ELECTRIFICATION OF RURAL AREAS:
A CASE STUDY OF BALOCHISTAN, PAKISTAN

by

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ABSTRACT

Access to modern energy technologies is necessary for socioeconomic development of communities worldwide. Although access to energy has not yet been established as a basic human right, it is considered as a derived human right. Rural communities are facing severe energy injustice. These communities are typically scattered over large geographical areas that are far away from nearby cites, which makes electrification projects challenging due to the high capital costs and low rate of return. However, with the latest advances in distributed and renewable energy resources, off-grid systems are being considered as an emerging solution for rural electrification. In addition, mobile energy storage systems are gaining attention to overcome energy injustice in rural areas. This thesis focuses on the possible solutions for the electrification of rural regions, along with a discussion of some of the existing electrification projects around the world to offer a better understanding of how the world is approaching this problem and what the pros and cons of those different technologies are. It then proposed an optimization framework through which such projects can be modeled and implemented with both technical and social awareness. For proof-of-concept purposes and to validate the performance of the model, a case study has been considered based on union councils (demand areas) in Loralai/Bori Tehsil, in Balochistan, Pakistan.

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CHAPTER 1 PROBLEM STATEMENT

1.1 Background

Balochistan is one of the four provinces in Pakistan [1]. Rich in natural and renewable energy resources, it provides 58% of total coal production in Pakistan [2]. The region receives an average daily solar radiation of 5.9–6.2 kWh/m2, which is the highest compared to the rest of the country. The annual mean sunshine period is around 8–8.5 hours, with mean daily global insulation of 19–20 MJ/m2, making it the highest solar potential available in the world. Locations in Balochistan with high concentration of solar irradiation are ideal for installation of photovoltaic (PV) and concentrated solar power (CSP) systems [3], [4]. In addition, Balochistan has a good prospect of tidal energy. It has a coastline of more than 770 km along the Arabian sea. Lastly, Balochistan has the world's largest wind corridor and is considered the fittest place to establish wind power plants [4].

Balochistan is divided into divisions, with further partitioning of divisions into districts, districts into tehsils, and tehsils into union councils. In total, there are 8 divisions, namely, Kalat, Makran, Naseerabad, Quetta, Sibi, Zhob, Rakhshan, and Loralai. The focus of this research is on one tehsil within the Loralai division. Loralai is divided into 3 districts of Barkhan, Loralai, and Musakhel, Loralai district itself is further divided into 3 tehsils of Duki, Loralai/Bori and Mekhtar, [7]. The Loralai/Bori tehsil has been chosen as the focal point of this study due its low electrification rate and high levels of socioeconomic and sociodemographic vulnerabilities.

1.2 What is the Problem?

Around 77% of people in Balochistan live in rural areas, where the electrified area is only 20% [8]. In 2018, electricity demand was approximately 1,650 MW, which was raised to 2,500 MW in 2019. However, supply is restricted to 400 to 600 MW, which results in power outages of 10–12 hours in urban areas. In rural areas, electricity is available for only 3–4 hours each day. The installed generation capacity of Balochistan is 2,422 MW, most of which is transmitted to other provinces. The existing power system within the province is incapable of supplying loads beyond 600MW [9]. To make matters more complicated, the population of Balochistan is not concentrated; villages are scattered and dispersed. On average, households are 29.79 km away from nearby cities and 50.93 km from district center [10]. Villages may be small, with a population of around 100 people living in 20 houses. The electricity demand of a small house ranges from 50 to 100W [11]. Expanding the grid may not be feasible, because the cost per kWh is high. Lack of powerful and dedicated political representation in rural regions means that the residents' electricity needs have not received the proper attention from the province and government officials.

Table 1.1 Union councils in Loralai/Bori tehsil

Loralai/Bori Tehsil	
CHINA ALIZAI PC	
Union Council 1	Satakhel
LAHORE PC	
Union Council 2	Lahore
POONGA PC	
Union Council 3	Chargi
Union Council 4	Poonga
KACH AMAQZAI PC	
Union Council 5	Ispedar
Union Council 6	Laghai
SADDAR BORI PC	
Union Council 7	Birgenoon

1.3 Why is it Important?

Rural areas face severe energy injustice. Electricity and modern energy systems are essential for the socioeconomic growth and acceptable living conditions of rural populations. Of course, this is not specific to Pakistan. Around 20% of the world population (1.2 billion) have no access to electricity, 85% of whom are from rural areas [12]. According to a World Bank report, only 74% of population in Pakistan has access to electricity, which has remained static in the last two decades. Worldwide, Pakistan ranks 149 out of 196 countries, behind Afghanistan and Bangladesh in term of electricity availability in rural areas [13]. About 68% of Pakistanis live in rural areas, 37% of whom lack access to electricity [14].

1.4 Energy Justice

The content of this section is adopted from the author's work in [37].

1.4.1 Definitions

The goal of energy justice is to ensure that every individual has access to affordable electricity sustainable energy supply, and that is protected from inequities associated with negative effects and costs relating to infrastructure, operation, and maintenance of the power system [15]. Energy justice is classified as distributional, procedural, and recognition justice. Distributional justice intends to evaluate how the benefits and harms from energy systems are distributed within society. For instance, communities who live near fossil-fuel based power plants may experience environmental contamination and poor air quality (harms) more than those living farther away who gain access to cheap and reliable electricity (benefits) [15]. Procedural justice focuses on the fairness of the processes through which energy related policies are determined and energy-related projects are implemented. Ideally, every individual, either directly or through their representatives, should be able to participate in the decision-making process and have a say in the final outcomes. Information related to energy policies and projects should hence be disclosed in a complete, clear, and non-ambiguous way to all individuals, regardless of their income, social status, race, or gender [15]. Finally, recognition justice acknowledges that individuals are disproportionately affected by lack of access to energy and intends to identify parts of society that are misrepresented or overlooked [15].

1.4.2 Global Views on Energy Justice: Is Access to Energy a Human Right?

Although the concept of "Right to Energy" was presented at the UN for the first time in 1950s, access to energy is yet to be established as a legal human right. EU does not mention the right to energy as a human right, but it recognizes that access to affordable energy is a fundamental component to ensure the living standards of EU citizens. In 2015, the UN developed 17 Sustainable Development Goals (SDGs), which were adopted by 193 countries [16]. Five of targets related to SDG 7 "Affordable and Clean Energy" are as follows [17]:

- Reliable, sustainable, affordable, and modern energy sources and services.
- Increasing the percentage of renewable energy share in the global energy mix.
- Doubling the rate of improvement and enhancement in energy efficiency.
- Enhancing investment in development of clean energy and promoting related research.
- Upgrading the energy systems and services for developing countries.

1.4.3 Case studies related to energy justice.

Several studies have been conducted around the world, with the goal of analyzing the predictors of vulnerability regarding access to energy, assessing the impacts of energy injustice on the wellbeing of society, and evaluating how those inequities may lead to further vulnerabilities:

- Kanagawa and Nakata [18] conducted a study in rural areas of developing countries and concluded that many socio-economic and environmental impacts are directly associated with lack of access to modern energy technologies. Haanykia studied the impact of electrification in Zambia and observed a strong relation between community activities and electrification [19].
- A study conducted on the rural electrification of Bangladesh concluded that electrified households have 64.5% higher average annual income than village households with no electricity [20]. Chaurey et al. found a strong correlation between access to electricity and rural poverty [21]
- Education is identified as a key contributor to poverty reduction. Naturally, by having access to electricity, children can expand their school activities. Families can have lighting at night for

studying and use of TV/radio or other information and communication technologies for educational purposes. A case study conducted on Bangladesh rural electrification concluded that electrified households have a 70.8% literacy rate compared with village households with no electricity, at 54.3% [20].

- Dinkelman performed a case study in South Africa and observed that rural electrification is related to employment rate [22]
- By facilitating the usage of electric household appliances, which are safer and more efficient, individuals will be exposed to less severe health issues and can also dedicate their time to more productive and effective activities. According to the World Health Organization (WHO), around 2.4 billion people worldwide cook their meals using inefficient open fire stoves fueled by biomass (crop residue, animal dungs, and wood), coal, and kerosene [23]. Exposure to the air pollutants results in respiratory infections, tuberculosis, pneumonia, chronic obstructive pulmonary disease (COPD), cardiovascular events, low birthweight, and death both in children and adults [23], [24].
- In addition to creating an unhealthy environment and poor air quality in the house, excessive use of firewood can result in high deforestation rates in poorer countries. Lack of access to electricity has also been identified as one of the main obstacles behind providing clean potable water in rural areas [25], [26]
- Lack of access to electricity, in the form of street and household lighting, can also have a negative impact on crime rates. Arvate et al. [27] studied the relation between violent crimes and lightning in rural areas of Brazil, and concluded that rural electrification expansion can reduce the rate of murders and robbery on public streets and roads, because it facilitates offender identification.

CHAPTER 2 ELECTRIFICATION OF RURAL REGIONS

The content of this chapter is adopted from the author's work in [37].

2.1 Solutions for Rural Electrification

No one-size-fits-all solution exists for rural electrification. Different solutions differ in their technical, financial, societal, and environmental impacts that would be functions of the geographical location and electricity consumption patterns.

2.1.1 Power Grid Extension

The goal here is to extend the power distribution network to areas without electricity. This way, power provided to the area will be supplied from a (potentially) high reliability network with few operational uncertainties. Other benefits include low maintenance costs, flexibility to meet future demand, and regulated tariffs. However, the financial/technical feasibility of this approach depends on factors such as the distance of the area of interest from the main grid, number of households/or connections, and the income level of the residents. Projects where load area is at a relatively short distance from the main grid with concentrated households would be prime candidates, although such situations are rare in many rural areas [28]. In addition, if the main power grid does not have adequate generation capacity, which may be the case in many underdeveloped countries, grid extension will pose challenges for the main grid as well as potentially failing to provide reliable power to the rural area.

2.1.2 Off-Grid Systems

When grid extension is not cost-effective or practical, off grid solutions can be considered as an alternative. The latest advances in distributed energy resources, especially renewables and battery energy storage, have made this an affordable and attractive option in many countries. Most off-grid rural electrification systems in Asia, South Asia, Africa, and Latin America are based on solar photovoltaics (PV) [20]. Off-grid systems are generally categorized as decentralized solutions that supply a single consumer such as a household, shop, or farm, and centralized solutions in the form of microgrids and mini-grids supplying a group of customers.

2.1.2.1 Decentralized Off-Grid Systems

These systems are appropriate and cost-effective options when customers are geographically dispersed. Most systems use solar PV often with a battery system, e.g., solar home system (SHS), solar charging station (SCS), and solar lanterns [29]. Of course, the power provided by a typical household solar PV is only sufficient to supply loads such as lighting, fans, radio, or other small appliances, and not power heavy loads. Depending on the location, other options such as small-scale wind turbines or pico-hydro power plants can also be used in conjunction with solar PV. Of course, these systems may require relatively high installation costs, continuous maintenance, and a general technical knowledge, which may not be possible for some consumers.

2.1.2.2 Centralized Off-Grid Systems (Isolated Grids)

Unlike decentralized systems, these systems operate as a microgrid or a mini grid, supplying a number of customers in relative geographical proximity. Power generation technology adopted depends on the geographical location and availability of resources and can be solar PV, wind, micro hydro power, or diesel generators. According to the International Energy Agency (IEA), to achieve access to electricity for everyone by 2030, 40% of the total installed capacity has to come from mini grids [30]. Single-technology-based systems are viable options when the load is small. But as the demand increases, such systems become unreliable and costly because the renewable energy resource is intermittent in nature. Therefore, some researchers have proposed the concept of integrated renewable energy systems (IRES) that consist of multiple energy resources configured as DC coupled, AC coupled, or hybrid AC-DC [31].

2.1.3 Mobile Energy Storage Systems (MESS)

These are portable truck-mounted or towable battery storage systems equipped with physical interfaces that can charge their battery at a central facility such as a substation at the main power grid, drive to remote locations, and discharge their battery power before returning to the charging station. In recent years, they have gained much attention mainly from the perspective of power grid resilience during large scale outages and emergency conditions. Flexibility is the major advantage of MESS over stationary energy storage since they can be dispatched to any area in need. However, at the moment, MESS units are significantly more expensive than stationary batteries. These units require specific facilities to be able to make an electrical connection and discharge, making them more appropriate for situations where the community gather at a centralized location, for instance a community center or a chapter house in a reservation, to meet their basic needs such as access to a well for clean water, charging their phones, etc.

2.2 Examples of micro grid and mini grids

Some examples of micro grids and mini grids are provided in Table 2.1.

Table 2.1 Examples of mini and microgrid electrification projects around the world.

Location	Characteristics
West Bengal [7]	Remote villages with no easy access to the main grid. Electrification through 23 mini grids ranging in size from 25kW to 100kW, primarily based on solar PV. Managed by local cooperative committees in each village.

Table 2.1 Continued

Location	Characteristics
Nepal [7]	2,000 hydropower mini grids provide electricity to 1.5 million people. Average load factor is about 26%, so for many hours every day the system remains idle.
Cajamarca, Peru [8]	Standalone systems based on SHS concept allow for up to 4 hours of lighting. Project covers 3,910 households spread across 188 different communities
Tanzania [7]	Hybrid solar-diesel systems are being deployed as an alternative to diesel-only (because fuel is expensive).
Oaxaca, Mexico [8]	Some households in isolated and remote areas are electrified using third generation PV SHS systems. In 2022, 8,525 houses in 628 communities were electrified.
Sancti Spiritus, Cuba [9]	Around 28% of the population live in dispersed rural communities. Closest grid access point is 16 km via a dirt road. Various projects are implemented using centralized diesel generators and modular PV panels.
Village of Tuntutuliak (Western Alaska) [10]	Home to approximately 400 Yupik Eskimos. Within the region there are approximately 56 villages similar to Tuntutuliak. The primary source of electricity is diesel generators, but fuel is expensive. Solutions are developed using wind energy with residential thermal storage.
Navajo Reservation [11]	The Keyenta Solar Project provides a total of 56MW sufficient to power 36,000 homes.
Moapa Band of Paiutes tribe [12]	Recently completed, a hybrid microgrid project with power capacity of 250MW to deliver power to off grid Moapa Travel Plaza. The system consists of 3 energy efficient generators, concentrated PV, and a battery bank.

2.3 Pros and Cons

List of pros and Cons of different technologies for rural electrification are provided in Table 2.2 on page 8.

Table 2.2 Advantages and disadvantages of different technologies for rural electrification.

Technology	Advantages	Disadvantages
Grid Extension	• Flexible to handle load growth. • Higher reliability. • Lower maintenance cost. • Least effort required to set up new connections.	• High capital cost due to typically long distances. • High power losses and voltage drops over long distances, which may run into instability issues if the network is weak.
Off-Grid Solutions	• Generally, less costly than grid extension. • More suitable if load areas are geographically dispersed or are in hard-to-access areas. • Can be a green solution based on renewables, hence, reducing dependence on fuels.	• Capacity is typically limited. • Reliability is lower than grid extension. • May run into voltage and power quality issues. • If using renewables, may be impacted by resource intermittency. • Higher LCOE and maintenance costs. • Need to be merged with the grid if/when the power grid is eventually extended to the area.
MESS	• Very flexible and can provide power to remote areas. • Can be operational even when the main grid is damaged due to external events. • Does not require grid control and other power quality systems and measures.	• Needs road access. • Can only provide power to pre-determined locations with the proper connection means. • High cost

CHAPTER 3 PROPOSED METHODOLOGY

The content of this chapter is adopted from the author’s work in [37].

3.1 Design Criteria

There are a few guidelines and principles by which the electrification project must abide in order to ensure its feasibility and sustainability. It must be cost-effective, provide reliable power, be financially sustainable, and be designed towards the needs of the community.

3.1.1 Cost Effectiveness

Historically, this has been the most important design criterion. Installation cost of a project depends on many factors including the distance of the area from the main grid and its general accessibility, the availability of renewable energy resources in the area, expected peak demand, the number of households to be energized, and the geographical dispersion of potential load points. In addition to the installation cost, the cost of operation and maintenance must be considered to ensure that the project will be sustainable in the long run. Those variable costs can be impacted by the types of technologies adopted as well as the income level of the customer base, which indicates whether they will be able to pay their electricity bills. Cost of maintenance can be a function of accessibility of the area, the availability of skilled crew, and the level of complexity of the system (e.g., whether consumers can perform some troubleshooting themselves).

3.1.2 Energy Justice and Equity

Priority should be given to areas with socially vulnerable residents. Socioeconomic and demographic factors such as poverty rates (household income), preexisting medical conditions, age range of customers, and accessibility of the area can be considered either as decision rules or to develop metrics to quantify the priority of different areas. Households with residents below the age of 5 or over the age of 65, who are generally known to be more vulnerable to excess heat and cold, should be prioritized for electrification, so that more proper cooling and/or heating options are available to them. Residents with underlying health conditions would need a more stable temperature control indoors, access to refrigeration to store medicine, and/or access to electricity to run medical equipment. If the area is remote, access to refrigeration in the household is key in order to ensure that residents can store food items over long periods of time without having to visit grocery stores on a regular basis. Another important social constraint is related to cultural customs and traditions, especially in areas inhabited by indigenous people. Electrification projects must be designed in such a way that preserves the cultural identity of the residents and does not negatively impact their kinship with their natural surroundings.

3.1.3 Technical Constraints

Various technical constraints come into play in an electrification project:

- Distance from the main cities/towns and ease of access indicates whether grid extension options are viable. Not only does the cost of new lines depend on the distance to the area, but the type of conductors to be used and the
- Voltage level is also a function of distance (to limit voltage drop and power losses). Further, installing additional devices such as voltage regulators and capacitor banks may become necessary.
- The project must maintain the required level of reliability and quality of service. This is in general more challenging to ensure in off-grid systems.
- For off-grid solutions, availability of renewable energy resources will indicate the type of technologies that can be used. Solar is generally the technology of choice for remote areas, although a battery energy storage system is often needed, which would add to the cost. Technologies such as diesel generators are impacted by the fuel price volatility as well as ease of access, which is especially challenging if the area is remote.
- Dispersion of the load areas is also an important factor. Dense populations favor localized solutions, whereas dispersed households justify decentralized single household solutions such as SHS.
- The potential load growth also needs to be considered and could tip the balance towards more robust solutions such as grid extension, especially if the main grid is reliable and with adequate resources.
- The need for maintenance can pose challenges. Diesel generators and battery systems particularly require regular maintenance.
- Accessibility of the area and the type of roads (paved vs. dirt road) can determine whether mobile energy resources are technically viable options.

3.2 General Solution Framework

The most systematic way to approach an electrification project is to formulate it as a multi-objective optimization model (see Figure. 3.1 on page 11). These projects have traditionally been viewed from a merely engineering perspective, with optimality associated with cost-effectiveness and technological validity. However, global trends towards energy justice are shifting this paradigm, and decision-makers are increasingly adopting policies that encourage equitable access to electricity for all. This requires energy justice goals to be incorporated into the design objectives and perhaps be given equal importance. Objective functions can be minimizing the cost of deployment and operation, minimizing the unserved load, minimizing the external resources necessary such as fuel, and minimizing the environmental impacts. These objectives need to be solved subject to a variety of constraints, including:

- Total available budget for the project,
- Demand constraints including the numbers/locations of load points, expected hourly/daily consumption powers, and any load curtailment parameters such as the maximum number of hours a day or days a week that any load point can be left without electricity,
- Power flow and voltage constraints,
- The types of technologies that can be used and their maximum capacity whenever applicable. This could be subject to suitability of the technology, environmental concerns, or availability of resources,
- Constraints representing the availability of roads and the typical travel times between the main grid and the discharge locations if MESS is being considered.

The output of the model can be the number and locations of lines to be installed connecting the area to the main grid, the number, locations, and capacities of off-grid solutions along with their generation mix, and/or the number and capacities of MESS units to be deployed. Naturally, such an optimization problem must be solved over time in order to be able to properly model the operation and maintenance costs. Failure to do so will result in a solution that may be optimal from a deployment perspective, but not necessarily financially or operationally sustainable.

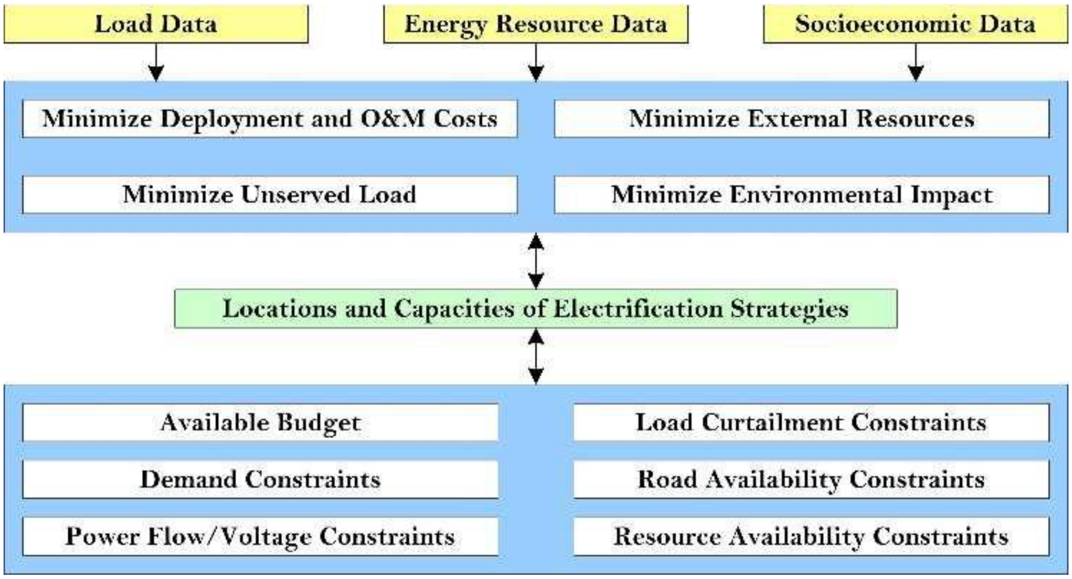

Figure 3.1 General framework for modeling electrification problems

The output of the model can be the number and locations of lines to be installed connecting the area to the main grid, the number, locations, and capacities of off-grid solutions along with their generation mix, and/or the number and capacities of MESS units to be deployed. Naturally, such an optimization problem must be solved over time in order to be able to properly model the operation and maintenance costs. Failure to do so will result in a solution that may be optimal from a deployment perspective, but not necessarily financially or operationally sustainable.

Such multi-objective models will naturally have design objectives that are at times contradictory to one another. Therefore, solution methodologies need to be adopted that seek Pareto optimality. This way, various objectives will be (partially) met in a way that no objective will dominate others. Furthermore, the model needs to be solved while considering various uncertainties that arise from the intermittent wind and solar resource availability, the volatility of fuel prices, and the uncertainty in demand, to name a few. Robust, probabilistic, or risk-based approaches can be used to ensure that the solution obtained is protected against such uncertainties. There are a number of ways in which energy justice can be incorporated into the problem formulation. Distributional justice can for instance be modeled as limiting the generation technologies to renewables so that air and/or water qualities are not compromised. If part of the profits is returned to the community, e.g., for renting the land to install a generator, profit maximization can also be included in the cost objective function. To model recognition justice, one can weigh the unserved load based on the vulnerability levels of the corresponding communities. Factors such as household income, age, socioeconomic status, and minority status can be used to derive composite vulnerability metrics assigned to load areas. The unserved load will then be minimized in a way that improves equity.

3.3 Proposed Idea

The electrification problem proposed in this study can be described as follows:

Given:

- A set of potential power grid substations that can be extended to remote areas.
- A set of potential power grid substations that can be used as charging stations for MESS.
- A set of potential locations to deploy off-grid systems.

Find:

- Optimum number and locations of nodes (substations) for grid extension.
- Optimum number and locations of off-grid systems.
- Optimum number and charging locations for MESS.

- Optimum size of the micro grids.

Such that:

- The highest possible number of communities are energized in an equitable, cost-effective, reliable, and sustainable manner.

3.4 Assumptions

The following assumptions are made:

- We have a number of remote demand areas d that need to be electrified. In this work, we consider demand as clusters of houses, rather than individual households. Each demand area has the following attributes: geographical coordinates, number of residents, expected hourly demand.
- There are three options for electrification of the remote areas: extending the main power distribution system, building off-grid microgrids, and/or using mobile energy storage systems (MESS) to provide temporary power to load areas.
- There exists a series of nodes n in the main distribution system that can extended to the remote areas. Power distribution system is modeled as infinite bus. However, there is a limit to the amount of power that can be provided through each node. Because lines are expected to extend over long distances, this limit can be attributed to voltage constraints and would be a function of the length of the line.
- There exists a series of locations m at remote areas where a microgrid can be deployed. A microgrid may be deployed at a demand area or may be electrically connected to it through overhead lines. The latter option may be used if the demand area is poor in terms of energy resources and hence, not a good location for setting up a microgrid. If a microgrid is connected to a demand area via a power line, it is assumed here that the line capacity matches the generation capacity of the microgrid.
- A MESS unit can discharge its battery at a demand area d. This may be a standalone community center where the residents can gather to get their needs.
- Since the dispatch here is conducted on a daily basis, to make the cost of deployment and operation comparable, all capital costs are converted to equivalent cost per day, which is achieved by dividing the equivalent annual cost by 365. Suppose the capital investment for a technology is C and its lifetime is N years. Further, assume the annual interest rate is i. Then, the annual equivalent investment is:

$$\mathrm{AEI} = C \cdot \frac{i \cdot (1+i)^N}{(1+i)^N - 1} \tag{3.1}$$

We then convert it to the daily cost of deployment by dividing AEI by 365. We apply this approach to the cost of deployment for microgrid, grid line, microgrid line, and MESS.

3.5 Nomenclature

3.5.1 Indices and Sets

c	Index used for charging stations where MESS units can charge their battery. This can be a dedicated charging station or a power substation.
d	Index used for demand areas, which may also serve as a location for MESS unit to discharge its battery (i.e., the community center)
i, j	Auxiliary indices used to indicate demand nodes or charging stations.
m	Index used for potential microgrid locations
n	Index used for power system nodes that can be extended to the remote areas
S_C	Set of charging stations for MESS units.
S_D	Set of demand areas.
S_M	Set of possible locations where a microgrid can be set up.
S_N	Set of power system nodes that can be extended to the remote areas.
S_V	Set of MESS vehicles.
t	Index used for time
T	Time horizon of the problem
v	Index used for the MESS vehicle

3.5.2 Parameters

c^{MESS}	Capital cost associated with the MESS and setting up a MESS charging station at a node [$/kW].
$c_{(\cdot)}^{\mathrm{O\&M}}$	O&M cost of providing power by technology (·) [$/kW]
c^{gen}	Capital cost of setting up a microgrid at location m [$/kW]. May depend on the type of generation technology used.
c^{line}	Cost of setting up a power line between two nodes. Considered to be linearly proportional to the distance between the nodes [$/km]

$E_{(\cdot)}$	Emissions produced by generation technology (·) [kg_{CO2}/kW]. Index (·) can be associated with the power coming from the power system node n, microgrid m, or MESS v.
$l_{(\cdot),d}$	Length of the overhead line between generation node (·) and demand area d [km]. Node (·) can be the power system node n or microgrid m.
$P_{d,t}^{\text{des}}$	Desired demand at demand area d at time t [kW]
$P_{m}^{\max}$	Maximum generation capacity for microgrid m [kW]. This can be due to environmental or resource related constraints.
$P_{n,d}^{\max}$	Maximum power that can be provided to demand area d from the line connected to node n [kW]. Note that this is a function of the length of the line from node n to demand area d. In other words, not all potential lines will have the same capacity. In the most general case, this value can change over the course of the day due to variations in ambient temperature.
$P_{v}^{\max}$	Rated capacity of MESS unit v [kW]
$P_{v}^{\min}$	Minimum permissible charge level for MESS unit v [kW]. Can be set to zero if the unit is allowed to discharge its entire battery capacity.
$\mathrm{T}_{\mathrm{i,j}}$	Time it takes for the MESS unit to drive from node i (charging station, demand area) to node j (charging station, demand area) [hours]. In this work, we assume that the travel times are integer values.
α_{d}	Vulnerability level of customers connected to demand area d. A value between 0 and 1, with higher values indicating higher vulnerabilities.

3.5.3 Variables

$p_{d,t}$	Power provided to demand area d at time t [kW]
$p_{m}^{\max}$	Generation capacity of microgrid m [kW].
$p_{m,d,t}$	Power provided to demand area d from microgrid m at time t [kW]
$p_{n,d,t}$	Power provided to demand area d from the line connected to node n at time t [kW]
$p_{v,c,t}$	Charge power provided to MESS unit v at charging station c at time t [kW]
$p_{v,d,t}$	Power discharged by MESS unit v at demand point d at time t [kW]
$p_{v,t}^{\text{ch}}$	Charge power provided to MESS unit v at time t [kW]
$p_{v,t}^{\text{dis}}$	Power discharged by MESS unit v at time t [kW]

$p_{v,t}$	Power of MESS unit v at time t [kW]
$u_{m,d}$	Binary variable indicating if microgrid m provides power to demand area d.
$u_{n,d}$	Binary variable indicating if power system node n is chosen for electrification of demand area d
u_v	Binary variable indicating if MESS unit v is used for electrification.
$u_{v,c,t}$	Binary variable indicating if MESS unit v is at charging station c at time t. The vehicle may or may not be charging its battery while stationed at a charging station.
$u_{v,c,t}^{\text{ch}}$	Binary variable indicating if MESS unit v is charging at charging station c at time t.
$u_{v,d,t}$	Binary variable indicating if MESS unit v is at demand node d at time t. The vehicle may or may not be discharging its battery while stationed at a demand node.
$u_{v,d,t}^{\text{dis}}$	Binary variable indicating if MESS unit v is discharging at demand node d at time t .

3.5.4 Formulation

The problem can be formulated as follows:

Minimize the load not served, adjusted by social vulnerability levels:

$$min \sum_{t \in T} \sum_{d \in S_D} \alpha_d \cdot (P_{d,t}^{\text{des}} - p_{d,t}) \tag{3.2}$$

Minimize the cost of the electrification project, divided into two terms, one for deployment and another for operation:

$$\min \left\{ \sum_{n \in S_N} \sum_{d \in S_D} u_{n,d} \cdot c^{\text{line}} \cdot l_{n,d} + \sum_{m \in S_M} \left(c^{\text{gen}} \cdot p_m^{\max} + \sum_{d \in S_D} u_{m,d} \cdot c^{\text{line}} \cdot l_{m,d} \right) + \sum_{v \in S_V} u_v \cdot c^{\text{MESS}} \cdot P_v^{\max} \right\} \tag{3.3}$$

$$min \sum_{t \in T} \left\{ \sum_{n \in S_N} \sum_{d \in S_D} c_n^{\text{O\&M}} \cdot p_{n,d,t} + \sum_{m \in S_M} \sum_{d \in S_D} c_m^{\text{O\&M}} \cdot p_{m,d,t} + \sum_{v \in S_V} c_v^{\text{O\&M}} \cdot p_{v,t}^{\text{ch}} \right\} \tag{3.4}$$

Minimize the emissions:

$$min \left\{ \sum_{t \in T} \left[\sum_{n \in S_N} \left(E_n \cdot \sum_{d \in S_D} p_{n,d,t} \right) + \sum_{m \in S_M} \left(E_m \cdot \sum_{d \in S_D} p_{m,d,t} \right) + \sum_{v \in S_V} \left(E_v \cdot \sum_{d \in S_D} p_{v,d,t} \right) \right] \right\} \tag{3.5}$$

3.5.4.1 Demand Constraints

Power balance equation at each node: at any point in time, power provided to each demand area is the sum of power provided by the three technologies and is limited by the desired amount.

$$\forall d \in S_D, \forall t \in T: p_{d,t} = p_{n,d,t} + p_{m,d,t} + p_{v,d,t} \tag{3.6}$$

$$\forall d \in S_D, \forall t \in T: 0 \leq p_{d,t} \leq P_{d,t}^{\mathrm{des}} \tag{3.7}$$

3.5.4.2 Grid Extension Constraints

Limit on the power level that can be provided grid extension.

$$\forall n \in S_N, \forall d \in S_D, \forall t \in T: 0 \leq p_{n,d,t} \leq u_{n,d} \cdot P_{n,d}^{max} \tag{3.8}$$

3.5.4.3 Microgrid Constraints

Constraint that indicates whether a microgrid at location m is chosen for electrifying demand d. In these equations, M is a large positive number.

$$\forall m \in S_M, \forall d \in S_D: M \cdot u_{m,d} \geq \sum_{t \in T} p_{m,d,t} \tag{3.9}$$

The total power provided by the microgrid to the loads is limited by its generation capacity (constraint (3.10)), itself limited by the maximum permissible generation capacity that can be built at location m (constraint (3.11)).

$$\forall m \in S_M, \forall t \in T: \sum_{d \in S_D} p_{m,d,t} \leq p_m^{max} \tag{3.10}$$

$$\forall m \in S_M: p_m^{max} \leq P_m^{max} \tag{3.11}$$

3.5.4.4 MESS Unit Constraints

Power balance equation for a MESS unit: At any point in time *t*, the battery charge at a MESS unit is equal to the value at the previous time step, adjusted by the amount of charge/discharge provided to/by the unit at time. This equation is based on the ‘energy balance’ not the ‘power balance,’ however, since our time step is one hour, energy and power will be equal in value.

$$\forall v \in S_V, \forall t \in T: p_{v,t} = p_{v,t-1} + p_{v,t}^{\mathrm{ch}} - p_{v,t}^{\mathrm{dis}} \tag{3.12}$$

Capacity constraint for MESS

$$\forall v \in \mathrm{S_V}, \forall t \in \mathrm{T}: P_v^{\min} \leq p_{v,t} \leq P_v^{\max} \tag{3.13}$$

A MESS can provide power to any demand area *d*, up to its rated capacity (see (3.14)). The vehicle can only discharge at a location if it is physically present at that location (see (3.15)). A MESS can be dispatched to different locations to discharge power only if it is chosen as an option for electrification (see (3.16)).

$$\forall v \in S_V, \forall t \in T: p_{v,t}^{\mathrm{dis}} = \sum_{d \in S_D} p_{v,d,t} \tag{3.14}$$

$$\forall v \in S_V, \forall d \in S_D, \forall t \in T: p_{v,d,t} \leq u_{v,d,t}^{\mathrm{dis}} \cdot P_v^{max} \tag{3.15}$$

$$\forall v \in S_V, \forall d \in S_D, \forall t \in T\colon u_{v,d,t}^{\text{dis}} \leq u_{v,d,t} \tag{3.16}$$

$$\forall v \in S_V, \forall d \in S_D, \forall t \in T\colon u_{v,d,t} \leq u_v \tag{3.17}$$

A MESS can charge its battery at any charging station *c*, up to its rated capacity (see (3.19)). The vehicle can only charge at a station if it is physically present at that location (see (3.20)). A MESS can be dispatched to different locations to discharge power only if it is chosen as an option for electrification (see (3.21)).

$$\forall v \in S_V, \forall t \in T\colon p_{v,t}^{\text{ch}} = \sum_{c \in S_C} p_{v,c,t} \tag{3.18}$$

$$\forall v \in S_V, \forall c \in S_C, \forall t \in T\colon p_{v,c,t} \leq u_{v,c,t}^{\text{ch}} \cdot P_v^{max} \tag{3.19}$$

$$\forall v \in S_V, \forall c \in S_C, \forall t \in T\colon u_{v,c,t}^{\text{ch}} \leq u_{v,c,t} \tag{3.20}$$

$$\forall v \in S_V, \forall c \in S_C, \forall t \in T\colon u_{v,c,t} \leq u_v \tag{3.21}$$

At any point in time, a MESS unit can be at a single location. Note that because of constraints (3.16) and (3.20), this also forces that at any point in time, a MESS unit can be charging, discharging, or neither.

$$\forall v \in S_V, \forall t \in T\colon \sum_{c \in S_C} u_{v,c,t} + \sum_{d \in S_D} u_{v,d,t} \leq 1 \tag{3.22}$$

Initial positions and battery charge levels of MESS units are known, e.g., it can be assumed that at the beginning of the dispatch period, MESS units are fully charged, located at a charging station, and ready to be dispatched.

$$\forall v \in S_V\colon p_{v,0} = P_v^{max} * u_v \tag{3.23}$$

$$\forall v \in S_V, \exists c \in S_C\colon u_{v,c,0} = 1 \tag{3.24}$$

If a vehicle is located at a particular location, e.g., a charging station or a demand area, it cannot immediately be available at another location. Instead, it will need at least the travel time between the two nodes. We model this as follows:

- Suppose we have two nodes *i* and *j*, and MESS unit *v* is discharging its battery at node *i* at time *t*: $u_{v,d,t} = 1$. In that case, it will take at least $T_{i,j}$ hours for the MESS to be able to discharge its battery at node *j*. This means that: $u_{v,d,t+1} = u_{v,d,t+2} = \cdots = u_{v,d,t+T_{i,j}} = 0$

We can model this mathematically as follows:

$$\forall v \in S_V, \forall i \in \{S_D \cup S_C\}, \forall j \in \{S_D \cup S_C\}, \forall t\colon \begin{cases} u_{v,j,t+1} \leq (1 - u_{v,i,t}) \\ u_{v,j,t+2} \leq (1 - u_{v,i,t}) \\ \vdots \\ u_{v,j,t+T_{i,j}} \leq (1 - u_{v,i,t}) \end{cases} \tag{3.25}$$

CHAPTER 4 MODEL VALIDATION AND DISCUSSION

4.1 Case Study

To validate the model and for proof-of-concept purposes, union councils in Loralai/Bori Tehsil are selected for electrification (see Chapter 1 for description of union councils). In total, 7 union councils (which are considered as demand areas *d*) are considered, with corresponding data listed in Table 4.1. The map of the settlement/PC in which these union councils are located is presented in Figure 4.1 on page 20, along with the locations of demand areas (*d*), grid nodes (*n*), microgrids (*m*), and the MESS charging station (*c*) shown in Figure 4.2 on page 20. Load profiles considered for the demand areas are illustrated in Figure 4.3 on page 21. These profiles are created based on general load patterns in rural Pakistan and are for demonstration purposes only.

Table 4.1 Loralai/Bori Tehsil union council data

Settlement/ PC	Union Council	Demand Area	Population	# of Houses	% of Electrified Houses	% of Resident 60 years and above	Location (Latitude, Longitude)
China Alizai	Satakhel	d_1	443	45	0	6.77	30.4768646, 69.3251851
Lahore	Lahore	d_2	820	148	4.05	4.88	30.6053999, 69.131302
Poonga	Chargi	d_3	312	33	3.03	2.88	30.3590741, 68.8475787
	Poonga	d_4	407	53	1.89	3.69	30.3297896, 68.7492935
Kach Amaqazai	Ispedar	d_5	756	122	0.82	4.76	30.4717797, 68.5345039
	Laghi	d_6	321	23	0	9.66	30.4520877, 68.4538979
Saddar Bori	Birgenoon	d_7	1,719	320	0	6.46	30.4716, 68.9206621

4.1.1 Parameters Used

The capital costs for setting up a power line between a grid node or a microgrid and demand areas is considered to be 248,550 \$/km. The capital costs for MESS, which includes the cost of the vehicle and the charging infrastructure, is considered 1,800 \$/kW. For microgrids, the cost of deployment is assumed to be 2,450 \$/kW, which is mainly associated with the generation resources. These values are chosen based on a review of the literature and for proof-of-concept purposes. Changing these values may impact the outcome of the optimization model but does not affect the generality of the proposed solution. To calculate the equivalent daily costs, the lifetime (N) for MESS, microgrid, and overhead lines is considered as 8, 25, and 50 years, respectively. The interest rate is assumed to be 5% for all three technologies. These values are then used in equation (1) to calculate the daily costs of the three technologies as shown in Table 4.2 on page 22.

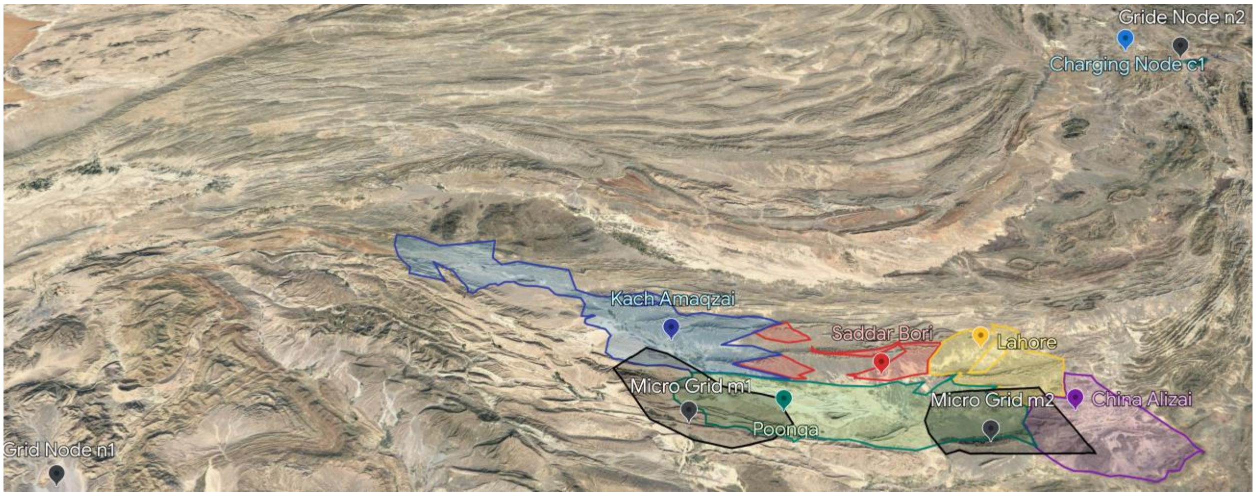

Figure 4.1 Map of settlements/PC in Loralai/Bori tehsil, Balochistan

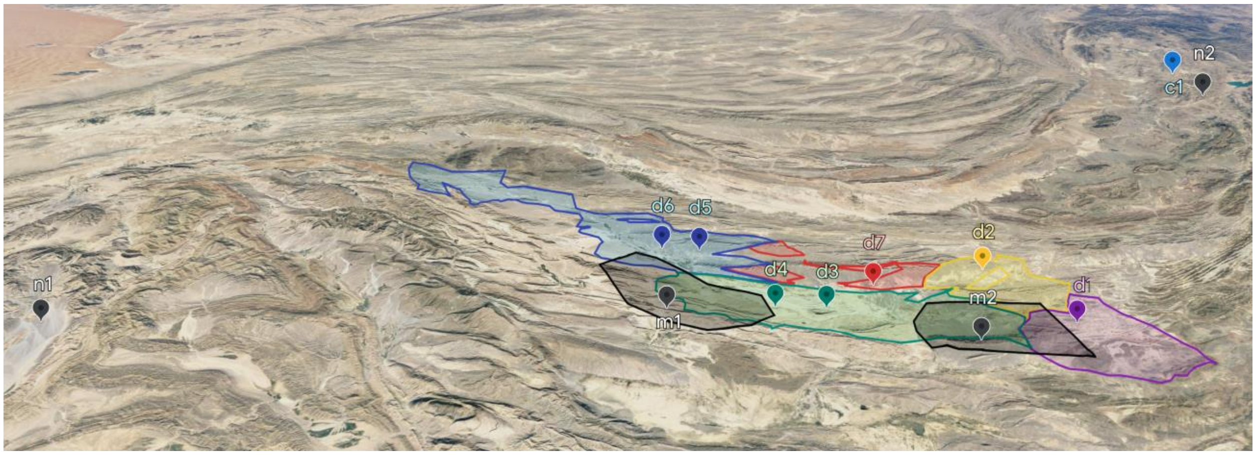

Figure 4.2 Map of the locations of demand areas (d), grid node (n), microgrid (m), and charging station (c) identified for the case study

The cost of operation and maintenance for electrification via the grid, microgrid, and MESS are estimated as 0.06, 0.04, and 0.08 \$/kWh, respectively. For the main grid and MESS, carbon emissions are estimated as 0.386 kg/kWh, whereas the value is considered to be zero for the microgrid (i.e., green generation). Distances between demand areas (*d*) and other nodes (grid nodes *n*, microgrids *m*) are provided in Table 4.3 on page 22. Table 4.4 on page 22 provides a list of appliances used in a typical household in rural Pakistan, with the estimated demands for each [11], which indicates a maximum daily demand of 775W per household.

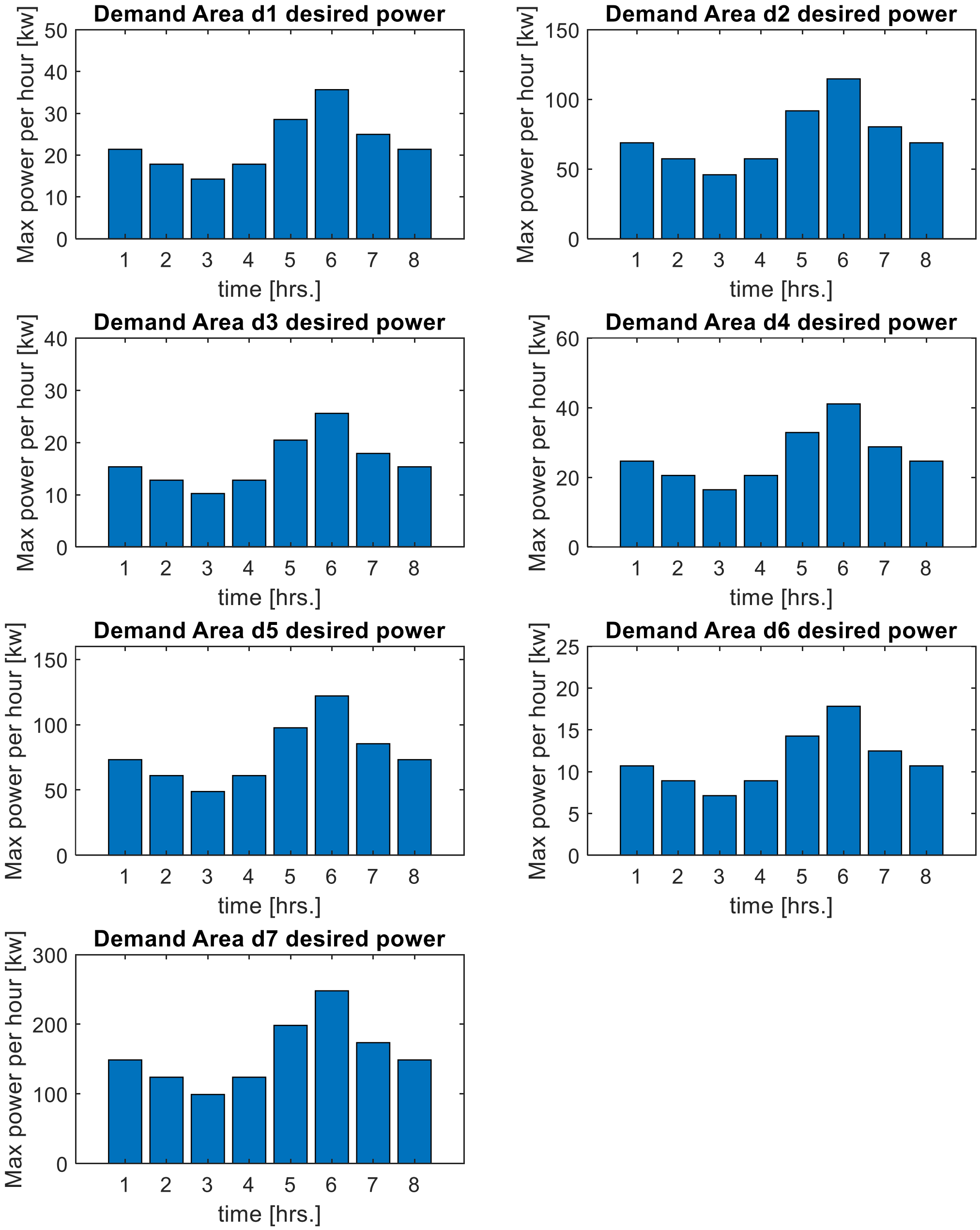

Figure 4.3 Load profiles considered for the demand areas (d)

Desired demands of the demand areas are calculated based on the number of households, maximum demand per household, and the daily load pattern over 8-time intervals. These are listed in Table 4.5 on page 22. The maximum power that can be supplied from the grid node to the demand areas is considered to be 1,000 kW. The travel time $T_{i,j}$ of MESS from node *i* (charging station, demand area) to node *j* (charging station, demand area) is listed in Table 4.6 on page 23 . It is also assumed that the MESS is fully charged at the beginning of the dispatch period. Finally, without loss of generality, the vulnerability factors α_d of demand areas (*d*) has been considered based on the percentage of the residents over the age of 60, shown in Table 4.7 on page 23.

Table 4.2 Capital cost of deployment of MESS, grid node and microgrid

Parameter	Value [$/kW]
c^{MESS}	0.7630
c^{gen}	0.4763
Parameter	**Value [$/km]**
c^{line}	37.30

Table 4.3 Distance (km) between demand areas and nodes (grid node and micro grid)

Nodes		Demand area						
		d_1	d_2	d_3	d_4	d_5	d_6	d_7
Grid Nodes	n_1	193.79	180.77	156	141.52	133.09	121.95	162.98
	n_2	178.77	176.04	198.53	206.96	205.31	212.49	185.69
Microgrids	m_1	72.31	58.24	33.93	19.1	14.45	17.58	39.75
	m_2	12.20	14.70	26.06	41.32	54.64	67.91	24.04

Table 4.4 Typical household appliances used in rural Pakistan and the demand for each one

Appliances	Power Rating	# of items	Total Power
Lights	25W	4	100W
Fans	75W	3	225W
Refrigerator	200W	1	200W
TV (17 inch)	150W	1	150W
miscellaneous	100	-	100
Total power			775W

Table 4.5 Estimated load of a typical household in rural Pakistan

Demand [kW]	Time[hrs.]							
	1	2	3	4	5	6	7	8
$P_{d1,t}^{\text{des}}$	21.39	17.82	14.26	17.82	28.52	35.65	24.95	21.39
$P_{d2,t}^{\text{des}}$	68.82	57.35	45.88	57.35	91.76	114.70	80.29	68.82
$P_{d3,t}^{\text{des}}$	15.34	12.78	10.23	12.78	20.46	25.57	17.90	15.34
$P_{d4,t}^{\text{des}}$	24.64	20.53	16.43	20.53	32.86	41.07	28.75	24.64
$P_{d5,t}^{\text{des}}$	73.20	61.00	48.80	61.00	97.60	122.00	85.40	73.20
$P_{d6,t}^{\text{des}}$	10.69	8.91	7.13	8.91	14.26	17.82	12.47	10.69
$P_{d7,t}^{\text{des}}$	148.80	124.00	99.20	124.00	198.40	248.00	173.60	148.80

Table 4.6 Travel time Ti,j of MESS from node i (charging station, demand area) to node j (charging station, demand area)

Travel time [hr.]	d_1	d_2	d_3	d_4	d_5	d_6	d_7	c
d_1	0	1	1	1	1	1	1	2
d_2	1	0	1	1	1	1	1	2
d_3	1	1	0	1	1	1	1	2
d_4	1	1	1	0	1	1	1	2
d_5	1	1	1	1	0	1	1	2
d_6	1	1	1	1	1	0	1	2
d_7	1	1	1	1	1	1	0	2
c	2	2	2	2	2	2	2	0

Table 4.7 Vulnerability factor of the demand areas

Load	α_d
d_1	0.80
d_2	0.65
d_3	0.50
d_4	0.55
d_5	0.60
d_6	0.90
d_7	0.70

4.2 Results and Discussion

4.2.1 Case Study 1: All Electrification Options, with Sufficient Overall Capacity

In this case study, it is assumed that all electrification options are available, and both the grid and microgrids have sufficient capacity to supply the demand on their own, i.e., each option can provide up to 650 kW. The capacity of MESS is assumed to be 250 kW. To run the multi-objective optimization model, each objective function is first run in isolation to find its single objective optima. Those values are then chosen directly or after a slight deterioration (for instance, when the value is zero) to provide the targets for the goal programming model. With the targets defined, all objectives are then run concurrently to find the Pareto optimal solution. The results of single objective and multi objective optimization are shown in Table 4.8 on page 24.

As a result of the multi-objective optimization, microgrids m_1 and m_2 are chosen for electrification since they are closest to the demand areas and produce zero carbon emissions. Further, microgrids have lower deployment costs compared to grid extension and lower operational costs compared to both MESS and grid extension. The size of the microgrid is the variable of optimization. The optimum size of microgrids m_1 and m_2 are determined as 180.9000 kW and 423.9035 kW, respectively, shown in Table 4.9 on page 24. The demand areas are electrified by the microgrid that is closer to them, which indicates that the distance from the microgrid matters. The powers supplied to the load and their source are shown in Table. 4.10 on page 25. Grid extension is not an attractive option in this case since it requires a high deployment cost due to the long distances. MESS is not a good choice either because of the long travel times, i.e., the earliest a MESS can arrive at any of the demand areas is after 3 hours. Grid node n_2 is considered as a charging station (c) which is two hours away from all demand areas. Other factors that go against choosing a MESS are the relatively high operational costs compared to microgrid and grid extension and higher carbon emissions compared to microgrids. The graphical representation of the optimization results is illustrated in Figure 4.4, and the graphs of the desired and supplied powers and the charging/discharging power of MESS are shown in Figure 4.5 on page 26. It can be seen that almost all demand targets are met.

Table 4.8 Optimum values of single objective and multi objective models.

Objectives	**Units**	**Single objective optimum**	**Target**	**Multi-objective optimum**
1	[kW]	0	0.01	0
2	[\$/kW]	4,820	4,820	5,190
3	[kg$_{CO2}$/kW]	0	0.01	0

Table 4.9 Optimum size of the microgrid.

Microgrids	**Microgrid size required (optimized) p_m^{Max}**	**Microgrid size available P_m^{Max}**
m_1	180.90	650
m_2	423.90	650

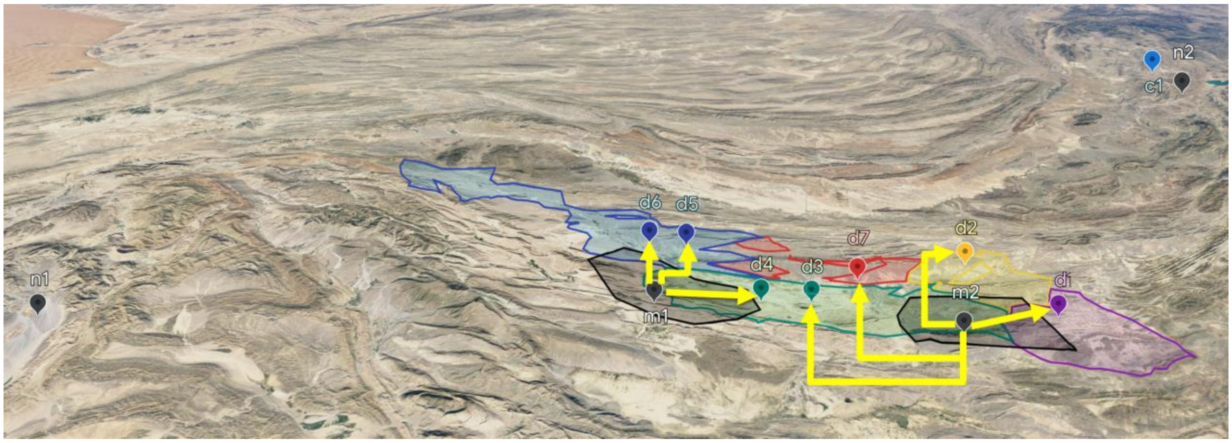

Figure 4.4 Graphical representation of the optimization result for case study 1.

Table 4.10 The desired demands and the actual demands provided, along with the source of power.

	Demand Areas								
Time (t)	$\boldsymbol{d_1}$			$\boldsymbol{d_2}$			$\boldsymbol{d_3}$		
	Source	$\boldsymbol{P_{d1,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d2,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d3,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**
1	$\boldsymbol{m_2}$	21.39	21.39	$\boldsymbol{m_2}$	68.82	68.82	$\boldsymbol{m_2}$	15.34	15.34
2	$\boldsymbol{m_2}$	17.82	17.82	$\boldsymbol{m_2}$	57.35	57.35	$\boldsymbol{m_2}$	12.78	12.78
3	$\boldsymbol{m_2}$	14.26	14.26	$\boldsymbol{m_2}$	45.88	45.88	$\boldsymbol{m_2}$	10.23	10.23
4	$\boldsymbol{m_2}$	17.82	17.82	$\boldsymbol{m_2}$	57.35	57.35	$\boldsymbol{m_2}$	12.78	12.78
5	$\boldsymbol{m_2}$	28.52	28.52	$\boldsymbol{m_2}$	91.76	91.76	$\boldsymbol{m_2}$	20.46	20.46
6	$\boldsymbol{m_2}$	35.65	35.65	$\boldsymbol{m_2}$	114.70	114.70	$\boldsymbol{m_2}$	25.57	25.57
7	$\boldsymbol{m_2}$	24.95	24.95	$\boldsymbol{m_2}$	80.29	80.29	$\boldsymbol{m_2}$	17.90	17.90
8	$\boldsymbol{m_2}$	21.39	21.39	$\boldsymbol{m_2}$	68.82	68.82	$\boldsymbol{m_2}$	15.34	15.34

	Demand Areas								
Time (t)	$\boldsymbol{d_4}$			$\boldsymbol{d_5}$			$\boldsymbol{d_6}$		
	Source	$\boldsymbol{P_{d4,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d5,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d6,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**
1	$\boldsymbol{m_1}$	24.64	24.64	$\boldsymbol{m_1}$	73.20	73.20	$\boldsymbol{m_1}$	10.69	10.69
2	$\boldsymbol{m_1}$	20.53	20.53	$\boldsymbol{m_1}$	61.00	61.00	$\boldsymbol{m_1}$	8.91	8.91
3	$\boldsymbol{m_1}$	16.43	16.43	$\boldsymbol{m_1}$	48.80	48.80	$\boldsymbol{m_1}$	7.13	7.13
4	$\boldsymbol{m_1}$	20.53	20.53	$\boldsymbol{m_1}$	61.00	61.00	$\boldsymbol{m_1}$	8.91	8.91
5	$\boldsymbol{m_1}$	32.86	32.86	$\boldsymbol{m_1}$	97.60	97.60	$\boldsymbol{m_1}$	14.26	14.26
6	$\boldsymbol{m_1}$	41.07	41.07	$\boldsymbol{m_1}$	122.00	122.0	$\boldsymbol{m_1}$	17.82	17.82
7	$\boldsymbol{m_1}$	28.75	28.75	$\boldsymbol{m_1}$	85.40	85.40	$\boldsymbol{m_1}$	12.47	12.47
8	$\boldsymbol{m_1}$	24.64	24.64	$\boldsymbol{m_1}$	73.20	73.20	$\boldsymbol{m_1}$	10.69	10.69

	Demand Areas		
Time (t)	$\boldsymbol{d_7}$		
	Source	$\boldsymbol{P_{d7,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**
1	$\boldsymbol{m_2}$	148.80	148.80
2	$\boldsymbol{m_2}$	124.00	124.00
3	$\boldsymbol{m_2}$	99.20	99.20
4	$\boldsymbol{m_2}$	124.00	124.00
5	$\boldsymbol{m_2}$	198.40	198.40
6	$\boldsymbol{m_2}$	248.00	248.00
7	$\boldsymbol{m_2}$	173.60	173.60
8	$\boldsymbol{m_2}$	148.80	148.80

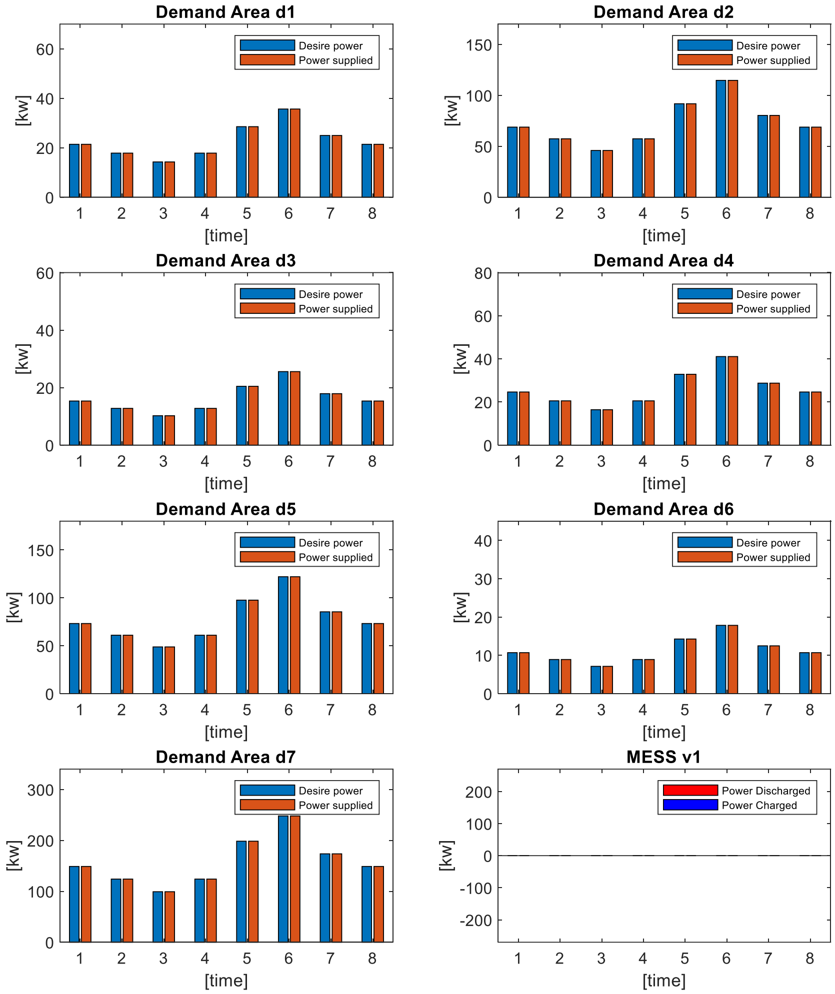

Figure 4.5 Desired and actual demands and MESS charge/discharge levels (bottom right) for case study 1.

4.2.2 Case Study 2: All Electrification Options (Single Microgrid), with Sufficient Overall Capacity

In this case, it is assumed that all electrification options are available except for microgrid m_2. The available size of microgrid m_1 is considered to be 650 kW, which means that it has sufficient capacity to supply the entire demand. The results of single objective and multi-objective optimization models are shown in Table 4.11 on page 27.

As a result of the multi-objective optimization, microgrid m_1 is chosen for electrification since it is closest to the demand areas and produces zero carbon emissions. Further, it has a lower deployment cost compared to grid extension and lower operational costs compared to both MESS and grid extension. The optimum size of microgrid m_1 is determined as 604.8250kW, as shown in Table 4.12 on page 27**.** The powers supplied to the loads and their sources are shown in Table 4.13 on page 27. Grid extension is not an attractive option here since it requires a high deployment cost due to the long distances. Similar to the previous case, MESS is not a good choice either because of the travel time. The graphical representation of the optimization results is illustrated in Figure 4.6 on page 28, and the graphs of the desired and supplied powers and the charging/discharging power of MESS are shown in Figure 4.7 on page 29. It can be seen that all demand targets are met. Further, the cost of deployment increases compared to that of case study 1, because the distances between microgrid m_1 to demand areas 1, 2, 3, and 7 are larger than those of microgrid m_2 (which is assumed unavailable in this case).

Table 4.11 Optimum values of single objective and multi objective models.

Objective	**Units**	**Single objective optimum**	**Target**	**Multi-objective optimum**
1	[kW]	0	0.01	0
2	[$/kW]	9,566	9,566	9,936
3	[$\mathrm{kg_{CO2}}$/kW]	0	0.01	0

Table 4.12 Optimum size of the microgrids.

Microgrids	**Microgrid size required (optimized)** p_m^{Max}	**Microgrid size available** P_m^{Max}
m_1	604.82	650
m_2	0	0

Table 4.13 The desired demands and the actual demands provided, along with the source of power.

	Demand Areas								
Time (t)	d_1			d_2			d_3		
	Source	$P_{d1,t}^{\mathrm{des}}$ **[kW]**	$p_{d1,t}$ **[kW]**	**Source**	$P_{d2,t}^{\mathrm{des}}$ **[kW]**	$p_{d2,t}$ **[kW]**	**Source**	$P_{d3,t}^{\mathrm{des}}$ **[kW]**	$p_{d3,t}$ **[kW]**
1	m_1	21.39	21.39	m_1	68.82	68.82	m_1	15.3450	15.34
2	m_1	17.82	17.82	m_1	57.35	57.35	m_1	12.7875	12.78
3	m_1	14.26	14.26	m_1	45.88	45.88	m_1	10.2300	10.23
4	m_1	17.82	17.82	m_1	57.35	57.35	m_1	12.7875	12.78
5	m_1	28.52	28.52	m_1	91.76	91.76	m_1	20.4600	20.46
6	m_1	35.65	35.65	m_1	114.70	114.70	m_1	25.5750	25.57
7	m_1	24.95	24.95	m_1	80.29	80.29	m_1	17.9025	17.90
8	m_1	21.39	21.39	m_1	68.82	68.82	m_1	15.3450	15.34
	Demand Areas								
Time (t)	d_4			d_5			d_6		
	Source	$P_{d4,t}^{\mathrm{des}}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P_{d5,t}^{\mathrm{des}}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P_{d6,t}^{\mathrm{des}}$ **[kW]**	$p_{d,t}$ **[kW]**
1	m_1	24.64	24.64	m_1	73.20	73.20	m_1	10.69	10.69

Table 4.13 Continued

Time (t)	d_4			d_5			d_6		
	Source	$P_{d4,t}^{\text{des}}$ [kW]	$p_{d,t}$ [kW]	Source	$P_{d5,t}^{\text{des}}$ [kW]	$p_{d,t}$ [kW]	Source	$P_{d6,t}^{\text{des}}$ [kW]	$p_{d,t}$ [kW]
2	m_1	20.53	20.53	m_1	61.00	61.00	m_1	8.91	8.91
3	m_1	16.43	16.43	m_1	48.80	48.80	m_1	7.13	7.13
4	m_1	20.53	20.53	m_1	61.00	61.00	m_1	8.91	8.91
5	m_1	32.86	32.86	m_1	97.60	97.60	m_1	14.26	14.26
6	m_1	41.07	41.07	m_1	122.00	122.00	m_1	17.82	17.82
7	m_1	28.75	28.75	m_1	85.40	85.40	m_1	12.47	12.47
8	m_1	24.64	24.64	m_1	73.20	73.20	m_1	10.69	10.69

	Demand Areas		
Time (t)	d_7		
	Source	$P_{d7,t}^{\text{des}}$ [kW]	$p_{d,t}$ [kW]
1	m_1	148.80	148.80
2	m_1	124.00	124.00
3	m_1	99.200	99.20
4	m_1	124.00	124.00
5	m_1	198.40	198.40
6	m_1	248.00	248.00
7	m_1	173.60	173.60
8	m_1	148.80	148.80

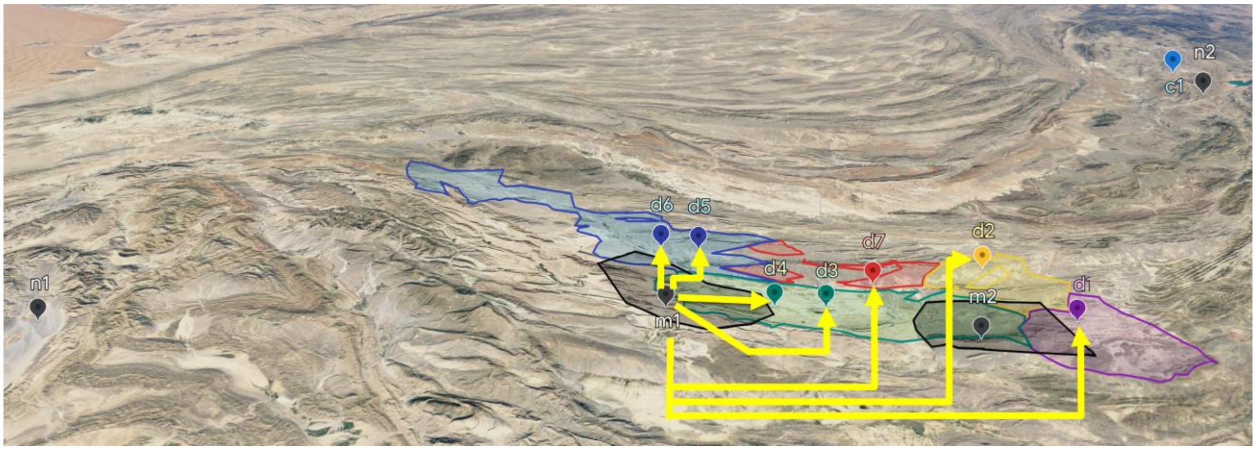

Figure 4.6 Graphical representation of the optimization result for case study 2.

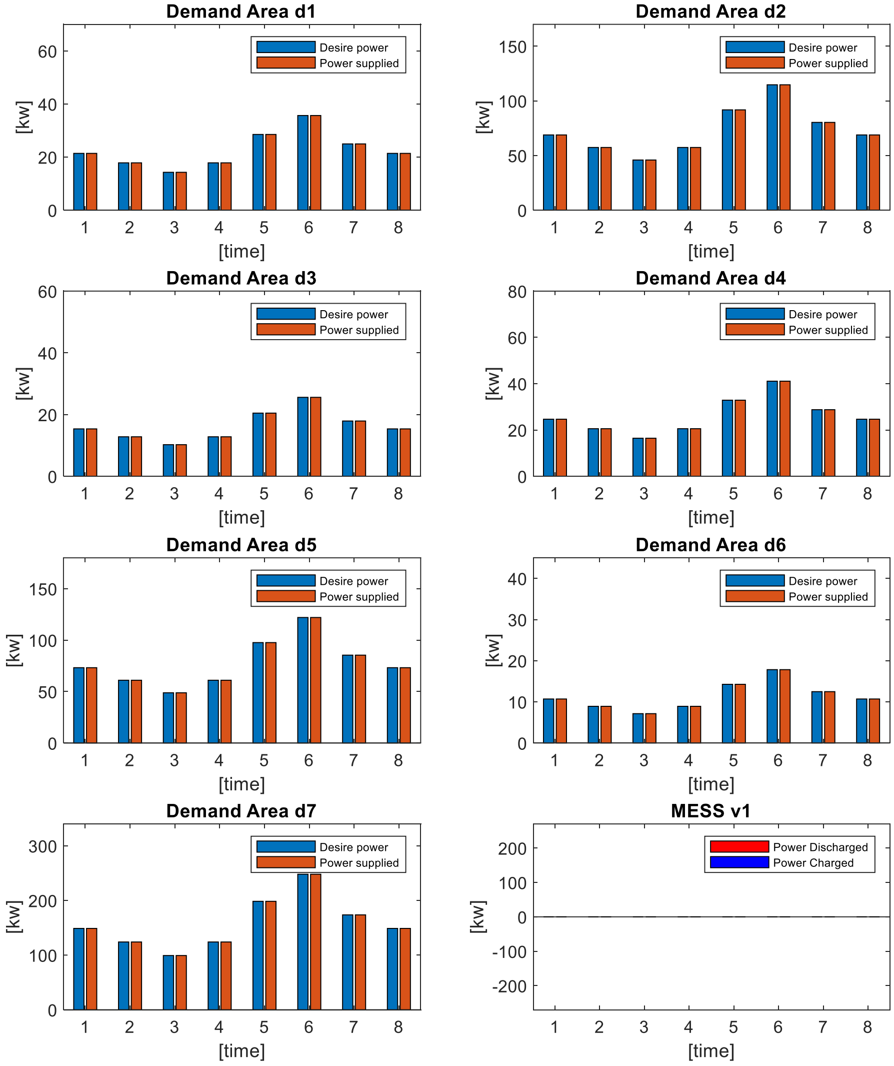

Figure 4.7 Desired and actual demands and MESS charge/discharge levels (bottom right) for case study 2.

4.2.3 Case Study 3: All Electrification Options, with Reduced Microgrid Capacity

Similar to case study 1, it is assumed here that all electrification options are available; however, the available sizes of microgrids m_1 and m_2 are considered to be 250 kW and 200 kW, respectively. The results of single objective and multi-objective optimization are shown in Table 4.14 on page 30.

Not surprisingly, microgrids m_1 and m_2 are both chosen for electrification since they are closest to the demand areas and produce zero carbon emissions. The optimum sizes of microgrids m_1 and m_2 are determined as 220.6781kW and 200 kW, respectively, shown in Table 4.15 on page 30. The powers supplied to the loads and their sources are shown in Table 4.16 on page 30. It can be seen that due to the insufficient capacity of microgrids, MESS is also used as an option. This increases the overall cost of deployment, in addition to the total emissions. MESS is used to provide power for only three hours to demand area d_7. The alternative would have been to extend the grid to that area, which would have made the solution more expensive. The operation modes of MESS are shown in Table 4.17 on page 32. The graphical representation of the optimization results is illustrated in Figure 4.8 on page 31, and the graphs of the desired and supplied powers and the charging/discharging power of MESS are shown in Figure 4.9 on page 32. It can be seen that all demand targets are met.

Table 4.14 Optimum values of single objective and multi objective models.

Objective	**Units**	**Single objective optimum**	**Target**	**Multi-objective optimum**
1	[kW]	0	0.01	0.0140
2	[$/kW]	4,820	4,820	6,766
3	[$\mathrm{kg}_{\mathrm{CO2}}$/kW]	0	0.01	96.5000

Table 4.15 Optimum sizes of the microgrids.

Microgrids	**Microgrid size required (optimized)** p_m^{Max}	**Microgrid size available** P_m^{Max}
m_1	220.67	250
m_2	200	200

Table 4.16 The desired demands and the actual demands provided, along with the source of power.

	Demand Areas								
Time (t)	d_1			d_2			d_3		
	Source	$P^{\mathrm{des}}_{d1,t}$ **[kW]**	$p_{d1,t}$ **[kW]**	**Source**	$P^{\mathrm{des}}_{d2,t}$ **[kW]**	$p_{d2,t}$ **[kW]**	**Source**	$P^{\mathrm{des}}_{d3,t}$ **[kW]**	$p_{d3,t}$ **[kW]**
1	m_2	21.39	21.39	m_2	68.82	68.82	m_2	15.34	15.34
2	m_2	17.82	17.82	m_2	57.35	57.35	m_2	12.78	12.78
3	m_2	14.26	14.26	m_2	45.88	45.88	m_2	10.23	10.23
4	m_2	17.82	17.82	m_2	57.35	57.35	m_2	12.78	12.78
5	m_2	28.52	28.52	m_2	91.76	91.76	m_2	20.46	20.46
6	m_2	35.65	35.65	m_2	114.70	114.70	m_2	25.57	25.57
7	m_2	24.95	24.95	m_2	80.29	80.29	m_2	17.90	17.87
8	m_2	21.39	21.39	m_2	68.82	68.82	m_2	15.34	15.34
	Demand Areas								
Time (t)	d_4			d_5			d_6		
	Source	$P^{\mathrm{des}}_{d4,t}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P^{\mathrm{des}}_{d5,t}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P^{\mathrm{des}}_{d6,t}$ **[kW]**	$p_{d,t}$ **[kW]**
1	m_1	24.64	24.64	m_1	73.20	73.20	m_1	10.69	10.69

Table 4.16 Continued

2	m_1	20.53	20.53	m_1	61.00	61.00	m_1	8.91	8.91
Time (t)	d_4			d_5			d_6		
	Source	$P^{des}_{d4,t}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P^{des}_{d5,t}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P^{des}_{d6,t}$ **[kW]**	$p_{d,t}$ **[kW]**
3	m_1	16.43	16.43	m_1	48.80	48.80	m_1	7.13	7.13
4	m_1	20.53	20.53	m_1	61.00	61.00	m_1	8.91	8.91
5	m_1	32.86	32.86	m_1	97.60	97.60	m_1	14.26	14.26
6	m_1	41.07	41.07	m_1	122.00	122.00	m_1	17.82	17.82
7	m_1	28.75	28.75	m_1	85.40	85.40	m_1	12.47	12.47
8	m_1	24.64	24.64	m_1	73.20	73.20	m_1	10.69	10.69

	Demand Areas		
Time (t)	d_7		
	Source	$P^{des}_{d7,t}$ **[kW]**	$p_{d,t}$ **[kW]**
1	m_1, m_2	148.80	148.80
2	m_1, m_2	124.00	124.00
3	m_1	99.200	99.20
4	m_1, m_2	124.00	124.00
5	m_1, m_2, v_1	198.40	198.40
6	m_1, m_2, v_1	248.00	248.00
7	m_1, m_2, v_1	173.60	173.60
8	m_1, m_2	148.80	148.80

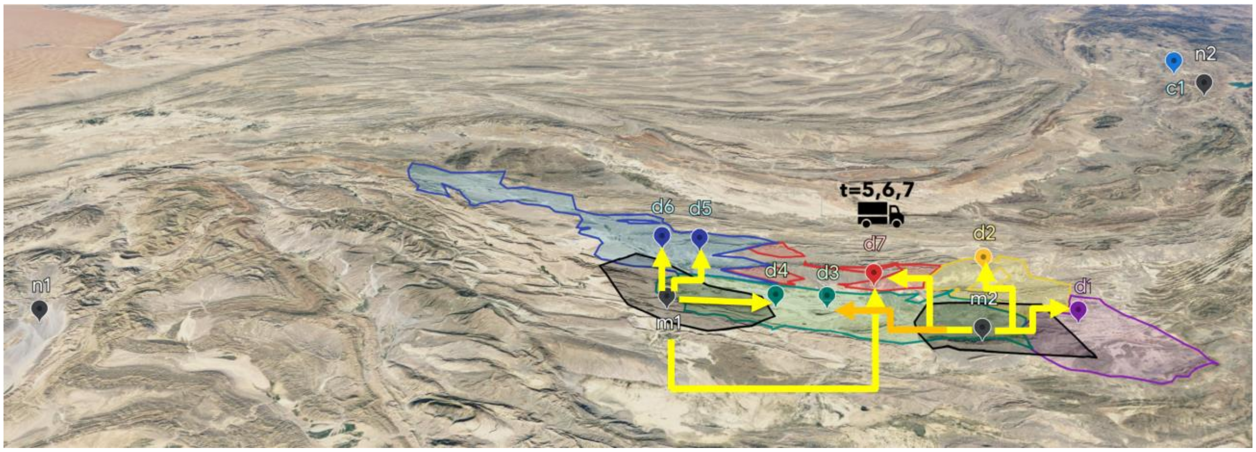

Figure 4.8 Graphical representation of the optimization result for case study 3.

Table 4.17 Charging/discharging levels of MESS.

MESS Operation				
Time (t)	**Discharging**		**Charging**	
	Location	$p_{v1,t}^{Dis}$ **[kW]**	**Location**	$p_{v1,1}^{Ch}$ **[kW]**
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	d_7	63.18	-	-
6	d_7	184.11	-	-
7	d_7	2.69	-	-
8	-	-	-	-

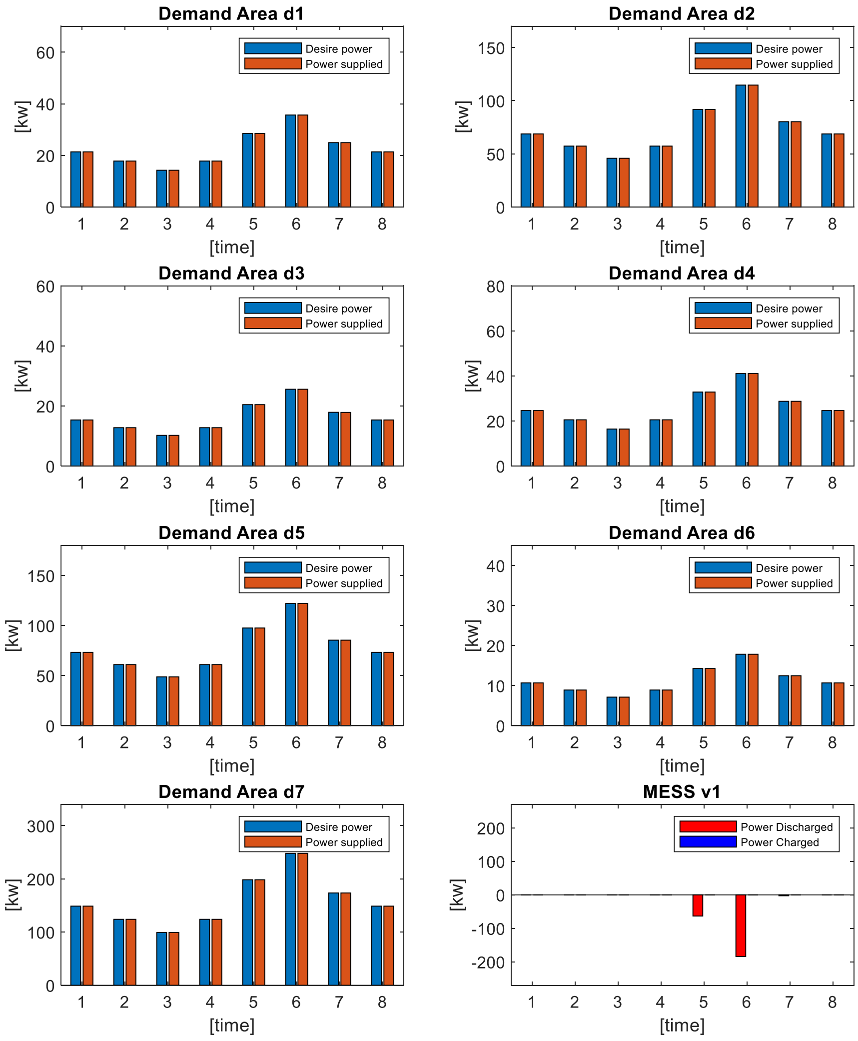

Figure 4.9 Desired and actual demands and MESS charge/discharge levels (bottom right) for case study 3.

4.2.4 Case Study 4: All Electrification Options, with Further Reduction in Microgrid Capacity

Similar to the previous case study, it is assumed that all electrification options are available here; however, the available sizes of the microgrids have been further reduced to 20 kW and 150 kW, respectively. The results of single objective and multi-objective optimization are shown in Table 4.18. Similar to all previous cases, microgrids *m*$_1$ and *m*$_2$ are both chosen for the electrification since they are the closest to the demand areas and offer zero emissions. However, due to their limited capacity, both grid extension and MESS have also been used as electrification options. MESS supplies power to *d*$_2$ to help avoid building an overhead line connecting the grid to that demand area. The remaining capacity of the MESS is used to supply demand *d*$_7$ for one hour. During the remaining hours, that area is supplied by grid extension from node *n*$_1$. The operation modes of MESS are shown in Table 4.21 on page 35. The optimum sizes of microgrids *m*$_1$ and *m*$_2$ are determined as 180.90 kW and 423.90 kW, respectively, as shown in Table 4.19**.** The graphical representation of the optimization results is illustrated in Figure 4.10 on page 35, and the graphs of the desired and supplied powers and the charging/discharging power of MESS are shown in Figure 4.11 on page 36. It can be seen that all demand targets are met.

Table 4.18 Optimum values of single objective and multi objective models.

Objective	**Units**	**Single objective optimum**	**Target**	**Multi-objective optimum**
1	[kW]	0	0.01	0.0216
2	[$/kW]	4,820	4,820	10,426
3	[kg$_{CO2}$/kW]	0	0.01	546.42

Table 4.19 Optimum size of the microgrids.

Microgrids	**Microgrid size required (optimized)** $\boldsymbol{p_m^{Max}}$	**Microgrid size available** $\boldsymbol{P_m^{Max}}$
$\boldsymbol{m_1}$	180.90	200
$\boldsymbol{m_2}$	105.51	150

Table 4.20 The desired demands and the actual demands provided, along with the source of power.

	Demand Areas								
Time (t)	$\boldsymbol{d_1}$			$\boldsymbol{d_2}$			$\boldsymbol{d_3}$		
	Source	$\boldsymbol{P_{d1,t}^{\mathrm{des}}}$ **[kW]**	$\boldsymbol{p_{d1,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d2,t}^{\mathrm{des}}}$ **[kW]**	$\boldsymbol{p_{d2,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d3,t}^{\mathrm{des}}}$ **[kW]**	$\boldsymbol{p_{d3,t}}$ **[kW]**
1	$\boldsymbol{m_2}$	21.39	21.39	$\boldsymbol{m_2}$	68.82	68.82	$\boldsymbol{m_2}$	15.34	15.30
2	$\boldsymbol{m_2}$	17.82	17.82	$\boldsymbol{m_2}$	57.35	57.35	$\boldsymbol{m_2}$	12.78	12.78

Table 4.20 Continued

	Demand Areas								
Time (t)	$\boldsymbol{d_1}$			$\boldsymbol{d_2}$			$\boldsymbol{d_3}$		
	Source	$\boldsymbol{P_{d1,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d1,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d2,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d2,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d3,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d3,t}}$ **[kW]**
3	$\boldsymbol{m_2}$	14.26	14.26	$\boldsymbol{m_2}$	45.88	45.88	$\boldsymbol{m_2}$	10.23	10.23
4	$\boldsymbol{m_2}$	17.82	17.82	$\boldsymbol{m_2}$	57.35	57.35	$\boldsymbol{m_2}$	12.78	12.78
5	$\boldsymbol{m_2}$	28.52	28.52	$\boldsymbol{m_2, v_1}$	91.76	91.760	$\boldsymbol{m_2}$	20.46	20.46
6	$\boldsymbol{m_2}$	35.65	35.65	$\boldsymbol{m_2, v_1}$	114.70	114.70	$\boldsymbol{m_2}$	25.57	25.57
7	$\boldsymbol{m_2}$	24.95	24.95	$\boldsymbol{m_2, v_1}$	80.29	80.29	$\boldsymbol{m_2}$	17.90	17.90
8	$\boldsymbol{m_2}$	21.39	21.39	$\boldsymbol{m_2, v_1}$	68.82	68.82	$\boldsymbol{m_2}$	15.34	15.34

	Demand Areas								
Time (t)	$\boldsymbol{d_4}$			$\boldsymbol{d_5}$			$\boldsymbol{d_6}$		
	Source	$\boldsymbol{P_{d4,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d5,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**	**Source**	$\boldsymbol{P_{d6,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**
1	$\boldsymbol{m_1}$	24.64	24.64	$\boldsymbol{m_1}$	73.20	73.20	$\boldsymbol{m_1}$	10.69	10.69
2	$\boldsymbol{m_1}$	20.53	20.53	$\boldsymbol{m_1}$	61.00	61.00	$\boldsymbol{m_1}$	8.91	8.91
3	$\boldsymbol{m_1}$	16.43	16.43	$\boldsymbol{m_1}$	48.80	48.80	$\boldsymbol{m_1}$	7.13	7.13
4	$\boldsymbol{m_1}$	20.53	20.53	$\boldsymbol{m_1}$	61.00	60.99	$\boldsymbol{m_1}$	8.91	8.91
5	$\boldsymbol{m_1}$	32.86	32.86	$\boldsymbol{m_1}$	97.60	97.60	$\boldsymbol{m_1}$	14.26	14.26
6	$\boldsymbol{m_1}$	41.07	41.07	$\boldsymbol{m_1}$	122.00	122.00	$\boldsymbol{m_1}$	17.82	17.82
7	$\boldsymbol{m_1}$	28.75	28.75	$\boldsymbol{m_1}$	85.40	85.40	$\boldsymbol{m_1}$	12.47	12.47
8	$\boldsymbol{m_1}$	24.64	24.64	$\boldsymbol{m_1}$	73.20	73.20	$\boldsymbol{m_1}$	10.69	10.69

	Demand Areas		
Time (t)	$\boldsymbol{d_7}$		
	Source	$\boldsymbol{P_{d7,t}^{\text{des}}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**
1	$\boldsymbol{n_1}$	148.80	148.80
2	$\boldsymbol{n_1}$	124.00	124.00
3	$\boldsymbol{n_1, v_1}$	99.20	99.20
4	$\boldsymbol{n_1}$	124.00	124.00
5	$\boldsymbol{n_1}$	198.40	198.40
6	$\boldsymbol{n_1}$	248.00	248.00

Table 4.20 Continued

7	$\boldsymbol{n_1}$	173.60	173.60
8	$\boldsymbol{n_1}$	148.80	148.80

Table 4.21 Charging/discharging levels of MESS

Time (t)	**Discharging**		**Charging**	
	Location	$\boldsymbol{p_{v1,t}^{Dis}}$ **[kW]**	**Location**	$\boldsymbol{p_{v1,1}^{Ch}}$ **[kW]**
1	**-**	**-**	**-**	**-**
2	**-**	**-**	**-**	**-**
3	$\boldsymbol{d_7}$	99.20	**-**	**-**
4	**-**	**-**	**-**	**-**
5	$\boldsymbol{d_2}$	35.22	**-**	**-**
6	$\boldsymbol{d_2}$	70.41	**-**	**-**
7	$\boldsymbol{d_2}$	17.63	**-**	**-**
8	$\boldsymbol{d_2}$	27.52	**-**	**-**

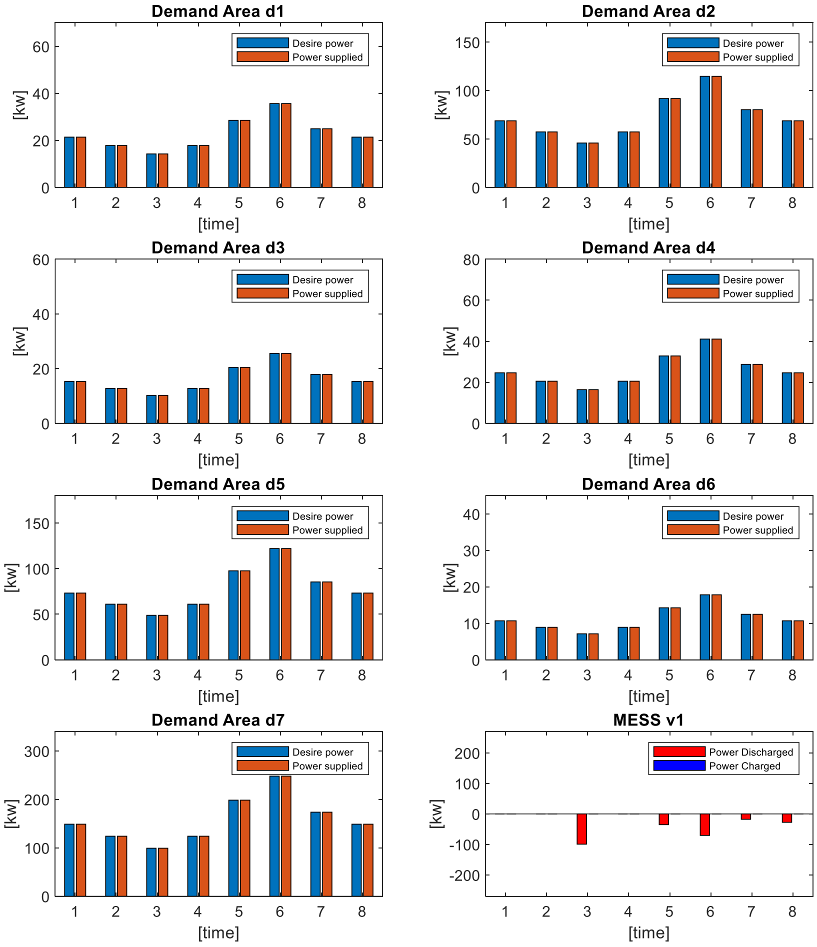

Figure 4.10 Desired and actual demands and MESS charge/discharge level (bottom right) for case study 4.

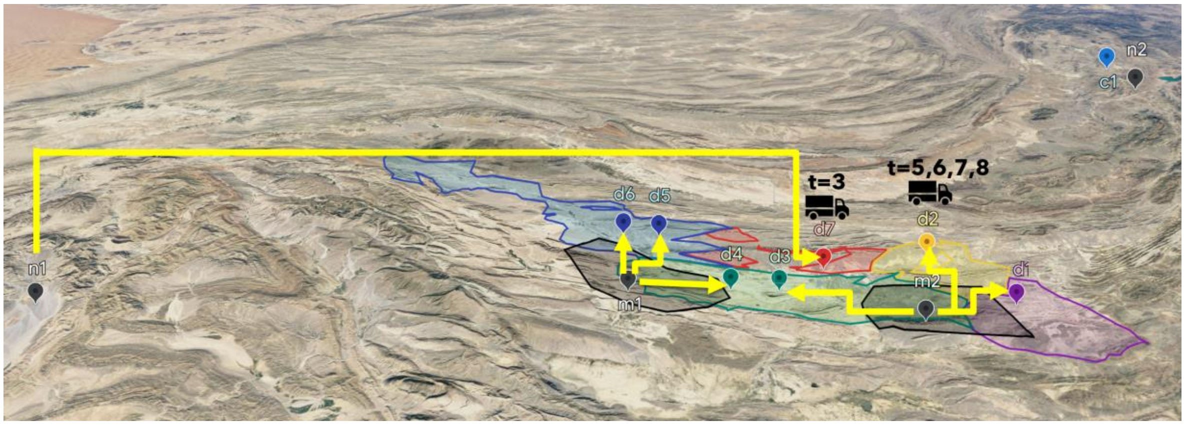

Figure 4.11 Graphical representation of the optimization result for case study 4.

4.2.5 Case Study 5: All Electrification Options, Insufficient Overall Capacity

The objective behind this case study is to assess the impact of insufficient generation capacity on supply demands. The available sizes of the microgrids m_1 and m_2 are considered to be 100 kW and 150 kW, respectively. The power capacity of the overhead line from the grid to the demand areas has been considered to be as low as 10kW. This extreme value is chosen for demonstration purposes and can for instance be attributed to situations where excessive voltage drops across a weak system do not allow transferring higher amounts of active power. Single objective and multi-objective optimization are shown in Table 4.22. It can be seen that all multi-objective functions are deteriorated compared to their single objective counterparts. All three electrification options have been chosen by the model. Microgrids m_1 and m_2 are both chosen for electrification based on the distance from the demand areas. Their optimum sizes are determined as 180.90 kW and 423.90 kW, respectively, shown in Table 4.23 on page 37**.** MESS supplies power to d_7 for 3 hours, which helps avoid the installation of an overhead line from the grid node to that demand area. The operation modes of MESS are shown in Table 4.25 on page 38. Demand areas 3, 4, 5, and 6 are supplied through grid extension via node n_1. The graphical representation of the optimization results is illustrated in Figure 4.12 on page 41, and the graphs of the desired and supplied powers and the charging/discharging power of MESS are shown in Figure. 4.13 on page 38, and 39 respectively. It can be seen that not all demand targets are met, but the model ensures that the more vulnerable loads are prioritized. Demand areas 3 and 4 constitute the lowest vulnerability loads and hence a lower priority.

Table 4.22 Optimum values of single objective and multi objective models.

Objective	**Units**	**Single objective optimum**	**Target**	**Multi-objective optimum**
1	[kW]	63.02	63.02	334.60
2	[$/kW]	4,820	4,820	25,594
3	[$\mathrm{kg_{CO2}}$/kW]	0	0.01	211.46

Table 4.23 Optimum size of the microgrids.

Microgrids	**Microgrid size required (optimized)** p_m^{Max}	**Microgrid size available** P_m^{Max}
m_1	100	100
m_2	149.38	150

Table 4.24 The desired demands and the actual demands provided, along with the source of power.

	Demand Areas								
Time (t)	d_1			d_2			d_3		
	Source	$P_{d1,t}^{des}$ **[kW]**	$p_{d1,t}$ **[kW]**	**Source**	$P_{d2,t}^{des}$ **[kW]**	$p_{d2,t}$ **[kW]**	**Source**	$P_{d3,t}^{des}$ **[kW]**	$p_{d3,t}$ **[kW]**
1	m_2	21.39	21.39	m_2	68.82	68.82	n_1	15.34	10.00
2	m_2	17.82	17.82	m_2	57.35	57.35	n_1	12.78	10.00
3	m_2	14.26	14.26	m_2	45.88	45.88	n_1	10.23	10.00
4	m_2	17.82	17.82	m_2	57.35	57.35	n_1	12.78	10.00
5	m_2	28.52	28.52	m_2	91.76	80.43	n_1	20.46	10.00
6	m_2	35.65	35.65	m_2	114.70	113.73	n_1	25.57	10.00
7	m_2	24.95	24.9500	m_2	80.29	80.2900	n_1	17.90	10.00
8	m_2	21.39	21.390	m_2	68.82	68.82	n_1	15.34	10.00

	Demand Areas								
Time (t)	d_4			d_5			d_6		
	Source	$P_{d4,t}^{des}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P_{d5,t}^{des}$ **[kW]**	$p_{d,t}$ **[kW]**	**Source**	$P_{d6,t}^{des}$ **[kW]**	$p_{d,t}$ **[kW]**
1	n_1	24.64	10.0	m_1, n_1	73.20	19.67	m_1, n_1	10.69	10.69
2	n_1	20.53	10.0	m_1, n_1	61.00	60.20	m_1, n_1	8.91	8.91
3	n_1	16.43	10.0	m_1, n_1	48.80	48.80	m_1, n_1	7.13	7.13
4	n_1	20.53	10.0	m_1, n_1	61.00	60.20	m_1, n_1	8.91	8.91
5	n_1	32.86	10.0	m_1, n_1	97.60	10.00	m_1, n_1	14.26	14.26
6	n_1	41.07	10.0	m_1, n_1	122.00	10.00	m_1, n_1	17.82	17.82
7	n_1	28.75	10.0	m_1, n_1	85.40	10.00	m_1, n_1	12.47	12.47
8	n_1	24.64	10.0	m_1, n_1	73.20	19.67	m_1, n_1	10.69	10.69

	Demand Areas		
Time (t)	d_7		
	Source	$P_{d7,t}^{des}$ **[kW]**	$p_{d,t}$ **[kW]**
1	m_1, m_2	148.80	148.80
2	m_1, m_2	124.00	124.00
3	m_1, m_2	99.200	99.20
4	m_1, m_2	124.00	124.00

Table 4.24 Continued

	Demand Areas		
Time (t)	$\boldsymbol{d_7}$		
	Source	$\boldsymbol{P^{\mathrm{des}}_{d7,t}}$ **[kW]**	$\boldsymbol{p_{d,t}}$ **[kW]**
5	$\boldsymbol{m_1, m_2, v_1}$	198.40	198.40
6	$\boldsymbol{m_1, m_2, v_1}$	248.00	248.00
7	$\boldsymbol{m_1, m_2, v_1}$	173.60	173.60
8	$\boldsymbol{m_1, m_2}$	148.80	148.80

Table 4.25 Charging/discharging levels of MESS.

Time (t)	**Discharging**		**Charging**	
	Location	$\boldsymbol{p^{Dis}_{v1,t}}$ **[kW]**	**Location**	$\boldsymbol{p^{Ch}_{v1,1}}$ **[kW]**
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	$\boldsymbol{d_7}$	62.23	-	-
6	$\boldsymbol{d_7}$	155.82	-	-
7	$\boldsymbol{d_7}$	31.94	-	-
8	-	-	-	-

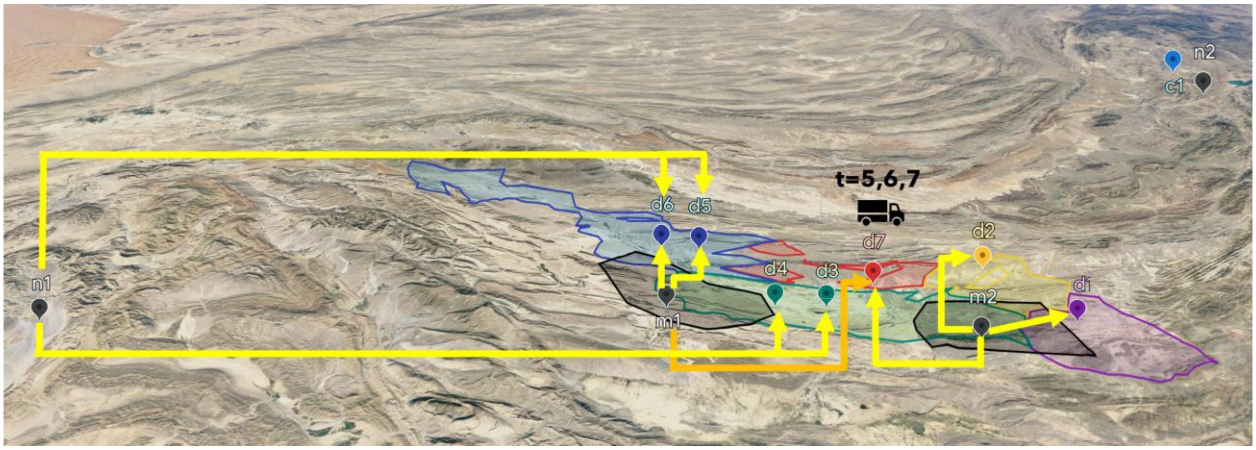

Figure 4.12 Graphical representation of the optimization result for case study 5.

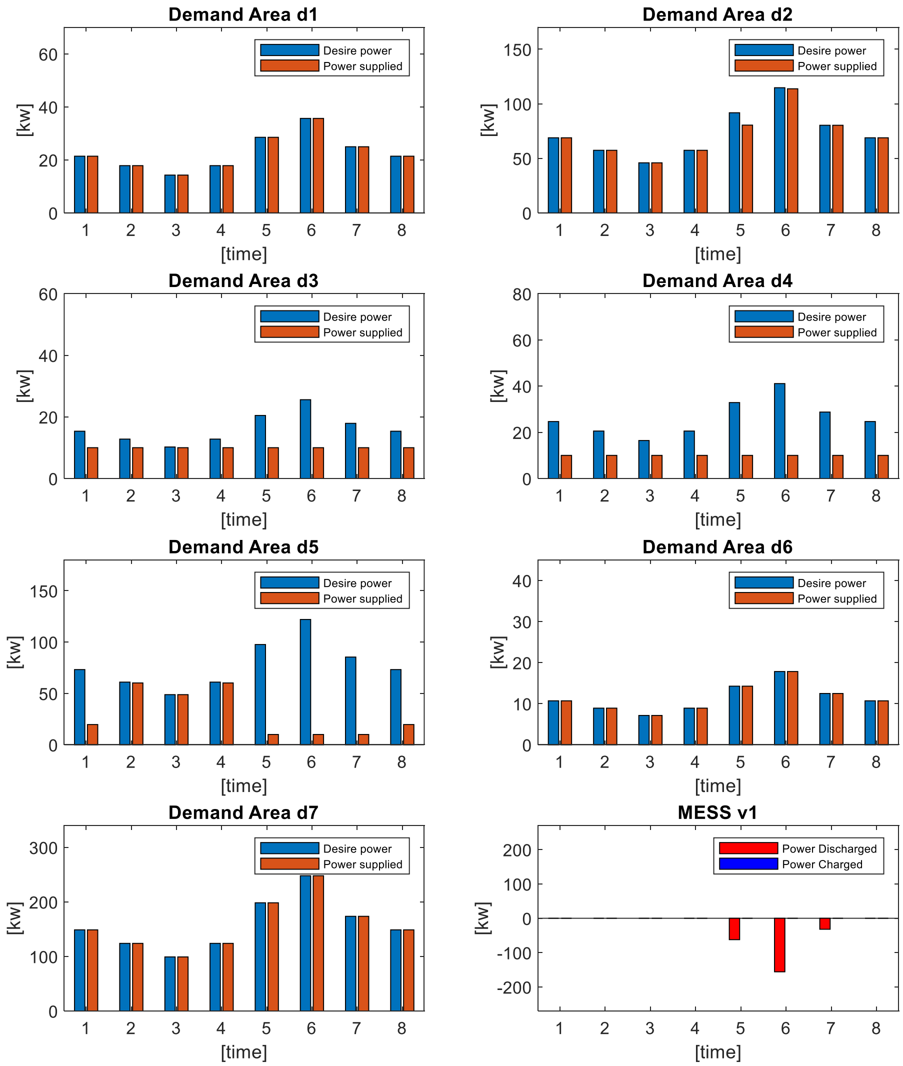

Figure 4.13 Desired and actual demands and MESS charge/discharge level (bottom right) for case study 5.

4.3 Summary of Findings

The results indicate that microgrids are the most viable option for remote electrification. The closer these resources are located to the demand areas, the more attractive they are. If the generation capacity from microgrids is insufficient, for instance due to limited energy resources or cost constraints, grid extension and MESS would become viable options. However, the former is an expensive option and highly dependent on the distances between the load areas and the main grid, which are often large. MESS can provide a solution in between. The overall costs are lower compared to grid extension. However, potentially long distances between load areas and charging stations can limit the effectiveness of this option.

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 Conclusion

Rural electrification is firmly coupled with energy, justice and equity. Technical and cost constraints may pose limitations on who can gain access to electricity and through what means. The sustainable development goals set by the UN bring universal access to affordable and reliable energy into the forefront of power grid capacity expansion projects.

In this thesis a multi-objective mathematical optimization model has been proposed for electrification of rural regions in order to ensure that reliability, sustainability, and cost effectiveness are all considered. Given that there are three possible solutions to electrify rural areas, i.e., gid extension, deployment of off grid systems, and dispatching mobile energy storage systems (MESS), the core aim of the model is to find the optimum number and locations of nodes (substations) for grid extension, optimum number, sizes, and locations of off grid systems, and optimum number and charging locations for MESS such that highest possible number of communities are energized in an equitable, cost-effective, reliable, and sustainable manner. The three objectives that need to be minimized are demand not served (weighted based on social vulnerabilities), the cost of system deployment and operation, and carbon emissions. Operational constraints related to demand, grid extension, microgrids, and MESS have also been incorporated. The proposed model is a novel approach that for the first time includes the three electrification options and evaluates them within a multi-objective framework.

Recognition of justice has been considered in this model as one of the objectives, i.e., demand not served (weighted based on social vulnerabilities). Vulnerability factors have been considered based on the percentage of people of age 60 or above. Demand areas which have a high percentage are considered as having high vulnerability factors. In this way, the more vulnerable the area is, the more priority is given to that area in terms of electricity supply.

For proof-of-concept purposes and to validate the performance of the model, a case study has been conducted based on union councils (demand areas) in Loralai/Bori Tehsil, in Balochistan, Pakistan. However, the proposed formulation is general and can be readily applied to any other geographical region. Different case studies have been performed to assess the impacts of variations in generation resources or other constraints on the outcome of the model. The results of this study indicate that, for this particular region and other regions of similar nature, priority should be given to microgrids regardless of their generation capacity. Microgrids are cost effective solutions and if designed based on wind, hydro, or solar generation, offer sustainable solutions to the electrification problem. Other options may be considered if the available generation capacity from microgrids is not sufficient to supply the demand. MESS units can be used as a second option in conjunction with microgrids, for instance, when the generation capacity of the microgrid is limited during the course of the day. Grid extension should be considered as the last resort in most severe cases. This is because existing power systems are generally far from remote rural regions and the cost of extending an overhead line to the remote area may be prohibitive. However, when other options are not available or sufficient, e.g., when natural resources for setting up microgrids are not available or when long distances between charging stations and demand areas make MESS units impractical, extension of the main grid can be considered as a viable option.

The model is generic and not specific to the above stated case study only. However, there might be situations in which all three electrification options are not viable at the same time. For example, the availability of roads is necessary for the operation of MESS. Similarly, there might be situations in which grid extension is not a viable option because of very large distances. Or off grid systems may not be feasible because of lack of potential for wind or solar in the close proximity of the demand areas.

5.2 Future Work

The main area for improvement is the integration of uncertainties into the problem formulation. These could be due to uncertainties in demand, solar energy, and wind energy.

Some secondary areas for improvement of the current study are as follows:

- The proposed model does not have an objective function related to the fuel cost of the MESS units. This can in particular become important in situations where MESS needs to travel long distances.
- MESS travel times between nodes are considered here to be integer values. This assumption is not necessarily true. Hence, the model can be improved by considering more granular travel routes and travel times.
- When it comes to microgrids, the locations and sizes (power generation capacity) are the only variables of optimization in this model. In a more realistic approach, one can also consider the types of energy resources in the microgrid as a variable.

Lastly, distributional and procedural justice are not included in the model. An objective function related to distribution justice may be considered in the model to ensure that the installation of energy resources does not lead to disproportionate distribution of negative effects, for instance, some visual or noise consequences of wind turbines. Procedural justice can be ensured by involving the local residents and considering their opinions in decision making process before finalizing any plan.

REFERENCES

[1] V. Kumar, “Political Map of Pakistan, Pakistan Provinces Map, Pakistan Political Map,” *MapsofWorld.com*, Nov. 29, 2021. https://www.mapsofworld.com/pakistan/pakistan-political-map.html (accessed Mar. 13, 2023).

[2] M. S. Malkani, M. Alyani, M. Khosa, F. Buzdar, and M. A. Zahid, “Coal Resources of Pakistan: new coalfields,” vol. V, pp. 7–22, Nov. 2016.

[3] N. Anwar, W. Mahar, and J. Khan, Renewable energy technologies in Balochistan: Practice, prospects and challenges. 2018.

[4] “Energy Sector – Board of Investment & Trade.” https://bboit.gob.pk/energy-sector/ (accessed Mar. 09, 2023).

[5] “Global Solar Atlas.” https://globalsolaratlas.info/map?m=site&c=27.190474,64.659156,8&s=28,66 (accessed Mar. 09, 2023).

[6] “Global Wind Atlas.” https://globalwindatlas.info (accessed Mar. 09, 2023).

[7] “Balochistan-Loralai -.” https://pakistanalmanac.com/balochistan-loralai/ (accessed Mar. 09, 2023).

[8] A. Rehman, S. Shah, S. Ali Raza Shah, S. Badshah, and M. Khattak, *Prospects of rural electrification of Balochistan province with renewable energy sources*. 2017, p. 100. doi: 10.1109/PGSRET.2017.8251808.

[9] S. A. A. Shah, G. D. Valasai, A. A. Memon, A. N. Laghari, N. B. Jalbani, and J. L. Strait, “Techno-Economic Analysis of Solar PV Electricity Supply to Rural Areas of Balochistan, Pakistan,” *Energies*, vol. 11, no. 7, Art. no. 7, Jul. 2018, doi: 10.3390/en11071777.

[10] M. Imran, O. Özçatalbaş, and K. Bakhsh, “Rural household preferences for cleaner energy sources in Pakistan,” *Environ. Sci. Pollut. Res.*, vol. 26, no. 22, pp. 22783–22793, Aug. 2019, doi: 10.1007/s11356-019-05588-y.

[11] A. Iqbal and M. T. Iqbal, “Design and Analysis of a Stand-Alone PV System for a Rural House in Pakistan,” *Int. J. Photoenergy*, vol. 2019, p. e4967148, Apr. 2019, doi: 10.1155/2019/4967148.

[12] “Electrification Challenge in Rural Areas - energypedia.” https://energypedia.info/wiki/Electrification_Challenge_in_Rural_Areas (accessed Jul. 10, 2022).

[13] F. the Newspaper, “Rural electrification and poverty decline,” *DAWN.COM*, 07:53:57+05:00. https://www.dawn.com/news/1660159 (accessed Mar. 09, 2023).

[14] Admin, “How can rural Pakistani communities’ electricity needs be met?,” *LIDC*, Dec. 03, 2019. https://lidc.ac.uk/how-can-rural-pakistani-communites-electricity-needs-be-met/ (accessed Mar. 09, 2023).

[15] A. McHarg, “Energy Justice: Understanding the ‘Ethical Turn’ in Energy Law and Policy,” in *Energy Justice and Energy Law*, Oxford: Oxford University Press, 2020. doi: 10.1093/oso/9780198860754.003.0002.

[16] “WEO-2017 Special Report: Energy Access Outlook – Analysis,” *IEA*. https://www.iea.org/reports/energy-access-outlook-2017 (accessed Jul. 16, 2022).

[17] C.-W. Shyu, “A framework for ‘right to energy’ to meet UN SDG7: Policy implications to meet basic human energy needs, eradicate energy poverty, enhance energy justice, and uphold energy democracy,” *Energy Res. Soc. Sci.*, vol. 79, p. 102199, Sep. 2021, doi: 10.1016/j.erss.2021.102199.

[18] M. Kanagawa and T. Nakata, “Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries,” *Energy Policy*, vol. 36, no. 6, pp. 2016–2029, Jun. 2008, doi: 10.1016/j.enpol.2008.01.041.

[19] C. Haanyika, “Rural electrification in Zambia: A policy and institutional analysis,” *Energy Policy*, vol. 36, pp. 1044–1058, Mar. 2008, doi: 10.1016/j.enpol.2007.10.031.

[20] D. Palit and K. R. Bandyopadhyay, “Rural electricity access in South Asia: Is grid extension the remedy? A critical review,” *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1505–1515, Jul. 2016, doi: 10.1016/j.rser.2016.03.034.

[21] A. Chaurey, M. Ranganathan, and P. Mohanty, “Electricity access for geographically disadvantaged rural communities—technology and policy insights,” *Energy Policy*, vol. 32, no. 15, pp. 1693–1705, Oct. 2004, doi: 10.1016/S0301-4215(03)00160-5.

[22] T. Dinkelman, “The Effects of Rural Electrification on Employment: New Evidence from South Africa,” *Am. Econ. Rev.*, vol. 101, no. 7, pp. 3078–3108, Dec. 2011, doi: 10.1257/aer.101.7.3078.

[23] “Household air pollution and health.” https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health (accessed Aug. 01, 2022).

[24] G. T. Tucho, “The Impacts of Policy on Energy Justice in Developing Countries,” in *Energy Justice Across Borders*, G. Bombaerts, K. Jenkins, Y. A. Sanusi, and W. Guoyu, Eds. Cham: Springer International Publishing, 2020, pp. 137–154. doi: 10.1007/978-3-030-24021-9_7.

[25] A. Omarova, K. Tussupova, P. Hjorth, M. Kalishev, and R. Dosmagambetova, “Water Supply Challenges in Rural Areas: A Case Study from Central Kazakhstan,” *Int. J. Environ. Res. Public. Health*, vol. 16, no. 5, p. 688, Mar. 2019, doi: 10.3390/ijerph16050688.

[26] I. Mako, K. Kalcngo, G. Mmoke, G. Binini, and O. Ponoola, “Remote Rural Area Water Scarcity Solution: An Innovative Green Energy Mobile DC Water Pump System,” in *2018 IEEE PES/IAS PowerAfrica*, Jun. 2018, pp. 474–479. doi: 10.1109/PowerAfrica.2018.8520969.

[27] P. Arvate, F. Falsete, F. Garcia Ribeiro, and A. Souza, Lighting and violent crimes: evaluating the effect of an electrification policy in rural Brazil on violent crime reduction. 2015. doi: 10.13140/RG.2.1.1921.1607.

[28] W. M. Amutha and V. Rajini, “Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER,” *Renew. Sustain. Energy Rev.*, vol. 62, pp. 236–246, Sep. 2016, doi: 10.1016/j.rser.2016.04.042.

[29] S. C. Bhattacharyya, D. Palit, and V. V. N. Kishore, “Suite of Off-Grid Options in South Asia,” in *Mini-Grids for Rural Electrification of Developing Countries: Analysis and Case Studies from South Asia*, S. C. Bhattacharyya and D. Palit, Eds. Cham: Springer International Publishing, 2014, pp. 11–36. doi: 10.1007/978-3-319-04816-1_2.

[30] “Mini-Grids Support Toolkit | Mini-Grids Support Toolkit | Energy | U.S. Agency for International Development,” Feb. 12, 2018. https://www.usaid.gov/energy/mini-grids (accessed Jul. 14, 2022).

[31] A. Chauhan and R. P. Saini, “A review on Integrated Renewable Energy System based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control,” *Renew. Sustain. Energy Rev.*, vol. 38, pp. 99–120, Oct. 2014, doi: 10.1016/j.rser.2014.05.079.

[32] L. Del-Río-Carazo, E. Acquila-Natale, S. Iglesias-Pradas, and Á. Hernández-García, “Sustainable Rural Electrification Project Management: An Analysis of Three Case Studies,” *Energies*, vol. 15, no. 3, Art. no. 3, Jan. 2022, doi: 10.3390/en15031203.

[33] A. López-González, B. Domenech, and L. Ferrer-Martí, “Sustainability Evaluation of Rural Electrification in Cuba: From Fossil Fuels to Modular Photovoltaic Systems: Case Studies from Sancti Spiritus Province,” *Energies*, vol. 14, no. 9, Art. no. 9, Jan. 2021, doi: 10.3390/en14092480.

[34] “America’s Energy Transition Must Include Tribal Lands.” https://www.scalemicrogridsolutions.com/blog/americas-energy-transition-must-include-tribal-lands (accessed Oct. 20, 2022).

[35] “FHWA - Center for Innovative Finance Support - Project Profiles.” https://www.fhwa.dot.gov/ipd/project_profiles/az_navajo_nation_kayenta_solar_program.aspx (accessed Oct. 22, 2022).

[36] D. Slanger, “Native Energy: Rural Electrification on Tribal Lands,” *RMI*, Jun. 24, 2014. https://rmi.org/blog_2014_06_24_native_energy_rural_electrification_on_tribal_lands/ (accessed Oct. 20, 2022).

[37] L. Mughal and S. Mohagheghi, “Electrification of Rural Areas: Energy Justice, Challenges, And Possible Solutions” in Proc. IEEE Green Technologies Conference, Denver, CO, April 2023, To Appear.

APPENDIX A PERMISSIONS

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