limit the application of most mathematical methods unless the problems undergo relaxation and approximation [107]. However, such alterations change the problem under consideration and may lead to optimal solutions which are infeasible in the real world. This and many other drawbacks of applying mathematical methods to real-world power system problems have led to a recent rise in the application of heuristic methods [148].

Heuristic optimisation algorithms, sometimes referred to as Modern Optimisation Techniques, can be categorised using various criteria, such as the inspiration of the method, use of memory in evaluating the method, usage of stochastic or deterministic rules, and the number of solutions considered in each iteration [149]. According to [150], the critical criteria in classifying heuristic algorithms is the number of solutions that a method evaluates on each iteration. In this respect, there are *single solution-based* heuristics and *population-based* heuristics. Single solution-based algorithms focus on exploiting a single solution by transforming it during a search. On the other hand, population-based heuristics explore the solution space by transforming several solutions at a time. Examples of widely applied heuristics in power system planning and their classification (single or population-based solutions) are presented in Table 9.

Table 9: Examples of heuristic (modern) optimisation methods

Heuristic Algorithm	**Inspiration**	**Solutions per iteration**
Genetic Algorithm (GA) [151]	Genetics and Evolution	Population-based
Particle Swarm (PS) [152]	Bird and fish movement	Population-based
Ant Colony [153]	Behaviour of ants	Population-based
Simulated Annealing (SA) [154]	Thermodynamics	Single solution based
Tabu Search (TS) [155]	Memory response	Single solution based

Heuristic optimisation algorithms, in Table 9, have been used to solve several power system planning problems [138],[80]. GA is used in [156] to evaluate a distributed generation problem and [157] for distribution network reconfiguration to achieve loss reduction. Authors in [42] apply PS in the optimal planning of MV and LV networks, TS and SA are used to achieve loss reduction in [158], and Ant Colony is applied in [159] for the planning of distribution networks. The application of heuristic algorithms in distribution planning motivates the choice of algorithm for solving MGIP later in this chapter. First, the MGIP problem is defined and modelled in the next sections.

3.4 Defining the MGIP problem

For the work being developed in this thesis it is necessary to define and appropriate mathematical formulation that can capture the MGIP problem, an illustrative example of which is shown Figure 11. When a decision has been made to integrate specific minigrids to the main grid[7], the intention in this case is to extend the main grid, from the terminal z_{grid}, into a location with a cluster of three minigrids, identified as Minigrid 1, 2 and 3 and in doing so provide main grid access to each of the minigrids akin to the operational model of Figure 7(b).

[7] The decision process for assessing whether to integrate a minigrid to the main grid or not is out of scope of the MGIP.

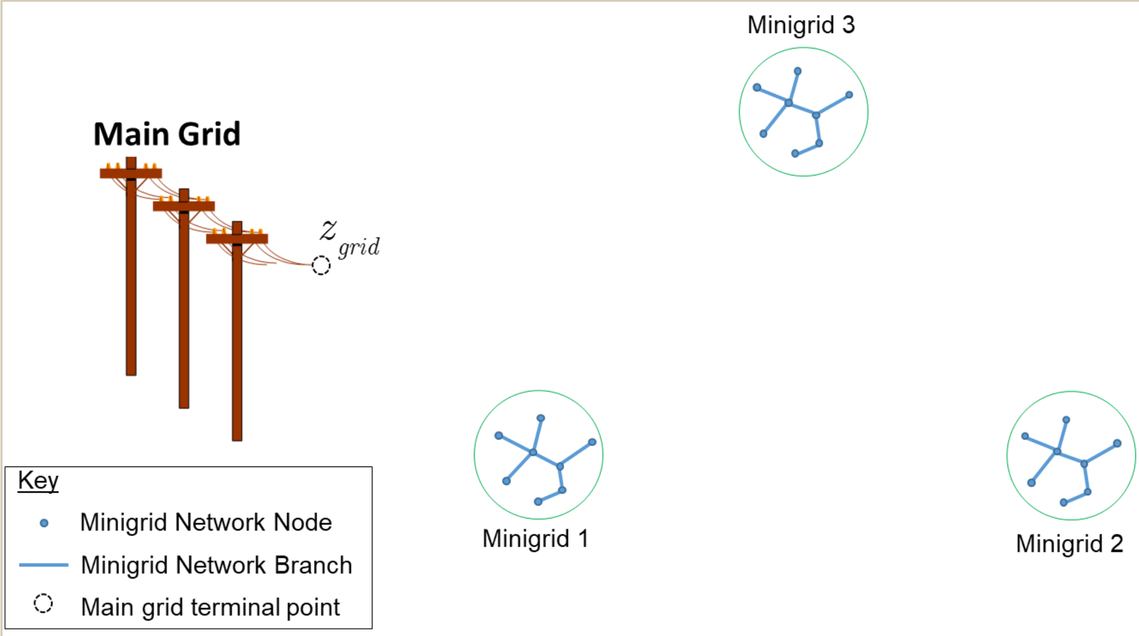


Figure 11: Arrival of the main grid to a cluster of three minigrids

Assuming that each minigrid is grid compatible and comprises the following:

- **Residual power generation source** hosted at one of the nodes. In other instances, this residual generation source is co-located with centralised storage, as in [21].
- **Demand** located at several nodes of the minigrid network with a known demand profile.
- **Minigrid network** connecting incumbent power generation node and demand nodes.

Therefore, for the situation presented in Figure 11, the minigrid integration planning problem is:

"What is the best way to integrate the three minigrids from the grid terminal point?"

A more general definition for the MGIP problem involving a known grid terminal point and a cluster of any number of isolated minigrids:

"What is the best way to integrate a cluster of isolated minigrids from a specified point of the nearby/arriving main grid?"

From the knowledge that post-electricity access power systems in developing countries are associated with high network losses [27], [28], poor reliability of supply [23], [30] and an inferior quality of supply [29], the best form of grid integration should ensure improvement in one or more of these features. Besides that, like in many DNP problems [119], [116], the MGIP should also minimise the cost of investment associated with the integration. At this stage of developing MGIP, the focus will be electrical loss reduction and minimisation of investment costs. Loss reduction is a critical objective because it is imperative for the grid integration of minigrids to alleviate the high network losses reported in developing countries [27], [28]. Minimising the cost of grid integration of minigrids is also critical because it influences the overall economics of the integrated electricity network.

The MGIP formulation presented in this thesis assumes an AC minigrid. The formulations will contain provisions for DERs, but those provisions will only be useful if the minigrids requiring grid integration have residual DERs. Otherwise, if the minigrids do not have residual DERs, any DER provisions within the MGIP formulation will equal to zero. Besides that, the MGIP in this thesis is time-coupled for a 24-hour window to capture the effects DERs like photovoltaic and storage which are popular in SSA minigrids and the intra-day variation in the demand profile.

3.4.1 Variables in MGIP

As discussed in Section 3.3.1.1, parameters likely to change and affect the objective function inform key variables of an optimisation problem. For the MGIP, key variables that may affect losses and investment cost include grid infeed point into each minigrid, length of the main grid network (connecting all minigrids to a point on the main grid) and size of grid integration transformer(s) [42], [54].

3.4.1.1 Grid infeed point into each minigrid

The grid infeed points into the individual minigrids are a key variable that can affect several operational issues within the minigrid, such as losses [54]. To illustrate this point, consider power losses within minigrids, in Figure 12 (a), (b) and (c), which have the same network with different grid integration scenarios. In Figure 12 (a), the minigrid is isolated from the main grid. On the other hand, the minigrid in Figure 12 (b) is grid-connected via Node 1, while the minigrid in Figure 12 (c) is grid-connected through Node 4. Node 1 hosts the minigrid generation source in all the scenarios, Figure 12 (a), (b) and (c), and the rest of the nodes are assumed to host demand.

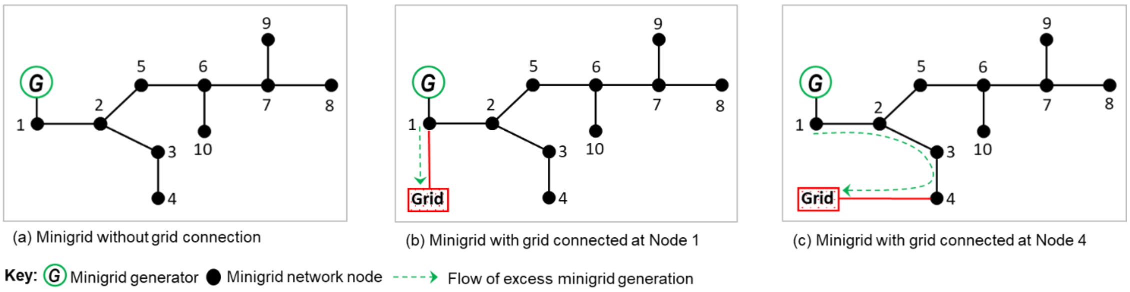


Figure 12: A minigrid under three different grid connection scenarios

The notation in the losses and power flow formulations that follow in this thesis are illustrated using the representative network with three nodes, *k*, *m* and *n*, and two branches *km* and *mn* shown in Figure 13.

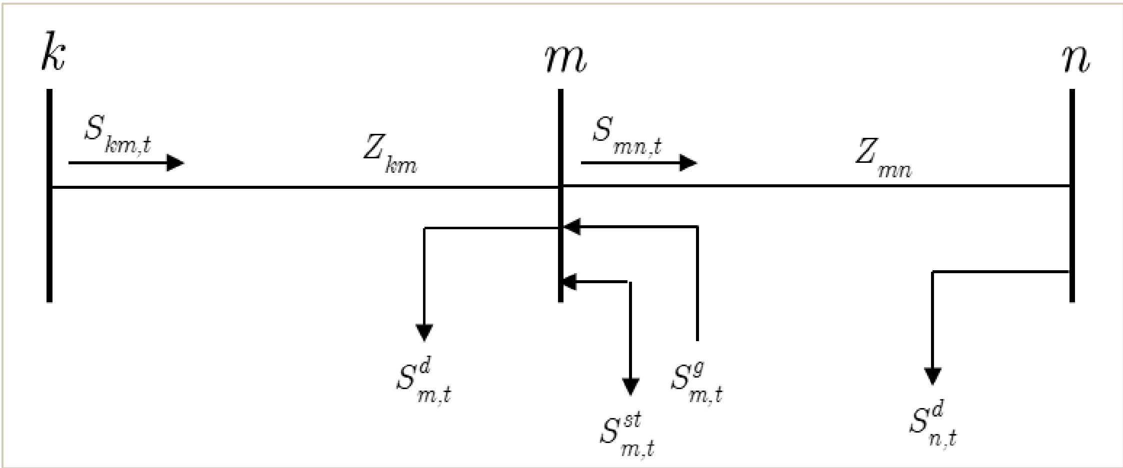


Figure 13: Representative network branch showing key variables in the power flow formulation

Here $S_{km,t}$ and $S_{mn,t}$ are the complex power flowing through any branch of the network at any point in time while Z_{km} and Z_{mn} are the complex impedances of those branches. Then $S^d_{m,t}$ is the complex demand at any node *m* of the network, $S^g_{m,t}$ is the complex power generated at node *m*, and $S^{st}_{m,t}$ is the complex power from or into the storage device at node *m* whose real part is negative when charging and positive when discharging.

In Figure 12 (a), where there is no grid connection to the minigrid network, the entire minigrid demand is supplied by the minigrid generator located at Node 1. Therefore, the hourly power losses in the minigrid network will be [64], [121]:

$$P_{loss,h} = \sum_{mn \in \boldsymbol{B}_{mg}} \frac{R_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2\right), \qquad \forall m,n \in \boldsymbol{N}_{mg} \tag{3.5}$$

Where $\boldsymbol{B}_{mg}$ is a set of all network branches within the minigrid and mn represents a single network branch with resistance R_{mn} ohms, and receiving end voltage of $V_{n,h}$. The active and reactive power through any minigrid branch, mn, at any hour h, is given by $P_{mn,h}$ and $Q_{mn,h}$ respectively.

In Figure 12 (b), where the grid infeed point into the minigrid is collocated with the minigrid generation source, the power losses will still be given by (3.5). This will remain unaltered in the power flow since the slack bus in Figure 12 (a) is the same as that in Figure 12 (b). The only difference between the situation in Figure 12 (a) and Figure 12 (b) is that the grid connection in Figure 12 (b) presents an opportunity for excess power from the minigrid generator to be exported to the main grid [27]; hence impacts may be anticipated in the upstream network. However, the quantification of such upstream impacts is beyond the scope of the work of this thesis.

In Figure 12 (c), where the grid infeed point into the minigrid is away from the minigrid generator, the minigrid node to which the main grid is connected becomes the reference node (or slack bus) of the power flow in the minigrid network. Consequently, the magnitudes of power flowing through the respective branches of the minigrid network become altered for two reasons. Firstly, the change in reference (or slack) bus provides a different relative measurement. Secondly, the flow of excess generation through the minigrid network into the upstream network. Therefore, the hourly power loss in the minigrid network of Figure 12 (c) will be given by:

$$\begin{aligned} P_{loss,h} = & \sum_{mn \notin \boldsymbol{\psi}_{mg}} \frac{R_{mn}}{V_n^2} \left(P_{mn,h}^2 + Q_{mn,h}^2\right) \\ & + \sum_{mn \in \boldsymbol{\psi}_{mg}} \frac{R_{mn}}{V_n^2} \left((P_{mn,h} - P_{n,h}^g - P_{n,h}^{st})^2 \right. \\ & \left. + \ (Q_{mn,h} - Q_{n,h}^g - Q_{n,h}^{st})^2\right), \\ & \forall (mn) \in \boldsymbol{B}_{mg}, \forall m,n \in \boldsymbol{N}_{mg} \end{aligned} \tag{3.6}$$

Here $\boldsymbol{\psi}_{mg}$ is a set of minigrid branches whose active and reactive power flows are affected by the excess power flow from the minigrid generator or storage. For example, in Figure 12 (c), where the grid is connected at Node 4, the membership of $\boldsymbol{\psi}_{mg}$will be $\boldsymbol{\psi}_{mg} = \{l_{12}, l_{23}, l_{34}\}$. Also, $P_{n,h}^{g}$ and $Q_{n,h}^{g}$ are the active and reactive power quantities generated by the minigrid generator at any time h, and $P_{n,h}^{st}$ and $Q_{n,h}^{st}$ are the hourly active and reactive power quantities from/into the storage within the minigrid. The rest of the terms are as defined for (3.5).

The mathematical formulation presented in this section identifies that point of grid infeed can affect the power flow around a minigrid network, consequently affecting network losses. Therefore, to deliver on the best operational solution to the minigrids (in keeping with the objectives set out previously) the presented formulations will be used in a subsequent section to inform the full modelling of the MGIP problem so that these opportunities can be capitalised upon.

3.4.1.2 Length of expanding main grid network

Since electricity access planning involves demarcating areas into the designations of grid electrified and offgrid electrified regions [10], [92], grid integration of minigrids in terms of the work of this thesis, shall entail grid expansion into areas that got their initial electrification through minigrids. Therefore, connecting the main grid to each of the minigrids in MGIP is a version of distribution network expansion planning [10]. In keeping with this, the length of the expanding grid network will inform part of the cost of investment to connect the grid with the formerly autonomous minigrid(s) [33].

To maintain radiality of the distribution network [160],[161], the main grid can only land on one of the many nodes within each minigrid. The total length of the main grid network expansion will depend on the location of the selected points of grid infeed into each minigrid network. When there is a cluster of minigrids, the grid infeed point of each minigrid network within the cluster will inform the reticulation of the main grid network connecting all minigrids to the main grid.

Radial grid expansion from a specified point of the grid to any of the minigrids in a cluster can be formally expressed using graph theory [160], [162], where an undirected weighted graph G is defined as:

$$G = (V, E, w) \tag{3.7}$$

Here, V is a set of vertices (or nodes), E is a set of edges connecting any two vertices, and w is a set of weights for each edge of the graph. In MGIP, the vertices will comprise the terminal point of the main grid (z_{grid}) and the set of grid infeed points into each minigrid network ($z_1, z_2, z_3, \dots, z_{mg}$). For example, in the grid integration of a cluster with three minigrids shown in Figure 11, the set of vertices (nodes) for the grid expansion network will be given by:

$$V = \{z_{grid}, z_1, z_2, z_3\} \tag{3.8}$$

As the main grid network will be expanding from the main grid to the minigrids, z_{grid} will be the source node of the graph. Hence edges of the graph will form a radial/tree network from z_{grid}. The weight of each edge will be the distance between the nodes it is connecting.

In MGIP, the grid expansion network layout can be established from a Minimum Spanning Tree (MST) [107] connecting the grid terminal point and the point of grid infeed into each minigrid. Therefore, the total length of the main grid network expansion will be the sum of the weight (or lengths) of each of the edges of the MST as follows:

$$L_{grid} = \sum_{mn \in \boldsymbol{B}_{mv}} L_{mn} = \sum w \tag{3.9}$$

Here, the length of a branch between any nodes m and n is L_{mn}, and $\boldsymbol{B}_{mv}$ is a set of MV network branches which will be the same as the set of edges, E. As shown in (3.9), graph theory shows that the total length of the main grid network expansion is also the same as the sum of all weights of the graph's edges [160].

3.4.1.3 Size of Transformer

A transformer will be required in MGIP if the main grid and minigrid clusters are at different voltage levels [42]. Therefore, selecting the size of this transformer becomes another key variable in the MGIP problem formulation. For each minigrid, the appropriately sized transformer would be placed at the identified grid infeed point. Combining the selection of the grid infeed point and transformer sizing, the MGIP becomes like transformer sizing and placement problems reported in [127], [42], and [123]. However, the transformer sizing and allocation component in MGIP is differentiated from ‘typical’ transformer sizing and placement in three main ways.

Firstly, not all minigrid integration problems in developing countries will require a transformer as some minigrids may be operated at the same voltage level as the incoming grid [36]. However, in scenarios where transformer sizing may not be required, selecting the grid infeed point into those minigrids will still be necessary. Therefore, even in problems that will not require the sizing and placement of transformers, other variables of MGIP will remain crucial for optimal integration of minigrids and the main grid.

Secondly, transformer sizing and placement works reported in [127] and [42] identify that the MV network and the LV network are deployed at the same time or on "*greenfield*" sites. However, the minigrid integration problem involves integrating a minigrid that was initially deployed for offgrid electrification and without the grid in mind [26], [33]. Therefore, although the network expansion to those minigrids will consist of new infrastructure, the prior presence of the minigrid networks means that MGIP involves connecting the main grid to sites whose LV network was developed prior to the arrival of the main grid or on "brownfield" sites. This is a key consideration for developing countries who are adopting a bottom-up approach and as a result to the work of this thesis.

Finally, transformer sizing and placement works reported in [127], [42], and [123] do not assume the presence of any DERs in the downstream network. On the contrary, in MGIP problems, there are DERs within the minigrids integrating with the main grid [33]. The presence of DERs in minigrids provides a new complexity that is not reported in transformer sizing and placement.

3.4.2 Objective function(s) of MGIP problem

In a similar way to DNEP problems, the MGIP can be modelled either as a *static* or *dynamic* problem – where static means that the decisions are made at a single point in time, and dynamic means the decisions are made at different points in the planning horizon [117]. Application of static formulations is reported in [51] within the design of scalable DNEP evolutionary algorithms, and [160] applies dynamic formulation to plan the deployment of autonomous minigrids in developing countries.

This section presents the static formulation of the MGIP problem, and it is used in that form for most parts of this thesis. The static formulation of MGIP is preferred because the selection of grid infeed point is made only once in grid integration of minigrids [36]. Although population growth and increased economic activities may alter the long-term amount and distribution of demand within the minigrid, the fixed choice on the grid infeed point into a local distribution network is plausible. It is consistent with approaches used in similar work on planning MV and LV networks reported in [127], [42], and [123] as it does not make any economic sense to be moving the grid infeed point around a network now and then in response to demand growth.

In the static approach of MGIP, the planning decisions will be made at the year/time when the minigrid is being integrated with the main grid. Depending on the preferences of the planner, several objective functions, like those in [45], can be considered. Here, the focus will be on minimising investment costs, to ensure least-cost planning [116], and reducing losses because power networks in developing countries are reported to be lossy [27], [28]. For example, [28] reports that power losses in SSA, one of the least electrified regions in the world, are in the region of 16% compared to the average of 9% in other developing countries. Later in this thesis, voltage profile improvement is also included in this formulation as energy access initiatives are associated with poor voltage profiles [29] which will need improving beyond achieving SDG7.

The investment costs within MGIP shall consist of the cost of assets required to enable the integration, i.e., grid network expansion and integrating transformers where necessary [21]. These costs may also include purchasing synchronising equipment, protection systems upgrades, etc., if the assets in the incumbent minigrid are not grid compatible [33], [36]. However, the work reported in this thesis assumes that the minigrid is 'grid ready' [27], [72] and the only investment required to achieve the grid integration of such minigrids being the cost of grid network expansion and transformers.

In most planning problems [51], [117], [119], electric energy losses are transformed into a cost term to easily combine with investment costs into a single objective optimisation problem. This approach is adopted in this thesis; hence the single objective MGIP function to minimise the cost of grid integration of minigrids is given as:

$$\min f = \min\left(C_{ann}^{inv} + C_{ann}^{loss}\right) \tag{3.10}$$

Where C_{ann}^{inv} and C_{ann}^{loss} are the annualised investment and loss cost, respectively.

3.4.2.1 MGIP annual investment cost

As stated earlier, the annual investment cost for MGIP problem comprises the network expansion to the minigrid networks and the cost of any transformers interfacing the expanding network with the minigrid networks. The static formulation of the annual investment cost will be given as:

$$C_{ann}^{inv} = CRF\left(C_{mv}\sum_{mn\,\in\,\boldsymbol{B}_{mv}} L_{mn} + \sum_{\substack{mg\,\in\,\boldsymbol{MG}\\ z_{mg}\,\in\,\boldsymbol{N}_{mg}\\ tfr\,\in\,\boldsymbol{TFR}}} C_{z_{mg}}^{tfr}\right) \tag{3.11}$$

Where, CRF is the annual cost recovery factor, C_{mv} is the cost of MV lines per unit length, L_{mn} is the length of the MV lines between any nodes *m* and n. Additionally, $C_{z_{mg}}^{tfr}$ is the cost of a transformer connecting the main grid and minigrid *mg* at grid infeed point z_{mg}.

The CRF represents the cost recovery factor for annualising the investment cost over a set period of years, and it is defined as [138]:

$$CRF = \frac{1}{\left(\frac{1}{d} - \frac{1}{(1+d)^T}\right)} \tag{3.12}$$

Where d is the discount factor in percentage and T length of the project in years.

3.4.2.2 MGIP annual cost of losses

The annual cost of losses for MGIP, in (3.10), shall comprise the sum of annual losses for both the expanding MV network and the minigrid networks multiplied by the unit cost of energy. Formally, the annual cost of losses will be:

$$C_{ann}^{loss} = 365 \times C_{energy} \times \sum_{h=1}^{24} \left(P_{loss,h}^{mv} + \sum_{mg \in \boldsymbol{MG}} P_{loss,h}^{mg,z_{mg}} \right) \tag{3.13}$$

In (3.13), the formulation assumes a daily profile to incorporate the effects of renewable power generation (mainly photovoltaic in SSA) and intra-day variation in the demand profile. Thus, the unit cost of energy is given by C_{energy}, and the rest of the terms in (3.13) are defined as follows:

$$P_{loss,h}^{mv} = \sum_{mn \in \boldsymbol{B}_{mv}} \frac{R_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right), \;\; \forall (mn) \in \boldsymbol{B}_{mv}, \forall m,n \in \boldsymbol{N}_{mv} \tag{3.14}$$

represents the hourly power loss in the expanding MV network and $P_{loss,h}^{mg,z_{mg}}$ is the hourly power loss in any minigrid network, *mg,* when the grid is connected at node z of that minigrid, denoted as z_{mg}, as follows:

$$\begin{aligned} P_{loss,h}^{mg,z_{mg}} = & \sum_{mn \notin \boldsymbol{\psi}_{mg,z_{mg}}} \frac{R_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right) \\ & + \sum_{mn \in \boldsymbol{\psi}_{mg,z_{mg}}} \frac{R_{mn}}{V_{n,h}^2} \left((P_{mn,h} - P_{n,h}^{g} - P_{n,h}^{st})^2 \right. \\ & \left. + \; (Q_{mn,h} - Q_{n,h}^{g} - Q_{n,h}^{st})^2 \right), \\ & \forall (mn) \in \boldsymbol{B}_{mg}, \forall m,n \in \boldsymbol{N}_{mg} \end{aligned} \tag{3.15}$$

The remainder of the parameters in (3.14) and (3.15) are as previously defined for (3.5) and (3.6)

3.4.3 Constraints for MGIP

Similar to grid integration of DERs [64], DNEP [117], and MP [118], the MGIP problem shall be constrained to the power flows equations of the resulting integrated network, voltage constraints, and the thermal capacity of the assets within the expanding main grid and associated minigrids as follows:

Power flow constraints

The first set of equality constraints for this optimisation MGIP will come from power flow equations. For a detailed development of the equations that follow, refer to [64], [117]. Recalling the notation presented in Figure 13, the active and reactive power balance at each network node, say m, will be given by:

$$\sum_{km \in \boldsymbol{B}} P_{km,h} - \sum_{mn \in \boldsymbol{B}} \left(P_{mn,h} + R_{mn} I_{mn,h}^2\right) + P_{m,h}^g + P_{m,h}^{st} - P_{m,h}^d = 0; \quad \forall k, m, n \in \boldsymbol{N} \tag{3.16}$$

$$\sum_{km \in \boldsymbol{B}} Q_{km,h} - \sum_{mn \in \boldsymbol{B}} \left(Q_{mn,h} + X_{mn} I_{mn,h}^2\right) + Q_{m,h}^g + Q_{m,h}^{st} - Q_{m,h}^d = 0; \quad \forall k, m, n \in \boldsymbol{N} \tag{3.17}$$

Here (3.16) ensures that there is active power balance on all nodes of the network i.e. the incoming active power at any node is equal to the outgoing active power. Similarly, (3.17) ensures that there is reactive power balance on all nodes in the network.

The voltage drop across any network branch is given by

$$V_{m,h}^2 - V_{n,h}^2 = 2\left(R_{mn} P_{mn,h} + X_{mn} Q_{mn,h}\right) + (R_{mn}^2 + X_{mn}^2) I_{mn,h}^2 \,; \quad \forall (\boldsymbol{mn}) \in \boldsymbol{B}, \forall \boldsymbol{m}, \boldsymbol{n} \in \boldsymbol{N} \tag{3.18}$$

and the square of the current, appearing in (3.16) to (3.18) through each network branch is given by:

$$I_{mn,h}^2 = \frac{P_{mn,h}^2 + Q_{mn,h}^2}{V_{n,h}^2}; \quad \forall(mn) \in B, \forall m, n \in N \tag{3.19}$$

The power flow constraints for MGIP, presented in (3.16) to (3.19), show that MGIP is a non-linear model as they contain a mixture of multiplication and squaring of terms at various points.

Voltage limits

The first inequality constraint for this problem will be that the voltages at all network nodes are within a set band, as follows

$$V_{min} \leq V_{m,h} \leq V_{max}; \quad \forall m \in N \tag{3.20}$$

The limits may be 1 ± 0.05 or 0.1pu. Unless stated otherwise stated, a band of 1 ± 0.05pu [64] is used in this thesis.

Thermal and capacity limits

Another set of inequality constraints come from the thermal and capacity ratings of the network assets. To ensure that all transformers are within their thermal limits the following constraints are obtained

$$S_{tfr}^{min} \leq S_{tfr,h}^{mg} \leq S_{tfr}^{max}; \quad \forall tfr \in \boldsymbol{TFR}, \forall mg \in \boldsymbol{MG} \tag{3.21}$$

Where $S_{tfr,h}^{mg}$ is the complex power flowing through any transformer, at any time *h*, connecting a minigrid *mg* to the main grid. S_{tfr}^{max} is the maximum thermal limit of the transformer in kVA, and $S_{tfr}^{min} = -S_{tfr}^{max}$, in case of reverse power flow.

It is important to ensure that all line branches are not overloaded, and this is expressed as

$$\left|I_{mn,h}\right| \leq I_{mn}^{max}; \ \forall (mn) \in \boldsymbol{B} \tag{3.22}$$

Where $I_{mn,h}$ is the current through any network branch, *mn*, at any time, h, and I_{mn}^{max} is the maximum current carrying capacity of that branch.

Every generator is to be operated within its thermal limits and hence

$$0 \leq P_{m,h}^{g} \leq P_{m}^{g,max}; \quad \forall g \in \boldsymbol{G}, \forall m \in \boldsymbol{N}_{mg} \tag{3.23}$$

Where $P_{m,h}^{g}$ is the hourly power output from any generator g located at node m within a minigrid network mg and $P_{m}^{g,max}$ is the maximum power output from that generator.

Constraints (3.24) ensures that any energy storage devices present in the network are operated within their power ratings in kW, and (3.25) makes sure that any storage device is not charged beyond its rated energy capacity and discharged below its minimum allowable state of charge.

$$0 \leq \left|P_{m,h}^{st}\right| \leq P_{m}^{st,max}; \quad \forall st \in \boldsymbol{ST}, \forall m \in \boldsymbol{N}_{mg} \tag{3.24}$$

$$C_{m}^{st,min} \leq C_{m,h}^{st} \leq C_{m}^{st,max}; \quad \forall st \in \boldsymbol{ST}, \forall m \in \boldsymbol{N}_{mg} \tag{3.25}$$

Where $P_{m,h}^{st}$ is the hourly power, in kW, into or from a storage device at node m within minigrid network mg and $P_{m}^{st,max}$ is the maximum power rating of that storage device. Also, $C_{m,h}^{st}$ is the energy discharge from the storage device, $C_{m}^{st,max}$ is the maximum energy capacity of the storage device, in kWh, and $C_{m}^{st,min}$ is the minimum energy capacity allowable on the storage device.

The storage inequality limits of (3.24) and (3.25), the following equality constraints also apply to the storage devices:

$$SOC_{m,h}^{st} = \frac{C_{m,h}^{st}}{C_{m}^{st,max}} \tag{3.26}$$

$$DoD_{m,h}^{st} = 1 - SOC_{m,h}^{st} \tag{3.27}$$

Where (3.26) defines the State of Charge (*SOC*) and (3.27) defines the Depth of Discharge (*DOD*) of any storage devices. These parameters are critical in determining when the storage devices are ready for charging, discharging, or idle.

This section has presented the MGIP problem considered in this thesis and proposes a solution approach, which incorporates complete power flow analysis and related constraints. Here the combination of the developed objective function, and the given constraints define the entire model of the MGIP and informs the characterisation and choice of method for solving the MGIP problem.

The presented formulation addresses key limitations to applying electricity access planning tools in grid integration of minigrids [50]. Firstly, it brings together the expanding grid and minigrids, which is not the case in electricity access planning tools. Secondly, most electricity access planning tools do not include a power flow analysis capability, which renders them unsuitable for improving parameters such as network losses and, subsequently, voltage profile improvement, which will be important beyond the achievement of SDG7 [23], [27].

3.4.4 MGIP problem model

The main objective of the MGIP problem, as developed in this thesis, is to minimise investment cost and power losses on grid integration of any number of minigrids. Therefore, the complete MGIP problem can generically be modelled as:

Objective function	:	(3.10)
Subject to	:	Equality constraints: (3.16) - (3.19), (3.26) - (3.27)
		Inequality constraints: (3.20) - (3.25)

At the planner's discretion, the objective function can be replaced with other single objectives or combinations of objectives to form a multi-objective MGIP problem [163].

Whatever the objective function, constraints (3.16) - (3.27) should be respected to ensure the electrical feasibility of the planning solutions.

Based on the type of variables, and linearity and convexity of functions, the general formulation of the MGIP problem, modelled above, can be characterised as a non-convex mixed-integer non-linear problem (MINLP) [144]. It is 'mixed' because it contains both continuous and discrete variables. Variables such as current, demand, generator outputs are continuous, while capacity of transformers and grid infeed points into the minigrids are discrete, as the transformer can only assume a certain size and the grid infeed point can only be one of the nodes within the minigrid.

The MGIP problem is inherently nonlinear because it incorporates power flow constraints which are themselves nonlinear [117]. Specifically, the MGIP presented in this chapter has square terms of voltage, current, and active and reactive power in (3.14) to (3.19). Apart from the square terms, the presented MGIP problem formulation also contains a multiplication (and division) of terms, e.g., in (3.16) and (3.19).

Regarding convexity, the MGIP problem is characterised as non-convex for three main reasons. Firstly, it is discontinuous due to discrete variables, like grid infeed points and transformer sizes. Secondly, MGIP has nonlinear equality constraints, like active and reactive power balance in (3.16) and (3.17), that makes it non-convex [64]. Lastly, the losses part of the objective function involves solving power flow equations that are also known to have several local optima [144].

The MGIP problem, like many MINLPs, combines the difficulty of solving problems with discrete variables and nonlinear (and non-convex) functions. To illustrate the combinatorial difficulty associated with MGIP, consider the grid being expanded to a cluster of $\mathrm{n}(\boldsymbol{MG})$[8] number of minigrids. Disregarding the choice of grid infeed points within each minigrid, connecting a cluster of any $\mathrm{n}(\boldsymbol{MG})$minigrids to a single point of the grid presents $(\mathrm{n}(\boldsymbol{MG})+1)^{(\mathrm{n}(\boldsymbol{MG})-1)}$ possible combinations to the grid expansion problem alone.

For the illustrative case shown in Figure 11, where the grid is being extended to three minigrid networks, $\mathrm{n}(\boldsymbol{MG})$ will be equal to 3. Therefore, there are 16 possible combinations of the grid expansion layout to connect those minigrids to the main grid.

[8] $\mathrm{n}(\boldsymbol{MG})$ is the number of elements in a set of minigrids $\boldsymbol{MG}$

These combinations grow rapidly with an increase in the number of minigrids within the cluster. For example, a cluster of 12 minigrid networks (studied later in this thesis) yields 1.8×10^{12} possible grid expansion combinations.

Therefore, the MGIP is characterised as a non-convex mixed-integer non-linear problem (MINLP) that presents a significant solution challenges. Regardless of the difficulties in solving MINLPs, mathematical and heuristic techniques have been used to solve these problems in literature [138], [147].

3.5 Evaluating the MGIP problem

Having defined and characterised the complete MGIP model in Section 3.4.4, this section presents how the MGIP can be evaluated by selecting an algorithm and the implementation process developed in this thesis.

3.5.1 Mathematical/heuristic approach to solving MGIP

In Section 3.3.3, it was demonstrated that DNP problems, similar to the MGIP problem, are evaluated using mathematical and heuristic methods. This section discusses the suitability of each group of methods to solve MGIP. A single method is identified to be applied to the MGIP problem under investigation in this thesis.

Mathematically, one popular way of solving MINLP, like MGIP, is by linearisation, where linear equivalents replace any nonlinear functions of the problem to turn the former MINLP into a MILP [164]. In the case of MGIP, this would involve linearising the nonlinear terms in (3.14) to (3.19). This approach is used in [165], where the primary and secondary distribution network models were linearised to apply MILP techniques in minimising investment and operational costs. Though the linearisation exercise is not trivial, it allows for the application of established linear programming methods that are readily available, efficient and guarantee convergence [161]. However, linearisation significantly alters the characteristics of the problem at hand such that the solution can become difficult or impossible to implement in real life. For example, the microgrid planning in [145] significantly linearises the electrical aspects of the model such that the electrical feasibility of the optimised microgrid projects are not demonstrated

Without linearisation, MINLP problems can also be solved mathematically using a range of commonly used techniques such as branch-and-bound, and Benders' decomposition, whose detailed implementation is in [141]. Whether through linearisation or any other methods presented above, mathematical solutions to MINLP problems, like the MGIP problem, have the following deficiencies [138], [144]:

a. They cannot be applied to optimisation problems that are not presented in standard form of a generalised mathematical programming problem. Therefore, they require deep mathematical knowledge to be applied.
b. They may lead to practically infeasible solutions, especially when the characteristics of the optimisation problem have been altered through linearisation.
c. They may result in a local solution and not a global one when solving for optimisation problems with nondifferentiable, nonlinear, and non-convex functions.

The MGIP problem presented in this thesis accounts for the electrical behaviour of downstream minigrid and expanding main grid networks and assets for optimal grid integration. Applying mathematical methods to solve the MGIP would require some modification, compromising the detailed articulation of the downstream network behaviour. Therefore, classical optimisation methods are not used in solving the MGIP presented in this thesis. Instead, the MGIP, like other MINLPs, can also be solved using heuristic methods, which are solutions developed from experimentation to seek good solutions without guaranteeing optimality [138], [150]. Although they do not guarantee optimality and do not state the optimality gap, heuristic methods offer some advantages over their classical mathematical counterparts.

Firstly, heuristic methods do not require detailed problem-specific formulation for their implementation; hence, they can be applied in a range of problems as a ‘black box’ methodology without demanding high mathematical knowledge from the planner [150]. Secondly, heuristic methods do not require the simplifications of linearisation (or approximation) of problem functions to deal with non-linearities [144]. Therefore, they are likely to give out solutions that are feasible in the real world. Thirdly, heuristic methods, especially population-based ones, simultaneously search several regions of the solution space hence less vulnerable to being trapped in a local optimum [150].

Based on the above evidence, this thesis uses a heuristic method to solve the MGIP problem. Specifically, the method of choice is a GA, which is an optimisation method based on Charles Darwin’s theory of natural evolution [151]. This method has been applied to problems related to MGIP, such as DER placement [40] and network expansion

[45]. Besides the advantages presented above, which apply to most heuristic methods, and wide application of GAs in DNP problems, GAs offer the following specific advantages and disadvantages [150].

Advantages of GA

a. Modularity – GAs are structured in a way that the evaluation of the objective function and constraints are separate from its search process. This modularity allows for GAs to be interfaced with ready-made simulation models that can evaluate the nonlinear functions of the problems.
b. As a population-based technique, GAs process several solutions simultaneously. This allows GAs to be implemented using parallel algorithms hence reducing processing time.
c. It can easily be applied to a multi-dimensional or multiobjective problem.
d. It constitutes a set of solutions and not one solution. Therefore, if the global optimum is not reached, the algorithm still provides good solutions that can be feasible.

Disadvantages of GA

a. Slower convergence compared to other methods. However, it can be argued that it is better to solve an MINLP like MGIP slower and get a feasible real-world solution than to solve it quickly after linearisations and approximation to get a solution that is not feasible in the real world.
b. There are no set rules for setting GA control parameters, such as population size, generations, and mutation and crossover probabilities, and these parameters have a significant impact on the algorithm's efficiency. However, using empirically generated parameters is a widely accepted practice in the literature [139], [157].
c. GA does not guarantee global optima. However, since GA works with the entire model of the problem, it provides a good compromise between the accuracy of an optimisation method and the fidelity of the optimisation problem. Therefore, the low accuracy of GA is countered with benefits that accrue from solving a truthfully represented problem.

This section has presented the suitability of both mathematical and heuristic methods to solving the MGIP problem. Due to its flexibility in implementation and wide applications in similar distribution network planning problems, the heuristic method of GA has been identified as a suitable solver for MGIP. In the subsequent chapter, the MGIP model is applied to some case studies. Still, before that, the next section considers the structure for evaluating the MGIP problem using GA.

3.5.2 Evaluating the MGIP problem using GA

GA is a population-based heuristic optimisation method that mimics the theory of natural selection and evolution in nature [150]. This optimisation method is widely used in DNP problems, e.g. [139], [157], and its basic structure is shown in Figure 14.

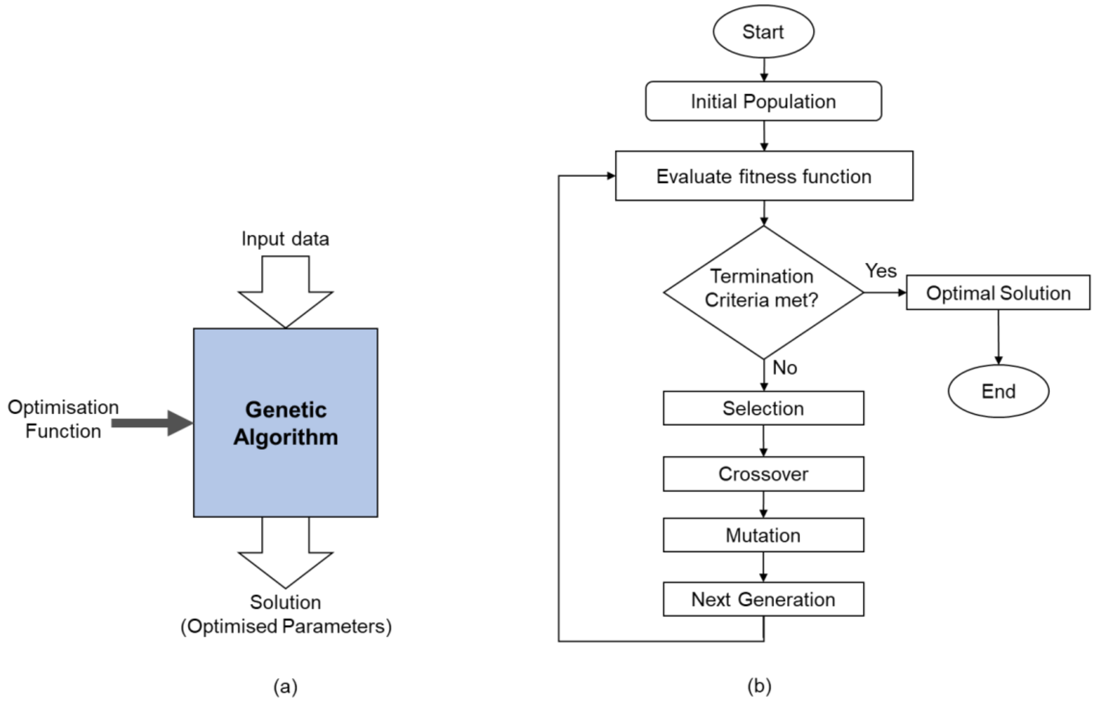


Figure 14: GA Optimisation. (a) Conceptual approach. (b) Flowchart [148]

The conceptual structure of the GA, in Figure 14 (a), presents the algorithm as a closed box accepting a predefined optimisation (or fitness) function and input data (such as independent variables) to come up with a solution. Figure 14(b) illustrates what generally happens within the closed box of Figure 14 (a). Since GA is based on genetic science, Figure 14(b) reveals that most GA terminologies, such as generation, population, selection, and so on, also originate from genetic science, and details on these and their implementation are in [151].

While authors like [51] use DNP problems to validate proposed advancements in evolutionary algorithms, like GA, the work in this thesis does not contribute to the algorithm itself. Instead, the current work uses GA to assess the proposed MGIP problem similar to [52], [157] and [166], where distribution network configuration, distributed generator sizing and placement, and multi-stage distribution network expansion problems are evaluated using GA, respectively. Motivated by the mentioned prior work, a structure for assessing MGIP is presented in Figure 15, and it consists of three main blocks of input, process, and output.

The structure for assessing MGIP, shown in Figure 15, is helpful to several stakeholders in the grid integration of minigrids. Firstly, the presented structure is helpful to planners as it specifies the data required by minigrid integration planners to conduct a robust study and develop an optimal integration plan. This is unlike in [36] and [37], where planning the grid integration of minigrids is not considered and the necessary data for such planning is not suggested. The data requirements specification is critical as the minigrid integration planner, usually from the power utility [72], will solicit this data from the minigrid operator. Therefore, a comprehensive and structured data specification facilitates such data collection.

Secondly, the structure in Figure 15 will be foundational to answering other questions related to minigrid integration planning. The presented structure is flexible enough to accommodate various aspects that could be studied in relation to the MGIP problem. For example, as stated earlier, this work does not contribute to the optimisation methods. However, the presented structure can be used to investigate efficient optimisation methods for solving MGIP by only focussing on the optimisation block of the structure.

Finally, the structure in Figure 15 can be instrumental in the development of a toolset for planning the grid integration of minigrids, which will be key in developing countries beyond achieving universal access. This toolset is necessary because currently, there are toolsets for offgrid, for example REM/RMM [43] and on grid planning, for example, DigSILENT [167], yet there is a lack of toolsets for planning the convergence of the two paradigms for achieving electricity access.

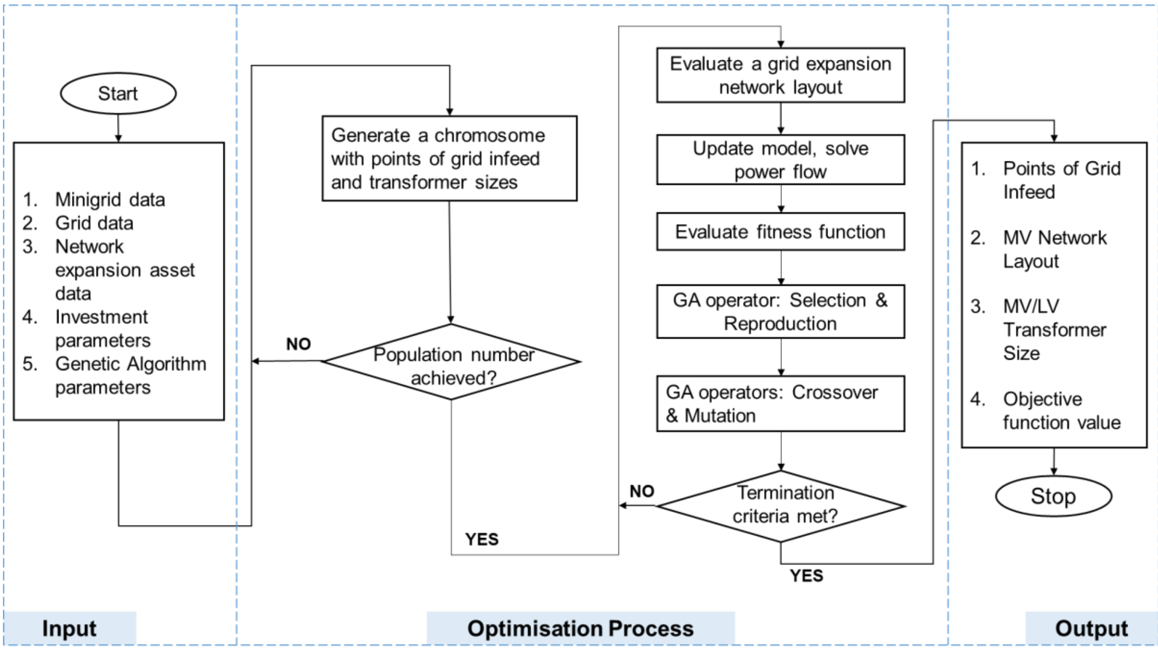


Figure 15: Structure for the evaluation of MGIP problem using GA

The details of the input, optimisation process and output blocks of the structure in Figure 15 are as follows:

3.5.2.1 Input for evaluating MGIP

This is the stage of the solution process where the necessary data and parameters are gathered for the evaluation of the MGIP problem. The data and parameters populated here include minigrid and grid data, network expansion asset data, investment parameters and GA parameters.

Minigrid(s) data input to MGIP

To evaluate the MGIP problem as specified in this thesis, a full electrical model of the candidate minigrid(s) and the geographical location of assets will be required. According to [160], the required minigrid models will involve the gathering of data categorised as electrical, profile, and geographic, whose details are in Table 10.

Table 10: Key minigrid input data for MGIP problem evaluation [160]

Data Type	Data
Electrical data	Nominal voltage
	Network nodes
	Network layout and connection
	Conductor parameters
	Generator size, type and location
	Storage size and location
	Demand size and location
Profile data	Demand/load profile
	Generator output profile
	Battery charging profile
Geographic data	x-y coordinates of all network nodes

The electrical data in Table 10 will serve two main functions. Firstly, it will form the basis of the electrical model of the minigrid. This model will be a crucial component in evaluating the power flow that informs objective function and constraints. Secondly, it will inform the new assets required to integrate the main grid with the minigrid. For example, if the voltage level of the minigrid is the same as that of the nearby main grid, the grid integration of such minigrid will not require a transformer.

The profile data helps enhance the electrical model by incorporating the time characteristics of demand, renewable generator output, and battery charging/discharging. Depending on the required level of detail, these profiles can be daily, weekly, monthly, or yearly [163]. Profiles for more extended periods represent the variations in demand and supply better, but they require longer time to get a solution [168]. For that reason, daily profiles are preferred in the case studies presented in this thesis.

The geographic data will mainly comprise the x-y coordinates (or any form of coordinates) that identify the geo-location of the network nodes and assets, such as lines and transformers, connected to those nodes [160]. These coordinates are helpful in evaluating the length of grid network expansion for different grid infeed points into the minigrid(s).

Grid data input to MGIP

Compared to the minigrid data, limited grid data is required to evaluate the MGIP problem because the formulation presented in this thesis does not focus on the reinforcement of the upstream grid network. Therefore, there will still be a need for electrical and geographic data of the point from which the grid is extended, similar to [31].

Key electrical data will include the identity/name of the grid terminal node from where the grid expansion will originate and the nominal voltage level of the grid at the grid terminal [7]. Unlike in the minigrid input data for MGIP, no profile data will be required for the grid input data for MGIP because this work assumes that there is no any other demand between the grid terminal point and the minigrid(s) requiring integration. Even if there existed a demand, the profile would be associated with that demand rather than the expanding main grid network. The x-y coordinates of the terminal grid node will be the only geographic data need. Table 11 shows a summary of the grid data required for the evaluation of MGIP problem.

Table 11: Key grid data requirement for MGIP [7], [31]

Data Type	Data
Electrical data	Nominal voltage
	Grid terminal node
Profile data	None
Geographic data	x-y coordinates of terminal grid node

Network expansion asset data and other costs

The key network expansion assets for the MGIP problem are electrical cables (or lines) and transformers [7]. The power lines will bridge the distance between the minigrid(s) and the grid terminal point. On the other hand, the transformers will interface the incoming grid line with the incumbent minigrids, if the main grid and minigrid(s) are at different voltage levels. Table 12 summarises the network asset data required for MGIP.

Table 12: Network expansion asset data for MGIP [169]

Data Type	Data
Line data	Cost per unit length
	Conductor parameters
Transformer data	Candidate transformer sizes
	Candidate transformer costs

The line data required for MGIP problem include the cost per unit length of network expansion at a particular nominal voltage and the conductor parameters. In some network expansion problems that focus on developed countries, such as [119], different conductor sizes assume different costs. While such approach is also valid, in most developing countries, the cost of conductors is diminished by development costs of network expansion per unit length. As such, in the developing world context, the main differentiator in the costs of network expansion is the nominal voltage at which that expansion is being carried out as noted in [7] and [169]. Therefore, the cost per unit length of expansion at a certain voltage level is adopted in this thesis, rather than the cost of individual conductor type.

Although the type of conductor used for grid expansion has a limited impact on the cost of the expansion, understanding the impact of the electrical characteristics is important. The electrical properties of the cables together with the size and other characteristics of the transformer, are used to model the electrical network between the grid terminal point and the minigrid(s) network. This model and that of the minigrid(s) is used to evaluate the loss aspects of the objective function and the power systems related constraints of MGIP problem.

Besides the transformer's electrical properties, the cost of transformers is also important. Typically, transformer costs are proportional to the size of the transformer [7]. Together with cost of network expansion per unit length, transformer costs inform the investment cost in the MGIP problem, for example, current rating.

Apart from the investment costs, the MGIP problem specified in this thesis also comprise of loss cost. Therefore, the cost of energy per unit is also another key parameter for the

MGIP problem. This is used to convert annual losses into annualised cost of losses in (3.13), which are added with the MGIP investment cost to have a total annual minigrid integration cost in (3.10)

Investment parameters

Investment parameters of the MGIP include discount rate (in percentage or per unit) and period of the project (in years). These are vital parameters in annualising the investment costs, for static planning modelling, or discounting/compounding them in a dynamic planning model [138].

GA control parameters

The setting of GA control parameters can become a research topic on its own, see [51]. The context and objective of such work is on improving the solution algorithm and there is little to no novelty associated with the problem being solved. However, the novelty of this thesis lies within the specification of the MGIP problem and not the solution algorithm. Therefore, the GA control parameters in this thesis are empirically generated, similar to other works like [139], [157].

3.5.2.2 Optimisation process for evaluating MGIP

The optimisation process block of the structure for evaluating the MGIP problem presented in Figure 15 has two major parts discussed in his section. These are initialisation and the evaluation of the GA. Both processes take advantage of the modularity of GA [150] by interfacing with a power flow module outside of the GA.

Initialising GA for MGIP

After accepting the input data and parameters, the GA is initialised. Initialisation involves the generation of a set of random initial population of solutions to the MGIP problem [150]. In the MGIP evaluation structure, the initialisation process, as shown in Figure 15, shall generate several chromosomes with the grid infeed points and transformer sizes for each minigrid requiring grid integration.

Evaluating GA for MGIP

After initialisation, the GA evaluates the MGIP problem, as shown in Figure 16. This stage takes advantage of the GA's ability to interface with external routines for grid expansion network layout and power flow analysis solver [64].

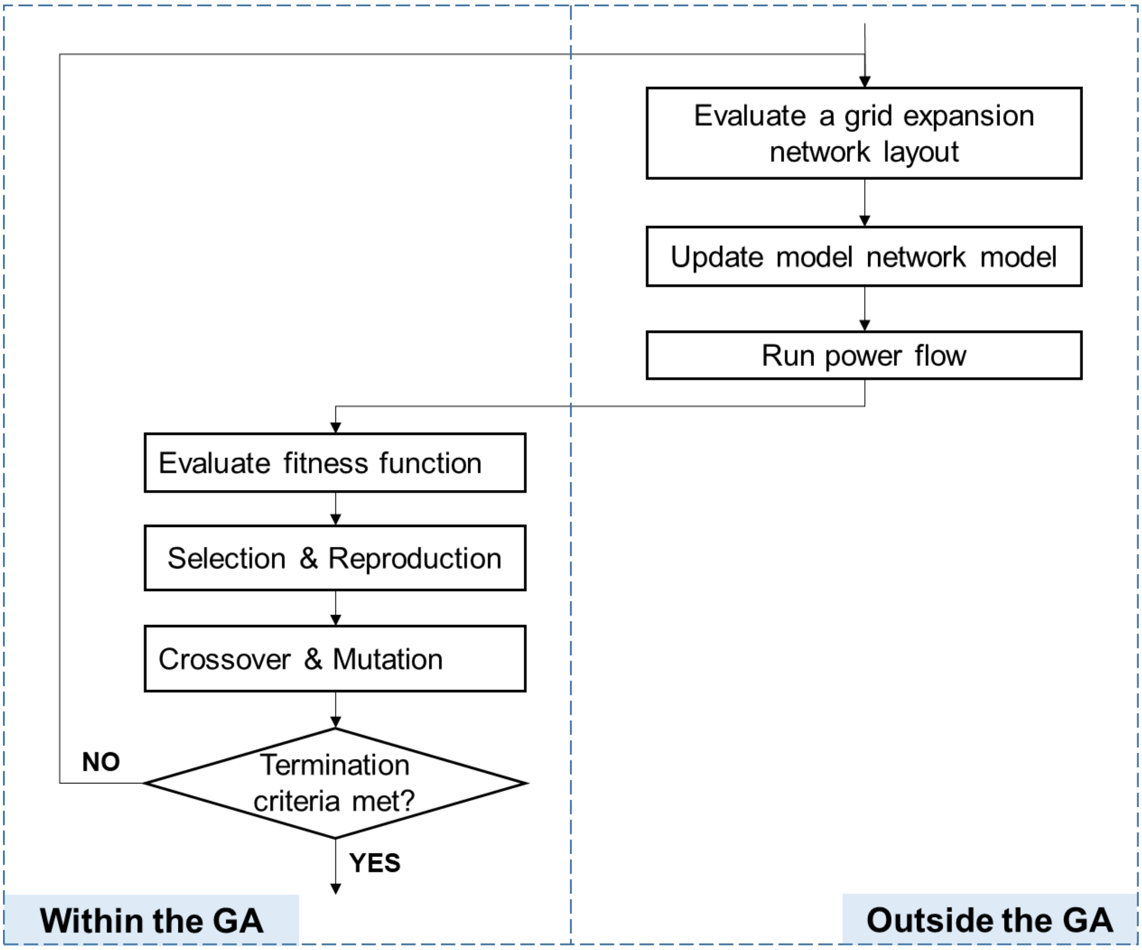


Figure 16: Structure of GA evaluation for MGIP

To establish the grid expansion/reticulation layout plan, the grid infeed points' location into the minigrids is crucial. They provide a landing point for the expanding main grid network from the grid terminal point to the minigrids. Therefore, the grid network expansion layout/reticulation is established by finding an MST between the grid terminal point and the set of grid infeed points into all minigrid(s) requiring grid integration [107], as discussed in Section 3.4.1.2.

Prim's algorithm [162] is used to evaluate the MST whose nodes (vertices) comprise of the grid terminal points and the point(s) of grid infeed into the minigrid(s). The weight of the branches are the distances between the nodes and Prim's algorithm establishes a spanning tree connecting all grid infeed point into the minigrids with the least sum of distances between nodes. The hub (or centre) node of the resulting MST is the grid terminal point.

The evaluation of grid expansion reticulation has two main outcome that are useful in MGIP. Firstly, the network layout from the grid terminal point to the minigrid(s) point of infeed is used to model the electrical connection between the main grid and the minigrids. Secondly, the total distance for the network layout is a critical input in the evaluation of the cost of investments.

After evaluating the grid expansion layout, the network model is updated with the latest reticulation between the main grid and the minigrid(s). Then, a power flow of the electrical network from grid terminal points to all the minigrids is evaluated [64], as shown in Figure 16. The power flow is vital for two main reasons. Firstly, it evaluates the electrical constraints associated with the MGIP as stated in the modelling section of the MGIP problem. The outcomes of the evaluation of constraints inform the feasibility of any solution. Secondly, the power flow is key in calculating losses used in evaluating the fitness function.

Following the update of the network model and power flow evaluation, the fitness function is evaluated, and each candidate solution is assigned a fitness value. This process is iterated until the GA is terminated. Following (3.10), the fitness value of the MGIP problem under investigation is evaluated from the summation of annual investment costs and annual cost of losses.

Once fitness values are established for each chromosome of a population, the chromosomes go through four GA operators of reproduction, selection, crossover and mutation to generate new candidate solutions [150]. Once the number of chromosomes from reproduction, crossover and mutation reaches the set population size, a new generation of solutions is said to be found. Then, the GA checks whether it should terminate the evaluation process or do another iteration. At the end of every iteration, the GA checks whether the termination criterion has been achieved. Once a termination criterion is met, for example reaching a certain number of generations, the GA terminates. Otherwise, the newly generated population of solutions using genetic operators are used in the next iteration.

3.5.2.3 Output of evaluating MGIP

At the end of solving the MGIP problem, the following primary and derived outputs are realised:

Point(s) of grid infeed – As part of the independent variables, grid infeed points into the minigrids are critical primary outputs after evaluating the MGIP problem. As stated earlier, grid infeed points are expected to influence both the cost of a grid network expansion to the minigrids and the post-integration performance of the individual minigrid networks.

Grid network expansion layout is derived from the grid infeed points into the minigrid(s) and grid terminal points. The layout is useful for the visualisation of how the main grid can be expanded to the minigrids. It is also key in visualising the grid infeed points relative to the location of generators or loads on each minigrid network.

MV/LV Transformer Size(s) – These are another set of primary outputs, especially when the minigrid network requiring grid integration is at a different voltage level from that of the main grid. This variable will affect the cost of grid integration as high-capacity transformers are expensive compared to their low capacity counterparts.

Objective function value – This is an evaluation of the objective function for the optimised grid infeed points and transformer sizes from the evaluation of the MGIP problem. Most parts of this thesis apply the objective function in (3.10). However, a different objective may also be applied depending on the preference of the planner.

Grid infeed points, transformer sizes and grid network expansion layout can provide a basis for comparing the MGIP problem proposed in this thesis with other methods. However, the value of the objective function forms a reasonable and quantifiable basis for such a comparison.

3.6 Chapter Summary

This chapter has presented the methodological approach for minigrid integration planning (MGIP) problem, which is proposed and explored in this thesis. The chapter begins by describing the different fates of minigrids when the grid is extended to their territories, namely, side-by-side operation, abandonment, and grid integration. Advantages, challenges, and implications on planning associated with each of the three options were also presented. It was established that unlike in abandonment and side-by-side operation, a systematic planning methodology for grid integration of minigrid was required to maximise the benefits associated with such integrations.

Before, the formal definition of the MGIP problem, critical aspects for specifying a distribution network planning (DNP) problem are reviewed. These aspects include problem definition, modelling and solution. Then, the MGIP problem is conceptually defined as, "*What is the best way to integrate a cluster of isolated minigrids from a* *specified point of the nearby/arriving main grid?*" After that, the variables, objective, and constraint functions of the MGIP are also presented.

The MGIP problem was found to have similarities with distribution network expansion planning (DNEP), and DERs integration which are fairly investigated in literature. However, the MGIP has been theoretically demonstrated to be a novel approach when compared to all these. One of the key aspects that distinguish the MGIP problem from other planning problems is that the point of grid integration is a critical independent variable in MGIP, and it is a fixed variable in either DNEP or DER integration.

After a mathematical characterisation, the MGIP has been demonstrated to fall into the mixed-integer nonlinear programming (MINLP) category, which comprises nondifferentiable, combinatorial and non-convex formulations. Due to its flexibility in implementation and wide applications in similar distribution network planning problems, the heuristic method of GA has been identified as a suitable solution algorithm for MGIP in the present work. A framework for solving MGIP using GA is presented and has three key blocks of data input, optimisation process and output. The work presented in this chapter gives the base methodology used to evaluate the MGIP case studies presented in the next chapter.

4 Minigrid Integration for Loss Reduction

4.1 Introduction

The previous chapter has presented the development and framework for applying the MGIP methodology for optimal planning of the grid integration of minigrids in developing countries. The proposed method accepts minigrids' network data, grid expansion data, and grid expansion investment parameters to develop an optimal grid expansion layout, minigrid integration transformer sizes, and grid infeed points into the minigrids. One of the key offerings of this methodology is that it presents a detailed articulation of the downstream minigrids instead of merely focussing on the expanding grid network. This chapter demonstrates the evaluation of MGIP for two case studies relevant to the grid integration in developing countries.

The first case study involves the grid integration of a single minigrid. In this case study, various DER and load scenarios of the candidate minigrid are investigated. For each scenario, the effect of minigrid DERs and load scenarios on the optimal minigrid integration plan are revealed. The second case study involves the grid integration of a cluster of twelve (12) minigrids. This case study demonstrates the application of MGIP methodology on a larger scale planning problem and the associated cumulative benefits.

Before presenting the case studies in this chapter, the minigrid data that has been used to develop the case studies is presented. There are many scenarios that MGIP could be demonstrated on, and the case studies presented in this chapter are not considered exhaustive, yet they cover the most likely post universal access scenarios in developing countries.

4.2 MGIP case study data

This section presents input data for the case studies reported in this chapter, comprising of data involving minigrids, the arriving grid, network expansion data, and associated investment.

4.2.1 Minigrid(s) data for case studies

Minigrid Networks

Due to lack of readily available standardized minigrid networks from developing countries, network data from [170], whose layouts are shown in Appendix-Table 1 (within Appendix 1), are used to represent minigrid networks. The node in each of these networks are numbered sequentially, similar to the illustrative example in Figure 12. There are three main reasons that support the suitability of applying these networks to the assess the MGIP problem.

Firstly, the IEEE Test Feeder Working Group[9] recommends that any test feeder can be used to investigate microgrid (or minigrid) related problems [171]. A survey of the available test networks [172] reveals that Network 1 in Appendix-Table 1, is one of the low capacity and low voltage IEEE test networks comparable to minigrids in SSA. Therefore, since Network 1 is originally from [170], then the rest of the networks from this source can also be considered useful in this respect.

Secondly, the networks from [170] comprise of both electrical network data and the geographic data of the network nodes. This combination makes these networks suitable for testing the application of MGIP problem as it requires both the electrical network model and geographic data of the network nodes. The electrical model provides outcomes of the power flow analysis that informs the electrical performance of the minigrid networks. The geographic data is key in evaluating the network layout of the expanding main grid to the minigrid(s).

Thirdly, the secondary distribution voltages in most countries in SSA are operated at 50Hz with a voltage range of 220V to 240V which is akin to the European standard [7]. As such, all AC grid compatible minigrids also use the same standards [96], [98] Therefore, since the networks in [170] are for a typical European network, they would require minor adjustments to reflect a typical minigrid network in SSA. Changes that have been made to these networks include demand values and demand profiles, and the introduction of centralised generation and storage facilities where necessary.

Minigrid demand, storage and generator profiles

[9] https://cmte.ieee.org/pes-testfeeders/

Figure 17 shows generator, storage and demand profiles, representative of post-SDG7 minigrids in developing countries [21]. Different profiles could be used for this purpose [7], [173], but the ones in Figure 17 are sampled based on the following sources and assumptions:

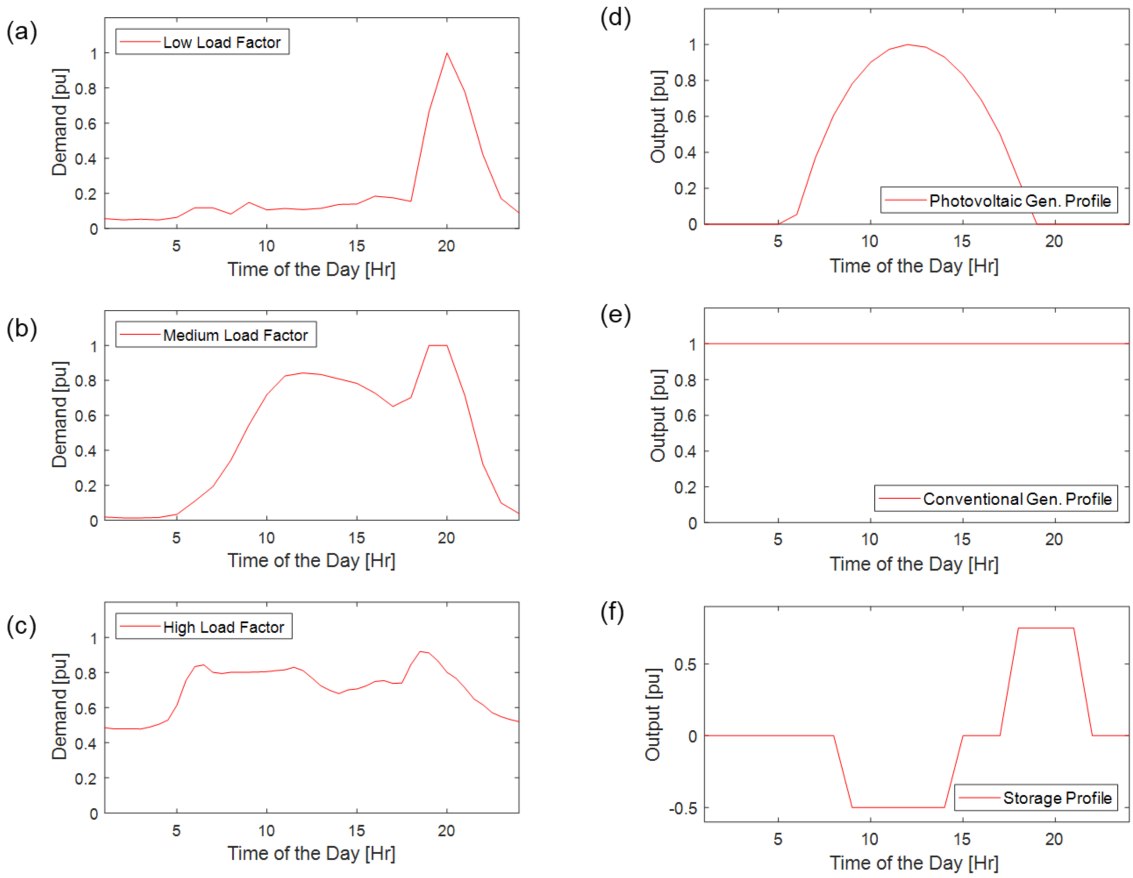


Figure 17: Generator, storage, and demand profiles for the case studies

- Figure 17(a) – Based on the demand profiles in [173], this is a demand profile with a low demand factor of 21%. This is a baseline demand factor for minigrids without any forms of economic use of energy or electric cooking as reported in [21].

- Figure 17(b) – Based on the data in [21], this demand profile has a medium demand factor of 46%. This demand profile is between the baseline minigrid demand factor of 22% and 80%, the highest demand factor that minigrids may attain with the introduction of more economic use of electricity and electric cooking [21].
- Figure 17(c) – Based on data from [174], this demand profile has a high demand factor of 69%. Although this is lower than the high demand factor of 80%

suggested in [21], it represents a realist value as grid level demand factors are up to 70% [175].

- Figure 17(d) – A representative photovoltaic generation profile for sub-Saharan Africa region based on data from [176].
- Figure 17(e) – A profile that assumes that a conventional generator, for example a mini hydro power plant, is generating at full power output for 24 hours of the day.
- Figure 17(f) shows a profile for charging and discharging the minigrid storage. The storage is charged during the day when PV generation is the highest and discharged in the evening when demand is high. It a combination of peak shaving in [177] and cycle-charging in [7].

Despite the lack of standardised minigrid networks specific to developing countries, the present work benefits from the guidance in [171] for selecting a test network for minigrid/microgrid applications. From the advice in [171], network models from [170] are used in this thesis with demand and generation profiles representative of a developing country minigrid [7], [21], [173].

4.2.2 Grid data for case studies

The main grid extending to the minigrids in the subsequent case studies is assumed to operate at a Medium Voltage (MV) of 11kV, one of the common MV distribution network voltage levels for grid expansion [7]. Although MV grid terminal voltages of 22kV and 33kV, and LV voltages of 0.4kV may be expected in developing countries [22], [169], different voltage levels would not significantly affect the implementation of MGIP.

If an MV grid terminal point were at 22kV or 33kV, the cost of transformers and network expansion per unit length would be higher than that of 11kV, the base MV voltage level in these case studies, because a higher voltage level requires more insulation [7]. On the other hand, if the grid terminal point were at 0.4kV, there would be no need to install a transformer, reducing the number of MGIP independent variables. Besides, the cost of network expansion per unit length of 0.4kV network would be less than 11kV, which is a higher voltage. However, large-scale grid expansion is rarely done at LV [32].

Therefore, a grid terminal point of 11kV is useful for two main reasons. Firstly, it is one of the MV level voltages which are used for grid expansion in SSA. Secondly, being at a different voltage level than the minigrids, which are at 0.4kV, allows for the full implementation of MGIP with all key independent variables, i.e. grid infeed points and transformers.

4.2.3 Network expansion asset data and other costs for case studies

These case studies use a recent World Bank reported [169] cost of expanding the 11kV per kilometre of $33,000 and sensitivity of MGIP results to this input is reported in the Appendix 3. Since the conductor size does not significantly affect the cost of network expansion per km, as discussed previously and noted in [7], a single conductor type was applied for the MV network expansion in the present work and its parameters are in Table 13.

Table 13: MV network expansion conductor parameters [170]

Parameter Name	Value	Unit
Resistance	0.4460	Ω/km
Reactance	0.0740	Ω/km
Ampacity	165	A

For the minigrid integration transformer options, the capacities and cost of candidate 11/0.4kV transformers are shown in Table 14. Each of the transformers are modelled with a percentage reactance of 4%.

Table 14: Candidate 11/0.4kV transformer data [7], [169]

Size/Capacity (kVA)	Cost ($)
50	1,435
100	2,173
200	3,246
315	4,247
500	6251
800	7512
1000	9355

The base cost of electrical energy and losses in these case studies is \$0.12/kWh [169]. The sensitivity of MGIP to the cost of energy/losses is presented in the Appendix 3.

4.2.4 MGIP investment parameters for case studies

The parameters for the minigrid integration investment used in these case studies are a conservative project evaluation period of 15 years and discount rate of 10% per annum [7]. Sensitivity of MGIP results to the project evaluation period and discount rate is presented in Appendix 3.

4.3 MGIP case studies

In this section, the MGIP proposed in this thesis, is applied to plan the grid integration of a single minigrid and then a cluster of minigrids. Through case studies, the outcomes of applying the MGIP methodology are compared to three other methods that may be deemed applicable for the grid integration of minigrids.

The first comparative approach to MGIP is based on the recommendations from [36] where the authors suggest that grid infeed point should be as close as possible to the incumbent minigrid generation facilities. Here, the grid infeed points are identified as the location of the incumbent minigrid DERs, which are usually at a single node within a minigrid [7], [130]. The transformer size is established by choosing a transformer size with higher thermal capacity than the known peak demand of the minigrid. This approach to grid integration of minigrids is basic and does not require any analysis or optimisation and hereinafter it will be called *No-opt*.

The second comparative approach to MGIP is based on [125], where the grid infeed point into minigrids is identified as the minigrid node that is closest to the geographic centroid of the spread of network nodes. The integration transformer size is established by choosing a size with higher capacity than the known peak demand of the minigrid. This approach is also applied in REM/RNM [43], a commonly used electricity access planning tool. This method uses geographical location of the minigrid network nodes to establish the point of grid infeed hence it will be called *Geo-opt* in this thesis.

The third comparative approach to MGIP is based on [161] and [21] where parameters of the expanding main grid (MV network) are optimised but the electrical behaviour and performance of the secondary network is neglected. The grid infeed points into the minigrids are identified as the minigrid node that will minimise the MV network required for the grid integration of minigrids. The transformer size is determined using power flow methods and the size which is higher than the maximum power flowing into/out of the minigrid is recommended. This approach is different from the No-opt and Geo-opt because it includes power flow analysis as part of the decision making. Since its focus is solely on minimising the expanding MV network between the grid infeed points and the grid terminal point, this approach will be identified as *MV-opt*.

4.3.1 Grid integration planning of a single minigrid

In this case study, various scenarios for the basic case of planning the grid integration of a single minigrid are investigated. For this case study, consider a minigrid shown in Figure 18 to be grid integrated from point A's grid terminal.

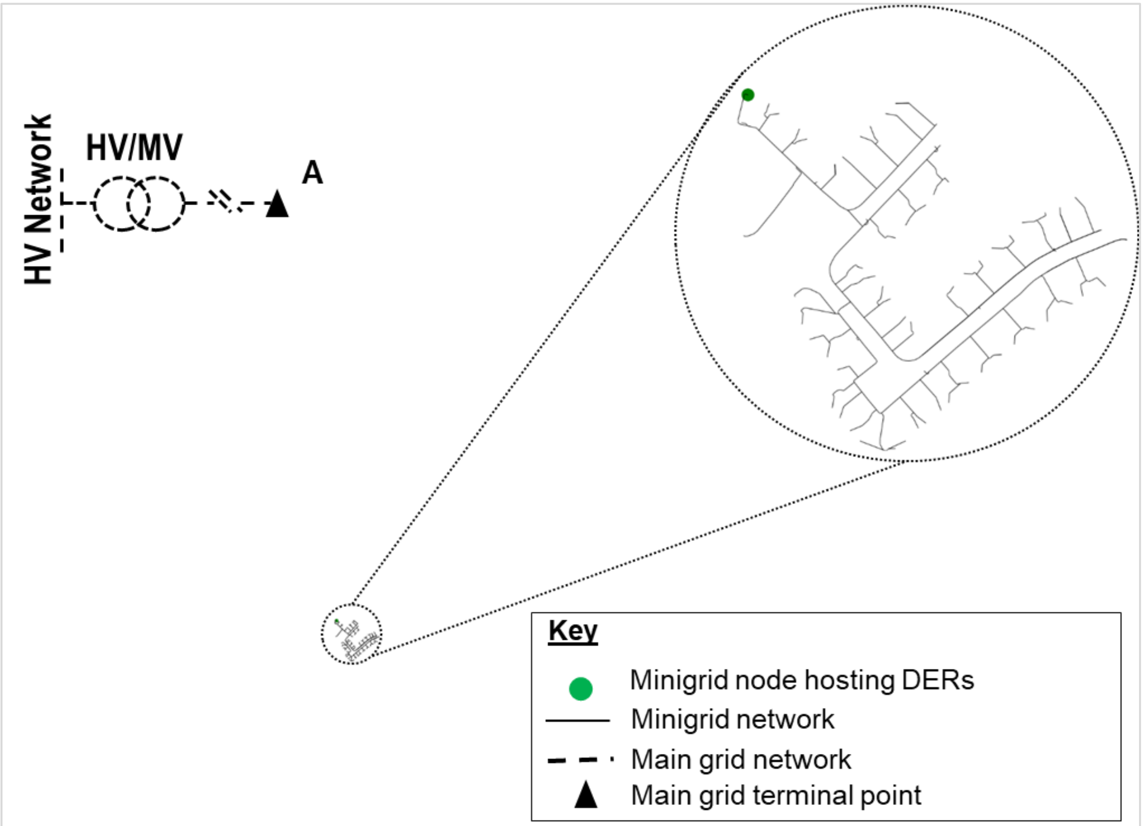


Figure 18: Single minigrid requiring grid integration from grid terminal A

The MGIP objective function for the grid integration of the minigrid in Figure 18 will be the sum of annual investment and loss cost (see (3.10). The four scenarios, presented in Table 15, are investigated for the grid integration of the single minigrid in Figure 18. The columns of Table 15 are intepretted as follows: “Scenario ID” identifies the scenario, “Minigrid DER” states the type of DER within the minigrid, “Demand Profile” specifies the demand profiles (from Figure 17) applied in the scenario is used, and “Represented

Operational Model" identifies the operational model, from Section 3.2.3, that each scenario represents.

Table 15: Scenarios for grid integration planning of a single minigrid

Scenario ID	**Minigrid DER**	**Demand Profile**	**Represented Operational Model**
Scenario 1	None	MD	SPD
Scenario 2	PV	LW, MD, HG[10]	SPP or SPP&D
Scenario 3	PV + Storage	LW, MD, HG	SPP or SPP&D
Scenario 4	Conventional generator	LW, MD, HG	SPP or SPP&D

4.3.1.1 Grid integration planning of a minigrid without DERs (Scenario 1)

Scenario 1 is representative of SPD [36], where the minigrid DERs are decommissioned due to energy cost or environmental concerns, e.g. case of diesel generators in Cambodia, or technological grid incompatibility [33]. This case study scenario applies a medium demand factor demand profile, as in Figure 17(b). This demand factor is preferred because it represents a compromise between the optimistic 80% and baseline 22% for future minigrids from [21]. Also, when the other demand factors were investigated, comparable results and conclusions were drawn from this scenario.

Solution time for the integration of a single minigrid model at an hourly resolution was approximately five minutes on a standard desktop. Having undertaken the minigrid integration planning investigations using the four methods of No-opt, Geo-opt, MV-opt and MGIP, the outcomes and their discussions are as follows:

Grid infeed points, transformer sizes, and MV network layout

Table 16 shows the resulting grid infeed points for each of the No-opt, Geo-opt, MV-opt and MGIP methods. Besides the grid infeed points reported in Table 16, it was also

[10] LW = Low demand factor. MD = Medium demand factor. HG = High demand factor.

established that all the four approaches came up with an integration transformer size of 315kVA.

Table 16: Grid infeed points for grid integration of a minigrid without DERs

Parameter	Method for planning integration			
	No-opt	Geo-opt	MV-opt	MGIP
Grid infeed point	1	116	1	46

Figure 19 shows the network expansion layout for all four approaches and where the grid expansion lines would land on the minigrid network. Since both the No-opt and MV-opt have a common grid infeed point into the minigrid (from Table 16), their lines are overlaid on top of each other, hence Figure 19 seem only to have three lines.

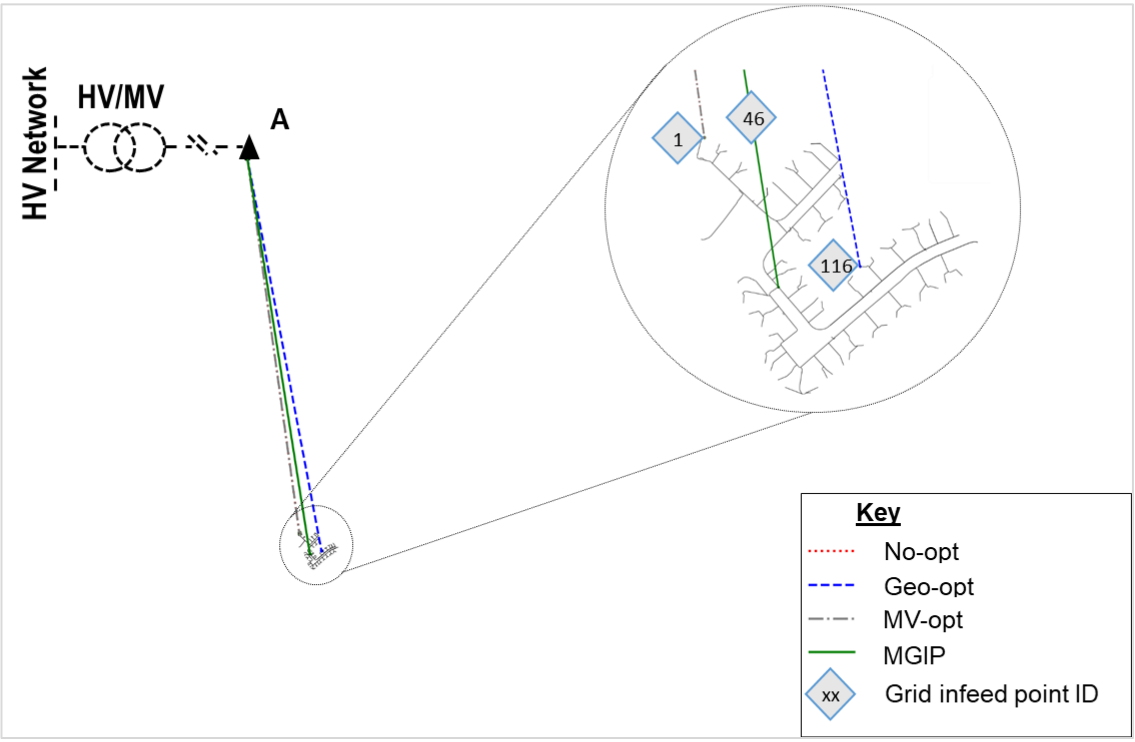


Figure 19: Network expansion layout for grid integration of a minigrid without DERs

The following key observations and discussions can be drawn from the results presented in Table 16 and illustrated in Figure 19.

There is variety in grid infeed points among the methods. Table 16 shows that among the four minigrid integration methods, there is variety in the grid infeed points identified by the different methods. Apart from No-opt and MV-opt, which yield the same grid infeed point, both MGIP and Geo-opt yield unique grid infeed points. The variety in grid infeed points demonstrates these approaches for planning the grid integration of minigrids will lead to different solutions (a feature that is not captured in other work). Therefore, the best integration planning method would be the one whose grid infeed points results in the best value of the objective function of the MGIP problem. Later in this section, the values of the objective functions for the solutions of the four methods are compared against each other to establish which method, and indeed, which grid infeed point is the best among them.

No-opt and MV-opt may not always yield a common grid infeed point. Table 16 shows that MV-opt and No-opt yield common grid infeed point and Figure 19 helps to understand why that is so in this case study. From the visualisation of the grid network expansion and their landing points in Figure 19, one can note that Node 1 (where the minigrid generator was located) is closer to the grid terminal point *A* than the rest of the nodes in the minigrid network. Since MV-opt looks to minimise the cost of network connecting the grid to the minigrid, the method identifies the Node 1 as grid infeed point, which is also the solution for No-opt. Although No-opt and MV-opt yield a common grid infeed point in this case study scenario, there is no indication that they are similar methods for grid integration planning of minigrids. Appendix 2 shows that if the grid terminal point were elsewhere, apart from Point A, MV-opt and No-opt will yield different grid infeed points.

MGIP and Geo-opt may demand longer MV lines than No-opt and MV-opt. From the network expansion layout in Figure 19, it can be observed that both the MGIP and Geo-opt will require longer MV network expansion lines than MV-opt and No-opt due to the respective distances from the grid incomer. This observation agrees with the assertions made in Section 3.4.1.2 that the grid infeed points affect the length, and eventual cost, of the line connecting the grid terminal point and the minigrid. This observation discussed further under objective function evalution.

All four methods yield the exact same transformer sizes. Despite the variety in grid infeed points, this case study scenario reveals that there is no variety in the resulting transformer sizes as all the four methods yield a 315kVA transformer. This confirms that for a minigrid network that does not have any incumbent DERs, the determination of the minigrid integration transformer's size can be by knowledge of the peak demand of the minigrid and a set of standard transformer sizes. Once these two parameters are known, the size of the integration transformer can be decided using basic engineering calculations without requiring a power flow analysis.

While basic engineering calculations could lead to satisfactory determination of the size of minigrid integration transformers, they may be inadequate at times. For example, when the minigrid network has some DERs that suppresses or shifts the peak demand [178]. Basic engineering calculations would also be inadequate during a dynamic planning study [138] – where the impact of the choice of transformer size is evaluated at the date of integration and for the next ten or more years.

Objective function evaluation for grid integration planning of a single minigrid without DERs

Figure 20 presents the outcomes of the objective function, in (3.10), for each grid infeed points corresponding to No-opt, Geo-opt, MV-opt and MGIP given in Table 16.

Figure 20 (a) presents the total annual minigrid integration cost, corresponding minigrid integration investment, and energy loss contribution. Figure 20 (b) and (c) show a breakdown of the different methods' annual investment and energy loss costs. Figure 20 (d) illustrates the total cost reduction when the total cost of all the integration methods are compared to No-opt. Figure 20 (e) and (f) show the respective contribution of investment and losses to the total cost reduction in Figure 20 (d). Thus, Figure 20 indicates the following:

MGIP yields the lowest annualised minigrid integration cost. Figure 20 (a) shows that the MGIP method yields the least cost annualised minigrid integration cost compared to the other three. The MGIP method is followed by MV-opt and No-opt in the cost metric, with the same annual integration costs. Lastly, the Geo-opt method leads to the highest annual cost of grid integration.

The superiority of MGIP is highlighted further in Figure 20 (d), where the annual costs of integration for all the methods are compared with costs of integration using the No-opt method. In this comparison, the cost of grid integration using the MGIP method is 38% lower than No-opt. Since MV-opt and No-opt have the exact integration cost in this scenario, their cost difference is 0%. However, the cost of integration using Geo-opt is

10% worse than that of No-opt. Therefore, MGIP is the best method to minimise the annual cost of grid integration of minigrids.

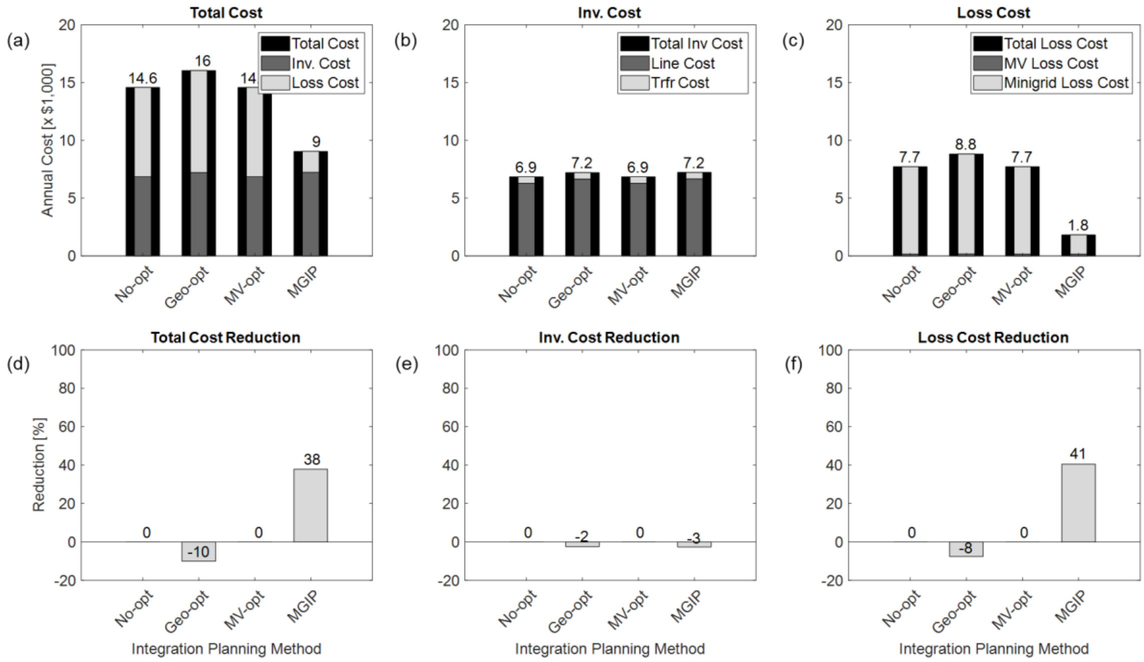


Figure 20: Objective function values for grid integration of a minigrid without DERs using different integration methods

Loss reduction is the main driver behind the superiority of MGIP. The breakdown of total integration costs, presented in Figure 20 (a), shows that the reducing cost of losses in this method drives the cost reduction in MGIP. This observation is also reinforced by Figure 20 (d) to (f). The 38% cost reduction in Figure 20 (d) is a composite number comprising of a 3% increase in cost for the investment cost and a 41% reduction in cost for the cost of losses, shown in Figure 20 (e) and Figure 20 (f) respectively.

Although Figure 20 (b) and (e) show that the MV-opt and No-opt yield the best annualised investment costs, there is no significant difference among the four methods' investment costs. The lack of significant difference in investment cost can be expected because an LV minigrid typically covers a very small area compared to the distances covered under grid expansion of the MV network. Of course, different grid infeed point affects the length of the incoming grid extension but at most in hundreds of metres and not kilometres. Once this additional line length is translated into cost and amortised over the length of the project life, it has a minimal effect on the annual cost of the line and hence on the MGIP objective function.

Minigrid losses are paramount to MGIP than MV losses. Figure 20 (c) shows that the cost of losses primarily consists of minigrid losses than MV network losses. The dominance of minigrid losses can also be observed in Figure 21 (a) to (c), where the losses, in MWh, for each integration method are presented and broken down into MV losses and minigrid losses. Figure 21 (a) to Figure 21 (c) show that the minigrid energy losses contribute about 98% of the total losses in the integration study.

The high losses in the minigrid network compared to the MV network should be expected for two main reasons. Firstly, the minigrid network is at low voltage, leading to significantly high current flows and high network losses. Secondly, the MV network in this case study only comprises the line connecting the main grid terminal point A and the minigrid. Therefore, in the grid integration of a single minigrid, there is not much of the MV network to contribute to losses compared to the several network branches within the minigrid network.

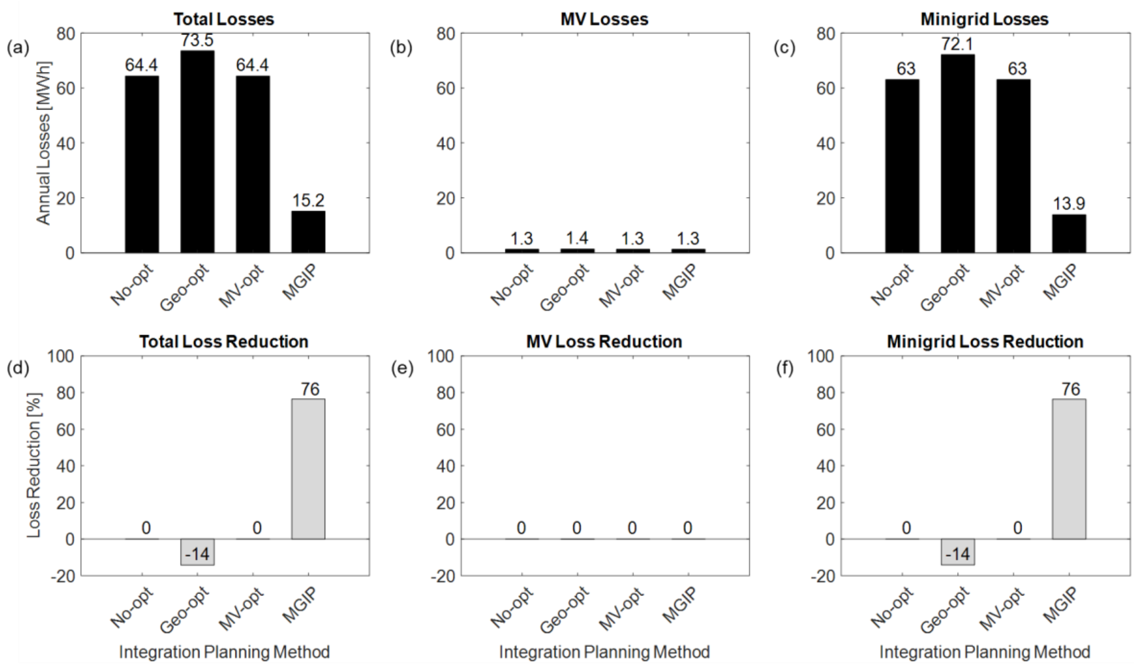


Figure 21: Losses and loss reduction for grid integration of a single minigrid without DERs

Therefore, the prior observation that the MGIP method solution is heavily driven by loss reduction can further be refined by identifying that the MGIP is the best method because it significantly reduces minigrid losses. When compared to the No-opt method, Figure (d) shows that the MGIP has an effect of reducing losses by 76%, and about 99% of those energy savings are from the minigrid component of the losses, as shown in Figure (e) and Figure (f).

In this case study, a loss reduction of 76% translates into an annual energy saving of 49MWh. If this minigrid was in Malawi, for example, a country with average annual electricity consumption of 108kWh per capita [179], 49MWh is enough to meet the annual electricity needs of around 450 people. Therefore, if such savings from using MGIP are made on several minigrids, saved energy can only increase.

Grid infeed points drive minigrid losses, which drive the benefits from MGIP. Lastly, the results presented here demonstrate that the grid infeed points significantly affect the objective function of the minigrid integration planning. Figure 20 (a) shows that different grid infeed points lead to different annualised integration costs. For example, No-opt and MV-opt have the same grid infeed point and consequently the same annualised integration cost. On the other hand, the unique value of annualised costs for MGIP and Geo-opt in Figure 20 also corresponds to having unique grid infeed points as reported in Table 16.

In conclusion, this section has demonstrated that the MGIP is the best method for planning the grid integration of minigrid as it leads to the minimum annualised integration cost. Further, the results also reveal that the minigrids loss term drives the annualised cost of integration. Since transformer sizing was found to be the same for all the grid integration methods, the critical independent variable in this case study was established to be the grid infeed point. The results in this section confirm the assertions made in Section 3.4.1.1 that grid infeed points would drive minigrid losses. Therefore, using the MGIP and associated systematic identification of grid infeed points is key in optimal grid integration of minigrids.

The observations presented and discussed here are based on studies for the grid integration of a minigrid without any incumbent DERs. However, as reported in [33], grid integration of minigrids may involve a minigrid containing DERs as in Scenarios 2, 3 and 4 from Table 15.

4.3.1.2 Grid integration planning of a minigrid with DERs (Scenarios 2, 3 and 4)

Scenarios 2, 3, and 4 are like SPP, SPP&D and some aspects of compensation in the convergence of minigrids and the main grid [36]. The minigrid DERs and network are retained and integrated with the main grid upon convergence with the main grid. These case study scenarios investigate the grid integration of the single minigrid, in Figure 18, with different penetration levels of PV, PV and storage, or conventional generator, using profiles in Figures 17 (d) to (f) . The demand profiles of low, medium, and high demand factors, as in Figures 17(a) to (c) are applied for each combination of DERs investigated.

For brevity, this section presents and discusses the No-opt and MGIP results for the grid integration of a single minigrid with various DERs and demand profiles as follows:

Grid infeed points and transformer size

Table 17 shows the optimal grid infeed points, and Table 18 shows the corresponding transformer sizes for the grid integration of the single minigrid with different demand factors, DERs and DER penetration. For the No-opt method, a comparator in these scenarios, the point of grid infeed is Node 1 (minigrid generator location). The corresponding No-opt transformer size for all DER types, DER penetration, and load profiles is 315kVA.

Table 17: MGIP grid infeed points for grid integration planning of single minigrid with various DERs and demand profiles

<table>
<tr><th rowspan="2">DER Pen.[11]</th><th colspan="3">PV</th><th colspan="3">PV + Storage</th><th colspan="3">Conv. generator</th></tr>
<tr><th>LW</th><th>MD</th><th>HG</th><th>LW</th><th>MD</th><th>HG</th><th>LW</th><th>MD</th><th>HG</th></tr>
<tr><td>0%</td><td>46</td><td rowspan="6">46</td><td rowspan="6">46</td><td>46</td><td rowspan="6">46</td><td rowspan="6">46</td><td>46</td><td>46</td><td>46</td></tr>
<tr><td>20%</td><td>46</td><td>46</td><td>39</td><td>46</td><td>46</td></tr>
<tr><td>40%</td><td>20</td><td>43</td><td>1</td><td>46</td><td>94</td></tr>
<tr><td>60%</td><td>5</td><td>37</td><td>1</td><td>20</td><td>46</td></tr>
<tr><td>80%</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>100%</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
</table>

Figure 22 shows the location of the grid infeed points, reported in Table 17, within the minigrid network under investigation.

[11] DER Penetration – DER peak power capacity as a percentage of minigrid peak demand [81]

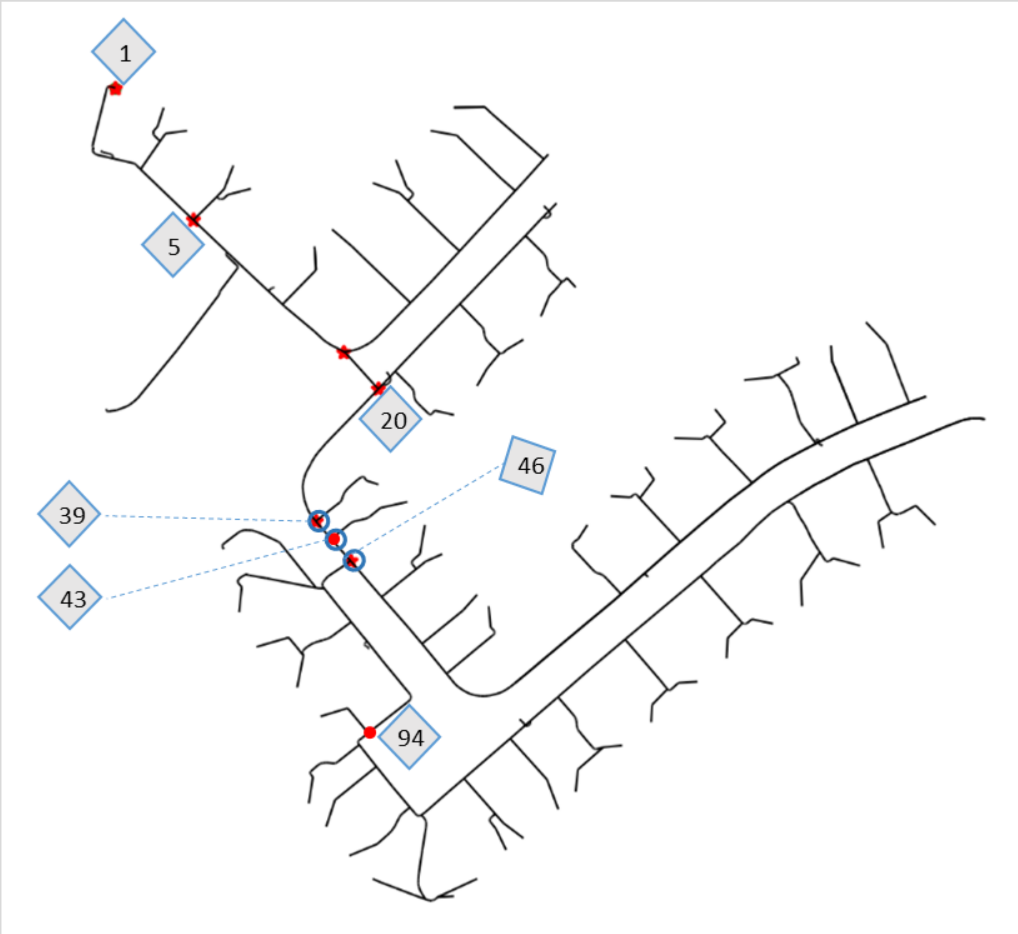


Figure 22: Location of grid infeed points reported in Table 17

Table 18: MGIP transformer sizes for grid integration planning of a single minigrid with various DERs and demand profiles

DER Pen.	PV			PV + Storage			Conv. generator		
	LW	MD	HG	LW	MD	HG	LW	MD	HG
0%	315	315	315	315	315	315	315	315	315
20%				315	315	315	200	200	200
40%				200	200	200	200	200	200
60%				200	200	200	200	200	100
80%				200	200	200	200	200	100
100%				315	100	200	315	315	200

The results in Table 17, Figure 22 and Table 18 motivate the following discussions:

MGIP reveals a characteristic optimal node for most of the scenarios. Table 17 reveals that Node 46 is a popular (or characteristic) optimal grid infeed point for different load profiles and DER combination. For example, Node 46 is the only optimal grid infeed point for all PV and PV + storage penetration scenarios under medium and high demand factors. Although there is a mixture of different points of grid infeed for the other combinations of DERs and load profiles, Node 46 is still one of the solutions. When compared with the No-opt grid infeed solution (Node 1), it is observed that the MGIP characteristic grid infeed node is not the node that hosts the minigrid DERs, Node 1 in this case.

The characteristic optimal grid infeed point for a minigrid can be identified when DER penetration is at 0%, as shown in Table 17. For ease of decision making, the minigrid integration planner should know the characteristic grid infeed point of the network under investigation as other combinations of DERs and loading may not yield the characteristic grid infeed point as discussed in the next point.

Increasing DER penetration moves the optimal MGIP grid infeed point away from the characteristic node towards the DER location. Table 17 also reveals that an increase in the DER penetration moves the MGIP optimal point of grid infeed towards the node hosting the minigrid DER (Node 1 or No-opt grid infeed point). This observation is accurate for low load profile with PV and PV + storage and all load scenarios when a conventional generator is connected.

The optimal grid infeed solution from MGIP may be tending towards the node hosting DERs because as the DER penetration increases, the positive impacts of a grid infeed point away from minigrid generator are outweighed by the negative effects of the increasing size of the minigrid DERs. However, considering that arrival of the main grid can spur load growth in the minigrid [21], it is reasonable for the planner to consider the prospect of such load growth over time. to assume that the demand profile in such minigrids will change over time.

The likely change in demand profile over time suggests that integrating the main grid to the less common nodes in Table 17 would not be a plausible long-term solution. If the demand is not expected to change significantly over time, the integration planners can recommend to connect to the uncommon grid infeed points that the MGIP yields under low load and high DER penetration scenarios. Otherwise, a connection to the characteristic node of the minigrid network under investigation can be recommended with the assumption that inherent minigrid demand will grow significantly hence affecting the DER penetration.

MGIP transformer sizing is not affected by PV without storage. Like the results of Scenario 1 Figure 19 shows that both MGIP and No-opt yield the same transformer size, 315kVA for the scenario with residual PV within the minigrid. This should be expected as PV generator without storage does not change the peak demand into the minigrid. For example, as shown in Figure 17(d), PV generates between 06:00 and 18:00 while the peak demand occurs around 19:00 and 20:00 in the load profiles presented in Figure 17(a) to (c). Therefore, as long as the peak demand remains unaltered, which will be the case if a minigrid's only residual DER is PV, the transformer sizes from the power flow based method, MGIP and non-power flow based, No-opt will remain the same.

The only way that PV without storage can influence transformer sizing is when the value of peak power export into the main grid exceeds the value of peak demand in the evening. This scenario would occur if the PV penetration level of considerably more that 100% was considered. However, the investigation reported in this thesis has limited residual PV penetration to 100% of the peak minigrid demand.

MGIP transformer sizing is affected by storage and conventional generator. Figure 19 reveals a variety of optimal transformer sizes for DERs of PV + storage and conventional generators. This variety of integration transformer sizes is unlike the results when the PV is used, where only one transformer size of 315kVA was being realised. Based on the demand factor and DER penetration levels, Table 18 shows that PV + storage and Conventional generator scenarios have 100kVA, 200kVA, and 315kVA as optimal transformer sizes for the integration. For example, in the medium demand factor scenario of PV + storage, Figure 19 shows that 315kVA transformer sizes are optimal for DER penetrations of 0% and 20% while 200kVA transformer sizes for generator penetration of 40% to 100%.

The variety in solutions to the transformer sizes can be attributed to the effect of energy storage and conventional generation on the net power leaving or coming into the minigrid. Since the conventional generator is assumed available and generating at full capacity for the entire day, its effect on the peak load is more significant than a PV generator without any storage. Also, since the energy storage discharges some power in the evening hours of the day, it reduces the amount of power required to flow into the minigrid to service the evening peak. The changes, caused by storage or conventional generators, in maximum net import or export from the minigrid affect the MGIP method's determination of the integration transformer size.

The determination of the transformer sizes through observing the magnitude of net power flow between minigrid and the main grid is vital because it avoids overinvesting in transformers [127]. However, such an approach becomes problematic when the minigrid DER fails, and the entire minigrid demand must get supply from the main grid. Given that the peak demand in the minigrid under investigation is 250 kW (see Appendix-Table 1), a 200kVA or 100kVA integration transformer may not be adequate to serve peak power demand when the minigrid generator is out of service. Therefore, transformer sizing for minigrid integration should be done to accommodate most of the possible scenarios that can occur in the minigrid network.

The results presented in this section demonstrate that, in most cases, the MGIP method identifies grid infeed points that are unique from those of No-opt method. As the DER penetration capacity increases, the optimal grid infeed points from MGIP move towards the location of the minigrid generator hub (or grid infeed point for the No-opt method). Since one may not intuitively know the tipping point for such combinations and shift of the best grid infeed point, the MGIP method provides a systematic approach of identifying the grid infeed point into a minigrid regardless of the demand profile or minigrid DER type and penetration level.

Objective function evaluation for grid integration of a minigrid with various DERs

Figure 23 shows the annualised costs of integrating the minigrid with three different DER scenarios of PV, PV + storage, conventional generator, using the MGIP and No-opt methods. Figure 23 (a) reports the integration costs for the minigrid with a low demand factor, while the results in Figure 23 (b) and (c) are for the minigrid with medium and high demand factors, respectively.

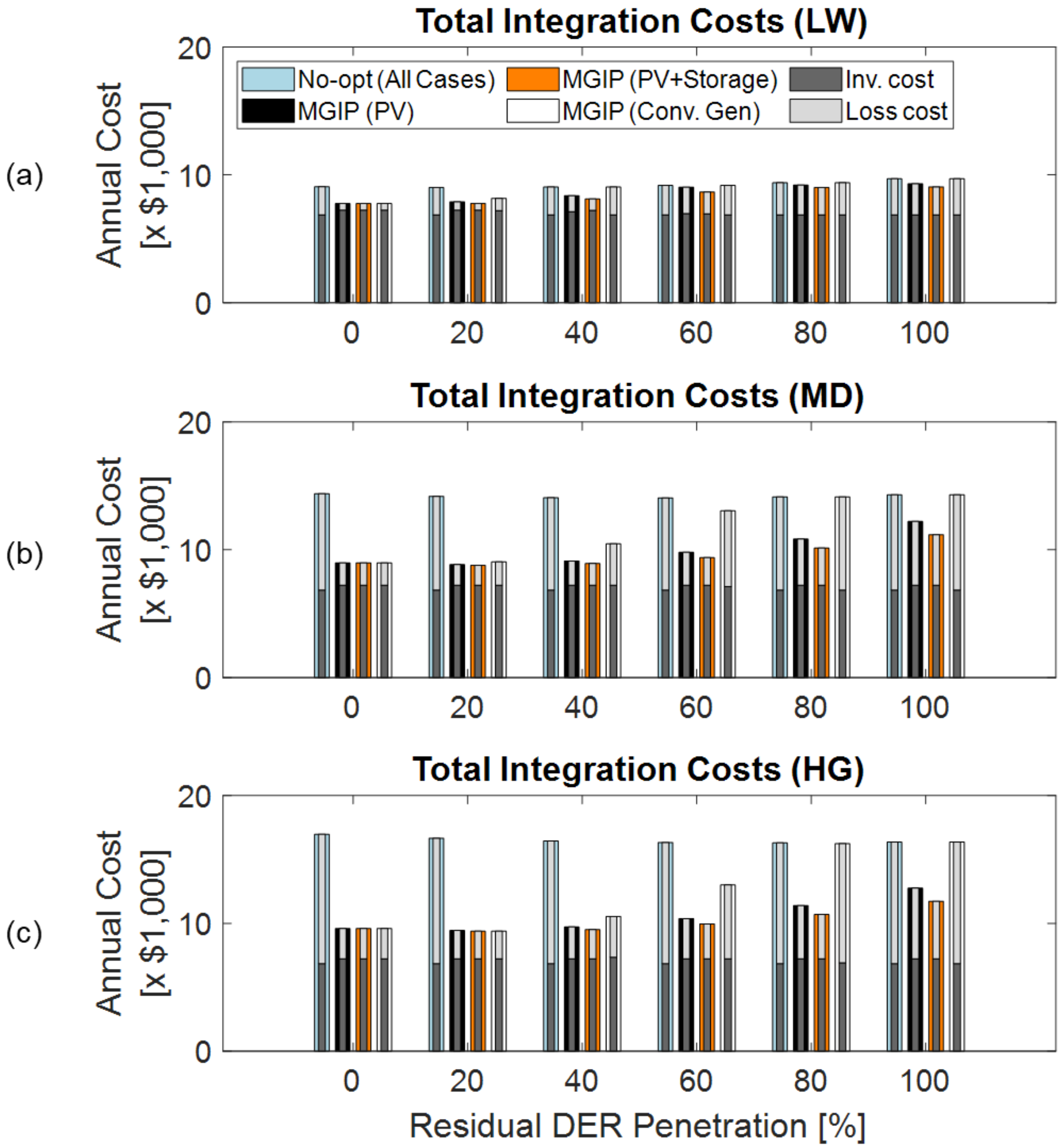


Figure 23: Annual integration costs for a single minigrid with various DER scenarios

Figure 24 shows the cost reduction benefits that could be realised from using MGIP compared to No-opt method for integrating the single minigrid with DERs to the grid. Similarly, Figure 24 (a) reports the integration cost reduction for the low demand factor scenarios, while the results in Figure 24 (b) and (c) are for medium and high demand factors respectively.

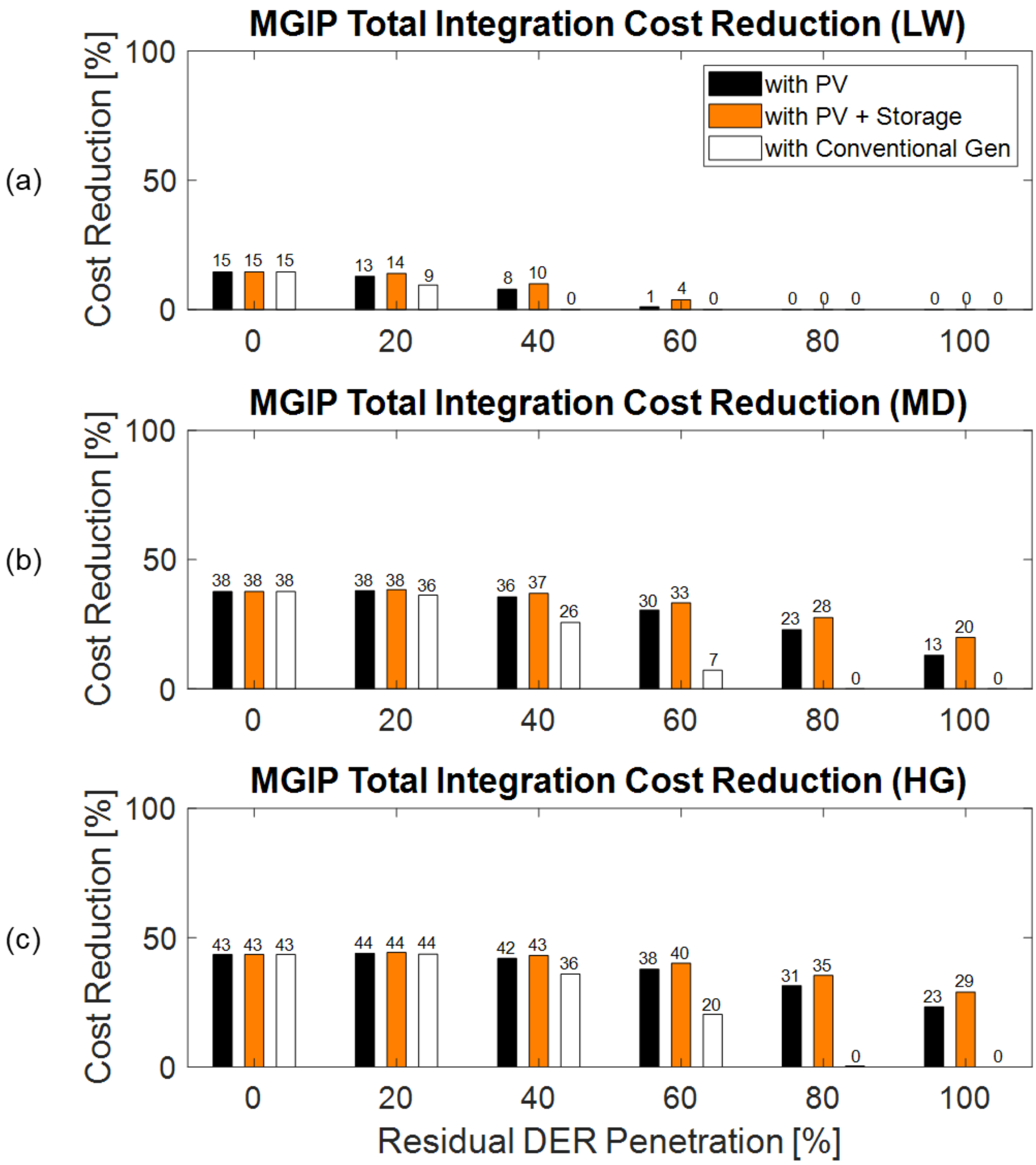


Figure 24: Cost reduction benefits of MGIP on a single minigrid with different demand profiles, DERs, and DER penetration

From Figure 23 and Figure 24, the following observations and conclusions can be made:

In most cases, MGIP is better than No-opt. A side-by-side comparison of annual integration costs for No-opt and MGIP in Figure 23 reveals that MGIP leads to lower objective function values in most cases. In the breakdown of the yearly cost of integration, it is evident that the MGIP is better than No-opt because MGIP has less annual cost of losses. This observation is consistent with observations made in the grid integration of a minigrid without any DERs. The superiority of MGIP is also highlighted in Figure 24, where MGIP leads to significant cost reductions except in specific scenarios of DER and loading where the cost reduction is 0%.

Benefits from the MGIP method increase with an increasing demand factor. The trend of results in Figure 23 and Figure 24 show that the economic benefits accrued from the MGIP method increase with an increasing minigrid demand factor. For example, Figure 24 (a) to (c) show that at 0% PV penetration, the annual integration cost of MGIP is 15%, 38% and 43% better than No-opt for low, medium and high demand factors, respectively. This trend can be observed for the other DER scenarios throughout the results in Figure 24.

The benefits of MGIP increase with increasing demand factors because the annual losses significantly influence them. The minigrid has fewer annual losses for low demand factors than medium and high demand factors, as shown in Figure 23. Therefore, for the same level of loss reduction (in the percentage of initial losses), the annual cost reduction will be higher for a lossy minigrid because the losses form a major part of the costs than for a less lossy one.

Benefits from the MGIP method decrease with increasing DER penetration. Results in Figure 23 also show that the benefits accrued from the MGIP method generally decrease with an increasing DER penetration compared to the No-opt method. For example, in the low demand factor scenario in Figure 24 (a), at 0% PV penetration, the annual integration cost of MGIP is 15% better than No-opt, while at 100% PV penetration, the MGIP is 0% better than No-opt. A similar trend is observed in the other DERs, PV + storage and conventional generator, in Figure 24(a) and the rest of the cases in Figure 24(b) and (c).

This trend can be attributed to the combined impact of grid infeed point and size of DERs on the losses within the minigrid network. Consider the losses component of the MGIP annual cost of integration in Figure 23 (b). For 0% DER penetration, there is a significant difference in cost of losses between No-opt and MGIP. This difference is attributable to the difference of grid infeed points into the minigrid (No-opt is Node 1 and MGIP is Node 46, see Table 17). Since there is no other source of power within the minigrid at 0% DER penetration, the change in losses is attributed to the difference in grid infeed points between MGIP and No-opt.

As the DER penetration increases, Figure 23 (b) show changes in the annual cost of losses for MGIP but the annual cost of losses for No-opt remain almost the same. The lack of change in the cost of losses for No-opt confirms the assertions made in Section 3.4.1.1, that when the grid infeed point is co-located with the minigrid generator, the size of the generator does not influence minigrid losses. On the contrary, when the grid infeed point is elsewhere in the minigrid network, as it is in the MGIP method, the size of the minigrid DER affects minigrid losses.

Due to higher DER penetration levels, the residual generator in the minigrid does not only serve adjacent demand, but it also exports some of the excess power to the upstream network through the grid infeed point. This introduces additional power flows in the minigrid as the grid infeed point is away from the minigrid generator location. Depending on the size of the minigrid DER, the additional power flow can increase or decrease losses in the minigrid. As the DERs penetration increases further, the additional losses caused by the minigrid generation reduces the loss reduction benefits that were gained through identifying an optimal grid infeed point. That is why Figure 23 (b) shows that a PV penetration level of 100% will lead to higher MGIP integration costs than at 20% penetration for the same point of grid infeed.

The interactions between grid infeed point, minigrid generator, and losses significantly influence the solutions of the MGIP method. For example, in the low demand factor scenario in Figure 24 (a), as the benefits from MGIP decreases from 15% to 0%, the optimal grid infeed point also changes from Node 46 to Node 1 (as reported in Table 17). The observed change in optimal grid infeed point further indicates that the influence of additional power flow and losses due to DER penetration is, at some point, greater than the benefits of selecting an optimal grid infeed point away from the minigrid generator node.

Therefore, the benefits of MGIP diminishes with increasing residual DER penetration in the minigrid. Under certain circumstances, like high PV penetration and low demand factor, the benefits from MGIP can be reduced to zero as the effect of additional generation capacity on losses in the minigrid outweigh the benefits of identifying grid infeed point away from the minigrid generator.

The type of minigrid DER influences the MGIP total minigrid integration cost. Figure 23 shows that the type of residual DER affects the annual cost of minigrid integration. This can be observed in the higher DER penetration levels where the cost of integrating a conventional generator using MGIP is like the cost of grid integration using No-opt. However, for higher penetration of PV + storage and PV only, the total MGIP integration cost is still lower than for the No-opt method.

A breakdown of the annualised cost in Figure 23 reveals that the difference in the various DER scenarios originates from the cost of losses and not investments. Conventional generator leads to high cost of losses because, upon grid integration, it can generate power for both the minigrid and the upstream network. In periods of low demand within the minigrid, the generated power will be exported to the upstream grid. Such exports are generally not part of the initial planning operation of autonomous minigrids for electricity access in developing countries. As a result, the exports lead to power flows that would not have been possible in the isolated state of the minigrid and hence increased losses.

On the other hand, PV without storage leads to lower losses than conventional generator because PV power is only available for a limited time of the day. However, PV + storage has the lowest cost of losses because of the ability of the energy storage to store some of the PV generated power and discharge it in the evening when the PV does not usually generate any power. Because the storage is co-located with the PV generator, the storage's charging cycle minimises the power capacity that the PV generator injects into the wider minigrid network. This injection of power also reduces the minigrid losses by shaving the minigrid's evening peak demand.

Besides the prior observation that size or penetration of minigrid DER influence the annual cost of integration, these results suggest that the type of residual minigrid DERs also affect the cost of minigrid integration.

The results presented in this section have further demonstrated the superiority of using the MGIP method even when the minigrid has some residual DERs. From these results, it can be concluded that benefits from using MGIP increase with an increasing demand factor in the minigrid and decreases with a rising penetration level of the residual DERs. Also, different combinations of residual DERs have been observed to affect the outcomes of MGIP differently, with PV + storage being the best among the DER combinations investigated here.

4.3.2 Grid integration of a cluster of minigrids

In this case study, the grid integration of a cluster of minigrids is investigated to demonstrate the application of MGIP in the grid integration of more than one minigrid. For this case study, consider the twelve minigrid networks shown in Figure 25 to be integrated with the grid from point A's grid terminal. The networks in Figure 25 are those presented in Appendix-Table 1 and are randomly placed at different distances and orientations from Point A without any perceived 'favourable' allocation or order. The presented example is one of several studies conducted on this cluster of minigrids and in each case, the location and orientation of the minigrid networks were changed.

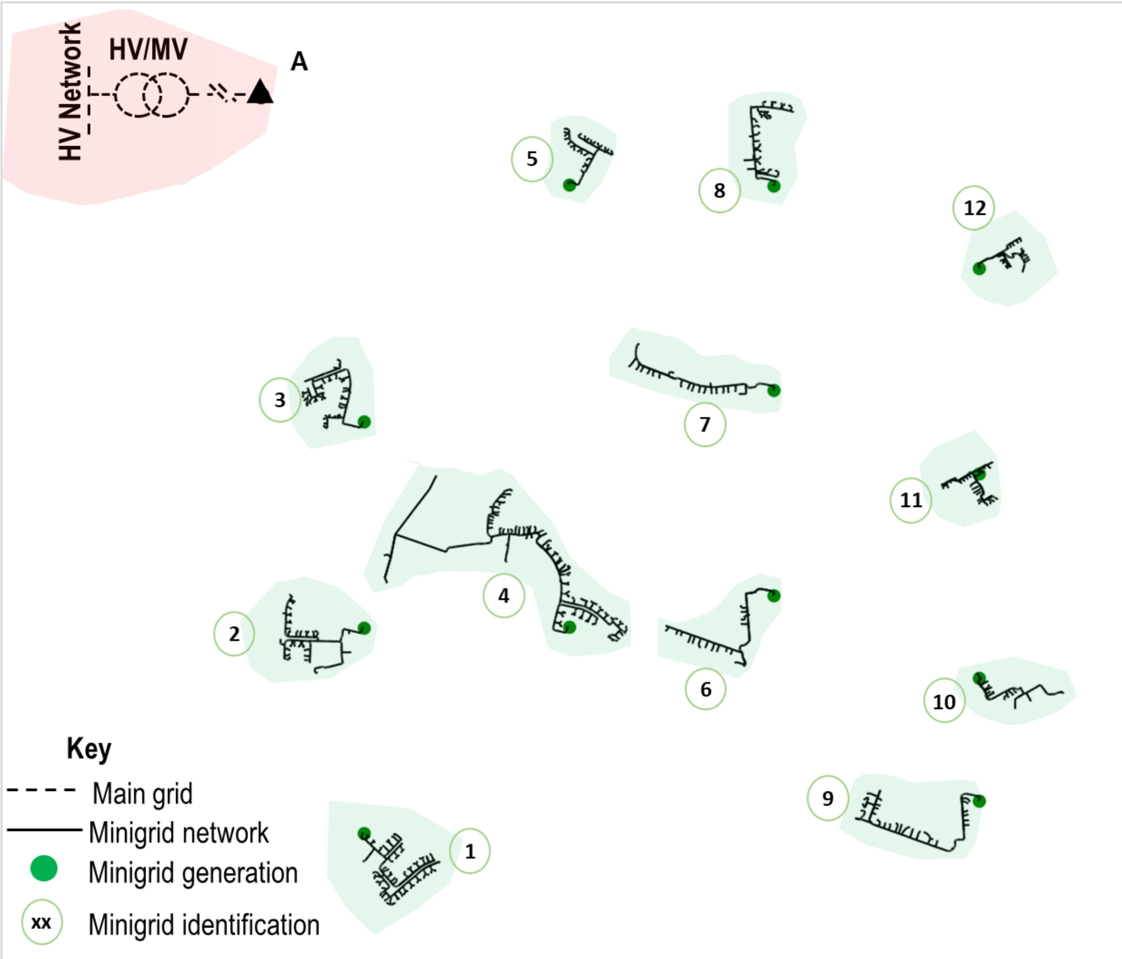


Figure 25: Cluster of twelve minigrids requiring grid integration

Using MGIP, the objective function for grid integration planning of the cluster of minigrids in Figure 25 will be as in (3.10) as follows:

$$\min f = \min\left(C_{ann}^{inv} + C_{ann}^{loss}\right) \tag{4.1}$$

Since there are twelve minigrids, there will be a set of twelve grid infeed points, one into each minigrid network, $z_{mg} \in \boldsymbol{Z} = \{z_1, z_2, z_3, \dots, z_{12}\}$. Connecting the MV side ofthese grid infeed points to the main grid terminal, z_{grid}, will result in a twelve branched MV network. Since the minigrids are assumed to be operating at low voltage, each grid infeed point will also host a transformer connecting the incoming grid to the minigrid network. Therefore, the annual investment cost for the grid integration minigrids in Figure 25 will be given by:

$$C_{ann}^{inv} = CRF\left(C_{mv}\sum_{mn=1}^{12} L_{mn} + \sum_{mg=1}^{12} C_{z_{mg}}^{tfr}\right); \tag{4.2}$$

$$\forall (\, mn) \in \boldsymbol{B}_{mv},\, z_{mg} \in \boldsymbol{N}_{mg}, tfr \in \boldsymbol{TFR}$$

The annual cost of losses will be:

$$C_{ann}^{loss} = 365 \times C_{energy} \times \sum_{h=1}^{24}\left(P_{loss,h}^{mv} + \sum_{mg=1}^{12} P_{loss,h}^{mg,z_{mg}}\right); \tag{4.3}$$

The MV network hourly losses for the grid integration will be:

$$P_{loss,h}^{mv} = \sum_{mn=1}^{12} \frac{R_{mn}}{V_{n,h}^2}\left(P_{mn,h}^2 + Q_{mn,h}^2\right); \quad \forall (mn) \in \boldsymbol{B}_{mv}, \forall m, n \in \boldsymbol{N}_{mv} \tag{4.4}$$

The sum of hourly minigrid losses will evaluate to:

$$
\begin{aligned}
\sum_{mg=1}^{12} P_{loss,h}^{mg,z_{mg}} = & \left[\left(\sum_{mn \notin \boldsymbol{\psi}_{1,z_1}} \frac{R_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right) \right. \right. \\
& + \sum_{mn \in \boldsymbol{\psi}_{1,,z_1}} \frac{R_{mn}}{V_{n,h}^2} \left((P_{mn,h} - P_{n,h}^g - P_{n,h}^{st})^2 \right. \\
& \left. \left. + \ (Q_{mn,h} - Q_{n,h}^g - Q_{n,h}^{st})^2 \right) \right) \\
& + \left(\sum_{mn \notin \boldsymbol{\psi}_{2,z_2}} \frac{R_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right) \right. \\
& + \sum_{mn \in \boldsymbol{\psi}_{2,z_2}} \frac{R_{mn}}{V_{n,h}^2} \left((P_{mn,h} - P_{n,h}^g - P_{n,h}^{st})^2 \right. \\
& \left. \left. + \ (Q_{mn,h} - Q_{n,h}^g - Q_{n,h}^{st})^2 \right) \right) + \cdots \\
& + \left(\sum_{mn \notin \boldsymbol{\psi}_{12,z_{12}}} \frac{R_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right) \right. \\
& + \sum_{mn \in \boldsymbol{\psi}_{12,z_{12}}} \frac{R_{mn}}{V_{n,h}^2} \left((P_{mn,h} - P_{n,h}^g - P_{n,h}^{st})^2 \right. \\
& \left. \left. \left. + \ (Q_{mn,h} - Q_{n,h}^g - Q_{n,h}^{st})^2 \right) \right) \right] ; \ \forall (mn) \in \boldsymbol{B}_{mg}, \forall m, n \\
& \in \boldsymbol{N}_{mg}
\end{aligned}
\tag{4.5}
$$

Where each point of grid infeed into the individual minigrids splits the minigrid network branches into two sets. For example, any point of grid infeed into Minigrid 1 (from Figure 25), z_1, splits the network branches into two sets. Firstly, a set of branches that are not part of the network that lies between the minigrid generator/storage and the point of grid infeed represented by $\boldsymbol{\psi}_{1,z_1}$ in (4.5). Secondly, a set that includes network branches in the electrical path between the minigrid generator/storage and the grid infeed point, z_1.

The MGIP integration planning problem for the 12 minigrids presented here is also constrained to the equality and inequality constraints presented previously in (3.16) to (3.27).

In this case study, the results from No-opt, Geo-opt, MV-opt and MGIP methods when integrating a cluster of minigrids to the main grid Figure 25 are compared. Each minigrid network is assumed to have a PV generator, which is a typical minigrid renewable generation technology is SSA [33], [43], with varying penetrations. A medium load profile, as shown in Figure 17(b), is used.

Solution time for a the integration of a cluster of twelve minigrids model at an hourly resolution was approximately forty minutes on a standard desktop. The results for planning the grid integration of a cluster of 12 minigrids are as follows:

Grid infeed points, transformer size and network expansion layout

Table 19 shows the grid infeed points for each minigrid within the cluster, each method and different PV penetration levels considered.

Table 19: Grid infeed points for the integration of cluster of minigrids

Integration Method	PV Pen.	Minigrid ID					
		#1	#2	#3	#4	#5	#6
MGIP	0%	46	55	7	151	35	81
	25%	64	75	50	218	6	152
	50%	60	86	31	209	44	156
	75%	60	95	60	207	11	134
	100%	94	67	47	220	18	172
MV-opt	All[12]	7	56	108	320	28	102
Geo-opt	All	116	55	70	124	14	132
No-Opt	All	1	1	1	1	1	1
Integration Method	PV Pen.	Minigrid ID					
		#7	#8	#9	#10	#11	#12
MGIP	0%	40	42	38	154	73	69
	25%	41	34	102	103	136	29
	50%	53	44	90	156	118	8
	75%	57	25	32	67	71	86
	100%	31	50	6	30	97	72
MV-opt	All	10	29	24	165	145	89
Geo-opt	All	41	36	48	146	100	95
No-Opt	All	1	1	1	1	1	1

Table 20 shows the integration transformer sizes for each minigrid network.

[12] All DER penetration levels – 0% to 100%

Table 20: Transformer sizes for the grid integration of a cluster of minigrids

Minigrid ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Transformer size (kVA)[13]	315	100	200	315	100	100	100	100	200	50	100	50

From Table 19 and Table 20, the following points are highlighted:

There is a greater variety of grid infeed points in MGIP than the other methods. Table 19 shows that MGIP results into a variety of grid infeed points across the five scenarios of PV penetration. In contrast, grid infeed points for MV-opt, Geo-opt and No-opt are independent of levels of PV penetration. For example, from Table 19, MGIP yields nodes 151, 218, 209, 207 and 220 as grid infeed points into minigrid 4, depending on the various levels of PV penetration. However, independent of PV penetration level, grid infeed points for minigrid 4 using MV-opt, Geo-opt and No-opt are 320, 124 and 1, respectively.

The variety in grid infeed nodes from MGIP demonstrates that MGIP is sensitive to the changes in the composition of residual assets in the minigrids requiring grid integration. Such sensitivity should not be expected from the other three methods because of the way grid infeed points are established. MV-opt establishes grid infeed points by minimising cable length for MV network expansion; hence, additional minigrid assets have no effect on that. Geo-opt found grid infeed points by determining the node of the minigrid that is closest to the centre of all the individual minigrid network nodes. Such approach is also unaffected with any addition to the minigrid network assets. Lastly, the arbitrary nature of identifying grid infeed points for No-opt also means that the composition of residual minigrid assets does not influence the solution.

MGIP results for a cluster of minigrids are more sensitive to minigrid DERs than those of single minigrid. As noted in the discussion above, MGIP results in Table 19 are sensitive to the changes in the DER situation of the minigrids in the cluster. For example, there are various grid infeed points for Minigrid 1 in Table 19 compared to the Node 46

[13] For all integration planning methods and PV penetration scenarios

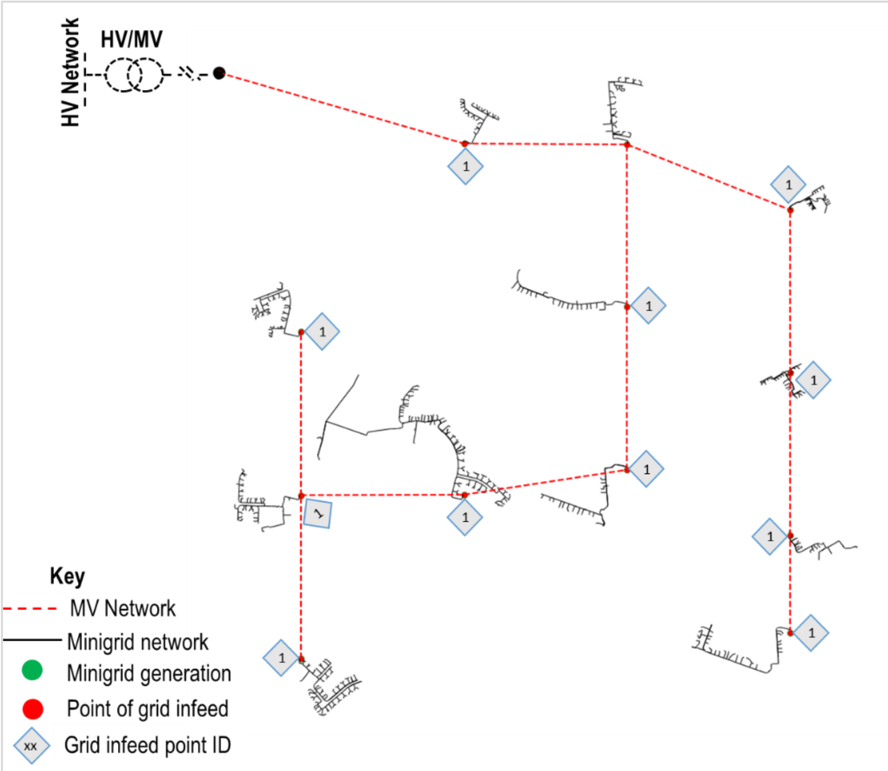
identified for all PV penetration levels for grid integration of a single minigrid with the same (medium) demand factor reported in Figure 17.

The sensitivity observed during the evaluation of grid integration of the cluster of minigrids can be attributed to having more than one minigrid in the cluster. In that case, the grid infeed points are not only determined by what happens with the connection of one individual minigrid, but it considers the sum of what happens with each minigrid in the cluster. Therefore, integration of a cluster of minigrids introduces more interaction and need for compromise between investment and losses than in the grid integration of a single minigrid.

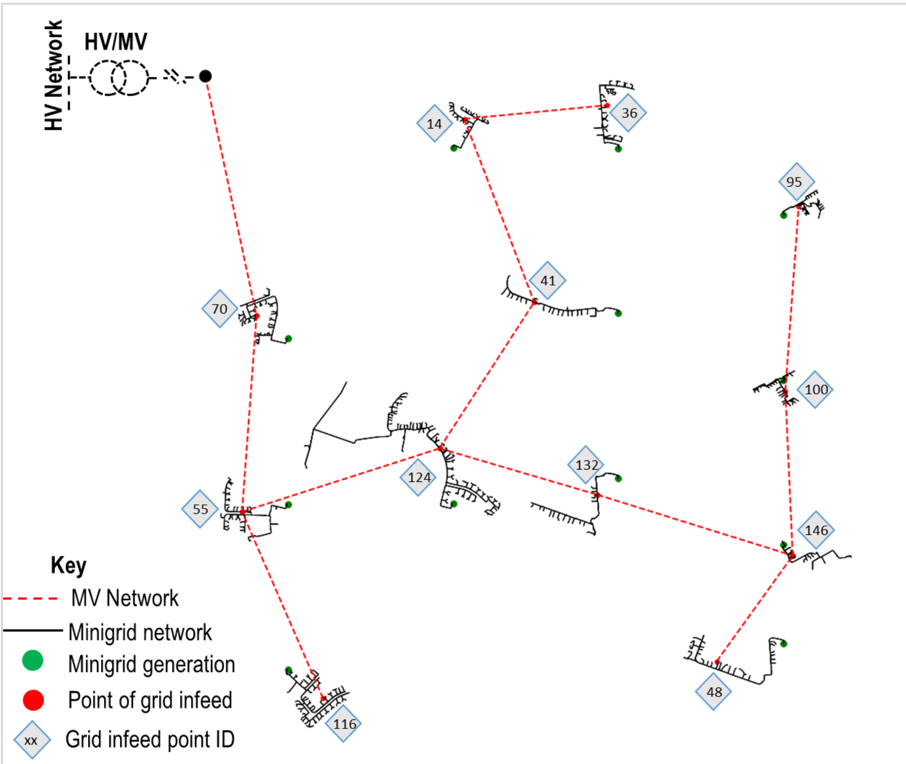
Grid infeed points for MGIP, MV-opt and Geo-opt are away from the nodes hosting the minigrid generator. Table 19 reinforces observations made in the grid integration of a single minigrid. For minigrids with a trunk-and-branch topology like those considered here, grid infeed points are likely to be away from the node that hosts the generator. None of the methods that apply some optimisation, Geo-opt, MV-opt and MGIP, yields node 1 (the node that hosts the generator) as the preferred grid infeed point. This demonstrates that, without robust analysis, it is challenging to pre-determine the best grid infeed point into a minigrid, whether be it an individual minigrid level or when they are in a cluster. The type of residual DERs and their penetration has a significant impact on identifying this point of grid infeed which the arbitrary selection approach in the No-opt method does not take into account.

Transformer sizes remain the same for all scenarios studied. Table 20 shows that there is a variety of transformers across minigrid networks, depending on their size. This should be expected because the minigrids within the cluster have different peak demands, see Appendix-Table 1. For example, Minigrid 3 has a peak demand of 160kW, and from a thermal capacity perspective, it is appropriate that a 200kVA transformer is specified for the grid integration of this minigrid in Table 20. However, minigrid transformers for each individual minigrid remain the same for all PV penetration scenarios. This concurs with previous discussions on the grid integration of a single minigrid – where it was established that PV without storage does not affect the evening peak; hence it does not also affect the transformer sizing.

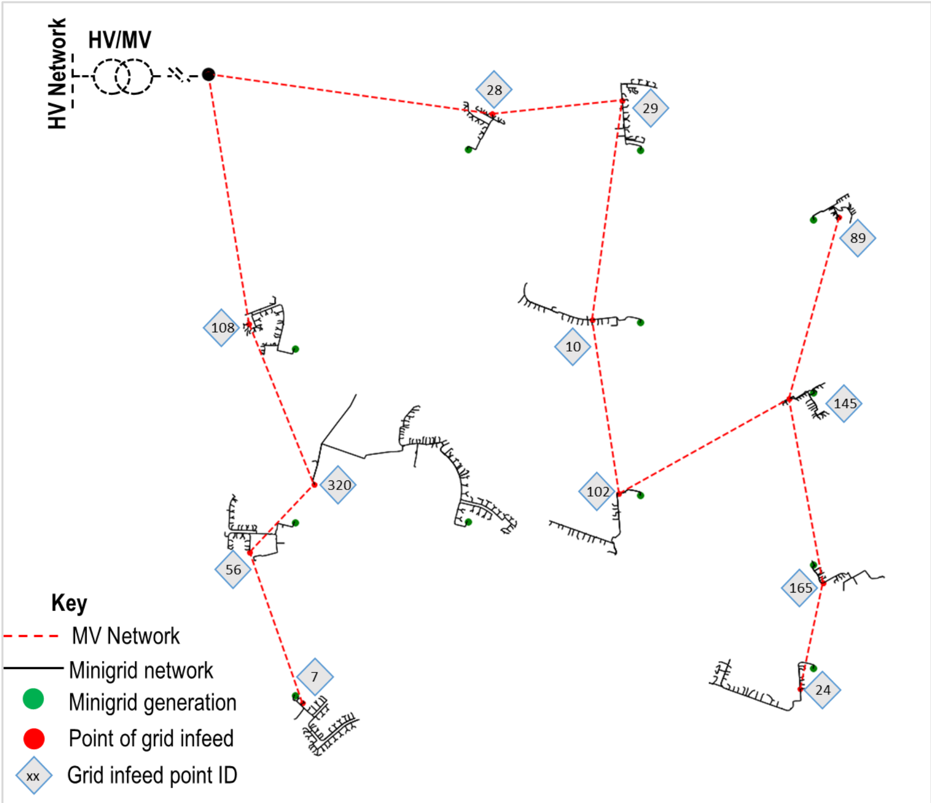
Different points of grid infeed, different MV network layouts. Figure 26 shows that different methods for grid integration planning result in different network layouts from the grid terminal point to the minigrids within the cluster. For MGIP, the presented MV reticulation in Figure 26(d) is for points of grid infeed at 50% DER penetration.



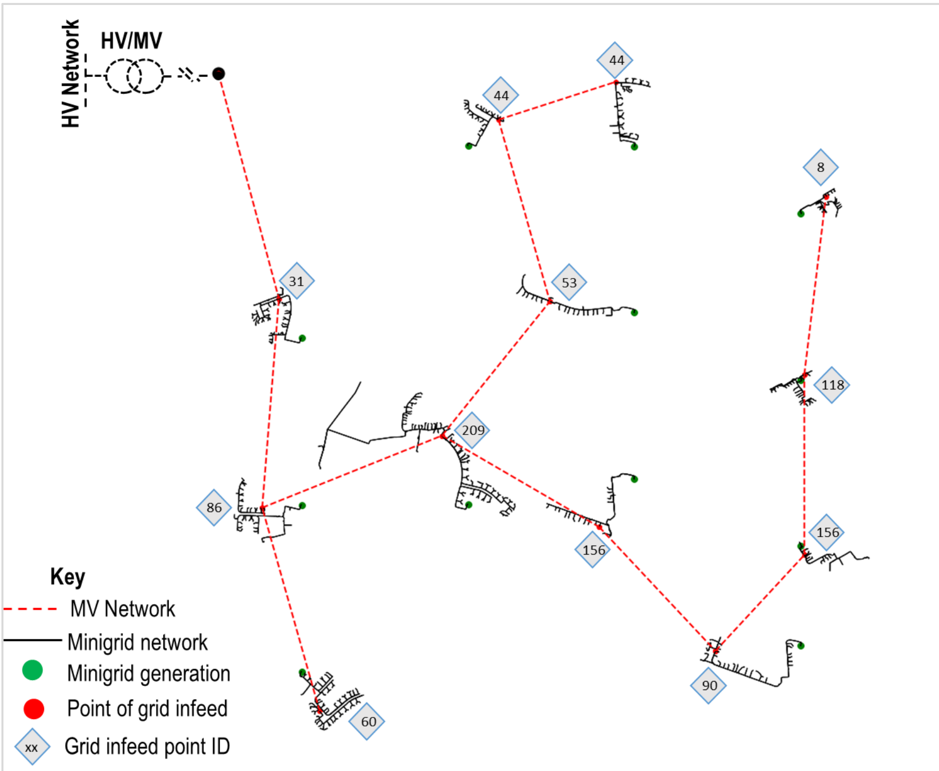
(a) No-opt layout



(b) Geo-opt layout



(c) MV-opt MV layout



(d) MGIP layout

Figure 26: Network expansion layouts to a cluster of minigrids determined by each minigrid integration planning method

The MV network layout in Figure 26 are distinctively different apart from a similarly looking layout in Figure 26(b) and (d). The difference in the layouts is expected because all the minigrid integration methods yielded different grid infeed points (Table 19) and the network layout is influenced by their location. Although Figure 26 (b) and (d) have a similar layout, the points of connecting the MV network to the individual minigrids are not the same. For example, the point of grid infeed into minigrid 9 (located in the bottom right corner) in Figure 26(b) is around the mid-point of the network while in Figure 26(d) is towards the tail of the network. Therefore, even when the MV layout looks similar, the point of grid infeed into the minigrids are different hence affecting the outcome of the objective functions which are discussed later is this section.

The other thing worth noting is that the MV network layout in Figure 26 (a), (b) and (d) representing No-opt, Geo-opt and MGIP comprise of a single branch emanating from the grid terminal point to connect all the minigrids in the cluster. However, the layout in Figure 26(c), representing MV-opt has two feeders emanating from grid terminal point. This should be expected because MV-opt focusses on minimising the length of the MV network and associated losses. The losses are likely to be more on the single branch supplying power to all the minigrids than on the two feeders in Figure 26(c).

Objective function evaluation for grid integration planning of a cluster of 12 minigrids

Figure 27 shows the total annual cost of integrating the cluster of minigrids using four different approaches of No-opt, Geo-opt, MV-opt and MGIP.

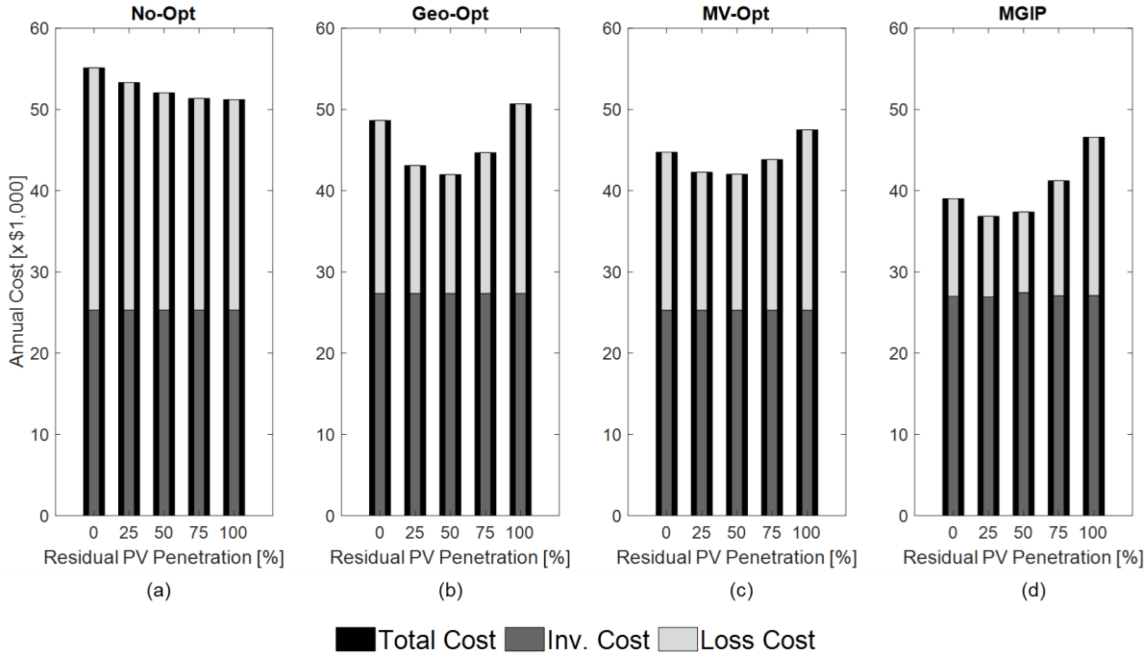


Figure 27: Annual cost of integrating a cluster of minigrids using four different methods

From Figure 27, the following things can be observed:

MGIP has better total annual grid integration costs than the rest of the methods. Figure 27(d) shows that MGIP has the lowest annualised cost for the grid integration of the cluster of minigrids. This observation is consistent with the previous case study on the grid integration of a single minigrid network. A breakdown of the annualised costs in Figure 27(d) suggests that the loss component significantly drives the superiority of MGIP as the investment component remains approximately the same. This should be expected because, as discussed previously, a minigrid network covers a small area. Therefore, the line cost difference caused by a variety of grid infeed points is not that pronounced compared to the cost differences in the loss term.

MGIP energy savings can go a long way in developing countries. Figure 28 shows the annual losses for each of the integration methods. Comparing with the No-opt method, at 25% PV penetration, MGIP leads to an annual energy saving of about 150MWh.

In context, such an annual energy saving can go a long way in developing countries. For example, it can meet Tier 4 access level yearly energy needs (1250kWh according to [7]) of 120 households. Alternatively, if such an annual saving were achieved in Malawi, for example, with an average annual electricity consumption per capita of 108kWh [162], 150MWh would meet the need of approximately 1,388 consumers. With the World Bank predicting the deployment of over two-hundred thousand solar PV minigrids by 2030, most of which will be in SSA [13], the loss reduction benefits reported here will be significant. Although these benefits are lower for higher residual PV penetration, as shown in Figure 27(d) and noted in the grid integration planning of a single minigrid, the benefits of systematic planning of grid integration of minigrid should not be ignored.

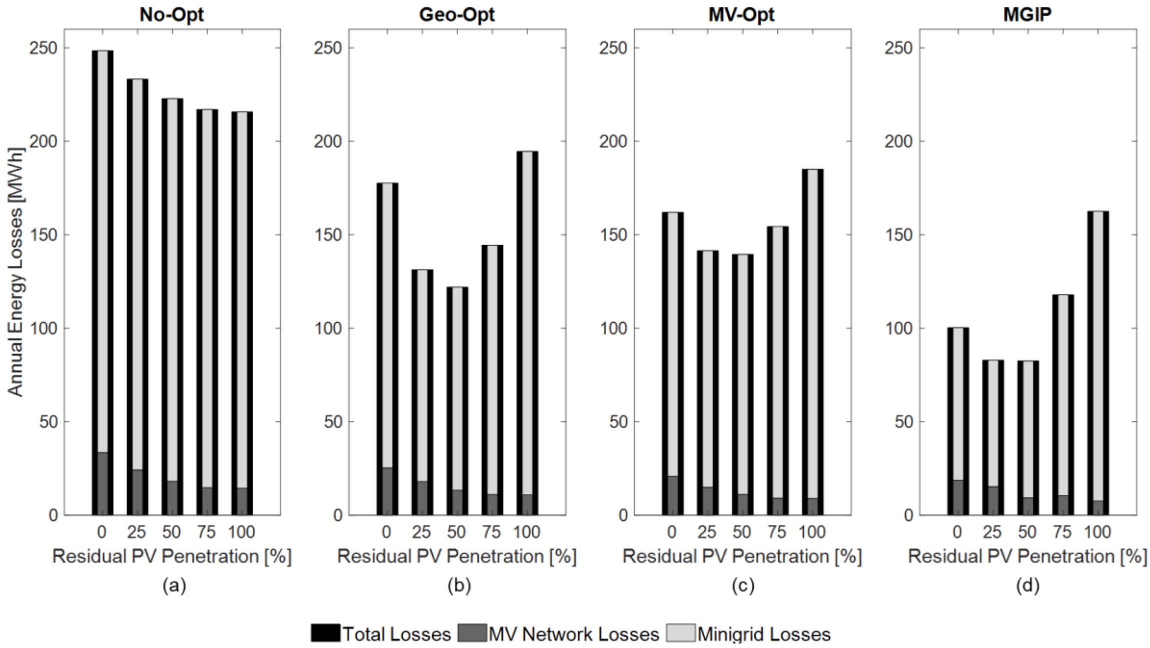


Figure 28: Annual energy losses for integrating a cluster of minigrids using four different methods

MGIP loss reduction benefits are lower at very high PV penetration levels. Figure 29 shows the loss reduction benefits from all the integration methods when compared against No-opt. The results in Figure 28 confirm previous observations that benefits from MGIP diminish at higher PV penetration levels. However, what is noticeable in the integration of cluster of minigrids is that there is a pronounced peak of benefits at 25% penetration. In the individual minigrid cases, this peak was in the same region but slightly subdued because of the size of the minigrid. However, above 25% PV penetration, the benefits from MGIP begin to diminish like in the other case study reported previously.

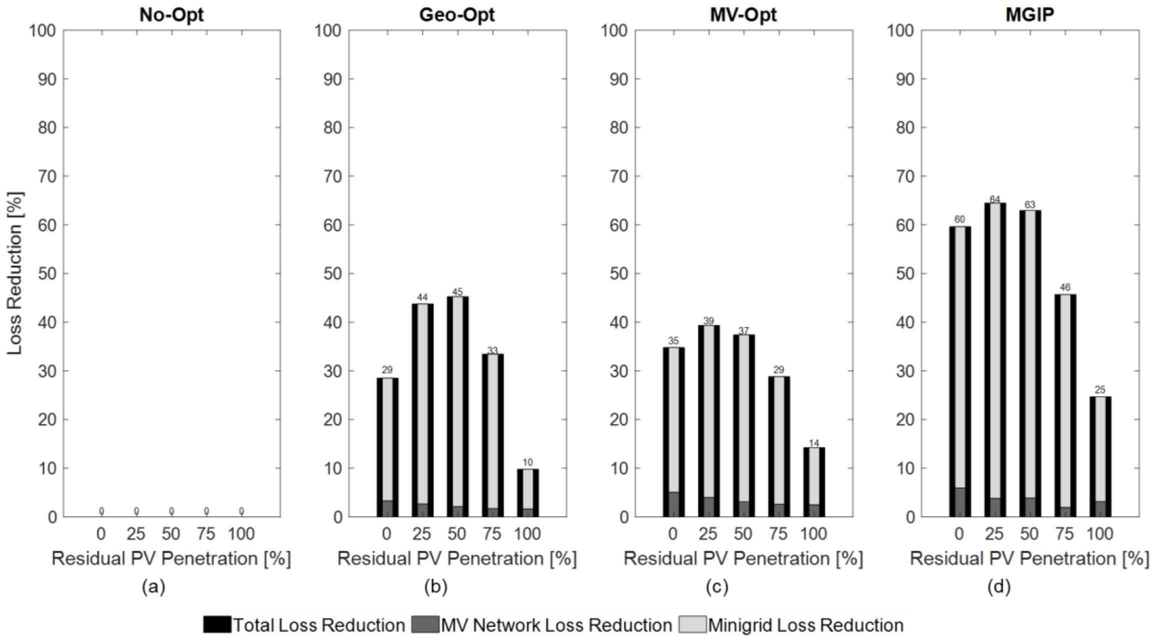


Figure 29: Annual loss reduction of integrating a cluster of minigrids using four different methods when compared to the No-opt method

Although the minigrid integration planner, typically from the utility company, will not explicitly have control of the size of the incumbent minigrid generator, the knowledge that some penetration levels yield better results can be helpful. For example, if the incumbent generator is PV with storage, knowledge of optimal penetration levels can inform storage facilities' charging/discharging profiles. The planners can use the relationship between co-located PV and storage to maximise the benefits of optimal grid integration by altering their effective penetration level. Similar storage usage is also presented in the literature, for example, [180], [181], uses storage to optimise the distribution network and related distribution energy resources.

The recasting of the MGIP problem in (4.1) to (4.5) for planning the grid integration of 12 minigrids considered here reveals that MGIP can be applied to large-scale grid integration planning problems. It also confirms the size, complexity and combinatorial nature of the MGIP problem when the grid integration of more than one minigrid is considered. The evaluation of the grid integration of a cluster of 12 minigrids verifies that No-opt, Geo-opt and MV-opt are not acceptable methods for systematic planning of grid integration of minigrid. The benefits of using MGIP for planning the grid integration of minigrids include a loss reduction of up to 64% compared to the No-opt method recommended in [30] and reported in the grid integration planning of minigrids in Cambodia, Indonesia, and Nepal [33].

4.4 Chapter Summary

This chapter has presented two main case studies that are used to consider planning actions concerning the grid integration of minigrids in developing countries. The case studies demonstrate the efficacy of MGIP, the significant offering of the present work, which is a systematic approach to grid integration planning that considers grid expansion and the articulation of the electrical performance of the downstream minigrid networks beyond the grid integration.

The case study on the grid integration of a single minigrid is provided to help minimise complexity and as a means of understanding the key drivers of the MGIP solution. The case study with a cluster of minigrids reveals the application of MGIP on a larger scale more complex problem with a range of features that infuence the overall solution. In both cases, the results from MGIP are compared with alternative ways of planning the grid integration of minigrids where MGIP was found to be economically and technically better.

Highlights from the presented case studies include:

- Based on its loss reduction potential, MGIP is better than the alternative methods for planning the grid integration of minigrids in developing countries, considered in this work. No-opt method disregards the existing DERs in the minigrid and their influence on the loss performance of the system. Geo-opt does not involve any power flow analysis hence it cannot guarantee any loss reduction optimality. Lastly, MV-opt leads to better investment cost for grid expansion to integrate the minigrids but does not capture the detailed performance of the downstream grids.
- The superiority of MGIP in loss reduction is significantly driven by its ability to articulate the minigrid networks and eventually minimise the cost of losses through optimal selection of grid infeed points into the minigrids. This attribute of MGIP distinguishes it from DER or microgrid planning because they both involve a fixed grid location and the size and location of DERs are a major parameter.
- The benefits of MGIP are affected by size, location, and type of minigrid residual DERs and minigrid demand profile. Although the MGIP does not involve DER sizing, selection and location, the size, location, and type of incumbent DERs

affect the benefits accrued from MGIP. For example, this chapter has shown that DER penetrations of more than 50% lead to less loss reduction benefits than lower DER penetrations. Also, for the same DER penetration, best performance has been realised from PV with storage, PV, and conventional generators in that order. For different demand profiles, this work has revealed that the loss reduction benefits from MGIP increase with an increasing demand factor.

- The presented MGIP can be applied widely in a variety of different circumstances and can also be scaled to plan the grid integration of a cluster of minigrids. In this chapter, the MGIP has been applied on a basic case of integration and single minigrid and on a more advanced case of integrating a cluster of twelve minigrids. This has been used to clearly demonstrate that the applied methodology can be used to plan the grid integration of several nearby minigrids simultaneously.

The work presented in this chapter is based on a single objective formulation of the MGIP problem, and the case studies used are of trunk and branch minigrid topologies. In the next chapter, a multi-objective MGIP is presented and evaluated. Also, the effect of alternative minigrid topology on the application of MGIP is also considered.

5 Further MGIP Benefits and Integration of Multi-Feeder Minigrids

5.1 Introduction

In the previous chapter, several case study scenarios were used to demonstrate the loss reduction benefits of MGIP. This chapter advances the application of the MGIP method in two main ways. Firstly, it presents other benefits of using the MGIP method. Secondly, it proposes a pre-assessment tool that can be used to assess the application of the MGIP method on specific minigrid characteristics.

Apart from reducing network losses [52], literature, e.g. [80], [182], demonstrates that the optimal integration of DERs in established network also improves other parameters such as voltage profile improvement [114], and reactive power losses [183]. This chapter uses a multi-objective formulation of the MGIP to investigate if the MGIP is comparable to ODERP in also reducing reactive power losses and improving voltage profiles.

After quantifying the other advantages of MGIP, apart from loss reduction, a pre-assessment tool that planners can use to assess the usefulness of applying MGIP on specific grid integrations of minigrids is presented.

5.2 Multi-objective MGIP (MO-MGIP) Problem

The MGIP formulation in Chapter 3 aggregates integration investment costs and energy losses into a single objective cost function. While this approach is well-established in network planning, for example, in [115], it has its disadvantages. Firstly, it limits the plans focus to financial/economic perspectives and ignores other objectives that cannot be easily monetised, for example, voltage profile improvement [51]. Secondly, it conceals the possible comparison and trade-offs between non-monetised and monetised objectives, limiting the planner's perspective on the relationship among several planning objectives [163].

In recent works on distribution network planning (DNP), multi-objective planning methods are applied to go beyond finding a singular planning solution but understand the nature of trade-offs or correlation among objectives [80][163]. The importance of understanding the effect of the different terms if the objective function and their influence helps the planner to identify those that can be influenced. Like single objective problems, there are *classical* and *evolutionary* algorithms for evaluating multi-objective planning problems, with each group of algorithms having its advantages and disadvantages, for more details, refer to [140], and the discussion in Section 3.3.3. However, multi-objective evolutionary algorithms [140] have received an increased application in DNP due to their relative ease of implementation and ability to evaluate a population of solutions simultaneously, for example, in [163] and [142].

This section uses the well-established literature of multi-objective distribution network planning [80], [142] to define the multi-objective minigrid integration planning problem (MO-MGIP). Then, the defined MO-MGIP is applied in the grid integration planning of a single minigrid and a cluster of minigrid networks to quantify other benefits of MGIP and establish the relationships among the studied objectives.

5.2.1 MO-MGIP Problem Definition and assumptions

5.2.1.1 Problem Variables

From the theory of MGIP presented in Chapter 3 and the evidence from the studies in Chapter 4, grid infeed point is a more influential variable in MGIP than transformer size. Therefore, the grid infeed point will be the independent variable of MO-MGIP, and transformer size will be fixed to a thermal capacity that can accommodate the peak demand of the minigrids under investigation.

5.2.1.2 Objective Functions

Several objective functions, such as substation and feeder investment, feeder active and reactive power loss, voltage drop, reliability and power export/import into the minigrid [45], can be included in the formulation of MO-MGIP. Motivated by the objectives for the multi-objective index reported in [183], this thesis will consider four objectives of investment cost, active power losses, reactive power losses, and voltage profile improvement. Therefore, the objective function of MO-MGIP will be:

$$\min F = \boldsymbol{min}\,([f_1, f_2, f_3, f_4]) \tag{5.1}$$

Where f_1 is the annual investment cost given by (3.11), f_2 is the daily power losses in kWh provided by (3.13). f_3 and f_4 are the reactive power loss and sum of voltage deviations respectively. Drawing on [121], f_3 is given by:

$$f_3 = \sum_{h=1}^{24} \left(Q_{loss,h}^{mv} + \sum_{mg \in \boldsymbol{MG}} Q_{loss,h}^{mg,z_{mg}} \right) \tag{5.2}$$

$Q_{loss,h}^{mv}$ represents the hourly reactive power loss in the expanding MV network, which is defined as:

$$Q_{loss,h}^{mv} = \sum_{mn \in \boldsymbol{B}_{mv}} \frac{X_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right), \quad \forall (mn) \in \boldsymbol{B}_{mv}, \forall m, n \in \boldsymbol{N}_{mv} \tag{5.3}$$

And $Q_{loss,h}^{mg,z_{mg}}$ is the hourly reactive power loss in any minigrid network, mg, when the grid is connected at node z_{mg} of that minigrid. $Q_{loss,h}^{mg,z_{mg}}$ is given by:

$$\begin{aligned} Q_{loss,h}^{mg,z_{mg}} = & \sum_{mn \notin \boldsymbol{\psi}_{mg,z_{mg}}} \frac{X_{mn}}{V_{n,h}^2} \left(P_{mn,h}^2 + Q_{mn,h}^2 \right) \\ & + \sum_{mn \in \boldsymbol{\psi}_{mg,z_{mg}}} \frac{X_{mn}}{V_{n,h}^2} \big((P_{mn,h} - P_{n,h}^{g} - P_{n,h}^{st})^2 \\ & + (Q_{mn,h} - Q_{n,h}^{g} - Q_{n,h}^{st})^2 \big), \\ & \forall (mn) \in \boldsymbol{B}_{mg}, \forall m, n \in \boldsymbol{N}_{mg} \end{aligned} \tag{5.4}$$

The objective function f_4 is the sum of voltage deviations given by:

$$f_4 = \sum_{n \in N} |V_n - 1| \tag{5.5}$$

where V_n, is the per unit voltage at node n of the associated networks.

5.2.1.3 Problem Constraints

The constraints of MO-MGIP presented in (5.1) to (5.5) are the same as those of MGIP presented in Section 3.4.3.

5.2.2 Pareto-optimality and visualising multi-objective solutions

5.2.2.1 Pareto-optimality

The main aim of multi-objective optimisation is to find the global optimum solution with the least effort. It is not always possible to do this uniquely and as a result in the MO case pareto optimal solutions can be used to find a family of best (globally optimal solutions) in such a way to provide transparency across the individual objective terms [80]. In this way the planner can see the trade-offs that result across each solution in achieving the optimal. Pareto solutions a set of solutions such that an objective cannot be improved without degrading the other [184]. When plotted in the objective space, a plot between any two objectives, the objective values of pareto solutions define part of the feasible objective space's boundary, also known as the *pareto-front*. Figure 30 shows an illustration of objective space and pareto-front.

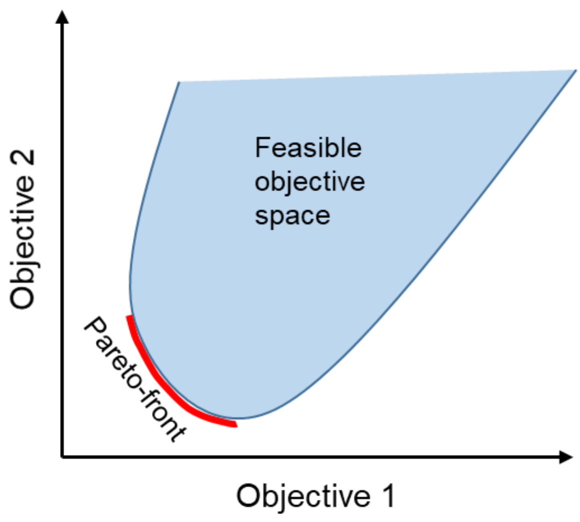


Figure 30: Illustrating objective space and pareto-front

5.2.2.2 Visualising multi-objective results

Since multi-objective optimisation problems present several results, one of the commonly used ways to extract meaning from such results is to visualise their objective space. According to [140], visualising the objective space of a multi-objective optimisation problem results may involve scatter-plot, parallel coordinates (or value path), bar chart, and star coordinate methods. This thesis uses scatter plots as in similar works reported in [51], [147].

For a multi-objective problem with M objectives, the visualisation of results using the scatter-plot method involves plotting $\binom{M}{2}$ or $\frac{M(M-1)}{2}$ scatter plots among the M objective functions. Each pair of objectives is plotted on two orthogonal axes to ascertain their relationship – whether conflicting, positively correlated, or uncorrelated. Relationships between objectives can be established by observing the shape of the pareto-fronts or using linear correlation indices [140]. However, it is also recognised that linear correlation indices should be used with care, especially when objectives have a non-linear relationship.

5.2.3 MO-MGIP on grid integration of a single and cluster of minigrids

This case study aims to demonstrate the application of MO-MGIP in planning minigrid integration and establish the relationship among the objectives under investigation, as stated in (5.1). These aims are achieved by setting up a minigrid and a cluster of minigrids requiring grid integration from Terminal A, as shown in Figure 31 and Figure 32.

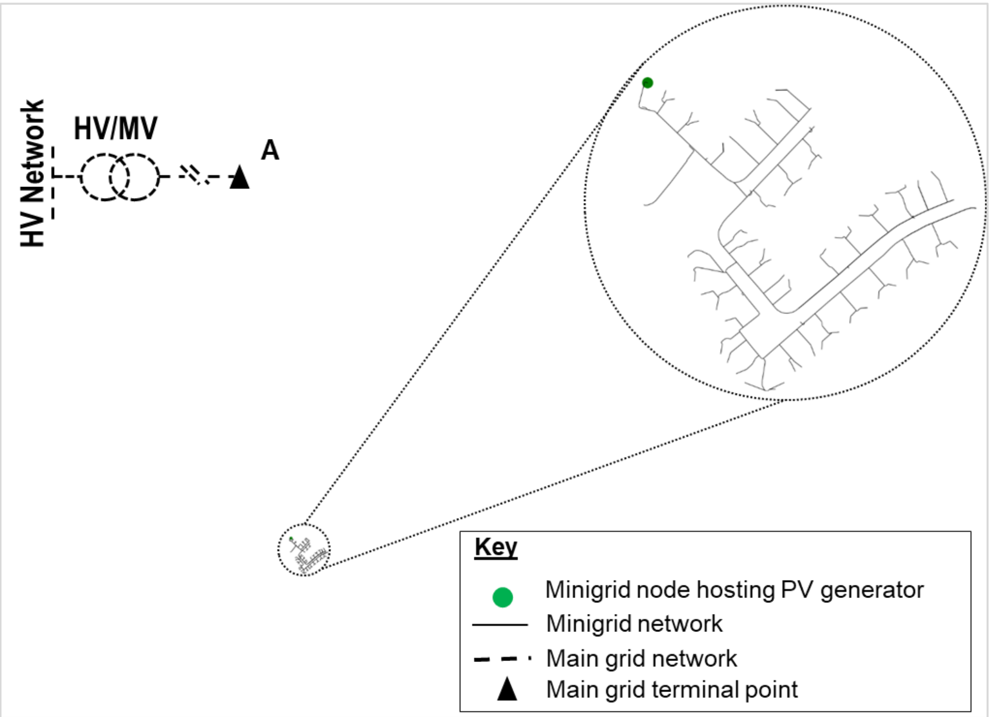


Figure 31: Minigrid requiring grid integration

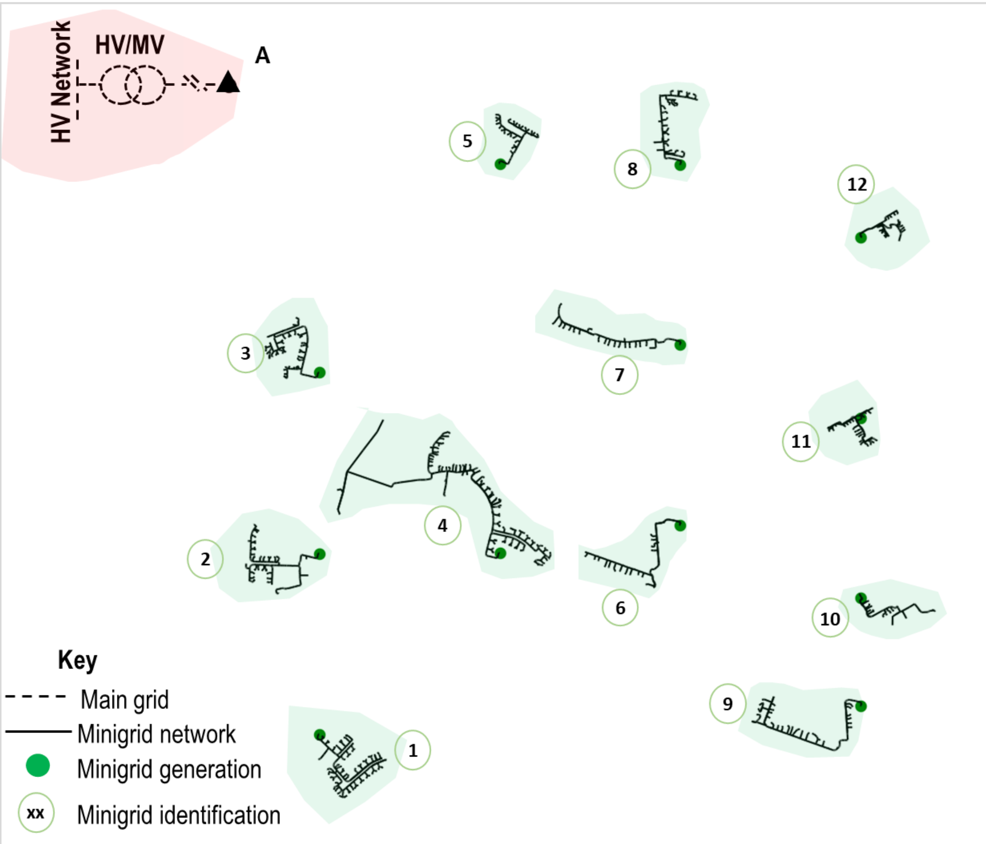


Figure 32: Cluster of twelve minigrids requiring grid integration

This case study investigates representative scenarios where the minigrid networks have a single PV generator source whose penetration level is varied from 0% to 100% in steps of 25% and the demand profile of medium demand factor is used.

Multi-objective function evaluation

Figure 33 show a scatter plot of single- and multi-objective solutions for the grid integration planning of a single minigrid with 100% PV penetration. For the MO-MGIP, the evaluated multi-objective function comprises of four objectives namely; investment cost, active power losses, reactive power losses and voltage deviations as presented in (5.1). For the single objective evaluations, the approach for identifying grid infeed points for No-opt, MV-opt, Geo-opt and MGIP as presented in Section 4.3 are applied. Then, corresponding values for investment cost, active power losses, reactive power losses and voltage deviations are obtained to compare with the MO-MGIP results.

A similar plot for results of MO-MGIP applied on a cluster of minigrids is presented in and Figure 34. Plots for 0%, 25%, 50% and 75% PV penetration and are in Appendix 4.

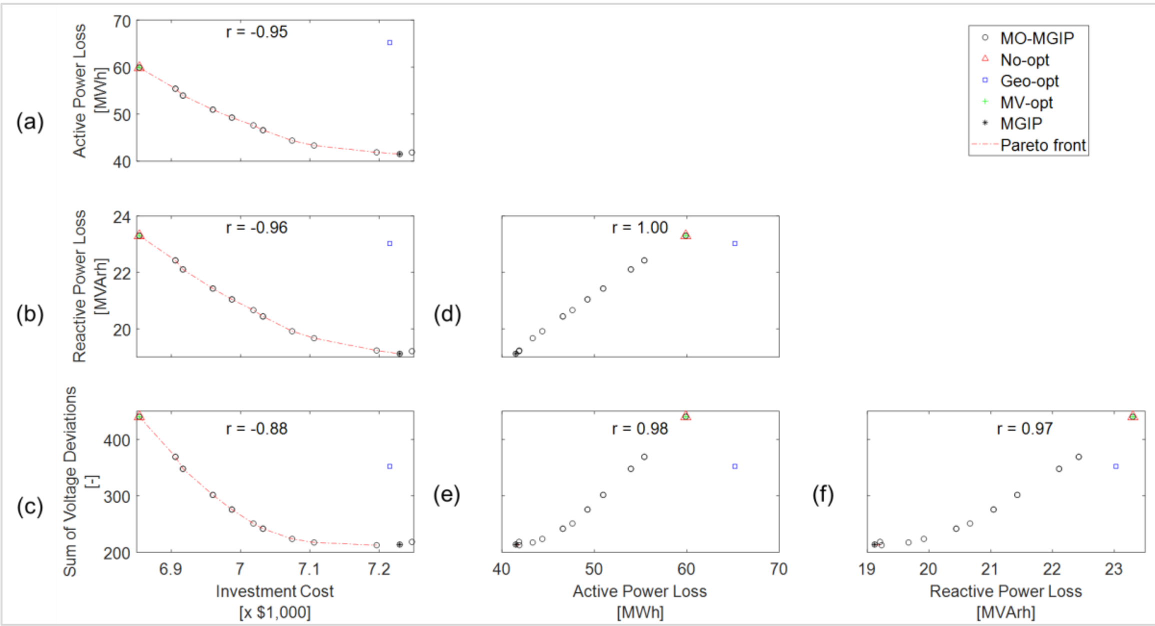


Figure 33: Single- and multi-objective solutions for grid integration of a single minigrid with 100% PV penetration

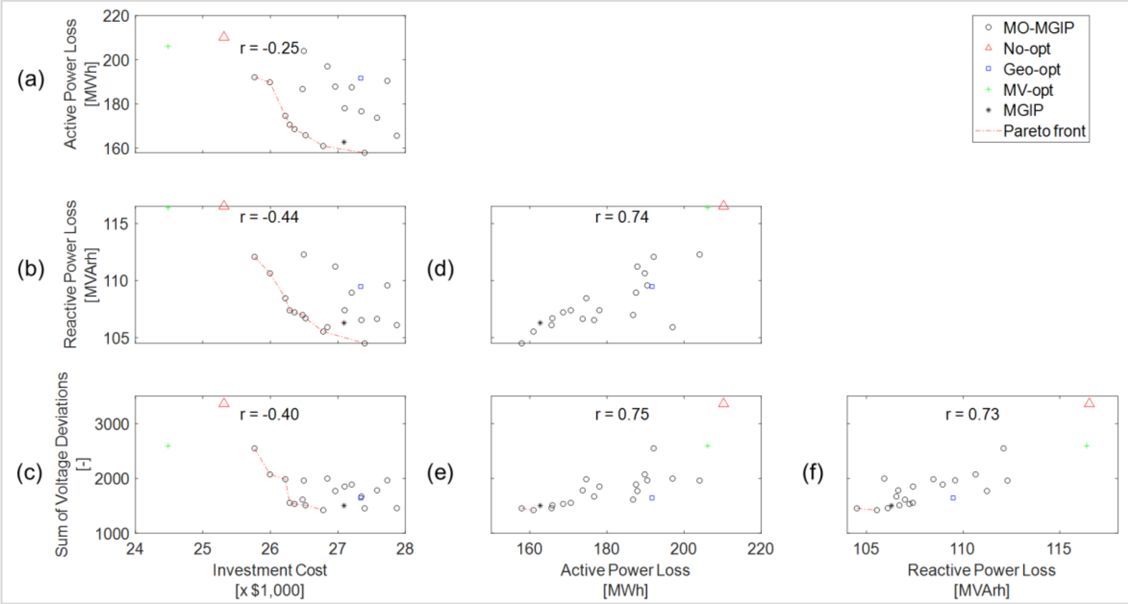


Figure 34: Single and multi-objective solutions for grid integration of cluster of minigrids at 100% PV penetration

The following observations can be made from the results presented in Figure 33 and Figure 34:

MO-MGIP demonstrate that investment costs conflict with the other objectives. **Figure 33**(a), (b) and (c) show that the investment cost for integrating the minigrid under investigation conflicts with active power losses, reactive power losses and voltage deviation. Similarly, **Figure 34** (a) – (c) also show that investment costs remain in conflict with active power loss, reactive power loss and voltage deviation in the grid integration of a cluster of minigrids. Although the shapes of the pareto fronts in **Figure 34** (a) – (c) are not as distinctively convex as those in **Figure 33** (a) – (c), the inverse relationship among the objectives can be clearly observed. This conflict is demonstrated in two main ways.

Firstly, Figure 33(a) - (c) have a convex shaped pareto-front which is an indication of conflicting objectives in a minimisation multi-objective problem [140]. Secondly, Figure 33(a) - (c) also show that the objectives are negatively corelated to each other. The correlation coefficients between investment costs and active energy loss, reactive energy loss and voltage deviations are -0.95, -0.96, and -0.88 respectively. These correlation coefficients indicate a very strong negative correlation between investment cost and any of active power loss, reactive power loss and voltage deviation. In the grid integration of a cluster of minigrids, the correlation coefficients among the highlighted objectives are much lower, -0.25, -0.44, and -0.40 in Figure 34 (a) – (c). These lower correlation values only indicate that grid integration of a cluster of minigrids has a variety of solutions as the associated pareto curve in Figure 34 (a) – (c) supports the conflict among the objectives.

Therefore, minigrid integration planners should aim to get the right compromise between minigrid integration investment costs and post grid integration network performance. A method that considers the unique situation associated with grid integration planning of minigrids, with flexibility to be cast as a single- and multi- objective, like the one proposed in this thesis, will be invaluable for such analysis and decision making.

MO-MGIP demonstrate that active losses, reactive losses, and voltage deviations are positively correlated. Figure 33 (d) - (f) and Figure 34 (d) – (f) show that active loss, reactive loss and voltage deviation are all positively corelated to each other. This positive correlation should be expected as they are all negatively correlated with investment costs and are all functions of current flow in the power lines. The positive correlation of these objectives can be observed from two main perspectives.

Firstly, the pareto front of the multi-objective solutions only comprise of a single point, and two points at most, in Figure 33 (d) - (f) and Figure 34 (d) – (f). This demonstrates a lack of conflict among the objectives. Secondly, the multi-objective solutions of these objectives have very high correlation coefficients (1 between active losses and reactive losses, 0.98 between voltage deviation and active loss, and 0.97 between voltage deviation and reactive loss in Figure 33 (d) - (f)). Lower correlation coefficients are observed in Figure 34 (d) – (f), which are a testament to spread of the solution rather a lack of positive correlation.

This observation is important because it gives the planner the confidence that considering only one of these objectives will be enough rather than considering all of them during a study. The choice of the objective to be considered will vary from study to study depending on the primary aim of the study. For example, if loss reduction is the primary aim of the study, it is important to explicitly include loss reduction as an objective and expect reactive power losses and voltage profile improvement to be optimises implicitly.

MO-MGIP highlight the weakness of No-opt and MV-opt. It has already been discussed in this thesis that the main disadvantage of using No-opt and MV-opt is they both do not consider the performance of the minigrid networks. This has been further highlighted in Figure 33 and Figure 34 (a) – (c).

Figure 34 (a) – (c) show that the solutions of MV-opt and No-opt are isolated from the multi-objective solutions and lead to very high losses. Despite being on the pareto front, in Figure 33, No-opt and MV-opt solutions do not show any compromise among the objectives. They lead to the lowest investment cost but highest losses and voltage deviations.

Therefore, MO-MGIP reinforces previous observations that MV-opt and No-opt are less likely to result into optimal grid integration plans for formerly autonomous minigrids as they neglect the performance of the local minigrid networks. On the other hand, MGIP ensures moderate compromise between investment costs and the other objectives.

MO-MGIP demonstrate that grid integration of minigrids using Geo-opt leaves the outcome to chance rather than robust analysis. Figure 33 shows that Geo-opt does not improve any grid integration objectives investigated in the multi-objective plan for grid integration. In most of the scatter plots, e.g., Figure 33 (a) – (c), the Geo-opt solution (shown as a blue square) is away from the multi-objective solutions and the location of Geo-opt solutions in the objective space is distinct from that of MV-opt and MGIP solutions. This emphasises the main weakness of Geo-opt method which is that it neglects the network expansion to the minigrid, and the power flow associated with grid integration of minigrids.

Unlike in the grid integration of a single minigrid (in Figure 33), Figure 34 shows that the Geo-opt solutions for grid integration of a cluster of minigrids are closer to the multi-objective solutions. While the risk of implementing an extremely sub-optimal integration plan seem to reduce within a cluster of minigrids, using Geo-opt remains unpredictable as it does not involve any power system analysis.

Therefore, the location of Geo-opt solutions in the objective space further reinforces that integrating minigrids using Geo-opt solutions entails leaving everything to chance rather than robust analysis. Hence it should not be recommended for grid integration planning of minigrids.

Summary of further MGIP benefits

In this section, MO-MGIP has been used to reveal further benefits of using the MGIP approach developed in the work of this thesis in relation to grid integration planning of minigrids. These can be summarised as follows:

- Where necessary, the MGIP problem can be cast as a multi-objective problem. This might be useful for planners to investigate the relationship that exist between different objectives and solutions, and how those relationships change with changes in parameters like number of minigrids in a cluster.
- The MO-MGIP further reinforces various weaknesses associated with grid integration planning of minigrids using Geo-opt, Mv-opt and No-opt. On the other hand, the MO-MGIP reiterates the strength of MGIP in the grid integration planning of minigrids.
- The MO-MGIP reveals that besides loss reductions, MGIP also improves voltage profile and reactive power loss reduction. This is consistent with the general relationship between those objectives reported in DNP and DER planning in developed country contexts. Therefore, MGIP can have the same impact as planning the grid integration of DERs in mature networks.

5.3 Multi-feeder Minigrid Loading Index (MMLI)

The case studies that have been reported so far in this thesis have involved the grid integration of single feeder minigrids with a radial topology. This is a a typical minigrid topology which is also called *trunk-and-branch* [130] and [7]. An example of this shown in Figure 35(a). However, minigrid networks can also take another topology called *hub-and-spoke* [130] and [7]. An example of this is shown in Figure 35(b). Extending the work of this thesis this section focusses on planning the grid integration of hub-and-spoke minigrids comprising of several radial feeders. For the purposes of this thesis, they will be referred to as *multi-feeder minigrids*.

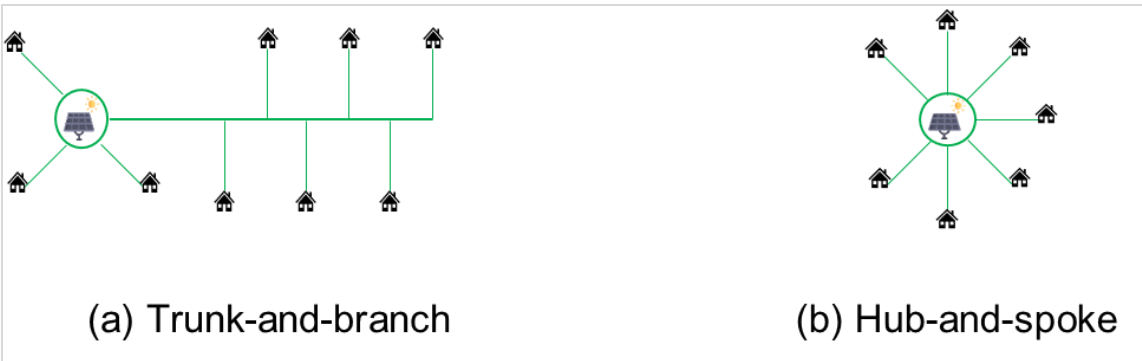


Figure 35: Typical minigrid topologies

The minigrid integration planning methodology proposed in this thesis can be used to plan the grid integration of multi-feeder minigrids (or minigrids with more than one radial feeder emanating from the generation hub). This is so because any additional feeder to a minigrid is effectively additional network nodes which are candidates of the optimal grid infeed points. However, depending on the topology, size, and loading of respective feeders, a rigorous integration planning process may not be necessary for every minigrid requiring grid integration. As such, this section proposes a pre-assessment tool for planners to ascertain the need to apply MGIP for grid integration planning of specific minigrids. The pre-assessment tool will be called Multi-feeder Minigrid Loading Index (MMLI).

5.3.1 Theory and application of MMLI

Assume a minigrid with a number of feeders N requiring grid integration. If $\boldsymbol{L}$ is the set of the minigrid feeders' peak demands, it will be given by

$$L = \{fdr_1, fdr_2, fdr_3, \dots, fdr_N\} \tag{5.6}$$

Where, fdr_1 is the peak demand of feeder j of the minigrid. Then, the MMLI will be defined as

$$\text{MMLI} = \max\left\{\frac{fdr_1}{fdr_T - fdr_1}, \frac{fdr_2}{fdr_T - fdr_2}, \dots, \frac{fdr_j}{fdr_T - fdr_N}\right\} \tag{5.7}$$

Where, fdr_T is the total minigrid peak demand, which is defined as

$$fdr_T = \sum_{\boldsymbol{j=1}}^{\boldsymbol{N}} fdr_j \tag{5.8}$$

Table **21** presents peak demand data for four three-feeder minigrids and corresponding MMLI, as examples for illustrating the use of (5.7). For example, using the data for Minigrid 1, (5.7) evaluates to:

$$\mathrm{MMLI} = \max\left\{\frac{250}{410-250}, \frac{60}{410-60}, \frac{100}{410-100}\right\} = \max\{1.6, 0.2, 0.3\} = \mathbf{1.6}$$

And the share of load in the highly loaded feeder in Minigrid 1 is, 250/410, which evaluates to 61%. Table **21** shows that an MMLI of greater that 1 is reflective of the share of load in the highly loaded feeder to be above 50% of the minigrid demand.

Table 21: Calculating MMLI for three-feeder minigrids

Minigrid ID	Feeder Peak Demand (kW)			MMLI	Share of Load in Highly Loaded Feeder
	Feeder 1	Feeder 2	Feeder 3		
#1	250	60	100	1.6	61%
#2	80	75	40	0.7	41%
#3	70	35	40	0.9	48%
#4	20	35	200	3.6	78%

The value of minigrid's MMLI can be interpreted as follows:

$$\mathrm{MMLI}\begin{cases} \leq 1 - \text{No feeder is dominantly loaded, } \textbf{no need} \text{ to run MGIP} \\ > 1 - \text{One feeder is dominantly loaded, } \textbf{need} \text{ to run MGIP} \end{cases} \quad (5.9)$$

Here the term "dominantly loaded feeder", means a feeder that hosts more than 50% of the minigrid peak demand. Lack of a dominantly loaded feeder indicates that the best grid infeed point for that minigrid may be at or close to the minigrid generator location. This implies that there are little to no loss reduction benefits of running the full MGIP method. However, an MMLI value of greater than 1 symbolises the presence of a dominantly loaded feeder. Consequently, it denotes that the minigrid generator location is not necessarily the best point for grid infeed into the minigrid, hence the need to use MGIP. The best point of grid infeed will be from the dominantly loaded feeder.

Using the interpretation of MMLI set out in (5.9), the MMLI values calculated in Table 21 can inform the minigrid integration planner in the following manner:

- Minigrids 1 and 4 will require the use of MGIP because they have MMLI values of 1.6 and 3.6, respectively, which are greater than 1. So instead of allowing MGIP to search for the grid infeed points in all feeders of the multi-feeder minigrids, the search can be restricted to Feeder 1 in minigrid 1 and Feeder 3 in minigrid 4 because they are the dominantly loaded feeders, hosting 61% and 78% of their respective minigrids.
- Minigrids 2 and 3 may not require the use of MGIP because of their MMLI values are 0.7 and 0.9 respectively. Therefore, their best grid infeed point will be the location of the minigrid generator. By inspection, one would assume that Feeder 1 of minigrid 3 is dominant. However, when compared to the sum of load in the other feeders, Feeder 1 of minigrid 3 would not be considered dominant as it takes 48% of the entire demand hence, an MMLI of less than 1 results.

Figure 36 presents the grid integration planning of minigrids with and without MMLI.

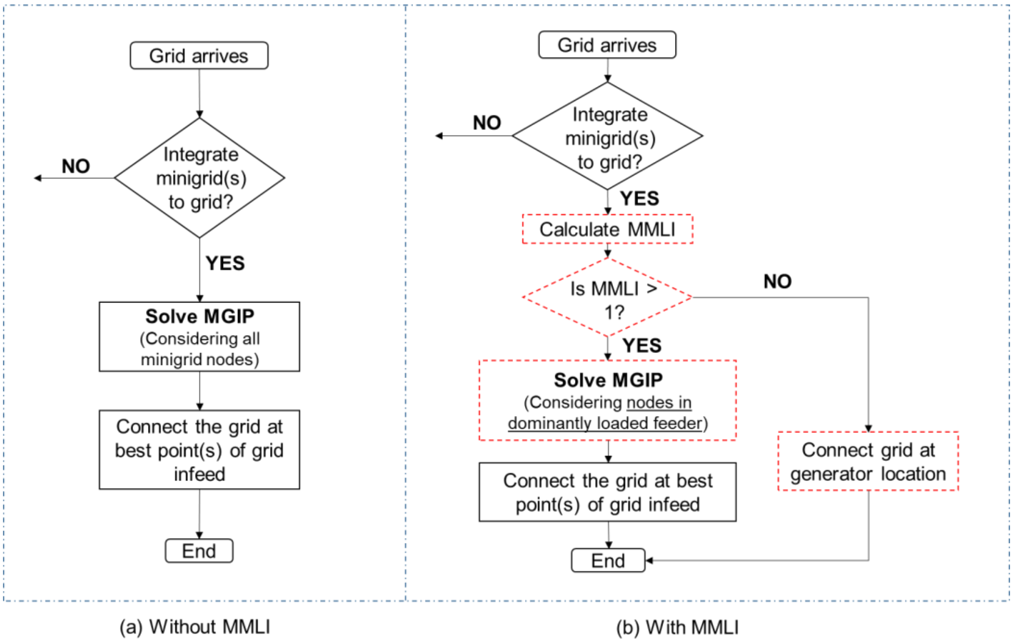


Figure 36: Minigrid integration planning process with and without MMLI

Figure 36 (a) shows that in the absence of MMLI, when the grid arrives, the first decision is whether the minigrid can be integrated with the main grid or not, as suggested in [21]. If the minigrid is grid compatible and can be integrated with the main grid, then the MGIP proposed in this thesis will be conducted to ascertain the transformer size and grid infeed point.

Figure 36(b) on the other hand identifies that the incorporation of MMLI introduces further steps in the grid integration planning process. Firstly, for an MMLI less than or equal to 1, the MGIP is not used for the given minigrid under consideration, and the grid infeed point for that minigrid is set to be at the generator location. Secondly, for MMLI of more than 1, the MGIP is applied to identify a point of grid infeed into the minigrid. The search for this point of grid infeed is restricted to the nodes of the dominant feeder within that minigrid. The case studies that follow demonstrates the application and benefits of MMLI included in the MGIP for minigrid integration planning.

5.3.2 Planning the grid integration of multi-feeder minigrids using MMLI

Consider two grid compatible multi-feeder minigrid networks labelled X and Y as presented in Figure 37 requiring grid integration. These minigrid networks, derived from combining single feeder minigrid networks presented in Appendix-Table 1, are used to compare planning the grid integration of minigrids using MGIP with and without MMLI.

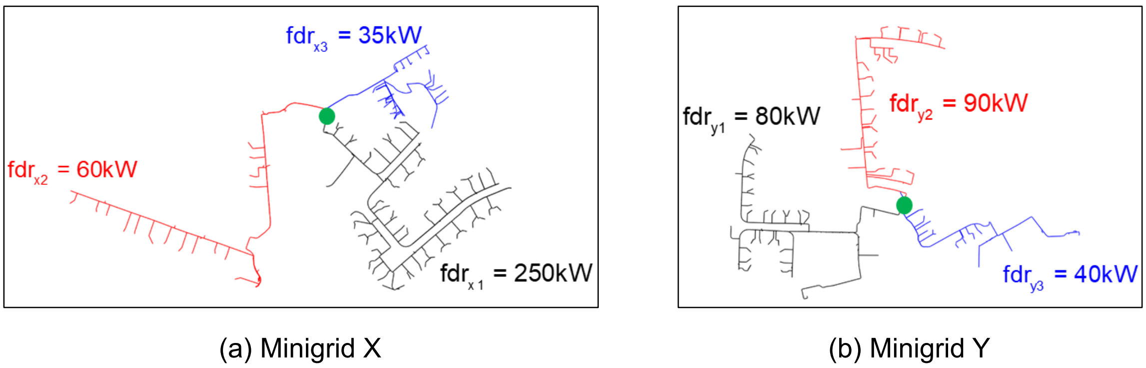


Figure 37: Multi-feeder minigrids requiring grid integration

In this case study, the minigrids in Figure 37 have three DER scenarios (PV generators without storage, PV generators with storage, and conventional power generator). For each DER scenario, the DER penetration is varied between 0% and 100% at intervals of 25% and the demand load profile with medium demand factor is used.

The results of conducting and assessing these case studies and their discussion is as follows:

MMLI values of the multi-feeder minigrids

Table 22 shows the MMLI values of the minigrids in Figure 37 and the share of minigrid demand in each feeder.

Table 22: MMLI values for minigrids X and Y

Minigrid ID	Feeder ID	Feeder Demand (kW)	Share of Minigrid Demand (%)	MMLI
X	x_1	250	72	2.63
	x_2	60	17	
	x_3	35	10	
Y	y_1	80	38	0.75
	y_2	90	43	
	y_3	40	19	

From Table 22, Minigrid X and Minigrid Y have MMLI values of 2.63 and 0.75 respectively. According to the interpretation of MMLI, provided in (5.9), here are the key implications of the MMLI values presented in Table 22:

Minigrid X will require the use of MGIP as it has a dominantly loaded feeder. An MMLI of 2.63 in Minigrid X indicates that there is a dominantly loaded feeder. Indeed, the dominantly loaded feeder is feeder x_1 with a peak demand of 250kW. Compared to the total demand of Minigrid X, feeder x_1 takes 72% of the total demand which is greater than 50% dominance threshold. Thus, Minigrid X has a dominantly loaded feeder, the optimal point of grid infeed into this feeder is not expected to be at the minigrid generation hub, hence MGIP will be required.

Minigrid Y will not require MGIP as it does not have a dominantly loaded feeder. An MMLI of 0.75 in Minigrid Y implies that there is no dominant feeder in this minigrid. Although feeder y_2 hosts the highest demand among the feeders, it hosts 43% of the total minigrid demand which is less that the 50% threshold for feeder loading dominance. Due to an MMLI of less than 1 being determined, the best grid infeed point into Minigrid Y should be expected to be at the generator hub (Node 1) or very close by node.

Therefore, for grid integration without applying MMLI, the planner will still run the full MGIP method. However, for grid integration planning with MMLI, the planner would choose to skip running the full MGIP and decide to connect the incoming grid at the same node which hosts the minigrid generation equipment.

Points of grid infeed of the multi-feeder minigrids

Table 23 shows the grid infeed points obtained from planning the grid integration of minigrids without and with MMLI, procedures presented in Figure 36(a) and Figure 36(b) respectively. In most scenarios, these results show the same points of grid infeed into the minigrids when determined with and without MMLI

From the results in Table 23, the following observations can be made:

***MMLI pre-qualifies the need for a rigorous minigrid integration study*.** The results in Table 23 demonstrate that using MMLI, a planner can pre-determine the need for a rigorous identification of grid infeed point into a minigrid. Whenever a rigorous grid integration planning exercise is not needed, MMLI can lead to considerable time and computational savings for the planners.

The MMLI of 2.63 in Minigrid X is an indication that the best grid infeed point for that minigrid may not be at the generation hub hence the need to run a full MGIP study to identify the point of grid infeed. The results of the study, in Table 23, confirms the necessity of a rigorous grid integration planning process since for most DER scenarios, the optimal point of grid infeed is not the minigrid generator location. The only scenarios where one would assume that MGIP was not necessary are when the conventional generator penetration is 75% and 100% and the best point of grid infeed is Node 1 for Minigrid X. In the grid integration of Minigrid X, there would be no time saving associated with MMLI helping to decide the need for a detailed MGIP study.

On the other hand, an MMLI of 0.75 in Minigrid Y is an indication that the generation hub (or Node 1) may be the best point of grid infeed for the grid integration of this minigrid. This assertion is confirmed with the results in Table 23, where the rigorous identification of grid infeed point ended up with Node 1 (node hosting minigrid generator) as the best point of grid infeed for most of the scenarios. Although Node 3 and Node 6 of feeder y_2 are identified as best points of grid infeed for some DER scenarios, most scenarios have Node 1 as the most prevalent optimal grid infeed. These results would have been the same if a detailed MGIP was not done by following the procedure for planning grid integration with the use of MMLI as presented in Figure 36(b).

Table 23: Optimal grid infeed points for multi-feeders minigrids with and without MMLI

DER Type	DER Pen. (%)	Minigrid X		Minigrid Y	
		Without MMLI	With MMLI	Without MMLI	With MMLI
PV Only	0	20 (x_1)	20 (x_1)	1	1
	25	46 (x_1)	46 (x_1)	1	1
	50	46 (x_1)	46 (x_1)	1	1
	75	46 (x_1)	46 (x_1)	1	1
	100	20 (x_1)	20 (x_1)	1	1
PV + Storage	0	20 (x_1)	20 (x_1)	1	1
	25	46 (x_1)	46 (x_1)	1	1
	50	46 (x_1)	46 (x_1)	3 (y_2)	1
	75	46 (x_1)	46 (x_1)	6 (y_2)	1
	100	46 (x_1)	46 (x_1)	1	1
Conventional generator	0	20 (x_1)	20 (x_1)	1	1
	25	46 (x_1)	46 (x_1)	6 (y_2)	1
	50	46 (x_1)	46 (x_1)	1	1
	75	1	1	1	1
	100	1	1	1	1

1 = Node 1 of either minigrid

20 (x_1) = Node 20 of feeder x_1 within minigrid X

The ability to use MMLI as a pre-assessment tool for establishing the need for a detailed minigrid integration study can help planners to save time. Instead of conducting a detailed study for every minigrid, a quick analysis of the feeder loading can inform the point of grid infeed, especially when the MMLI is less than 1. For each minigrid that does not require detailed identification of grid infeed point, the planner will save the time that would have otherwise been used for a detailed study.

MMLI gives an indication of which feeder may be hosting the best point of grid infeed. The results in Table 23 reinforces the assertion in MMLI interpretation and application (Section 5.3.1) that the best grid infeed point of a minigrid with an MMLI of more than 1 is likely be in the dominantly loaded feeder. Despite the differences in the evaluation of MGIP in Figure 36 (a) and (b), Table 23 show that they yield the same grid infeed points for Minigrid X, all of which fall within Feeder x_1. This demonstrates that in minigrid integration planning, the search for best grid infeed points can be restricted to the nodes in the most loaded feeder of the minigrid. Restricting the search for grid infeed point to nodes in the predominantly loaded feeders reduces the size of the overall solution space and also the computational time for solving the problem as shown in Figure 38. For each DER scenario reported in Figure 38 the integration studies (with or without MMLI) for Minigrid X with PV only were run 20 times. It is clear from the figure that in the main, all the cases considered without MMLI took longer than the equivalent problems with MMLI. Furthermore, that there is obvious compute times savings across the board for the with MMLI cases.

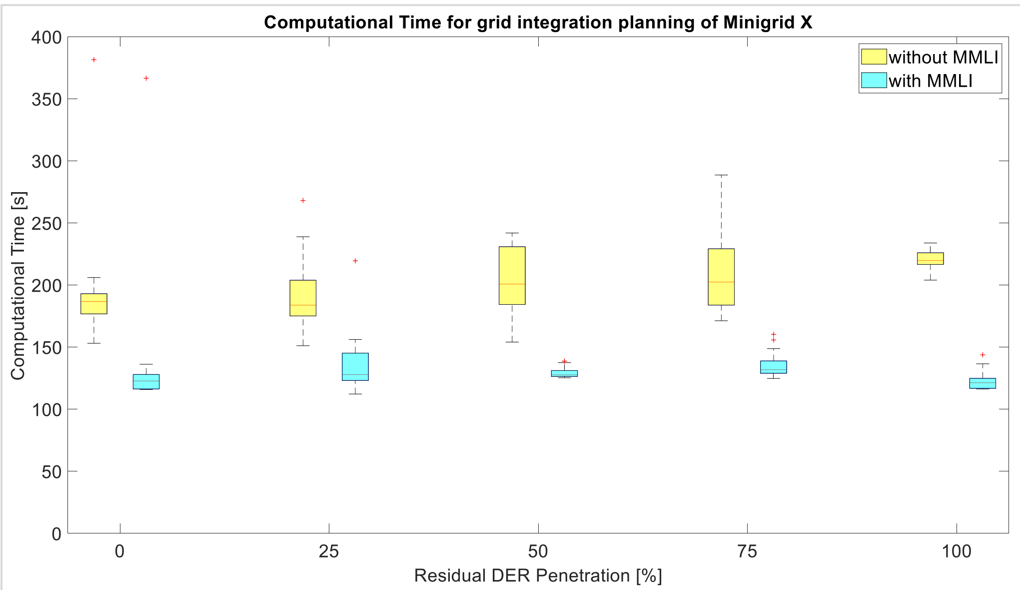


Figure 38: Computational time for planning grid integration with and without MMLI

Figure 38 reveals that the optimisation process used in this thesis is not particularly fast as it takes more than 100s to provide a solution with or without the use of MMLI. This slowness is no surprise as this the work in this thesis has not focused on determining the fastest optimisation algorithm as in [51]. However, Figure 38 shows considerable time saving associated with the use of MMLI which restricts the search for the grid infeed point of minigrids to those nodes within the highly loaded feeder.

Besides the savings in computational time, MMLI and knowing which feeder may be hosting a grid infeed point for a multi-feeder minigrid helps the planner to empirically validate the results of a particular minigrid integration study. For example, if a minigrid has an MMLI of more than 1 and upon running the full minigrid integration study, the best grid infeed point is identified outside the dominantly loaded feeder, such a solution may be a guide for the planners to re-investigate the plan. The aim of this reinvestigation may be to verify the obtained results or identify new parameters affecting the results of obtained results.

Therefore, at this point, the introduction of the MMLI calculation into grid integration planning process is useful in two ways. Firstly, it helps to save computational time in the overall optimisation by reducing the solution space from all nodes within the multi-feeder minigrid to nodes within a dominantly loaded feeder. Secondly, it gives the planner the ability to validate the results of a minigrid integration plan by assessing whether the point of grid infeed lies within the dominantly loaded feeder. If that is not the case, further investigations can also be initiated to verify the obtained results or identify new variables that are affecting the results of the MGIP solution.

Minigrid losses in the multi-feeder minigrids and MMLI

Figure 39 shows the loss reduction benefits for integrating minigrids X and Y, using grid infeed points in Table 23, when compared to No-opt (defined in Section 4.3).

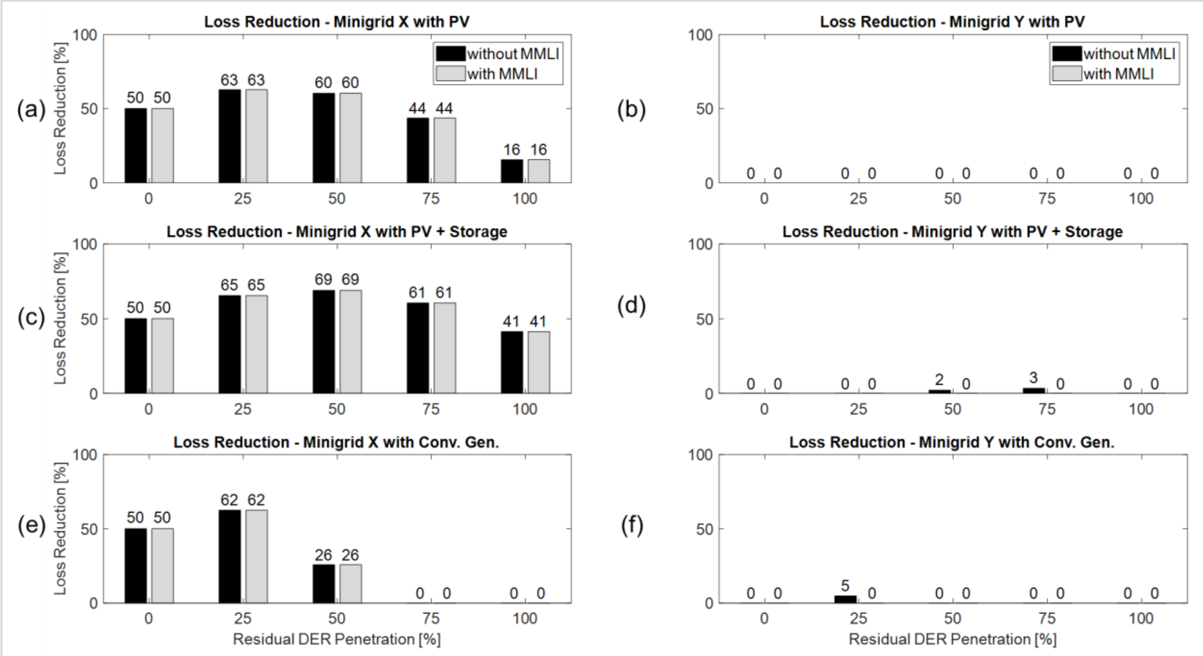


Figure 39: Loss reduction with and without MMLI

Figure 39 The following observations are made:

High value of MMLI denotes significant loss reduction potential within the minigrids. **Figure 39** shows that the minigrid with a high value of MMLI, Minigrid X, has the most loss reduction potential than that with a lower MMLI value, Minigrid Y. Particularly, **Figure 39** (a), (c), and (e) report loss reduction of up to 69% within Minigrid X which has an MMLI of 2.63. On the other hand, Minigrid Y has an MMLI of 0.75 and the highest loss reduction potential across all the DER scenarios is 5% reported in **Figure 39**(f) at 25% penetration of the conventional generator.

Therefore, planners can use MMLI to decipher the loss reduction potential that may be associated with a detailed grid integration planning of a certain minigrid. The higher the MMLI, the higher the loss reduction potential. This will be key for planners to prioritise their minigrid integration planning activities on minigrids that promise the highest loss reduction benefits.

Incorporation of MMLI in the minigrid integration planning study does not significantly affect the results. Largely, **Figure 39** shows that the incorporation of MMLI in the minigrid integration planning procedure does not significantly affect the results of the planning exercise. Specifically, **Figure 39** (a), (c), and (e) show that for all DER and penetration scenarios within Minigrid X, there is no difference in loss reduction realised form the planning exercise with and without MMLI. This observation is also true for

Minigrid Y, presented in **Figure 39** (b), (d) and (f), except for a few scenarios where the detailed identification of grid infeed point lead to a slight loss reduction, 2% to 5% for a minigrid with an MMLI of 0.75 and not expected to require detailed integration planning.

Although loss reduction of 2% to 5% would be considered negligible, these results suggest that the use of MMLI in the grid integration planning of multi-feeder minigrids harbours an inherent uncertainty. This uncertainty is not there when MMLI is greater than 1 as a detailed integration study is still conducted. However, as shown in **Figure 39** (b), (d) and (f), when MMLI is less than 1, some minigrid scenarios may still require detailed minigrid integration planning study as the combination of DERs may lead to loss reduction benefits. The quantification of the inherent uncertainty associated with using MMLI in grid integration of minigrids is the subject of the next case study.

5.3.3 Uncertainty associated with MMLI in planning the grid integration of multi-feeder minigrids

In the previous section, the benefits of including MMLI in the minigrid integration planning process have been demonstrated using two minigrid networks with three feeders, respectively. Here, 220 individual three-feeder minigrid networks are used to establish the uncertainties associated with MMLI. The three-feeder minigrids were derived from combining the 12 single feeder minigrids, presented in Appendix-Table 1, into unique sets of three[14].

Like the previous section, each minigrid network investigated here has three DER scenarios (PV generators without storage, PV generators with storage, and conventional power generator). For each DER scenario, the DER penetration is varied between 0% and 100% at intervals of 25% and the demand load profile with medium demand factor is used.

The results for this case study include the relationship that exists between MMLI and loss reduction; and the uncertainty associated with MMLI usage.

Relationship between loss reduction and MMLI

Figure 40 presents scatter plots showing the relationship between loss reduction and MMLI, under various DER scenarios. These results are obtained from the grid integration planning of the 220 individual multi-feeder minigrid networks used in this case study. For

---

[14] Mathematically, $\binom{12}{3} = 220$

ease of legibility, results from DER penetration of 0%, 50% and 100% are presented. Results for the other penetration levels are also consistent with the trend in Figure 40.

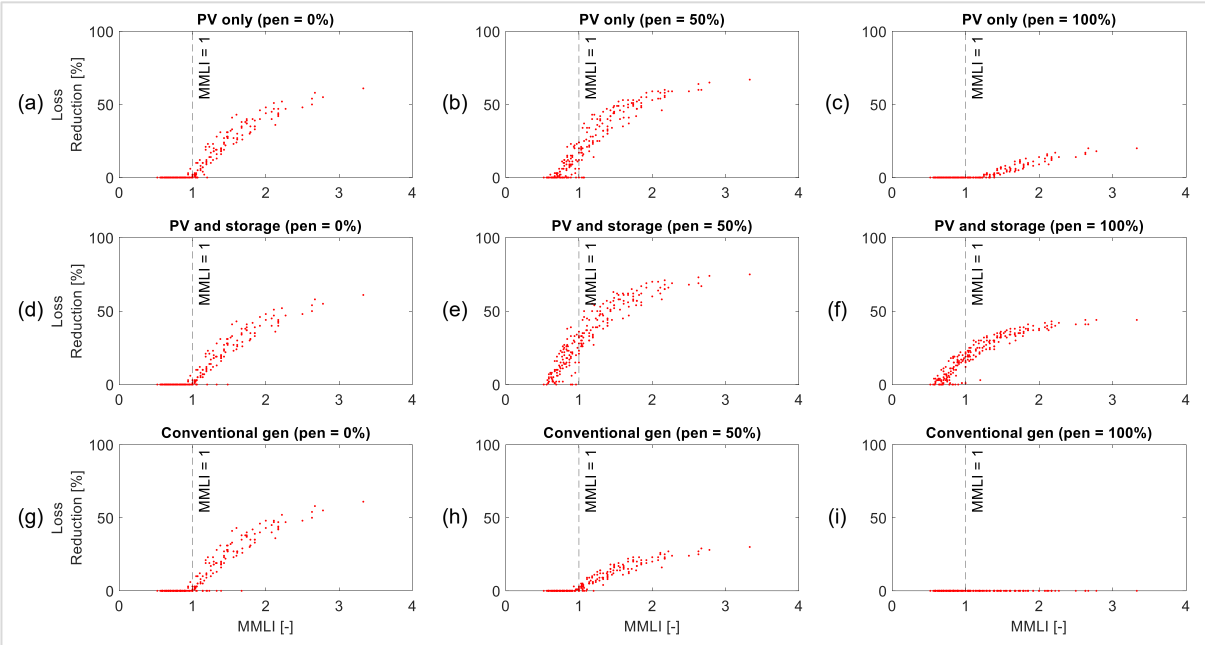


Figure 40: Relationship between loss reduction and MMLI

The following can be observed from Figure 40:

Loss reduction and MMLI are positively correlated. Figure 40 shows that there is a positive relationship between MMLI and loss reduction. Therefore, for any two similar minigrid networks, integration planners should know that a minigrid with higher MMLI guarantees the most loss reduction benefits than that with a lower MMLI value.

Despite the positive relationship between loss reduction benefits and MMLI, loss reduction plateaus for higher values of MMLI. This phenomenon is demonstrated in the scatter plots in Figure 40 (a) to (h) where changes in loss reduction between MMLI values of 1 and 2 is much steeper than changes between MMLI values of 2 and 3. This observation explains why most of the single feeder radial minigrids, with an MMLI of infinity (∞), reported in previous case studies, for example those reported in Figure 21 have a maximum loss reduction of 76%.

Regardless of the MMLI value, high DER penetration reduces loss reduction potential. Across the scatterplots in Figure 40, the loss reduction in the minigrids is not only affected by MMLI but also type and penetration of DER. For example, Figure 40(c) reports low loss reduction benefits, compared to Figure 40(a) and (b), because it reports of minigrids with 100% penetration of PV generators. Similarly, across the types of DERs, there are different loss reduction benefits form minigrids with PV only, Figure 40 (a) – (c), when compared to minigrids with PV and storage, Figure 40 (d) – (f) or a conventional generator, Figure 40 (g) – (i).

Therefore, MMLI results should not be used in isolation. Instead, the planner should also know that there are other parameters that may affect the loss reduction benefits in an optimally grid integrated minigrid.

The usage of MMLI as a pre-assessment tool is most effective in the absence of DERs. The scatterplots presented Figure 40(a), (d) and (g) show that the usage of MMLI as a pre-assessment tool to decide whether to apply full MGIP or not is effective in the absence of DERs. This is demonstrated by the fact that in these three scatter plots, the MMLI=1 line separates 0% and greater than 0% loss reduction values.

However, the rest of the scatterplots in Figure 40 show that the MMLI=1 line does not always constitute the boundary between the possibility of using optimal grid integration planning to achieve some loss reduction benefits and not. For example, Figure 40 (b) shows that for a PV penetration of 50% some minigrid with an MMLI of less than 1 would record loss reduction benefits through optimal rigorous selection of a grid infeed point. On the other hand, Figure 40 (c) shows that with 100% PV penetration, none of the minigrids with an MMLI of less than 1 would record a loss reduction benefit from optimal grid infeed selection. This can also be said of minigrids with 100% penetration of conventional generators in Figure 40 (i).

Therefore, these results show that using MMLI as a pre-assessment tool works very well when there is no DERs in the minigrid network, while the presence of DERs in the minigrids affect the effectiveness of MMLI as a pre-assessment tool. The extent to which DERs affect the effectiveness of MMLI as a pre-assessment tool is not full revealed in the scatter plots of Figure 40. In the following section, this is addressed by quantifying the uncertainty associated with using MMLI in minigrid integration planning of the 220 multi-feeder minigrids presented in this case study.

Uncertainty associated with the usage of MMLI

Table 24 shows four sets of probabilities demonstrating the uncertainty that may be associated with the usage of MMLI in the grid integration planning of 220 minigrids studied in this case study. These probabilities are:

- P(LR>0|MMLI>1) – The probability of realising a loss reduction of greater than 0% from a thorough MGIP when a minigrid has an MMLI of greater than 1.
- P(LR=0|MMLI>1) – The probability of not realising any loss reduction (0%) from a thorough MGIP when a minigrid has an MMLI of greater than 1.

Table 24: Uncertainty associated with the use of MMLI in planning the grid integration of multi-feeder minigrids

DER Type	DER Penetration	MMLI > 1 (n = 116)		MMLI ≤ 1 (n=104)	
		P(LR>0)	P(LR=0)	P(LR>0)	P(LR=0)
PV Only	0%	0.96	0.04	0.05	0.95
	25%	0.99	0.01	0.40	0.60
	50%	0.97	0.03	0.57	0.43
	75%	0.99	0.01	0.37	0.63
	100%	0.66	0.34	0.00	1.00
PV + Storage	0%	0.96	0.04	0.05	0.95
	25%	1.00	0.00	0.53	0.47
	50%	1.00	0.00	0.94	0.06
	75%	1.00	0.00	0.99	0.01
	100%	1.00	0.00	0.83	0.17
Conventional generator	0%	0.91	0.09	0.05	0.95
	25%	0.97	0.03	0.63	0.38
	50%	0.96	0.04	0.08	0.92
	75%	0.00	1.00	0.00	1.00
	100%	0.00	1.00	0.00	1.00

LR = Loss Reduction

- P(LR>0|MMLI≤ 1) – The probability of realising loss reduction of greater than 0% from a thorough MGIP when a minigrid has an MMLI of less than or equal to 1.
- P(LR=0|MMLI≤ 1) – The probability of not realising any loss reduction (0% loss reduction) from a thorough MGIP when a minigrid has an MMLI of less than or equal to 1.

From the definition of the theory and application of MMLI, presented in Section 5.3.1, the desirable outcome is to have loss reduction of greater than 0% when MMLI is greater than 1 and a loss reduction of 0% when MMLI is less than or equal to 1. Therefore the use of MMLI would be considered certain for high values of P(LR>0|MMLI>1) and P(LR=0|MMLI≤ 1), and uncertain if there are high values for n P(LR=0|MMLI>1) and P(LR>0|MMLI≤ 1).

Among the 220 three-feeder minigrids that were used to derive the probabilities in Table 24, 116 had an MMLI of greater than 1 and 104 had an MMLI of less than or equal to 1. The following observations can be drawn from the results presented in Table 24:

An MMLI of greater than 1 guarantees loss reduction benefit. Table 24 shows that minigrids with MMLI values of greater than 1 are more likely to yield loss reduction benefits upon using MGIP. For most scenarios with an MMLI of greater than 1, Table 24 reports a high probability of greater than 0.91 to realise some form of loss reduction from a thorough MGIP. The distribution of loss reduction values for the grid integration of the 116 minigrids with MMLI values of greater than 1 are shown in Figure 41.

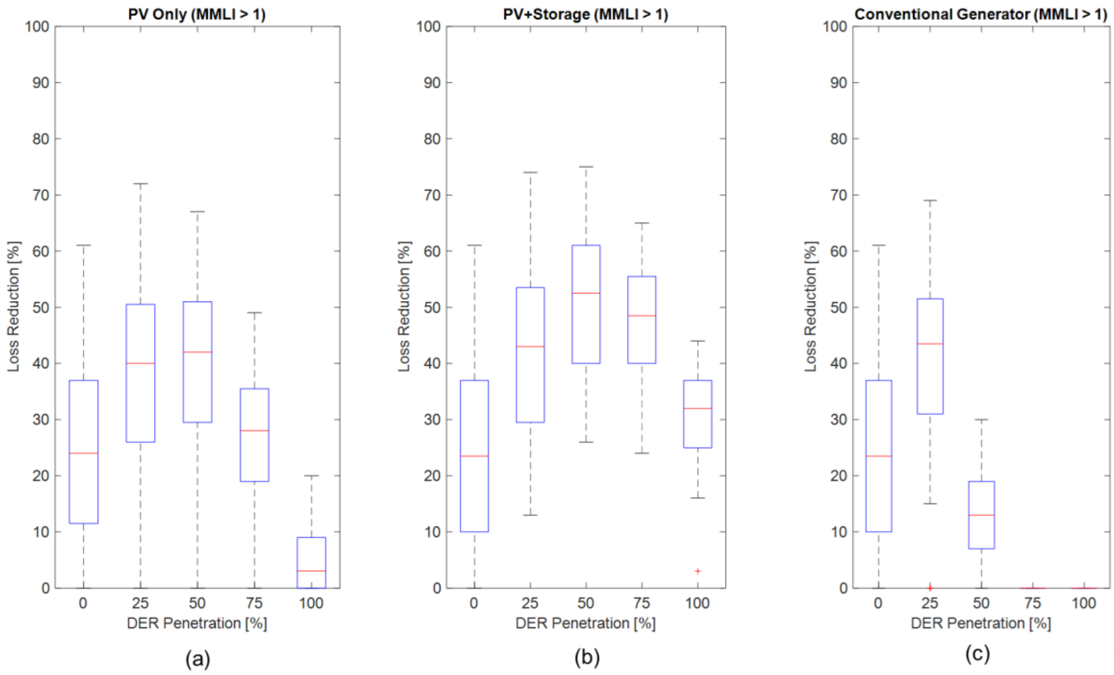


Figure 41: Distribution of post MGIP integration loss reduction values for 116 minigrids with MMLI greater than 1

Figure 41(a), (b) and (c) show that for an MMLI of greater than 1, there can be significantly high loss reduction values across the combination of DER mix and DER penetration. Both Table 24 and Figure 41 show that the only scenarios with MMLI>1 but reporting lower loss reduction potential are those with high DER penetration of PV and conventional generation. This should be expected because, as shown in Chapter 4 high generator penetration levels diminish the loss reduction benefits of minigrid integration planning unless energy storage is also present.

Therefore, the results in Table **24** and levels of loss reduction reported in Figure 41 demonstrate that when an MMLI is greater than 1, carrying out a full MGIP has a higher probability of recording loss reduction benefits than not. Hence, the application of MMLI is less uncertain when the MMLI is more than 1**.**

When MMLI is less than or equal to 1, the certainty of applying MMLI is significantly dependent on the presence of DERs and their penetration levels. Table 24 shows that when MMLI is less than 1, its application within the minigrid integration planning process is certain when the DER penetration level is 0% and uncertain for the other penetration levels. For each of the DER types (PV, PV + Storage and conventional), penetrations of greater than 0% exhibit an irregular trend of P(LR=0|MMLI≤ 1). Figure 42 shows the loss reduction potential within the 104 minigrids with MMLI of less than 1.

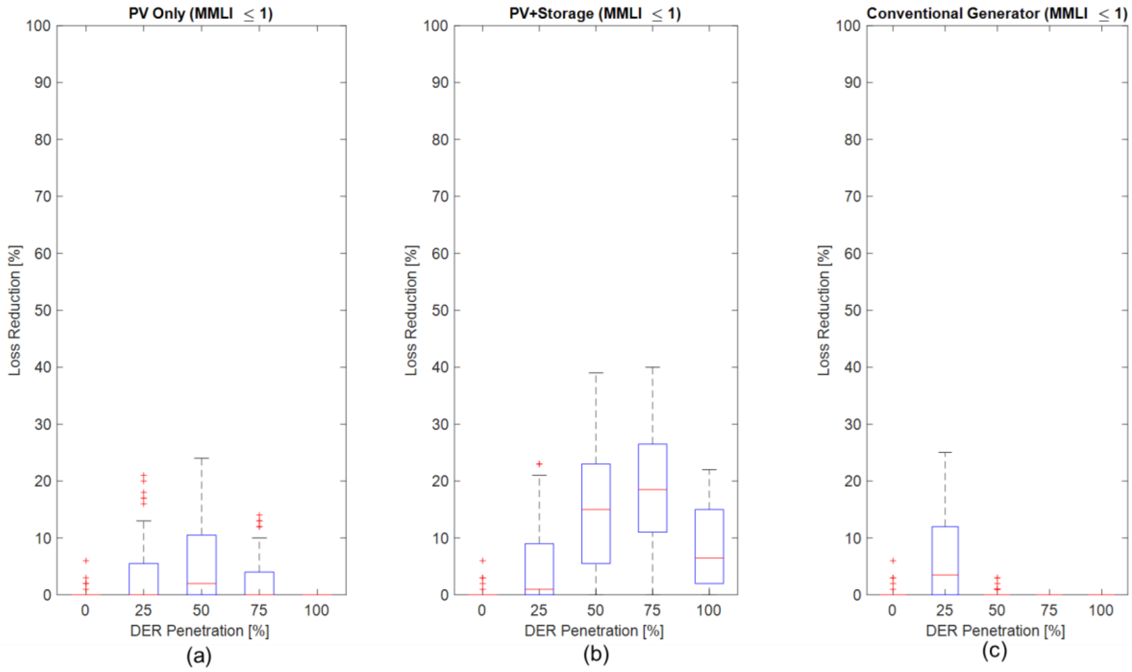


Figure 42: Distribution of post MGIP integration loss reduction values for 104 minigrids with MMLI less than or equal to 1

The impact of the uncertainty associated with the interpretation of MMLI value of less than 1 for various DER scenarios can also be observed from the distribution of post MGIP integration loss reduction values presented in Figure 42. Figure 42 (b) shows when MMLI is less than 1, and a rigorous MGIP integration study is not conduced, there is a chance of foregoing an average of up to 20% loss reduction benefits within the minigrid. Figure 42 (a) and (c) also shows similar behaviour despite on a less magnitude than in Figure 42 (b). Figure 42 confirms that the impact of the uncertainty associated with applying MMLI values of less than 1 changes with minigrid DER type and size. This should be expected considering that the formulation of MMLI in (5.7) does not take DERs into account.

Although the use of MMLI to skip a full MGIP process is associated with the uncertainty highlighted above, the usefulness of MMLI should not be diminished. To understand this usefulness of MMLI, consider the level of loss reduction reported for minigrid whose MMLI is greater than 1, in Figure 41, and minigrids whose MMLI is less than 1 in Figure 42. Evidently, Figure 42 shows that the level of loss reduction that can be foregone because of an MMLI of less than 1 is significantly less than those with MMLI of greater than 1. Consequently, MMLI can also be used to identify minigrids that promise the greatest loss reduction potential.

Therefore, minigrid integration planners should use the MMLI with full knowledge of its inherent uncertainty and associated risks. Otherwise, for some of the minigrids with an MMLI of less than 1, skipping the use of MGIP can lead to forfeiting significant opportunity to accrue loss reduction and related benefits from optimal grid integration planning.

Summary of grid integration planning of multi-feeder minigrids

Here is the summary of issues discussed in this section of the thesis that focussed on planning the grid integration of a multi-feeder minigrid:

- MGIP, as developed in this thesis, can be applied to the grid integration planning of both single feeder and multi-feeder minigrids without any modification.
- Some multi-feeder minigrids may not require full implementation of MGIP depending on their topology and presence or absence of residual DER
- The multi-feeder loading index (MMLI) is a pre-assessment tool that can be used to establish the need to use MGIP or not on a specific minigrid integration planning.
- The incorporation of MMLI in the minigrid integration process can lead to considerable time savings for the integration planner.
- MMLI is found the most effective when a minigrid has either no or a high penetration of some DERs e.g., photovoltaic, or conventional generators.
- The use of MMLI is significantly uncertain for an MMLI of less than 1 and when a minigrid has a renewable power generator, e.g., PV and storage.

5.4 Chapter Summary

In this chapter, two features that would improve grid integration planning of minigrids have been presented. The first aspect is multi-objective formulation and evaluation of MGIP which allows a broader understanding of the planning solutions than single objective solutions presented in the previous chapter. The second aspect in the introduction and application of multi-feeder minigrid loading index (MMLI) as a pre-assessment tool to decide whether planning the grid integration of a specific minigrid should involve detailed identification of grid infeed point or not.

The experimental results for grid MO-MGIP help to support the superiority of MGIP over the other alternative methods for minigrid integration planning. They also demonstrate that the flexibility of the MGIP method presented in this thesis to be modified into a multi-objective problem. In the end, they reveal that the MGIP method does not only lead to loss reduction, but also voltage profile improvements and reactive power loss reduction.

The experimental results for the application of MMLI reveal that it can lead to significant time savings in the planning process. However, the use of MMLI is effective when the minigrid has either no DERs or very high DER penetrations. For this reason, it has been established that using MMLI in planning the grid integration of multi-feeder minigrids with inherent DERs will involve a level of uncertainty. Planners should, therefore, be aware of the uncertainty and associated risk when using MMLI in the minigrid integration planning process.

Having formulated a problem that investigates further benefits of MGIP and the pre-assessment tool for deciding the usefulness of MGIP to a particular minigrid integration planning situation, the next chapter concludes the work of this thesis.

6 CONCLUSIONS AND FUTURE WORK

This chapter presents the conclusions, contributions, and implications of the work presented in this thesis. Besides that, it also offers limitations of the current work and opportunities of advancing this work in future.

6.1 Thesis findings

The main objective of the research work of this thesis was to establish how grid integration of autonomous minigrids can be systematically planned to address some of the post energy access challenges in developing countries. The existing work on the grid convergence and integration of minigrids is insufficient for two main reasons. Firstly, the technical aspects of such integration have received little attention compared to the policy, business, and regulatory aspects [25], [26], [35]. Secondly, the limited academic work that considers the technical aspects of grid and minigrid integration [36]–[38] do not explore the maximisation of benefits from such integration. Instead, they focus on reporting the grid connection of individual minigrids, e.g., [37] reports a case study in Tanzania, or propose technological solution, e.g., [38] propose a back-to-back converter for interfacing minigrids and the main grid.

Besides the lack of emphasis on planning the grid integration of minigrids, existing planning approaches in related fields of electricity access planning [50], DNEP [11] and ODERP can not sufficiently address the identified gap in knowledge [12]. Electricity access planning approaches, such as Homer [39], Open Source Spatial Electrification Tool (OnSSET) [47], Reference Electrification/Reference Network Model (REM/RNM) [43], are designed to decide between grid expansion and offgrid electrification [49] hence not suitable for convergence of the two electrification pathways. The other limitation of electricity access planning tools is that they do not include the capability for quantifying and optimising network losses and power quality issues which are significant challenges in developing countries beyond achieving SDG7 [27], [28],[29].

Although DNEP and ODERP include the capability for quantifying and optimising network losses and power quality issues, they do not have a direct application in the planning the grid convergence and integration of minigrids. DNEP involves solving a top-down grid expansion problem to a greenfield site or improving the existing network's capacity [51] while grid integration of minigrids involves solving a bottom-up expansion problem where the main grid is expanded to existing minigrid networks. On the other hand, ODERP involves optimising the size, location and selection of DERs to integrate into an existing network [52], [53] while in grid integration of minigrids, minigrid DERs are already selected, located and sized.

In response to this gap in knowledge, related objectives were also set out in Chapter 1, that provided focus for the technical work in terms of both improving grid integration solutions offered by planners and the quality of service to minigrid customers. Here in the conclusions, these guiding research questions as set out in Chapter 1 are revisited in light of the work of this thesis.

What does optimal grid integration of minigrids entail?

Grid integration of minigrids is a unique problem for post-electricity access in developing countries. Still, it bears many similarities to active distribution network planning, specifically DER integration and microgrid planning, in developed countries. DER integration and microgrids in mature networks were, initially, a way of advancing the adoption of low carbon energy technologies. However, it was realised that integrating low carbon energy technologies has positive and negative effects on techno-economic factors such as network losses, voltage profile, and investment cost and similar effects can should also be expected in developing countries. Consequently, these techno-economic factors were used as the basis for optimising DER integration and microgrids.

Using recent evidence from Southeast Asia [22], [33], where similar to SSA minigrids and the main grid were simultaneously deployed to address electricity access, this thesis has demonstrated that convergence and subsequent integration of the grid and autonomous minigrids is a necessary step post electricity access in developing countries. Despite various efforts in policy and regulations [35], [134], to facilitate the grid integration of minigrids, a significant gap was identified in optimising such integration. Through the articulation and use of MGIP method, developed through the work of this thesis, it has been demonstrated that like in DER integration and microgrid planning, techno-economic parameters such as network losses, investment cost, and voltage profile, can be used as the basis for positively optimising the grid integration of minigrids in developing countries.

Therefore, optimal grid integration of minigrids entails ensuring an improvement of the techno-economic parameters such as losses, investment cost and voltage profile of post-energy access integrated distribution networks in developing countries.

Are existing energy access or distribution network planning frameworks/tools/methodologies suitable for optimal grid integration of minigrids in developing countries?

Through a detailed review of the existing literature, the present work has demonstrated that existing energy access and distribution network planning frameworks and tools are not suitable for planning the grid integration of minigrids for two main reasons.

Firstly, the available tools split unelectrified regions into two main zones, those suitable for grid extension and those suitable for off-grid electricity access, using a least-cost approach. Essentially, electricity access tools are not developed for convergence of the main grid and minigrids but rather for divergence. Secondly, most electricity access tools cannot perform electrical power flow analysis. This implies that when planning the convergence of minigrid and the main grid such tools cannot guarantee the much-needed post-energy access power quality improvements and loss reduction that can be achieved in support of both grid operation and the benefit to consumers in developing countries. These objectives remain neglected in advancing electricity access and should not be overlooked, as they can offer real tangible benefits to achieving universal access to electricity now and going forward.

Secondly, although various aspects of DNP, such as DNEP, ODERP, and MP, have power flow analysis capability, they are not an exact fit for planning the grid integration of minigrids in developing countries. Specifically, DNEP is typically applied on greenfield networks or in reinforcing an existing network. However, grid integration planning of minigrids involves using a greenfield network to connect two already existing networks – the main grid and minigrids being expanded to. On the other hand, ODERP and MP are based on planning DERs with the grid in mind. However, in grid integration of minigrids, DERs and the associated autonomous network are installed first, as a minigrid, with little to no consideration of the main grid, which comes later through grid extension. The work of this thesis has dealt with this by proposing grid infeed points as the main variable in the grid integration of minigrids.

To what extent can differences and similarities between grid integration of minigrids and integration of distributed energy resources in developed countries be exploited?

The critical similarity between grid integration planning of minigrids and DNP is that both exercises seek to ensure the maximisation of techno-economic performance of the associated integrated networks. Therefore, like DNP, a power flow-based approach would be ideal for realising the techno-economic benefits from a minigrid integration planning exercise. However, the work of this thesis also shows a significant difference in the composition and status of assets when planning grid integration of minigrids and carrying out a typical DNP, as summarised inTable 25.

Table 25: Differences in the status of assets in minigrid integration planning and DNP

Asset	**Status at the planning stage**	
	Minigrid integration	DNP
Grid infeed point	Unknown	Known
Transformer size	Unknown	It depends on the exercise[15]
DER size, type, location	Known	Unknown

Motivated by the key similarity highlighted above and differences in Table 25 between planning the grid integration of minigrids and DNP, the research work of this thesis presents a novel formulation for planning the grid integration of a minigrid (or a cluster of minigrids) called MGIP. Specifically, MGIP articulates how residual minigrid network assets influence critical grid integration planning decisions of selecting a grid infeed point into a minigrid and integration with transformer sizing.

When applied to case studies akin to minigrids in SSA, single-objective MGIP and its multi-objective counterpart, MO-MGIP, are observed to be better in active and reactive

[15] For example, in DNEP transformer sizing an unknown parameter which is obtained from the plan. However, in DER planning, transformer size may already be known and be presented as one of the constraints for the planning problem.

power loss reduction, and voltage profile improvement when compared to alternative methods for minigrid integration planning, defined in this thesis as No-opt, Geo-opt and MV-opt. No-opt is based on a recommendation in [36] to connect the grid infeed as close as possible to the minigrid generator. Geo-opt is based on the [125] where the best point of grid infeed is assumed to the at the centroid of the cluster on nodes. MV-opt is based on DNP, [161] and [21] , where power flows are used to analyse parameters but the downstream networks are not articulated well or are not different from minigrids that are initially deployed for autonomous operation.

Thus, through making use of the similarities between typical DNP objectives and those of the future power systems integration in developing countries, the objectives of MGIP are established. Although DNP has similar objectives with MGIP, the differences in the key variables and the need for a better articulation of the downstream networks has led to the development of a the novel MGIP methodology which addresses a typical post SGD7 issue in a developing country.

How do residual minigrid DERs, demand profiles, and topologies affect the optimal grid integration of minigrids?

The benefits accrued from the application of MGIP have been observed to be sensitive to the type and size of minigrid residual DERs, minigrid topologies and demand profiles in that minigrid (or a cluster). For the same DER penetration, minigrids with PV and storage register the most loss reduction benefits compared to minigrids with conventional generators and PV generators only, as shown in Figure 24. Figure 24 also shows that the higher the minigrid demand factor, the higher the benefits accrued from using MGIP and vice-versa.

Therefore, the work of this thesis has shown some specific ways in which residual minigrid DERs, demand profiles and topologies affect grid integration of minigrids. For example, the presence of partially rated DERs lead to high benefits from optimal grid integration planning. This is so because highly rated DERs have the potential to increase power flows in certain parts of the network unless the grid infeed point is located at the DER hub.

In addition, the work of this thesis shows that the topology of the concerned minigrid affects the magnitude of benefits realised from using MGIP in planning the grid integration of minigrids. Specifically, minigrids with a trunk-and-branch topology are expected to realise the highest benefits from using MGIP. For minigrids with a hub-and-spoke topology, the benefits of using MGIP depend on the spread of demand amongst the feeders. A novel expression of share of power demand among feeders has been developed in this thesis using a measure called MMLI. Where an MMLI of greater than 1 suggests that the minigrid has a dominant feeder and the use of MGIP will be beneficial. Otherwise, an MMLI of less than or equal to 1 suggests little to no benefits in using MGIP, and the grid infeed point will be identified at or close to the minigrid DER.

Therefore, this thesis has demonstrated that in systematic planning of the grid integration of minigrids, planners should pay close attention to how factors such as DERs, topology and demand profiles interact.

6.2 Thesis contributions and implications

The presented thesis makes the following contributions and implications to knowledge, research and practice:

Definition and formulation of minigrid integration planning problem

Grid convergence and integration of the minigrids is a unique post-electricity access challenge associated with countries advancing their electricity access targets using grid extension and off grid means. So far, several efforts have been made to address the policy and regulatory challenges associated with grid integration of minigrids. However, work of this thesis, also reported in [54], [185], presents a novel contribution to the associated literature by defining, formulating and applying methods for optimising such integrations. This contribution can be stated in two ways.

Firstly, the thesis presents a conceptual definition of optimal grid integration of formally autonomous minigrids in developing countries. Unlike DER integration planning which ensures optimum integrated network performance through optimising the size, location and type of DERs within the network, optimal grid integration of minigrids is different in the developing country context. Instead, optimal grid integration planning of minigrids is defined as an exercise for establishing a grid infeed point into existing minigrids and sizing of associated integration asserts, like transformers, to ensure the optimum techno-economic performance of the integrated network.

Secondly, the MGIP is presented as a mathematical formalisation of optimal grid integration of minigrids in developing countries. The work presented in this thesis is the maiden definition and mathematical formalisation of this planning problem in developing countries. Compared to related works, from developed countries, this formalisation recognises the contextual circumstances associated with grid integration of minigrids. For example, it accommodates inherent DERs within the minigrids networks and considers the grid infeed point as a variable. This is unlike in developed countries where DER type, size and locations are decision variables and point of grid connection is already fixed.

Framework for evaluation of the minigrid integration planning problem

Besides the formalisation of the MGIP problem, the thesis also presents an associated framework for implementing the MGIP. This framework is used to test the MGIP in the current work, but it can also be useful in the following other ways:

- Gives an opportunity for the development of a module that can be embedded in existing power systems analysis tools to address the highlighted grid integration of minigrids challenges in developing countries. Existing tools that incorporate DNEP and ODERP modules and capabilities assume an established grid expanding to a greenfield or accommodating DERs. However, the method and framework in this thesis presents how to evaluate a post energy access developing country challenge where two existing networks, the main grid and a minigrid (or several minigrids), are integrating with each other at distribution level.
- In the absence of a module for planning the grid integration of minigrids within power systems analysis tool, the work of this thesis can be used by planning engineers with power utility companies in developing countries to develop bespoke algorithms for maximising the benefits of grid integration of minigrids.
- Gives an opportunity for further innovation in the applications of MGIP and algorithms for evaluation. For example, although the work of this thesis uses GA to evaluate the MGIP case studies, it does not make any contributions to the algorithm itself. By using the presented framework for evaluating MGIP, other researchers can develop a more efficient algorithm for solving the MGIP problem.

Guidelines for the application of MGIP on various minigrid topologies

This thesis recognises that not every minigrid integration planning problem needs to involve the detailed application of the MGIP. Therefore, a novel index, called MMLI [186] has been proposed. MMLI pre-assesses the indicative benefits of applying MGIP to minigrid integration planning problems involving minigrids of different topologies.

Using the MMLI, planners and minigrid operator can decipher whether a particular grid integration of a minigrid requires a detailed analysis of MGIP or not. Where detail MGIP analysis is not required, the planners will save a significant amount of time and effort in planning the grid integration of such minigrids. Although the thesis shows that the use of MMLI is not always accurate, MMLI remains a very useful pre-assessment tool for facilitating quick decision making in planning the grid integration of minigrids.

Implications on real-world policy and network planners

The presented methodology has implications at policy level as well as tactical level within the utility companies. At policy level, besides mechanisms to facilitate the deployment of grid ready minigrids, the use of MGIP and MMLI should also be highlighted as part of the criteria for making rational decisions when those the grid ready minigrids eventually require grid integration. Among other things, the policy should clearly state the responsibilities of both minigrid operators and utility companies in the grid integration of inigrids. From the premise of this thesis, the minigrid operator is responsible for the provision of minigrid network modelling data. The utility company is responsible for modelling and analysing the integration using MMLI and MGIP.

Tactically, the network planners will need two analytical skills to implement the MGIP. The first skill is the ability to electrically model the minigrids and main grid terminal and run a multi-period powerflow analysis. The second competence will be to wrap an optimisation algorithm around the powerflow model for optimising the points of grid infeed, transformer size and MV network length. A basic exhaustive exploration of the solution space may be an adequate approach for integrating a single minigrid. However, for a cluster of minigrids, a well-defined optimisation algorithm would be required.

6.3 Limitations and future work

The research in this thesis has the following limitations that can motivate future work in optimal grid integration of minigrids in developing countries:

Firstly, it only presents a homogeneous situation where a single or cluster of grid-ready minigrids requires grid integration. However, the post-electricity access environment is likely to be more heterogeneous than that with the main grid converging with grid compatible and incompatible minigrids, and other off-grid electricity access systems like SHSs. Therefore, the technical work presented here can be applied within a more extensive infrastructure planning framework beyond typical electricity access planning and combines optimal grid expansion, minigrid placement, SHS placement, then the convergence of the main grid and off-grid systems over a 10-to-30-year planning horizon.

Secondly, the present work only considers straight lines between grid terminal point and minigrids or among minigrids (akin to direct overhead lines). However, this would not always be the case in a given implementation, as line routing has several constraints, such as accessibility and terrain. Therefore, the inclusion of high-fidelity models of the physical constraints to the line routing can improve the practicality of the results of the routing in the presented work, possibly linked to the use of geographic information system data where it is available.

Thirdly, the present work only considers the network downstream of an identified grid terminal point and ignores the upstream network. However, the increased integration of minigrids with inherent DERs can influence the upstream network and the electrical demand observed at the transmission level. Therefore, a system-level assessment of high levels of grid integration of minigrids would be necessary to inform post energy access grid-level planning and operation of both networks and energy resources in developing countries. While this would bring more work to the utility company it offers the benefit of a more coordinated approach to the use of distributed generation which if managed properly could help alleviate grid 'blackouts'.

Fourthly, the work of this thesis assumes that the decision to integrate the grid and candidate minigrids has already been made. However, to inform that decision, a significant economic analysis has to be done to establish the worthwhileness of integrating the main grid and minigrids. Therefore, the economic assessment of the worthwhileness of grid integration of minigrids from the combined perspective of customers, minigrid operators and utility companies requires further investigation.

6.4 Concluding remarks

The work presented in this thesis proposes a systematic approach to plan the grid integration of minigrids in developing countries, called MGIP, and an associated pre-assessment tool, called MMLI. The presented methods are unique from those in the existing electricity access and distribution network planning domain. These approaches can help tailor power system planning tools to the post-energy access needs of developing countries. They can also become a basis for bespoke analytical tools within power utilities in developing countries. Lastly, the presented work provides a solid foundation for further technical study of post energy access issues in developing countries, a topic that has not received significant enough attention to date.

7 REFERENCES

[1] K. Bithas and P. Kalimeris, *Revisiting the Energy-Development Link*. Cham: Springer International Publishing, 2016.

[2] J. Goldemberg, T. B. Johansson, A. K. N. Reddy, and R. H. Williams, “Basic needs and much more with one kilowatt per capita (energy).,” *Ambio*, vol. 14, no. 4–5, pp. 190–200, 1985, doi: 10.2307/4313148.

[3] P. Alstone, D. Gershenson, and D. M. Kammen, “Decentralized energy systems for clean electricity access,” *Nat. Clim. Chang.*, vol. 5, no. 4, pp. 305–314, 2015, doi: 10.1038/nclimate2512.

[4] G. Frigo, M. Baumann, and R. Hillerbrand, “Energy and the Good Life: Capabilities as the Foundation of the Right to Access Energy Services,” *J. Hum. Dev. Capab.*, vol. 22, no. 2, pp. 218–248, 2021, doi: 10.1080/19452829.2021.1887109.

[5] United Nations Development Programme (UNDP), “Human Development Index (HDI),” *Human Development Reports*, 2021. http://hdr.undp.org/en/indicators/137506# (accessed Aug. 31, 2021).

[6] The World Bank, “Development Indicators,” 2021. https://data.worldbank.org/indicator (accessed Aug. 31, 2021).

[7] H. Louie, *Off-Grid Electrical Systems in Developing Countries*. Cham: Springer International Publishing, 2018.

[8] M. Bhatia and N. Angelou, “Beyond Connections Energy Access Redefined. ESMAP Technical Report;008/15,” p. 228, 2015.

[9] IPCC *et al.*, “Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” 2021. [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/.

[10] S. C. Bhattacharyya and D. Palit, “The nexus of grids, mini-grids and off-grid options for expanding electricity access,” 2019. [Online]. Available: https://energyeconomicgrowth.org/publication/nexus-grids-mini-grids-and-grid-options-expanding-electricity-access.

[11] O. Ruhnau, S. Bannik, S. Otten, A. Praktiknjo, and M. Robinius, “Direct or indirect electrification? A review of heat generation and road transport decarbonisation scenarios for Germany 2050,” *Energy*, vol. 166, pp. 989–999, 2019, doi: 10.1016/j.energy.2018.10.114.

[12] SEforAll, “Who we are | Sustainable Energy for All,” 2019. https://www.seforall.org/who-we-are (accessed Dec. 29, 2021).

[13] United Nations Department of Economic and Social Affairs, *The Sustainable Development Goals Report 2018*. UN, 2018.

[14] UN DESA, “THE 17 GOALS | Sustainable Development,” *Sustainable Development*, 2016. https://sdgs.un.org/goals (accessed Dec. 29, 2021).

[15] IEA, IRENA, The World Bank, and World Health Organization, “Tracking SDG 7: The Energy Progress Report 2021,” Washington DC, 2021. [Online]. Available: https://trackingsdg7.esmap.org/data/files/download-documents/2021_tracking_sdg7_report.pdf.

[16] United Nations, “Sustainable Energy ‘Golden Thread’ Linking 2030 Agenda with Pledge to Leave No One Behind, Especially Rural Women, Deputy Secretary-General Tells Side Event,” 2018. https://www.un.org/press/en/2018/dsgsm1202.doc.htm (accessed Dec. 29, 2021).

[17] IEA, “Defining energy access: 2020 methodology – Analysis - IEA,” *IEA*, 2020. https://www.iea.org/articles/defining-energy-access-2020-methodology (accessed Sep. 01, 2021).

[18] IEA, IRENA, UNSD, World Bank, and WHO, “Tracking SDG 7: The Energy Progress Report 2021,” Washington DC, 2021.

[19] International Finance Corporation (IFC), “From Gap to Opportunity : Business Models for Scaling Up Energy Access,” Washington, DC, 2012. [Online]. Available: https://www.ifc.org/wps/wcm/connect/21ba1015-76b7-4daf-9385-3667701bb0cb/EnergyAccessReport.pdf?MOD=AJPERES&CVID=jt.Impw.

[20] N. Narayan, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, “The Long Road to Universal Electrification: A Critical Look at Present Pathways and Challenges,” *Energies*, vol. 13, no. 3, p. 508, 2020, doi: 10.3390/en13030508.

[21] Energy Sector Management Assistance Program (ESMAP), “Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers,” World Bank, Washington, DC, 2019. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/31926.

[22] Rockefeller Foundation, “Beyond Off-grid: Integrating Mini-grids with India’s Evolving Electricity System,” 2017. [Online]. Available: https://www.rockefellerfoundation.org/report/integrating-mini-grids-indias-evolving-electricity-system/.

[23] E. Day, “Moving beyond energy access - the challenge and impact of unreliable electricity in emerging economies,” 2020. [Online]. Available: https://www.energyeconomicgrowth.org/publication/eeg-energy-insight-moving-beyond-energy-access-challenge-and-impact-unreliable.

[24] A. Korkovelos, H. Zerriffi, M. Howells, M. Bazilian, H.-H. Rogner, and F. Fuso Nerini, “A Retrospective Analysis of Energy Access with a Focus on the Role of Mini-Grids,” *Sustainability*, vol. 12, no. 5, p. 1793, Feb. 2020, doi: 10.3390/su12051793.

[25] B. Tenenbaum, C. Greacen, T. Siyambalapitiya, and J. Knuckles, From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa. The World Bank, 2014.

[26] J. Tjäder, S. Ackeby, and C. Bastholm, “The role and interaction of microgrids and centralized grids in developing modern power systems,” *India Smart Grid Week 2016, 15-19 March 2016 at Manekshaw Centre, DhaulaKuan, New Delhi, India*. 2016, [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:du-23497.

[27] Vivid Economics; ARUP, “Opportunities to enhance electricity network efficiency,” London, 2015.

[28] IEA, “Africa Energy Outlook 2019,” Paris, 2019. [Online]. Available: https://www.iea.org/reports/africa-energy-outlook-2019#energy-access%0Ahttps://www.iea.org/reports/africa-energy-outlook-2019%23africa-case.

[29] V. Jacome, N. Klugman, C. Wolfram, B. Grunfeld, D. Callaway, and I. Ray, “Power quality and modern energy for all,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 116, no. 33, pp. 16308–16313, 2019, doi: 10.1073/pnas.1903610116.

[30] J. Ayaburi, M. Bazilian, J. Kincer, and T. Moss, “Measuring ‘Reasonably Reliable’ access to electricity services,” *Electr. J.*, vol. 33, no. 7, p. 106828, 2020, doi: 10.1016/j.tej.2020.106828.

[31] P. Blechinger, C. Cader, and P. Bertheau, “Least-Cost Electrification Modeling and Planning—A Case Study for Five Nigerian Federal States,” *Proc. IEEE*, vol. 107, no. 9, pp. 1923–1940, Sep. 2019, doi: 10.1109/JPROC.2019.2924644.

[32] A. Berizzi, M. Delfanti, D. Falabretti, S. Mandelli, and M. Merlo, “Electrification Processes in Developing Countries: Grid Expansion, Microgrids, and Regulatory Framework,” *Proc. IEEE*, vol. 107, no. 9, pp. 1981–1994, 2019, doi: 10.1109/jproc.2019.2934866.

[33] B. Tenenbaum, C. Greacen, and D. Vaghela, *Mini-Grids and Arrival of the Main Grid*. Washington, DC.: World Bank, 2018.

[34] D. Schnitzer, D. L. Shinde, J. P. Carvallo, R. Deshmukh, J. Apt, and D. M. Kammen, “Microgrids for Rural Electrification : A critical review of best practices,” 2014.

[35] International Renewable Energy Agency (IRENA), “Policies and regulations for renewable mini-grids,” 2018. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Oct/IRENA_mini-grid_policies_2018.pdf.

[36] C. Greacen, R. Engel, and T. Quetchenbach, “A Guidebook on Grid Interconnection and Islanded Operation of Mini-Grid Power Systems Up to 200kW,” Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), California, 2013. [Online]. Available: https://publications.lbl.gov/islandora/object/ir%3A158819/datastream/PDF/view.

[37] C. Bastholm and F. Fiedler, “Techno-economic study of the impact of blackouts on the viability of connecting an off-grid PV-diesel hybrid system in Tanzania to the national power grid,” *Energy Convers. Manag.*, vol. 171, pp. 647–658, 2018, doi: 10.1016/j.enconman.2018.05.107.

[38] G. G. Talapur, H. M. Suryawanshi, L. Xu, and A. B. Shitole, “A Reliable Microgrid With Seamless Transition Between Grid Connected and Islanded Mode for Residential Community With Enhanced Power Quality,” *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 5246–5255, 2018, doi: 10.1109/tia.2018.2808482.

[39] T. Lambert, P. Gilman, and P. Lilienthal, “Micropower System Modeling with Homer,” in *Integration of Alternative Sources of Energy*, vol. 1, no. 1, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2006, pp. 379–418.

[40] P. S. Georgilakis and N. D. Hatziargyriou, “Optimal distributed generation placement in power distribution networks: Models, methods, and future research,” *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3420–3428, 2013, doi: 10.1109/TPWRS.2012.2237043.

[41] A. Ehsan and Q. Yang, “Optimal integration and planning of renewable distributed generation in the power distribution networks: A review of analytical techniques,” *Appl. Energy*, vol. 210, pp. 44–59, 2018, doi: 10.1016/j.apenergy.2017.10.106.

[42] I. Ziari, G. Ledwich, and A. Ghosh, “Optimal integrated planning of MV-LV distribution systems using DPSO,” *Electr. Power Syst. Res.*, vol. 81, no. 10, pp. 1905–1914, 2011, doi: 10.1016/j.epsr.2011.05.015.

[43] P. Ciller *et al.*, “Optimal Electrification Planning Incorporating On- And Off-Grid Technologies- And Reference Electrification Model (REM),” *Proc. IEEE*, vol. 107, no. 9, pp. 1872–1905, 2019, doi: 10.1109/JPROC.2019.2922543.

[44] P. A. Trotter, M. C. McManus, and R. Maconachie, “Electricity planning and implementation in sub-Saharan Africa: A systematic review,” *Renew. Sustain. Energy Rev.*, vol. 74, no. December 2016, pp. 1189–1209, 2017, doi: 10.1016/j.rser.2017.03.001.

[45] V. Vahidinasab *et al.*, “Overview of Electric Energy Distribution Networks Expansion Planning,” *IEEE Access*, vol. 8, pp. 34750–34769, 2020, doi: 10.1109/ACCESS.2020.2973455.

[46] K. Mahmoud, N. Yorino, and A. Ahmed, “Optimal Distributed Generation Allocation in Distribution Systems for Loss Minimization,” *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 960–969, 2016, doi: 10.1109/tpwrs.2015.2418333.

[47] D. Mentis *et al.*, “Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa,” *Environ. Res. Lett.*, vol. 12, no. 8, p. 85003, 2017, doi: 10.1088/1748-9326/aa7b29.

[48] Columbia University, “Network Planner.” https://qsel.columbia.edu/network-planner/ (accessed Sep. 30, 2021).

[49] S. C. Bhattacharyya and D. Palit, "The nexus of grids, mini-grids and off-grid options for expanding electricity access | EEG," 2019. [Online]. Available: https://energyeconomicgrowth.org/publication/nexus-grids-mini-grids-and-grid-options-expanding-electricity-access.

[50] P. Ciller and S. Lumbreras, "Electricity for all: The contribution of large-scale planning tools to the energy-access problem," *Renew. Sustain. Energy Rev.*, vol. 120, no. June 2019, p. 109624, 2020, doi: 10.1016/j.rser.2019.109624.

[51] N. H. Luong, "Design and Application of Scalable Evolutionary Algorithms in Electricity Distribution Network Expansion Planning," TU Delft University, 2018.

[52] A. A. Abou El-Ela, S. M. Allam, and M. M. Shatla, "Maximal optimal benefits of distributed generation using genetic algorithms," *Electr. Power Syst. Res.*, vol. 80, no. 7, pp. 869–877, 2010, doi: 10.1016/j.epsr.2009.12.021.

[53] E. El-saadany and R. Seethapathy, "Optimal Renewable Resources Mix for Distribution," vol. 25, no. March, pp. 360–370, 2010.

[54] M. Chikumbanje, D. Frame, and S. Galloway, "Enhancing Electricity Network Efficiency in sub-Saharan Africa through Optimal Integration of Minigrids and the Main Grid," in *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020*, Aug. 2020, pp. 1–5, doi: 10.1109/PowerAfrica49420.2020.9219976.

[55] J. Romero Aguero, A. Khodaei, and R. Masiello, "The Utility and Grid of the Future: Challenges, Needs, and Trends," *IEEE Power Energy Mag.*, vol. 14, no. 5, pp. 29–37, 2016, doi: 10.1109/mpe.2016.2577899.

[56] O. Zinaman *et al.*, "Power systems of the future," *Electr. J.*, vol. 28, no. 2, pp. 113–126, Mar. 2015, doi: 10.1016/j.tej.2015.02.006.

[57] F. P. Sioshansi, "Future of Utilities - Utilities of the Future: How Technological Innovations in Distributed Energy Resources Will Reshape the Electric Power Sector," *Futur. Util. - Util. Futur. How Technol. Innov. Distrib. Energy Resour. Will Reshape Electr. Power Sect.*, pp. 1–447, 2016, doi: 10.1016/C2015-0-00987-X.

[58] R. Shirley and B. Attia, "Unlocking Utilities of the Future in Sub-Saharan Africa," 2020. doi: 10.2139/ssrn.3634041.

[59] I. Pérez-Arriaga and C. Knittle, "Utility of the future: An mit energy iniative response to an industry in transition," 2016. [Online]. Available: energy.mit.edu/uof.

[60] R. E. Brown, C. Scott Wilson, and H. Van Nispen, "Becoming the Utility of the Future: Risks and Opportunities," *IEEE Power Energy Mag.*, vol. 14, no. 5, pp. 57–65, 2016, doi: 10.1109/MPE.2016.2573857.

[61] B. Jairaj *et al.*, "THE FUTURE ELECTRICITY GRID - Key questions and considerations for developing countries," *World Resour. Inst.*, p. 66, 2016, [Online]. Available: https://www.wri.org/sites/default/files/The_Future_Electricity_Grid.pdf.

[62] K. Hojčková, B. Sandén, and H. Ahlborg, "Three electricity futures: Monitoring the emergence of alternative system architectures," *Futures*, vol. 98, pp. 72–89, 2018, doi: 10.1016/j.futures.2017.12.004.

[63] M. Welsch *et al.*, "Smart and Just Grids for sub-Saharan Africa: Exploring options," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 336–352, 2013, doi: 10.1016/j.rser.2012.11.004.

[64] J. M. Gers, *Distribution system analysis and automation*. London: Institution of Engineering and Technology, 2013.

[65] A. B. Sebitosi and R. Okou, "Re-thinking the power transmission model for sub-Saharan Africa," *Energy Policy*, vol. 38, no. 3, pp. 1448–1454, 2010, doi: 10.1016/j.enpol.2009.11.025.

[66] P. Bronski *et al.*, "The Economics of Grid Defection: When and where distributed solar generation plus storage competes with traditional utility service," 2014.

[67] C. A. Severance, "A Practical, Affordable (and Least Business Risk) Plan to Achieve '80% Clean Electricity' by 2035," *Electr. J.*, vol. 24, no. 6, pp. 8–26, 2011, doi: 10.1016/j.tej.2011.06.004.

[68] M. Castaneda, M. Jimenez, S. Zapata, C. J. Franco, and I. Dyner, "Myths and facts of the utility death spiral," *Energy Policy*, vol. 110, pp. 105–116, 2017, doi: 10.1016/j.enpol.2017.07.063.

[69] R. Khalilpour and A. Vassallo, "Leaving the grid: An ambition or a real choice?," *Energy Policy*, vol. 82, pp. 207–221, 2015, doi: 10.1016/j.enpol.2015.03.005.

[70] F. A. Felder and R. Athawale, "The Life and Death of the Utility Death Spiral," *Electr. J.*, vol. 27, no. 6, pp. 9–16, 2014, doi: 10.1016/j.tej.2014.06.008.

[71] D. Schnitzer, S. Deepa, J. P. Carvalo, D. Ranjit, A. Jay, and K. Daniel, "Microgrids for Rural Electrification : A critical review of best practices based on seven

case studies Microgrids for Rural Electrification," 2014. doi: 10.13140/RG.2.1.1399.9600.

[72] P. J. Levi, "Feasability of Grid Compatible Microgrids," 2016.

[73] S. Groh, J. van der Straeten, B. Edlefsen Lasch, D. Gershenson, W. Leal Filho, and D. M. Kammen, Eds., *Decentralized Solutions for Developing Economies*. Cham: Springer International Publishing, 2015.

[74] B. Soltowski, D. Campos-Gaona, S. Strachan, and O. Anaya-Lara, "Bottom-Up Electrification Introducing New Smart Grids Architecture—Concept Based on Feasibility Studies Conducted in Rwanda," *Energies*, vol. 12, no. 12, p. 2439, 2019, doi: 10.3390/en12122439.

[75] S. Chowdhury, S. P. Chowdhury, and P. Crossley, *Microgrids and active distribution networks*. 2009.

[76] T. Levin and V. M. Thomas, "Can developing countries leapfrog the centralized electrification paradigm?," *Energy Sustain. Dev.*, vol. 31, pp. 97–107, 2016, doi: 10.1016/j.esd.2015.12.005.

[77] K. Bell and S. Gill, "Delivering a highly distributed electricity system: Technical, regulatory and policy challenges," *Energy Policy*, vol. 113, no. October 2017, pp. 765–777, 2018, doi: 10.1016/j.enpol.2017.11.039.

[78] C. Abbey *et al.*, *Planning and Optimization Methods for Active Distribution Systems*, no. August. Paris: CIGRE (International Council on Large Electric Systems), 2014.

[79] J. Rozenberg and M. Fay, "Beyond the Gap : How Countries Can Afford the Infrastructure They Need while Protecting the Planet ," World Bank Group, Washington, D.C., 2019. [Online]. Available: http://documents.worldbank.org/curated/en/189471550755819133/Beyond-the-Gap-How-Countries-Can-Afford-the-Infrastructure-They-Need-while-Protecting-the-Planet.

[80] A. Alarcon-Rodriguez, G. Ault, and S. Galloway, "Multi-objective planning of distributed energy resources: A review of the state-of-the-art," *Renew. Sustain. Energy Rev.*, vol. 14, no. 5, pp. 1353–1366, 2010, doi: 10.1016/j.rser.2010.01.006.

[81] S. M. Ismael, S. H. E. Abdel Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "State-of-the-art of hosting capacity in modern power systems with distributed generation," *Renew. Energy*, vol. 130, pp. 1002–1020, 2019, doi: 10.1016/j.renene.2018.07.008.

[82] I. Bisaga, N. Puźniak-Holford, A. Grealish, C. Baker-Brian, and P. Parikh, "Scalable off-grid energy services enabled by IoT: A case study of BBOXX SMART Solar," *Energy Policy*, vol. 109, pp. 199–207, 2017, doi: 10.1016/j.enpol.2017.07.004.

[83] G. A. Laudani and P. D. Mitcheson, "Comparison of cost and efficiency of DC versus AC in office buildings," *Transform. Top Tail Energy Networks, London*, 2015.

[84] T. Hakala, T. Lahdeaho, and P. Jarventausta, "Low-Voltage DC Distribution—Utilization Potential in a Large Distribution Network Company," *IEEE Trans. Power Deliv.*, vol. 30, no. 4, pp. 1694–1701, 2015, doi: 10.1109/tpwrd.2015.2398199.

[85] R. Majumder, M. Dewadasa, A. Ghosh, G. Ledwich, and F. Zare, "Control and protection of a microgrid connected to utility through back-to-back converters," *Electr. Power Syst. Res.*, vol. 81, no. 7, pp. 1424–1435, 2011, doi: 10.1016/j.epsr.2011.02.006.

[86] P. Hollberg and F. Fuso Nerini, "Swarm grids - Innovation in rural electrification," 2015.

[87] IRENA, Innovation Outlook Mini-Grids. 2016.

[88] M. Chikumbanje, D. Frame, and S. Galloway, "Minigrid integration in sub-Saharan Africaidentifying the 'optimal' point of connection," in *2020 6th IEEE International Energy Conference (ENERGYCon)*, Sep. 2020, pp. 625–630, doi: 10.1109/energycon48941.2020.9236457.

[89] I. J. Pérez-Arriaga, *Regulation of the Power Sector*, vol. 61. London: Springer London, 2013.

[90] D. Palit and B. Kaushik, "Exploring the Grey Areas," *Epw*, vol. 10, no. March, pp. 40–52, 2015.

[91] Republic of Rwanda, "Rwanda Energy Policy." p. 76, 2015, [Online]. Available: http://mininfra.gov.rw/fileadmin/user_upload/new_tender/Energy_Policy.pdf.

[92] S. Mahapatra and S. Dasappa, "Rural electrification: Optimising the choice between decentralised renewable energy sources and grid extension," *Energy Sustain. Dev.*, vol. 16, no. 2, pp. 146–154, 2012, doi: 10.1016/j.esd.2012.01.006.

[93] R. Deshmukh, J. P. Carvallo, and A. Gambhir, "Sustainable Development of Renewable Energy Mini- - - grids for Energy Access : A Framework for Policy Design National Laboratory," California, 2013. [Online]. Available:

http://www.canopusfund.org/fileadmin/redaktion/Documents/Sustainable_Development_of_Renewable_Energy_Mini-grids_for_Energy_Access.pdf.

[94] S. C. Bhattacharyya, "Mini-Grids for the Base of the Pyramid Market: A Critical Review," *Energies*, vol. 11, no. 4, 2018, doi: ARTN 81310.3390/en11040813.

[95] BloombergNEF, "State of the Global Mini-grids Market," Nov. 2020.

[96] Malawi Energy Regulatory Authority (MERA), "Regulatory Framework for Minigrids," 2020. [Online]. Available: https://mera.mw/download/regulatory-framework-for-mini-grid-july-2020/?wpdmdl=1675&refresh=5ffd70a63a0151610444966.

[97] Republic of Tanzania, "Electricity (Development of Small Power Projects)," 2018. Accessed: Mar. 16, 2021. [Online]. Available: https://www.ewura.go.tz/wp-content/uploads/2018/06/The-Electricity-Development-of-Small-Power-Projects-Rules-2018.pdf.

[98] Nigerian Electricity Regulatory Commission (NERC), "Regulations for Mini-Grid," 2016. [Online]. Available: https://nerc.gov.ng/index.php/component/remository/Regulations/NERC-Regulation-for-Mini-Grid/?Itemid=591.

[99] J. Tjader and S. Ackeby, "Discussion paper : The role and interaction of microgrids and centralized grids The role and interaction of microgrids and centralized grids in developing modern power systems – A case review," 2016.

[100] S. Ackeby, J. Tjäder, and C. Bastholm, "The role and interaction of microgrids and centralized grids in developing modern power systems," 2017, [Online]. Available: http://www.diva-portal.org/smash/record.jsf?pid=diva2:1180295.

[101] A. C. Zambroni de Souza and M. Castilla, "Microgrids design and implementation," *Microgrids Design and Implementation*. Springer, Cham, Switzerland, pp. 1–538, 2018, doi: 10.1007/978-3-319-98687-6.

[102] S. Sinha and S. S. Chandel, "Review of software tools for hybrid renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 192–205, 2014, doi: 10.1016/j.rser.2014.01.035.

[103] S. Bhattacharyya and D. Palit, "The nexus of grid, mini-grids and off-grid options for expanding electricity access," 2019.

[104] M. K. Shahzad, A. Zahid, T. Rashid, M. A. Rehan, M. Ali, and M. Ahmad, “Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software,” *Renew. Energy*, vol. 106, pp. 264–273, 2017, doi: 10.1016/j.renene.2017.01.033.

[105] K. Murugaperumal and P. Ajay D Vimal Raj, “Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification,” *Sol. Energy*, vol. 188, no. June, pp. 1068–1083, 2019, doi: 10.1016/j.solener.2019.07.008.

[106] C. Cader, P. Blechinger, and P. Bertheau, “Electrification Planning with Focus on Hybrid Mini-grids - A Comprehensive Modelling Approach for the Global South,” *Energy Procedia*, vol. 99, no. March, pp. 269–276, 2016, doi: 10.1016/j.egypro.2016.10.116.

[107] B. Martin, “Autonomous microgrids for rural electrification: joint investment planning of power generation and distribution through convex optimization,” Université Catholique de Louvain, 2018.

[108] A. Korkovelos, B. Khavari, A. Sahlberg, M. Howells, and C. Arderne, “The Role of Open Access Data in Geospatial Electrification Planning and the Achievement of SDG7. An OnSSET-Based Case Study for Malawi,” *Energies*, vol. 12, no. 7, p. 1395, 2019, doi: 10.3390/en12071395.

[109] J. F. Kappen, “Combined Project Information Documents / Integrated Safeguards Datasheet (PID/ISDS), Malawi - Electricity Access Project (P164331),” Washington DC, 2019.

[110] M.-C. U. L. & E. H. and R. TATA POWER DDL, “Design of the National Electrification Plan in Rwanda,” 2015. Accessed: Mar. 15, 2021. [Online]. Available: https://www.reg.rw/fileadmin/user_upload/Report_of_the_Design_of_the_National_Electrification_Plan_in_Rwanda.pdf.

[111] L. Mwalenga, R. Amatya, A. Gonzalez-Garcia, R. Stoner, and I. Pérez-Arriaga, “A Comprehensive Computer-Aided Planning Approach for Universal Energy Access. Case Study of Kilifi, Kenya,” p. 61, 2016.

[112] F. Kemausuor, E. Adkins, I. Adu-Poku, A. Brew-Hammond, and V. Modi, “Electrification planning using Network Planner tool: The case of Ghana,” *Energy Sustain. Dev.*, vol. 19, no. 1, pp. 92–101, 2014, doi: 10.1016/j.esd.2013.12.009.

[113] S. Ohiare, “Expanding electricity access to all in Nigeria: a spatial planning and cost analysis,” *Energy. Sustain. Soc.*, vol. 5, no. 1, 2015, doi: 10.1186/s13705-015-0037-9.

[114] R. Viral and D. K. Khatod, “Optimal planning of distributed generation systems in distribution system: A review,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5146–5165, 2012, doi: https://doi.org/10.1016/j.rser.2012.05.020.

[115] E. G. Carrano, L. A. E. Soares, R. H. C. Takahashi, R. R. Saldanha, and O. M. Neto, “Electric distribution network multiobjective design using a problem-specific genetic algorithm,” *IEEE Trans. Power Deliv.*, vol. 21, no. 2, pp. 995–1005, 2006, doi: 10.1109/TPWRD.2005.858779.

[116] S. K. Khator and L. C. Leung, “Power distribution planning: A review of models and issues,” *IEEE Trans. Power Syst.*, vol. 12, no. 3, pp. 1151–1159, 1997, doi: 10.1109/59.630455.

[117] J. López, D. Pozo, and J. Contreras, “Static and Dynamic Convex Distribution Network Expansion Planning,” in *Electric Distribution Network Planning*, Springer, 2018, pp. 41–63.

[118] A. Khodaei, S. Bahramirad, and M. Shahidehpour, “Microgrid Planning Under Uncertainty,” *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2417–2425, 2015, doi: 10.1109/TPWRS.2014.2361094.

[119] G. Munoz-Delgado, J. Contreras, and J. M. Arroyo, “Joint Expansion Planning of Distributed Generation and Distribution Networks,” *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2579–2590, 2015, doi: 10.1109/tpwrs.2014.2364960.

[120] S. Xie *et al.*, “Multi-objective active distribution networks expansion planning by scenario-based stochastic programming considering uncertain and random weight of network,” *Appl. Energy*, vol. 219, no. March, pp. 207–225, Jun. 2018, doi: 10.1016/j.apenergy.2018.03.023.

[121] F. Shahnia, A. Arefi, and G. Ledwich, Eds., *Electric Distribution Network Planning*, vol. 7, no. 5. Singapore: Springer Singapore, 2018.

[122] S. Haffner, L. F. A. Pereira, L. A. Pereira, and L. S. Barreto, “Multistage model for distribution expansion planning with distributed generation - Part I: Problem formulation,” *IEEE Trans. Power Deliv.*, vol. 23, no. 2, pp. 915–923, 2008, doi: 10.1109/TPWRD.2008.917916.

[123] J. E. Mendoza, M. E. López, H. E. Peña, and D. A. Labra, “Low voltage distribution optimization: Site, quantity and size of distribution transformers,” *Electr. Power Syst. Res.*, vol. 91, pp. 52–60, 2012, doi: 10.1016/j.epsr.2012.05.004.

[124] E. Díaz-Dorado, J. Cidrás Pidre, and E. Míguez García, “Planning of Large Rural Low-Voltage Networks Using Evolution Strategies,” *IEEE Trans. Power Syst.*, vol. 18, no. 4, pp. 1594–1600, 2003, doi: 10.1109/TPWRS.2003.818741.

[125] R. Gholizadeh-Roshanagh, S. Najafi-Ravadanegh, and S. H. Hosseinian, “A framework for optimal coordinated primary-secondary planning of distribution systems considering MV distributed generation,” *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1408–1415, 2018, doi: 10.1109/TSG.2016.2590425.

[126] R. A. Hincapie I., R. A. Gallego R., and J. R. S. Mantovani, “A decomposition approach for integrated planning of primary and secondary distribution networks considering distributed generation,” *Int. J. Electr. Power Energy Syst.*, 2019, doi: 10.1016/j.ijepes.2018.09.040.

[127] L. Gonzalez-Sotres, C. Mateo Domingo, A. Sanchez-Miralles, and M. Alvar Miro, “Large-Scale MV/LV Transformer Substation Planning Considering Network Costs and Flexible Area Decomposition,” *IEEE Trans. Power Deliv.*, vol. 28, no. 4, pp. 2245–2253, 2013, doi: 10.1109/tpwrd.2013.2258944.

[128] M. F. Shaaban, Y. M. Atwa, and E. F. El-Saadany, “DG allocation for benefit maximization in distribution networks,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 639–649, 2013, doi: 10.1109/TPWRS.2012.2213309.

[129] Z. Abdmouleh, A. Gastli, L. Ben-Brahim, M. Haouari, and N. A. Al-Emadi, “Review of optimization techniques applied for the integration of distributed generation from renewable energy sources,” *Renew. Energy*, vol. 113, pp. 266–280, 2017, doi: 10.1016/j.renene.2017.05.087.

[130] A. R. Inversin, “Mini-grid design manual,” Washington DC, 2000. [Online]. Available: http://documents.worldbank.org/curated/en/730361468739284428/Mini-grid-design-manual.

[131] C. Gamarra and J. M. Guerrero, “Computational optimization techniques applied to microgrids planning: A review,” *Renew. Sustain. Energy Rev.*, vol. 48, pp. 413–424, 2015, doi: 10.1016/j.rser.2015.04.025.

[132] C. Marnay *et al.*, "Microgrid evolution roadmap," *Proc. - 2015 Int. Symp. Smart Electr. Distrib. Syst. Technol. EDST 2015*, pp. 139–144, 2015, doi: 10.1109/SEDST.2015.7315197.

[133] Z. Ding, W. J. Lee, and J. Wang, "Stochastic resource planning strategy to improve the efficiency of microgrid operation," *IEEE Trans. Ind. Appl.*, vol. 51, no. 3, pp. 1978–1986, 2014, doi: 10.1109/TIA.2014.2375379.

[134] Pinensus, "Regulations for Minigrids Template." 2020, [Online]. Available: https://www.ruralelec.org/sites/default/files/Mini-Grid Regulation Template.pdf.

[135] S. Jamali *et al.*, "Protection Scheme of a Last Mile Active LVDC Distribution Network with Reclosing Option," *Energies*, vol. 11, no. 5, p. 1093, 2018, doi: 10.3390/en11051093.

[136] N. N. Opiyo, "A comparison of DC- versus AC-based minigrids for cost-effective electrification of rural developing communities," *Energy Reports*, vol. 5, pp. 398–408, 2019, doi: 10.1016/j.egyr.2019.04.001.

[137] V. Kleftakis, D. Lagos, C. Papadimitriou, and N. D. Hatziargyriou, "Seamless Transition Between Interconnected and Islanded Operation of DC Microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 248–256, 2019, doi: 10.1109/tsg.2017.2737595.

[138] H. Seifi and M. S. Sepasian, *Electric Power System Planning*. Springer, 2011.

[139] A. F. Crossland, D. Jones, and N. S. Wade, "Planning the location and rating of distributed energy storage in LV networks using a genetic algorithm with simulated annealing," *Int. J. Electr. Power Energy Syst.*, vol. 59, pp. 103–110, 2014, doi: 10.1016/j.ijepes.2014.02.001.

[140] K. Deb, Multi-Objective Optimization using Evolutionary Algorithms. Chichester, England, 2001.

[141] U. M. Diwekar, *Introduction to Applied Optimization*, vol. 22, no. 1. Cham: Springer International Publishing, 2020.

[142] G. Celli, E. Ghiani, S. Mocci, and F. Pilo, "A Multiobjective Evolutionary Algorithm for the Sizing and Siting of Distributed Generation," *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 750–757, 2005, doi: 10.1109/tpwrs.2005.846219.

[143] P. Pedregal, *Introduction to Optimization*, vol. 46. New York, NY: Springer New York, 2004.

[144] J. C. Das, Load Flow Optimization and Optimal Power Flow, vol. 2. CRC Press, 2017.

[145] B. Domenech, M. Ranaboldo, L. Ferrer-Martí, R. Pastor, and D. Flynn, “Local and regional microgrid models to optimise the design of isolated electrification projects,” *Renew. Energy*, vol. 119, pp. 795–808, 2018, doi: 10.1016/j.renene.2017.10.060.

[146] C. Bliek, P. Bonami, and A. Lodi, “Solving Mixed-Integer Quadratic Programming problems with IBM-CPLEX : a progress report,” *Proc. Twenty-Sixth RAMP Symp.*, no. M, pp. 171–180, 2014.

[147] A. M. Cossi, L. G. W. da Silva, R. A. R. Lázaro, and J. R. S. Mantovani, “Primary power distribution systems planning taking into account reliability, operation and expansion costs,” *IET Gener. Transm. Distrib.*, vol. 6, no. 3, p. 274, 2012, doi: 10.1049/iet-gtd.2010.0666.

[148] M. Fathi and H. Bevrani, *Optimization in Electrical Engineering*. Springer, 2019.

[149] C. Blum and A. Roli, “Metaheuristics in Combinatorial Optimization: Overview and Conceptual Comparison,” *ACM Comput. Surv.*, vol. 35, no. 3, pp. 268–308, 2003, doi: 10.1145/937503.937505.

[150] J. Radosavljevic, *Metaheuristic Optimization in Power Engineering*. Institution of Engineering and Technology, 2018.

[151] D. Beasley, D. R. Bull, and R. R. Martin, “An overview of genetic algorithms : Part 1, fundamentals,” *Univ. Comput.*, vol. 2, no. 15, pp. 1–16, 1993, [Online]. Available: http://www.geocities.ws/francorbusetti/gabeasley1.pdf.

[152] R. Poli, J. Kennedy, and T. Blackwell, “Particle swarm optimization: An overview,” *Swarm Intell.*, vol. 1, no. 1, pp. 33–57, 2007, doi: 10.1007/s11721-007-0002-0.

[153] M. Dorigo, “Optimization, learning and natural algorithms,” *Ph. D. Thesis, Politec. di Milano*, 1992.

[154] E. Aarts and J. Korst, “Chapter 2 Simulated annealing 2.1 Introduction of the algorithm,” *Simulated Annealing Theory Appl.*, p. 7, 1987, [Online]. Available: https://link-springer-com.ezproxy2.library.colostate.edu/content/pdf/10.1007%2F978-94-015-7744-1_2.pdf.

[155] Fred Glover, “Tabu Search - Part I,” *Orsa J. Comput.*, vol. 1, no. 3, pp. 190–206, 1989.

[156] K. Vinothkumar and M. P. Selvan, “Fuzzy embedded genetic algorithm method for distributed generation planning,” *Electr. Power Components Syst.*, vol. 39, no. 4, pp. 346–366, 2011, doi: 10.1080/15325008.2010.528533.

[157] M. Abdelaziz, “Distribution network reconfiguration using a genetic algorithm with varying population size,” *Electr. Power Syst. Res.*, vol. 142, pp. 9–11, 2017.

[158] Y.-J. Jeon and J.-C. Kim, “Application of simulated annealing and tabu search for loss minimization in distribution systems,” *Int. J. Electr. Power Energy Syst.*, vol. 26, no. 1, pp. 9–18, 2004, doi: 10.1016/s0142-0615(03)00066-8.

[159] R. Villasana, S. Member, and a J. Urdaneta, “Ant Colony System Algorithm for the Planning of Primary Distribution Circuits,” *Power*, vol. 19, no. 2, pp. 996–1004, 2004.

[160] B. Martin, E. De Jaeger, F. Glineur, and A. Latiers, “A Dynamic Programming Approach to Multi-period Planning of Isolated Microgrids,” in *Advances in Energy System Optimization*, 2017, pp. 123–137.

[161] G. Muñoz-Delgado, J. Contreras, and J. M. Arroyo, “Joint expansion planning of distributed generation and distribution networks,” *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2579–2590, 2014.

[162] D. Jungnickel, *Graphs, Networks and Algorithms*, vol. 5. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013.

[163] F. Pilo, G. Celli, E. Ghiani, and G. G. Soma, “New electricity distribution network planning approaches for integrating renewable,” *Wiley Interdiscip. Rev. Energy Environ.*, vol. 2, no. 2, pp. 140–157, 2013, doi: 10.1002/wene.70.

[164] J. A. Taylor, *Convex optimization of power systems*. Cambridge University Press, 2015.

[165] P. C. Paiva, H. M. Khodr, J. A. Domínguez-Navarro, J. M. Yusta, and A. J. Urdaneta, “Integral planning of primary-secondary distribution systems using mixed integer linear programming,” *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 1134–1143, 2005, doi: 10.1109/TPWRS.2005.846108.

[166] H. Falaghi, C. Singh, M.-R. Haghifam, and M. Ramezani, “DG integrated multistage distribution system expansion planning,” *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 8, pp. 1489–1497, 2011, doi: 10.1016/j.ijepes.2011.06.031.

[167] DigSILENT, “PowerFactory - DIgSILENT,” 2019. https://www.digsilent.de/en/powerfactory.html (accessed Mar. 17, 2021).

[168] A. C. Melhorn and J. Taylor, “Exploring the Requirements and Considerations for a Probabilistic Simulation Toolset Leveraging Opendss,” *25 th Int. Conf. Electr. Distrib.*, no. June, pp. 3–6, 2019.

[169] World Bank, “Malawi - Electricity Access Project,” Washington DC, 2019. [Online]. Available: http://documents.worldbank.org/curated/en/520771561341715792/Malawi-Electricity-Access-Project.

[170] A. Navarro-Espinosa, “Low Carbon Technologies in Low Voltage Distribution Networks : Probabilistic Assessment of Impacts and Solutions,” University of Manchester, 2015.

[171] K. P. Schneider *et al.*, “Analytic Considerations and Design Basis for the IEEE Distribution Test Feeders,” *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3181–3188, May 2018, doi: 10.1109/TPWRS.2017.2760011.

[172] PES/IEEE, “Resources PES Test Feeder,” *IEEE PES AMPS DSAS Test Feeder Working Group*, 2020. http://sites.ieee.org/pes-testfeeders/resources/ (accessed May 25, 2020).

[173] N. J. Williams, P. Jaramillo, B. Cornell, I. Lyons-Galante, and E. Wynn, “Load Characteristics of East African Microgrids,” *2017 Ieee Pes Powerafrica Conf.*, pp. 236–241, 2017.

[174] Electricity Supply Corporation of Malawi (ESCOM), “Total Power Generation Output.” ESCOM, Blantyre, Malawi, 2015.

[175] Millenium Challenge Account - Malawi (MCA-M), “ESCOM FINOP Project - Loss Study,” MCA-M, Lilongwe, 2015.

[176] S. Pfenninger and I. Staffell, “Renewables.ninja,” 2017. https://www.renewables.ninja/ (accessed Jul. 01, 2021).

[177] R. C. Dugan, J. A. Taylor, and D. Montenegro, "Energy Storage Modeling for Distribution Planning," in *Papers Presented at the Annual Conference - Rural Electric Power Conference*, May 2016, vol. 2016-July, pp. 12–19, doi: 10.1109/REPC.2016.11.

[178] D. T. C. Wang, L. F. Ochoa, and G. P. Harrison, "DG impact on investment deferral: Network planning and security of supply," *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1134–1141, 2010, doi: 10.1109/TPWRS.2009.2036361.

[179] Our World in Data, "Per capita electricity consumption." https://ourworldindata.org/grapher/per-capita-electricity-consumption?tab=chart&time=earliest..latest&country=~MWI (accessed Mar. 08, 2021).

[180] A. Nagarajan and R. Ayyanar, "Design and Strategy for the Deployment of Energy Storage Systems in a Distribution Feeder With Penetration of Renewable Resources," *IEEE Trans. Sustain. Energy*, vol. 6, no. 3, pp. 1085–1092, 2015, doi: 10.1109/tste.2014.2330294.

[181] N. Jayasekara, M. A. S. Masoum, and P. J. Wolfs, "Optimal Operation of Distributed Energy Storage Systems to Improve Distribution Network Load and Generation Hosting Capability," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 250–261, 2016, doi: 10.1109/tste.2015.2487360.

[182] B. Wojszczyk, R. Uluski, and F. Katiraei, "The role of distributed generation and energy storage in utilities of the future," *IEEE Power Energy Soc. 2008 Gen. Meet. Convers. Deliv. Electr. Energy 21st Century, PES*, 2008, doi: 10.1109/PES.2008.4596310.

[183] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, "Evaluating distributed generation impacts with a multiobjective index," *IEEE Trans. Power Deliv.*, vol. 21, no. 3, pp. 1452–1458, 2006, doi: 10.1109/TPWRD.2005.860262.

[184] A. Messac, *Optimization in Practice with MATLAB®*. Cambridge University Press, 2015.

[185] M. Chikumbanje, D. Frame, and S. Galloway, "Future grid integration of autonomous minigrids for loss reduction and voltage profile improvement in sub-Saharan countries," *Sustain. Energy, Grids Networks*, pp. 1-10 (in review), 2022.

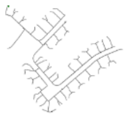
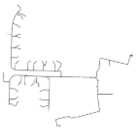
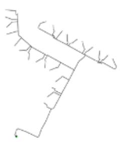
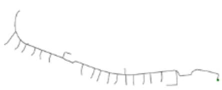
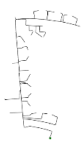
[186] M. Chikumbanje, D. Frame, and S. Galloway, “Multi-feeder minigrid loading index – a prequalifier to rigorous grid integration planning of minigrids,” in *2022 IEEE PES/IAS PowerAfrica*, 2022, pp. 1-5 (accepted for presentation).

8 APPENDICES

Appendix 1: Minigrid Networks for MGIP Case Studies

This appendix shows the minigrid networks that are used in the MGIP case studies reported in this thesis. The integration of a single minigrid and cluster of minigrids case studies reported in Section 4.3 use the networks in Appendix-Table 1 as presented.

Appendix-Table 1: Minigrid networks used in the MGIP case studies reported in this thesis [170], [172]

Minigrid ID	Network Layout	Peak Demand (kW)	Number of Nodes
1		250	205
2		80	111
3		160	123
4		200	341
5		80	58
6		60	232
7		75	97
8		90	62

Minigrid ID	Network Layout	Peak Demand (kW)	Number of Nodes
9		100	144
10		40	194
11		55	240
12		35	134

The 220 multi-feeder minigrids reported in Section 5.3.3 are derived from combining the minigrids in Appendix-Table 1 into unique sets of three. These combinations are presented in Appendix-Table 2

Appendix-Table 2: Details of multifeeder minigrid networks

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-1	1	2	3	250	80	160	1.04
MFM-2	1	2	4	250	80	200	0.89
MFM-3	1	2	5	250	80	80	1.56
MFM-4	1	2	6	250	80	60	1.79
MFM-5	1	2	7	250	80	75	1.61
MFM-6	1	2	8	250	80	90	1.47

[16] Each feeder number, 1 to 12 refers to the single feeder minigrids in Appendix-Table 1

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-7	1	2	9	250	80	100	1.39
MFM-8	1	2	10	250	80	40	2.08
MFM-9	1	2	11	250	80	55	1.85
MFM-10	1	2	12	250	80	35	2.17
MFM-11	1	3	4	250	160	200	0.69
MFM-12	1	3	5	250	160	80	1.04
MFM-13	1	3	6	250	160	60	1.14
MFM-14	1	3	7	250	160	75	1.06
MFM-15	1	3	8	250	160	90	1.00
MFM-16	1	3	9	250	160	100	0.96
MFM-17	1	3	10	250	160	40	1.25
MFM-18	1	3	11	250	160	55	1.16
MFM-19	1	3	12	250	160	35	1.28
MFM-20	1	4	5	250	200	80	0.89
MFM-21	1	4	6	250	200	60	0.96
MFM-22	1	4	7	250	200	75	0.91
MFM-23	1	4	8	250	200	90	0.86
MFM-24	1	4	9	250	200	100	0.83
MFM-25	1	4	10	250	200	40	1.04
MFM-26	1	4	11	250	200	55	0.98
MFM-27	1	4	12	250	200	35	1.06
MFM-28	1	5	6	250	80	60	1.79
MFM-29	1	5	7	250	80	75	1.61
MFM-30	1	5	8	250	80	90	1.47

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-31	1	5	9	250	80	100	1.39
MFM-32	1	5	10	250	80	40	2.08
MFM-33	1	5	11	250	80	55	1.85
MFM-34	1	5	12	250	80	35	2.17
MFM-35	1	6	7	250	60	75	1.85
MFM-36	1	6	8	250	60	90	1.67
MFM-37	1	6	9	250	60	100	1.56
MFM-38	1	6	10	250	60	40	2.50
MFM-39	1	6	11	250	60	55	2.17
MFM-40	1	6	12	250	60	35	2.63
MFM-41	1	7	8	250	75	90	1.52
MFM-42	1	7	9	250	75	100	1.43
MFM-43	1	7	10	250	75	40	2.17
MFM-44	1	7	11	250	75	55	1.92
MFM-45	1	7	12	250	75	35	2.27
MFM-46	1	8	9	250	90	100	1.32
MFM-47	1	8	10	250	90	40	1.92
MFM-48	1	8	11	250	90	55	1.72
MFM-49	1	8	12	250	90	35	2.00
MFM-50	1	9	10	250	100	40	1.79
MFM-51	1	9	11	250	100	55	1.61
MFM-52	1	9	12	250	100	35	1.85
MFM-53	1	10	11	250	40	55	2.63
MFM-54	1	10	12	250	40	35	3.33

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-55	1	11	12	250	55	35	2.78
MFM-56	2	3	4	80	160	200	0.83
MFM-57	2	3	5	80	160	80	1.00
MFM-58	2	3	6	80	160	60	1.14
MFM-59	2	3	7	80	160	75	1.03
MFM-60	2	3	8	80	160	90	0.94
MFM-61	2	3	9	80	160	100	0.89
MFM-62	2	3	10	80	160	40	1.33
MFM-63	2	3	11	80	160	55	1.19
MFM-64	2	3	12	80	160	35	1.39
MFM-65	2	4	5	80	200	80	1.25
MFM-66	2	4	6	80	200	60	1.43
MFM-67	2	4	7	80	200	75	1.29
MFM-68	2	4	8	80	200	90	1.18
MFM-69	2	4	9	80	200	100	1.11
MFM-70	2	4	10	80	200	40	1.67
MFM-71	2	4	11	80	200	55	1.48
MFM-72	2	4	12	80	200	35	1.74
MFM-73	2	5	6	80	80	60	0.57
MFM-74	2	5	7	80	80	75	0.52
MFM-75	2	5	8	80	80	90	0.56
MFM-76	2	5	9	80	80	100	0.63
MFM-77	2	5	10	80	80	40	0.67
MFM-78	2	5	11	80	80	55	0.59

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-79	2	5	12	80	80	35	0.70
MFM-80	2	6	7	80	60	75	0.59
MFM-81	2	6	8	80	60	90	0.64
MFM-82	2	6	9	80	60	100	0.71
MFM-83	2	6	10	80	60	40	0.80
MFM-84	2	6	11	80	60	55	0.70
MFM-85	2	6	12	80	60	35	0.84
MFM-86	2	7	8	80	75	90	0.58
MFM-87	2	7	9	80	75	100	0.65
MFM-88	2	7	10	80	75	40	0.70
MFM-89	2	7	11	80	75	55	0.62
MFM-90	2	7	12	80	75	35	0.73
MFM-91	2	8	9	80	90	100	0.59
MFM-92	2	8	10	80	90	40	0.75
MFM-93	2	8	11	80	90	55	0.67
MFM-94	2	8	12	80	90	35	0.78
MFM-95	2	9	10	80	100	40	0.83
MFM-96	2	9	11	80	100	55	0.74
MFM-97	2	9	12	80	100	35	0.87
MFM-98	2	10	11	80	40	55	0.84
MFM-99	2	10	12	80	40	35	1.07
MFM-100	2	11	12	80	55	35	0.89
MFM-101	3	4	5	160	200	80	0.83
MFM-102	3	4	6	160	200	60	0.91

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-103	3	4	7	160	200	75	0.85
MFM-104	3	4	8	160	200	90	0.80
MFM-105	3	4	9	160	200	100	0.77
MFM-106	3	4	10	160	200	40	1.00
MFM-107	3	4	11	160	200	55	0.93
MFM-108	3	4	12	160	200	35	1.03
MFM-109	3	5	6	160	80	60	1.14
MFM-110	3	5	7	160	80	75	1.03
MFM-111	3	5	8	160	80	90	0.94
MFM-112	3	5	9	160	80	100	0.89
MFM-113	3	5	10	160	80	40	1.33
MFM-114	3	5	11	160	80	55	1.19
MFM-115	3	5	12	160	80	35	1.39
MFM-116	3	6	7	160	60	75	1.19
MFM-117	3	6	8	160	60	90	1.07
MFM-118	3	6	9	160	60	100	1.00
MFM-119	3	6	10	160	60	40	1.60
MFM-120	3	6	11	160	60	55	1.39
MFM-121	3	6	12	160	60	35	1.68
MFM-122	3	7	8	160	75	90	0.97
MFM-123	3	7	9	160	75	100	0.91
MFM-124	3	7	10	160	75	40	1.39
MFM-125	3	7	11	160	75	55	1.23
MFM-126	3	7	12	160	75	35	1.45

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-127	3	8	9	160	90	100	0.84
MFM-128	3	8	10	160	90	40	1.23
MFM-129	3	8	11	160	90	55	1.10
MFM-130	3	8	12	160	90	35	1.28
MFM-131	3	9	10	160	100	40	1.14
MFM-132	3	9	11	160	100	55	1.03
MFM-133	3	9	12	160	100	35	1.19
MFM-134	3	10	11	160	40	55	1.68
MFM-135	3	10	12	160	40	35	2.13
MFM-136	3	11	12	160	55	35	1.78
MFM-137	4	5	6	200	80	60	1.43
MFM-138	4	5	7	200	80	75	1.29
MFM-139	4	5	8	200	80	90	1.18
MFM-140	4	5	9	200	80	100	1.11
MFM-141	4	5	10	200	80	40	1.67
MFM-142	4	5	11	200	80	55	1.48
MFM-143	4	5	12	200	80	35	1.74
MFM-144	4	6	7	200	60	75	1.48
MFM-145	4	6	8	200	60	90	1.33
MFM-146	4	6	9	200	60	100	1.25
MFM-147	4	6	10	200	60	40	2.00
MFM-148	4	6	11	200	60	55	1.74
MFM-149	4	6	12	200	60	35	2.11
MFM-150	4	7	8	200	75	90	1.21

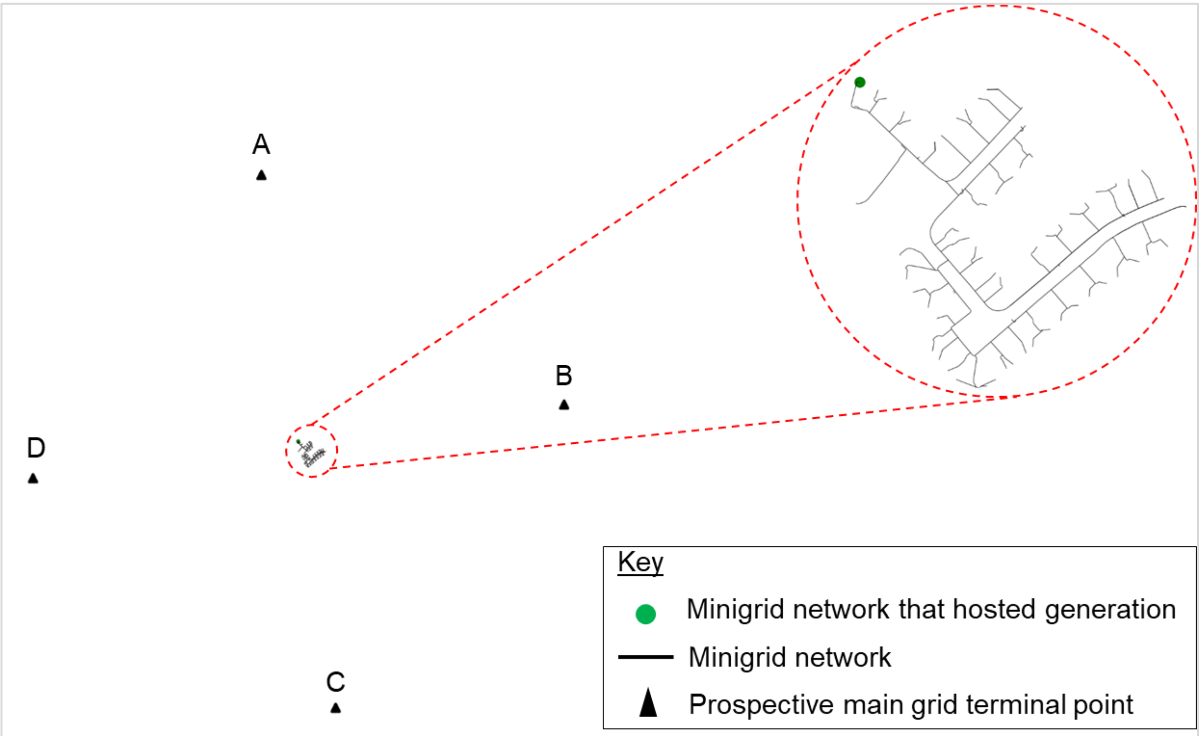
Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-151	4	7	9	200	75	100	1.14
MFM-152	4	7	10	200	75	40	1.74
MFM-153	4	7	11	200	75	55	1.54
MFM-154	4	7	12	200	75	35	1.82
MFM-155	4	8	9	200	90	100	1.05
MFM-156	4	8	10	200	90	40	1.54
MFM-157	4	8	11	200	90	55	1.38
MFM-158	4	8	12	200	90	35	1.60
MFM-159	4	9	10	200	100	40	1.43
MFM-160	4	9	11	200	100	55	1.29
MFM-161	4	9	12	200	100	35	1.48
MFM-162	4	10	11	200	40	55	2.11
MFM-163	4	10	12	200	40	35	2.67
MFM-164	4	11	12	200	55	35	2.22
MFM-165	5	6	7	80	60	75	0.59
MFM-166	5	6	8	80	60	90	0.64
MFM-167	5	6	9	80	60	100	0.71
MFM-168	5	6	10	80	60	40	0.80
MFM-169	5	6	11	80	60	55	0.70
MFM-170	5	6	12	80	60	35	0.84
MFM-171	5	7	8	80	75	90	0.58
MFM-172	5	7	9	80	75	100	0.65
MFM-173	5	7	10	80	75	40	0.70
MFM-174	5	7	11	80	75	55	0.62

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-175	5	7	12	80	75	35	0.73
MFM-176	5	8	9	80	90	100	0.59
MFM-177	5	8	10	80	90	40	0.75
MFM-178	5	8	11	80	90	55	0.67
MFM-179	5	8	12	80	90	35	0.78
MFM-180	5	9	10	80	100	40	0.83
MFM-181	5	9	11	80	100	55	0.74
MFM-182	5	9	12	80	100	35	0.87
MFM-183	5	10	11	80	40	55	0.84
MFM-184	5	10	12	80	40	35	1.07
MFM-185	5	11	12	80	55	35	0.89
MFM-186	6	7	8	60	75	90	0.67
MFM-187	6	7	9	60	75	100	0.74
MFM-188	6	7	10	60	75	40	0.75
MFM-189	6	7	11	60	75	55	0.65
MFM-190	6	7	12	60	75	35	0.79
MFM-191	6	8	9	60	90	100	0.67
MFM-192	6	8	10	60	90	40	0.90
MFM-193	6	8	11	60	90	55	0.78
MFM-194	6	8	12	60	90	35	0.95
MFM-195	6	9	10	60	100	40	1.00
MFM-196	6	9	11	60	100	55	0.87
MFM-197	6	9	12	60	100	35	1.05
MFM-198	6	10	11	60	40	55	0.63

Multi-feeder Minigrid ID	Feeder Combinations[16]			Feeder Demand			MMLI
	Fdr 1	Fdr 2	Fdr 3	Fdr 1	Fdr 2	Fdr 3	
MFM-199	6	10	12	60	40	35	0.80
MFM-200	6	11	12	60	55	35	0.67
MFM-201	7	8	9	75	90	100	0.61
MFM-202	7	8	10	75	90	40	0.78
MFM-203	7	8	11	75	90	55	0.69
MFM-204	7	8	12	75	90	35	0.82
MFM-205	7	9	10	75	100	40	0.87
MFM-206	7	9	11	75	100	55	0.77
MFM-207	7	9	12	75	100	35	0.91
MFM-208	7	10	11	75	40	55	0.79
MFM-209	7	10	12	75	40	35	1.00
MFM-210	7	11	12	75	55	35	0.83
MFM-211	8	9	10	90	100	40	0.77
MFM-212	8	9	11	90	100	55	0.69
MFM-213	8	9	12	90	100	35	0.80
MFM-214	8	10	11	90	40	55	0.95
MFM-215	8	10	12	90	40	35	1.20
MFM-216	8	11	12	90	55	35	1.00
MFM-217	9	10	11	100	40	55	1.05
MFM-218	9	10	12	100	40	35	1.33
MFM-219	9	11	12	100	55	35	1.11
MFM-220	10	11	12	40	55	35	0.73

APPENDIX 2: ALTERNATE GRID TERMINAL POINTS FOR GRID INTEGRATION OF SINGLE MINIGRID

In this appendix, alternate grid terminal points are used to replicate the investigation presented in Section 4.3.1. Besides the terminal point A, investigated in the body of the thesis, grid infeed from terminals B, C, and D, which are equidistant from Node 1 of the minigrid (node that hosted the minigrid generator) as presented in Appendix-Figure 1, are also investigated one after another. In this study, the minigrid network does not have any power generation or storage assets and the demand profile used in the loads is of medium demand factor.

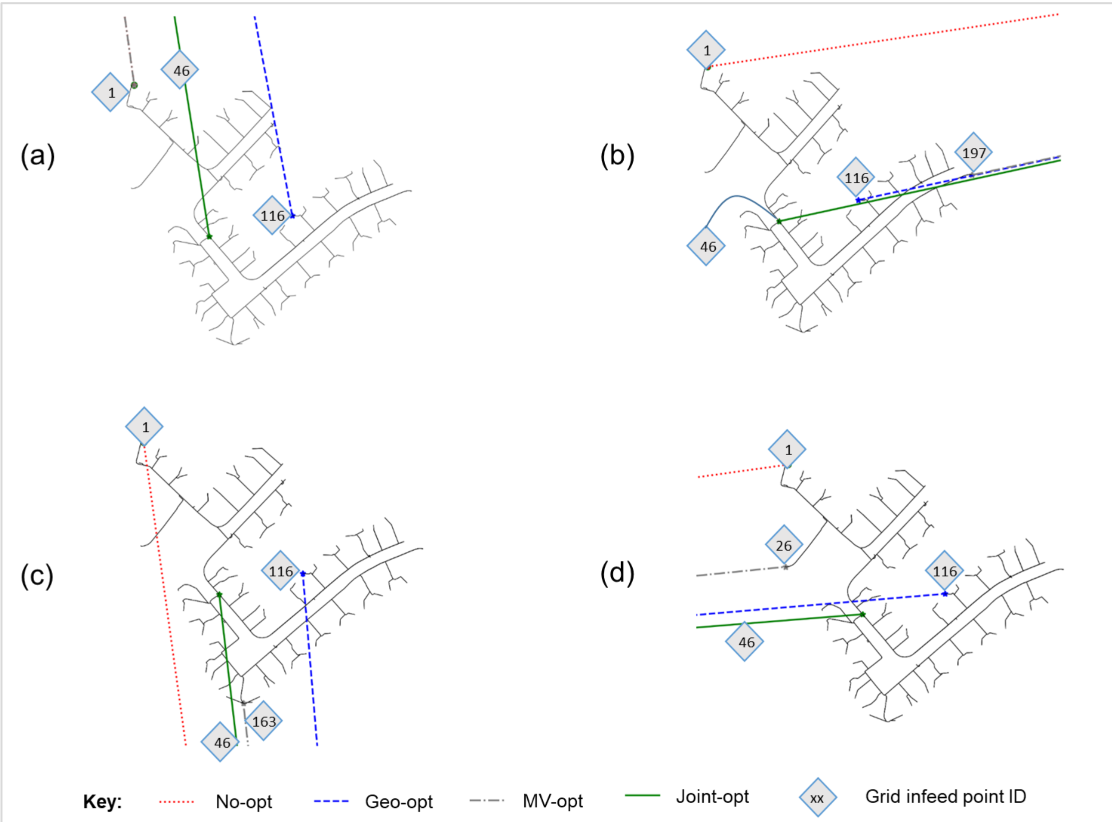


Appendix-Figure 1: The location of alternative grid terminal points

Appendix-Table 3 shows the grid infeed points for each of the alternate grid terminal points from using No-opt, Geo-opt, MV-opt and MGIP methods. The location of each of the grid infeed points and MV network layout is presented in Appendix-Figure 2. Appendix-Figure 2 (a), (b), (c) and (d) show the possible network expansion from terminals A, B, C and D respectively.

Appendix-Table 3: Grid infeed points into minigrid from alternate grid terminal points

Grid Terminal	Method for planning integration			
	No-opt	Geo-opt	MV-opt	Joint-opt
A	1	116	1	46
B	1	116	197	46
C	1	116	163	46
D	1	116	26	46



Appendix-Figure 2: Grid network expansion layout from terminals A, B, C and D, and associated infeed points IDs

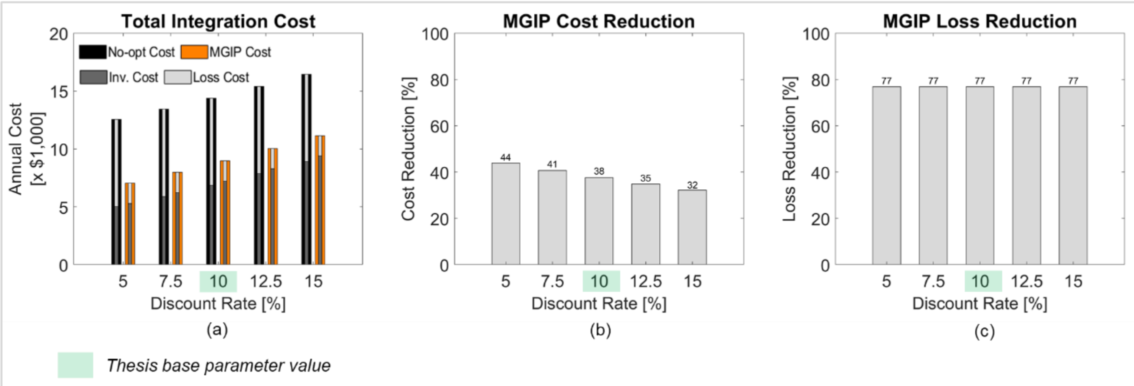
Appendix-Table 3 shows that in the alternate grid terminal points (B, C, and D), MV-opt and No-opt do not lead to the same grid infeed point. From Appendix-Figure 2, grid infeed points of MV-opt are always on the edge of the network closest to the grid terminal point as MV-opt attempts to minimise the length of the MV network to integrate the minigrid.

APPENDIX 3: SENSITIVITY OF MGIP TO KEY INPUTS

This appendix presents the sensitivity of the MGIP results to key input parameters of the case studies presented in Chapter 4. Case study 1 is used to investigate how the results respond to changes in (1) discount rate; (2) project period; (3) investment costs; (4) cost of losses; and (5) length of network.

Sensitivity of MGIP to discount rate

Appendix-Figure 3 shows the total integration cost for No-opt and MGIP, and cost and loss reduction benefits of MGIP at different discount rates.

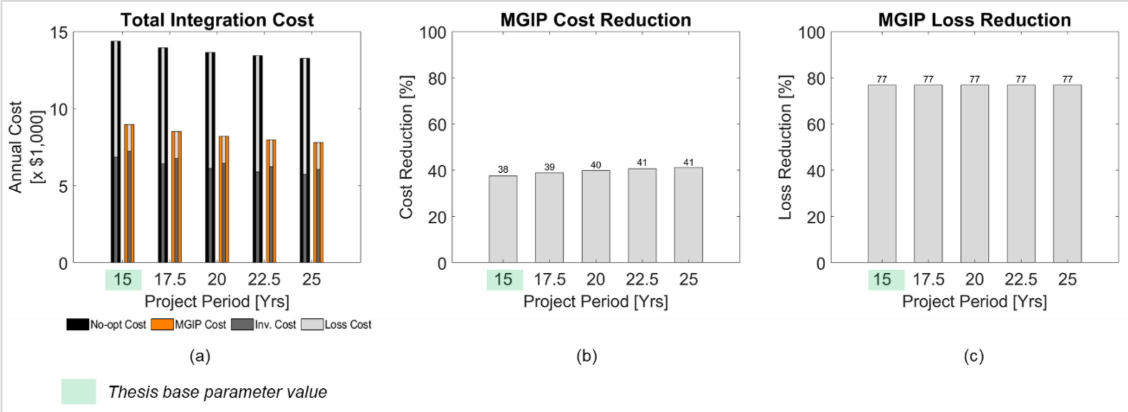


Appendix-Figure 3. Sensitivity to discount rate

Appendix-Figure 3(a) demonstrates that discount rate is directly proportional to the annualized investment cost which affects the total annual integration costs. However, cost of losses is not affected as the formulation in Chapter 3 is a static and not dynamic. Thus, Appendix-Figure 3(b) shows that change in discount rate will affect the total cost reduction benefits of MGIP but loss reduction benefits remain the same. Therefore, a different discount rate would not undermine the conclusions of this thesis.

Sensitivity of MGIP to annuitisation period of the project

Appendix-Figure 4 shows the total integration cost for No-opt and MGIP, and cost and loss reduction benefits of MGIP at different annuitization periods.

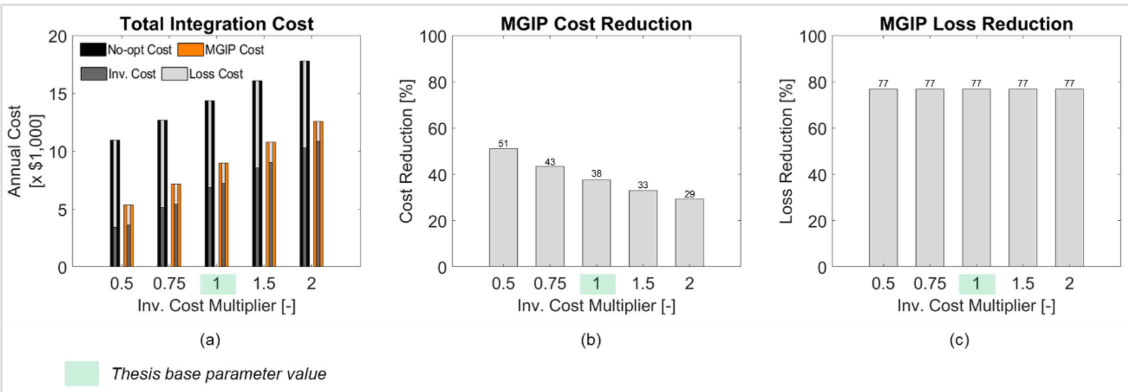


Appendix-Figure 4. Sensitivity to annuitisation period of the project

Appendix-Figure 4(a) demonstrates that annuitization period is inversely proportional to the annualized investment cost which affects the total annual integration costs. However, cost of losses is not affected as the formulation in Chapter 3 is a static and not dynamic. Thus, Appendix-Figure 4(b) shows that an increase in annuitisation period would reduce the annualized investment cost hence increasing the cost reduction potential of MGIP. In the other hand, Appendix-Figure 4(c) shows that the loss reduction benefits for MGIP remain the same. Therefore, a different project period would not undermine the conclusions of this thesis.

Sensitivity of MGIP to investment costs

Appendix-Figure 5 shows the total integration cost for No-opt and MGIP, and cost and loss reduction benefits of MGIP at different investment costs.

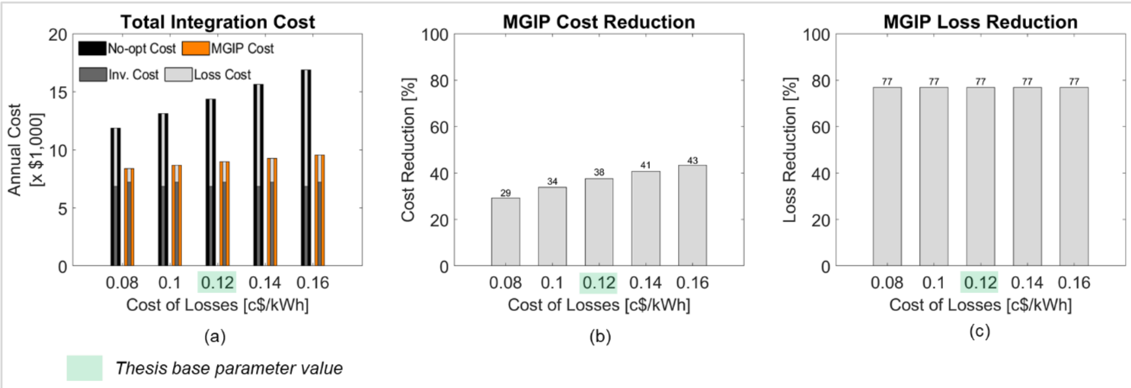


Appendix-Figure 5. Sensitivity to investment cost

Appendix-Figure 5 (a) demonstrates that change in investment cost is directly proportional to the annualized investment cost which affects the total annual integration costs. However, cost of losses is not affected as the formulation in Chapter 3 is a static and not dynamic. Appendix-Figure 5 (b) shows that an increase in investment cost reduces the cost reduction potential of MGIP while the loss reduction benefits remain the same, in Appendix-Figure 5 (c). Therefore, a different investment cost would not undermine the conclusions of this thesis.

Sensitivity of MGIP to cost of energy/losses

Appendix-Figure 6 shows the total integration cost for No-opt and MGIP, and cost and loss reduction benefits of MGIP at cost of losses.

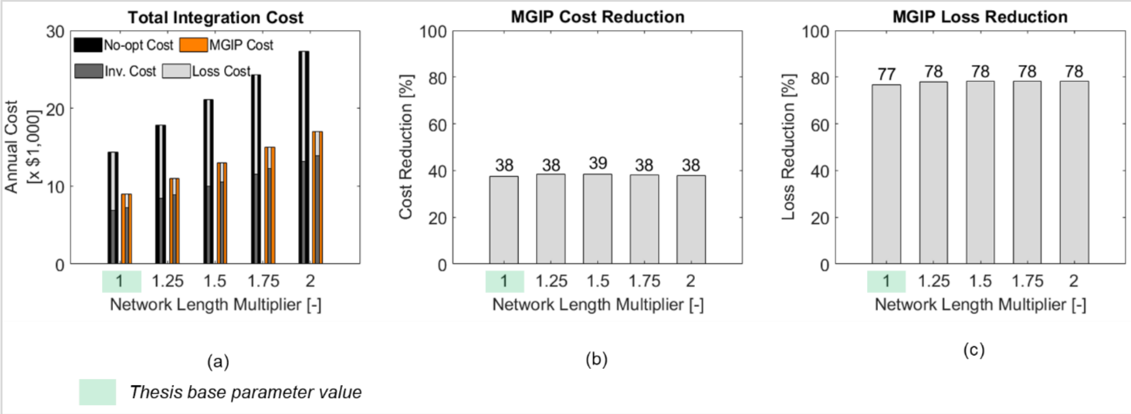


Appendix-Figure 6. Sensitivity to cost of losses or energy

Appendix-Figure 6 (a) demonstrates that the cost of losses works as a scaling factor to the annual cost of losses which affects the total annual integration costs. However, investment costs are not affected as they are independent from the cost of losses. Since most of MGIP cost reduction benefits are drawn from loss reduction, Appendix-Figure 6 (b) shows that an increase cost of losses leads to higher cost reduction benefits as losses dominate the cost term of the objective function. However, the loss reduction benefits remain the same as shown in Appendix-Figure 6 (c). Therefore, a different cost of losses would not undermine the conclusions of this thesis.

Sensitivity of MGIP to minigrid network length

Appendix-Figure 7 shows the total integration cost for No-opt and MGIP, and cost and loss reduction benefits of MGIP with various lengths of the grid expansion and minigrid network branches.



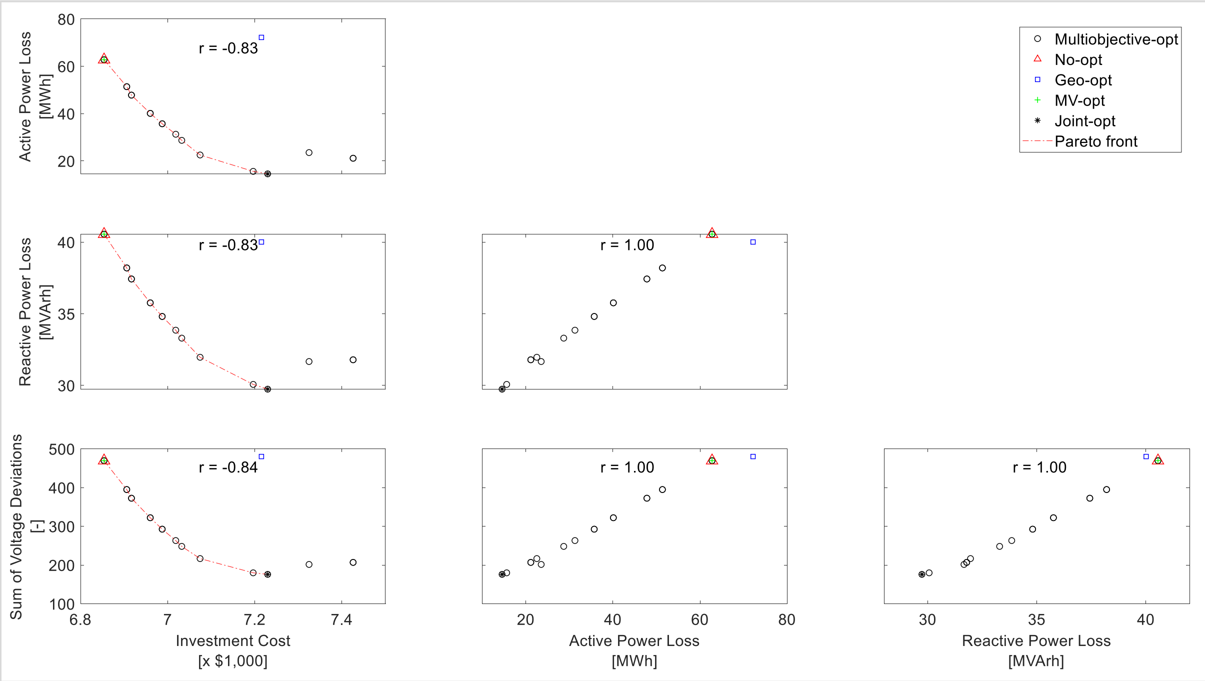
Appendix-Figure 7. Sensitivity to length of network branches

Appendix-Figure 7(a) demonstrates increasing the length of the network branches increases both the investment cost as well as the cost of losses. It increases the investment cost because longer network expansion lines demand more investment than shorter ones. Also, longer network lines lead to higher losses as losses are proportional to the length of the network branches. With both investment cost and network losses changing with the same factor (network length multiplier), Appendix-Figure 7(b) and (c) show change in network length will have marginal impact on the cost reduction and loss reduction benefits of MGIP. Therefore, a length of network branches would not undermine the conclusions of this thesis.

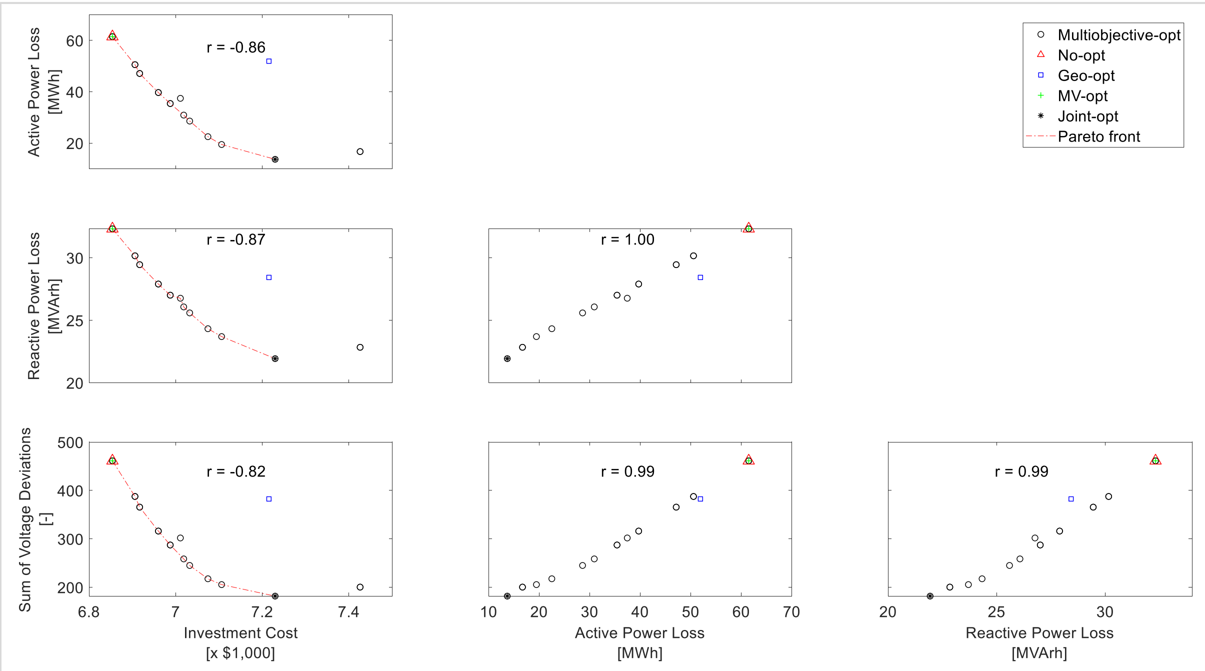
Appendix 4: Scatter-plots for MO-MGIP Results - Single and Cluster of Minigrids

This appendix presents the remainder of the results for the case studies and discussions presented in Section 5.2.3.

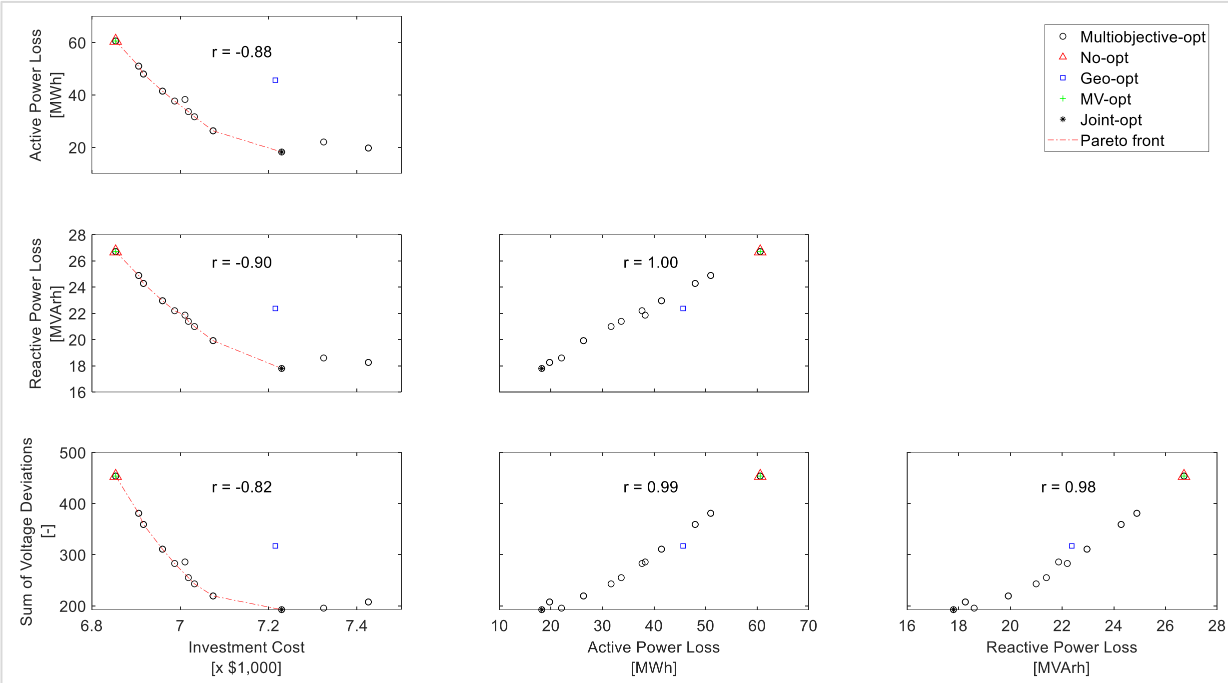
A. Single minigrid – 0% PV Penetration



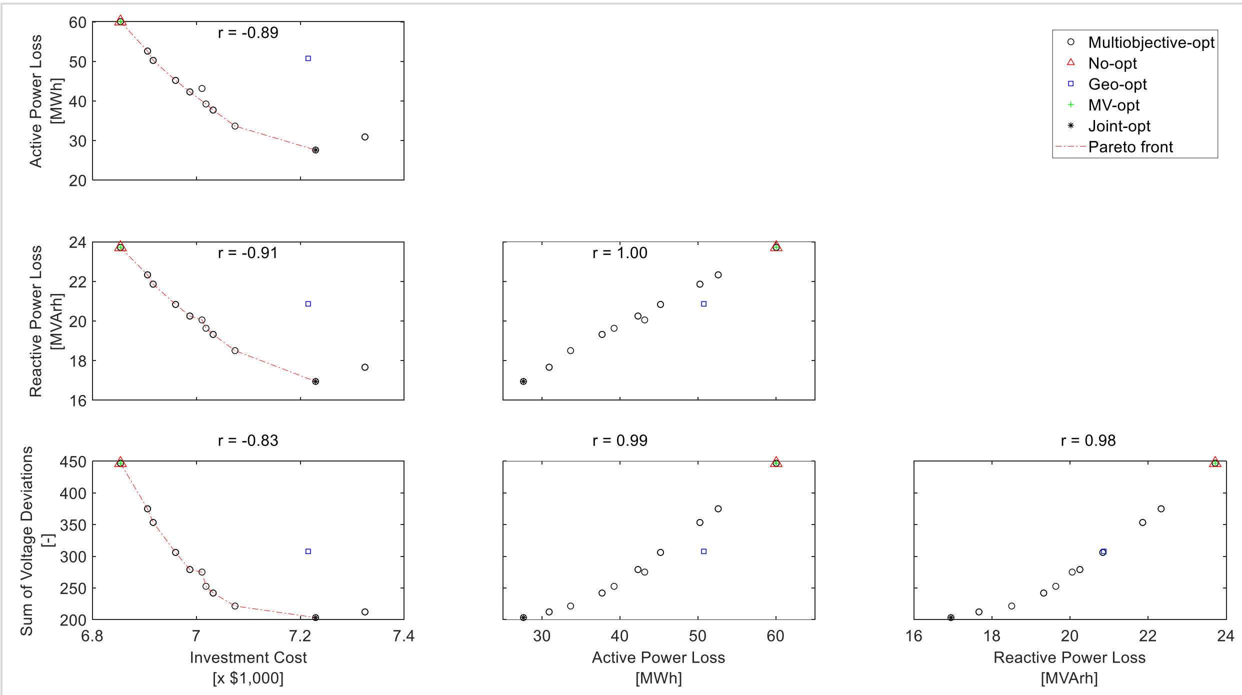
B. Single minigrid – 25% PV Penetration



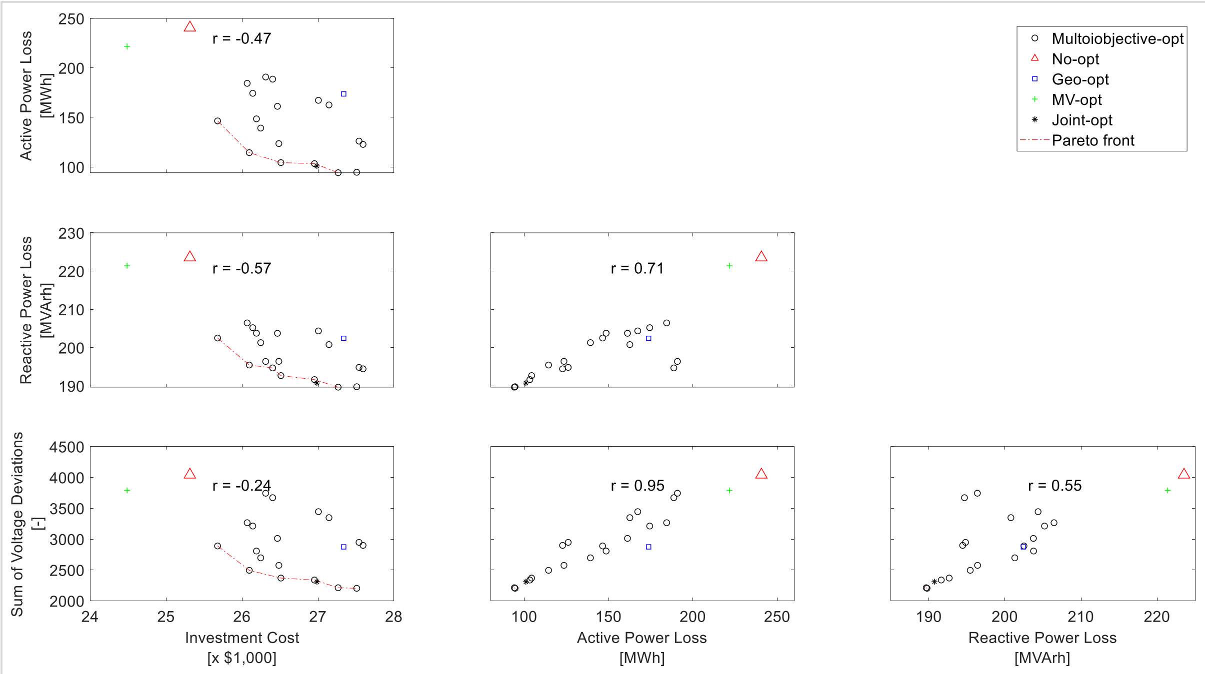
C. Single minigrid – 50% PV Penetration



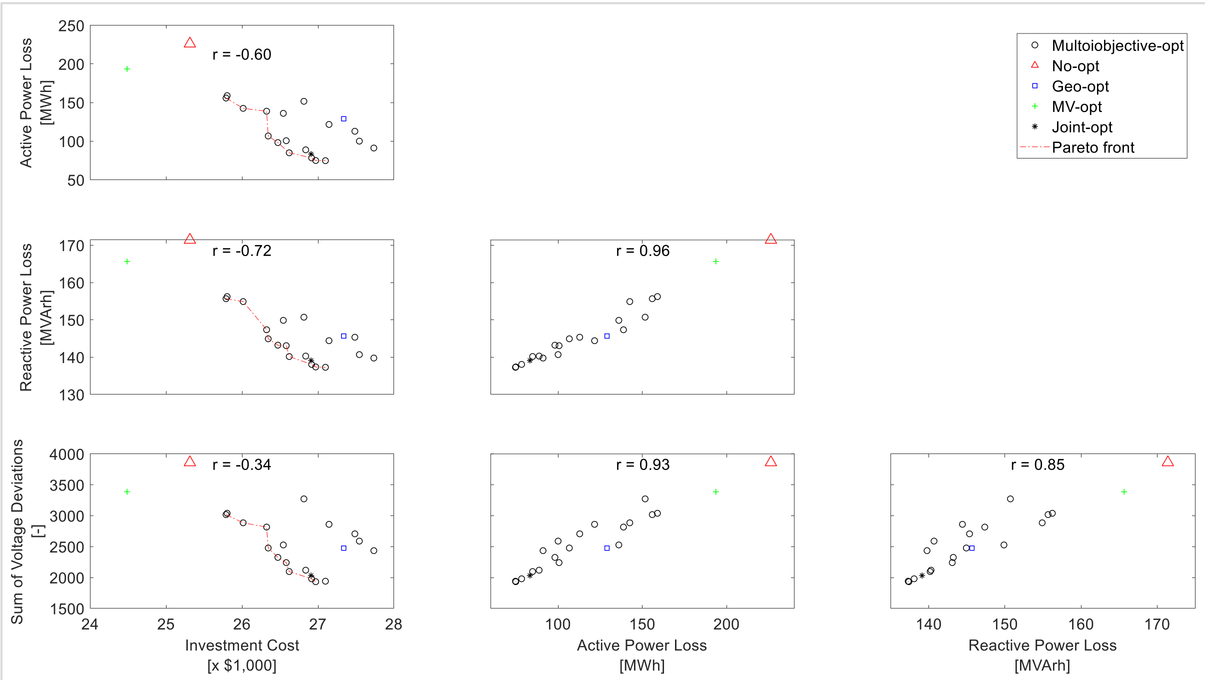
D. Single minigrid – 75% PV Penetration



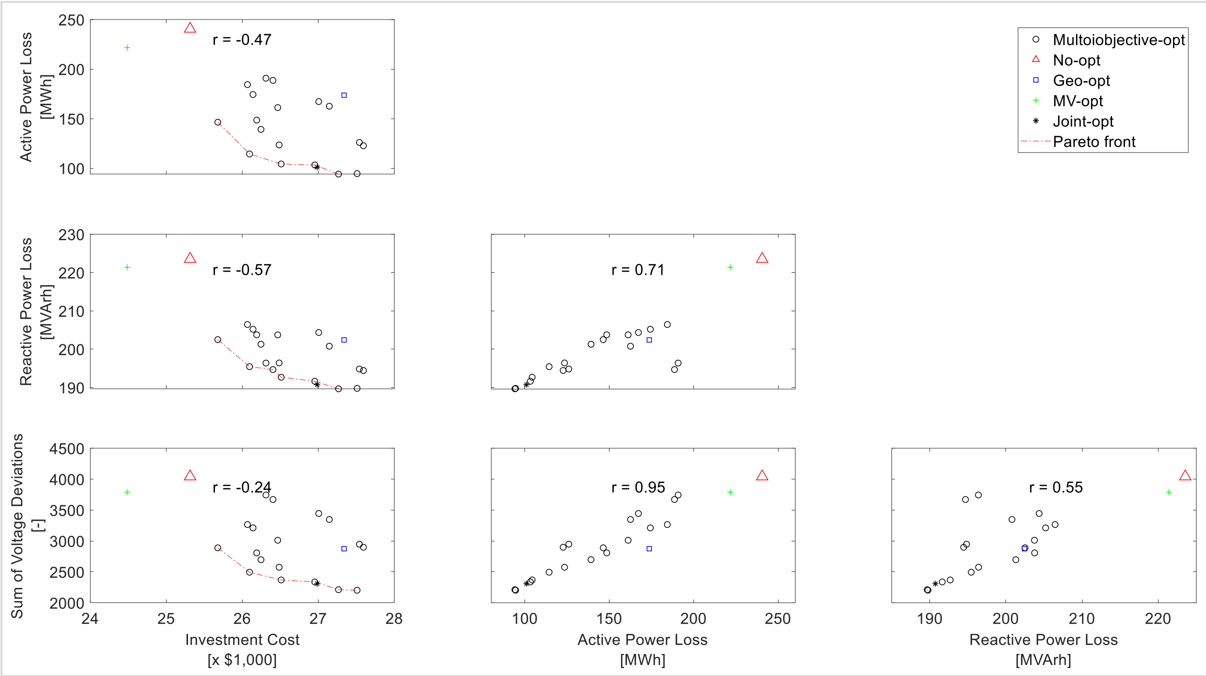
E. Cluster of minigrids – 0% PV Penetration



F. Cluster of minigrids – 25% PV Penetration



G. Cluster of minigrids – 50% PV Penetration



H. Cluster of minigrids – 75% PV Penetration