© *The Pakistan Development Review*
61:3 (2022) pp. 463–490
DOI: 10.30541/v61i3pp.463-490

A Techno-Economic Analysis of Widespread Microgrid/Minigrid Deployment in Pakistan's Electrical Power Sector

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In the recent past, the Government of Pakistan has undertaken certain appreciable initiatives in the electrical power sector, which is undergoing an extensive reform and restructuring process, particularly in the areas of decarbonisation and deregulation. Although Pakistan is blessed with abundant natural energy resources, a significant percentage of the population remains without electricity access since the expansion of the centralised grid is uneconomical due to certain reasons, including but not limited to limited financial resources and a scattered population. In this regard, micro/mini-grid (MG) deployment offers an excellent opportunity to address this problem, improve the life quality of the people of Pakistan, and help improve the economy. The study is predominately based on simulation and analysis-based research methods wherein the techno-economic analysis is performed keeping in view the technical and commercial aspects and also MG impacts on Pakistan's power grid and prospective customers of MGs.

According to this study's findings, in comparison to fossil fuel-based MGs, renewable energy-dominated MGs offer a lucrative investment opportunity/financial viability and also contribute to reducing adverse effects on the environment. Even though MGs present a cost-effective solution for the remote unelectrified areas of Pakistan, they may suffer from technical issues if not properly designed. Direct current MGs and the application of MGs for irrigation purposes present interesting cases with respect to reducing the overall cost of energy. Some of the important factors to be considered to evaluate the feasibility of MGs are the electricity demand pattern, supply reliability requirement, discount rate, and project lifetime, among other things.

There is an urgent need for a comprehensive policy and regulatory framework since the existing one is insufficient to effectively upscale MGs deployment in Pakistan. While assessing electricity provision options for remote unelectrified areas of Pakistan, the electricity planners must consider and evaluate MGs before proposing huge investments in transmission and distribution infrastructure. One of the important considerations is to align the design of MGs with the affordability for the customers in each specific geographical area, to create a win-win situation for all the stakeholders.

1. INTRODUCTION

In pursuit of energy access and low-cost sustainable energy, there is a need to move away from the integrated grid due to its inefficient and unsustainable nature, which results in a high cost of electricity to the consumers. In this regard, the CTBCM is the beginning of the decentralisation of the power sector in Pakistan. However,

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microgrids/mini-grids (MGs) fit into the jigsaw of the decentralised power sector as they can provide sustainable and low-cost energy to the consumers of electricity promising more value for money. MGs are gradually taking the center stage in the future outlook of the power sector both in Pakistan and globally.

1.1. Rationale for Mg Development

MG is a small network of electricity generators and storage that use local energy resources (mostly renewables or hybrid) to generate electricity that can function independently as well as in connection with the grid. Globally, the size of MGs ranges from 1 kW to 10 MW.

A significant area of Pakistan is yet to be electrified even though the country is bestowed with huge natural energy resources geographically spread throughout the land. Due to various reasons, such as limited financial resources and scattered population/electricity demand (particularly in Balochistan), the expansion of the national/DISCO grid to most of the unelectrified locations is not economically viable. Therefore, MGs have a huge potential to improve the quality of life quality of the people of Pakistan and complement the economy. Fortunately, unstructured efforts have already started in the country. Globally, MGs have become a mainstream solution for providing energy access to everyone. It is, therefore, inevitable to upscale the setting up of MGs wherever required and, of course, potentially possible. Following are some of the important factors that necessitate the upscaling of MGs for providing energy access at a low cost to the people of Pakistan:

(1) Sharp and sustained increasing trend of end-consumer tariff.
(2) A large number of unelectrified areas in Pakistan are not expected to be electrified soon.
(3) Decreasing cost trend of MGs deployment due to significant reduction in the individual component costs of MGs, such as converters, solar PV panels, wind turbines, etc.
(4) The availability of huge potential for renewable energy resources, such as solar, wind, hydro, etc.
(5) A substantial number of areas in Pakistan have difficult terrain making grid access difficult.
(6) Detrimental environmental impacts being faced by Pakistan in recent years due to a significant share of conventional fuels in electricity generation and the usage of other inefficient fuels due to a lack of generation adequacy.
(7) Hampering economic development due to lack of electricity access in remote areas.
(8) Prevailing supply unreliability to remote areas.

The Government of Pakistan (GOP) promulgated the National Electricity Policy in 2021 which stresses the sustainability of the electrical power sector in Pakistan. It means that the GOP has decided to pass electricity prices in full to end-consumers by withdrawing subsidies, contrary to other developing nations of the world. The policy direction for sustainability in Pakistan’s electricity sector will have considerable implications for the people of Pakistan who are already paying a very high per unit tariff for electricity.

Considering the internal report of one of the credible institutions of Pakistan's power sector (it is an internal working report and is expected to be publicised soon), the existing average tariff, i.e., Rs 14.85/kWh is forecasted to be Rs 24.28/kWh in the year 2030 excluding taxes. This forecast is based on certain optimistic assumptions of factors listed below. Any variation in these factors may significantly increase the forecasted end-user tariff.

(1) A rising trend of inefficiencies in the integrated electrical grid.
(2) A continuing trend of incurring the sunk cost of committed power projects.
(3) Introduction of the CTBCM and a high probability of an increase in end-user tariff due to market power, inexperience, and increase in stranded costs, etc.
(4) Sharp currency devaluation.
(5) Increase in fuel prices.

Considering the above-mentioned factors and the GOP's target of sustainability in the electricity sector, the people of Pakistan, who can afford the substantial investment, have already started opting for stand-alone roof-top solar PV with and without net-metering provision. A major drawback of stand-alone PV is the unavailability of solar power during the late evening/night time as well as the supply during rain or bad weather. MGs, thus, provide a more complete solution for the issues of higher costs and supply reliability.

Off-grid MG deployment for remote rural areas is a globally accepted solution. The feasibility of MG deployment for various scenarios is analysed in detail in this study. However, it is important to mention here that there are certain challenges in MG design, development, and implementation that need to be addressed for the successful implementation of MG in Pakistan.

After the 18th amendment to the Constitution of Pakistan, the provincial governments can take decisions regarding the generation, transmission, and distribution of electricity in their respective territories. Instead of following a strenuous and long process, which includes project approval at a centralised level and building extensive generation, transmission, and distribution infrastructure, MG deployment is a sustainable solution for the provincial governments in Pakistan.

The far-flung areas of Pakistan are without electricity for approximately 16 hours a day due to multiple reasons, including theft and distribution system unreliability. The reliability of supply through MGs development is another important aspect that is explored in this study.

It is important to mention here that this study does not recommend the deployment of MGs everywhere in Pakistan; rather it highlights certain favourable factors, scenarios, and applications where the MG deployment stands far more promising as compared to other potential options. A few of the possible scenarios are:

(1) Remote rural areas.
(2) Difficult terrain areas where grid access is difficult.
(3) Communities having rich mini/micro hydro potential.
(4) Areas having flexible load demand profiles (or can be easily adjusted).
(5) Hospitals and military installations, which cannot afford unreliable supply.
(6) Housing societies/commercial centres having net metering provision.

(7) Communities/areas where provincial/territorial governments want a viable alternative for the provision of electricity other than the nationally integrated grid.

Since the study has been mandated to analyse unconventional solutions for electricity-related issues in Pakistan, it required simulation-based techno-economic evaluation. Techno-economic evaluation is the key to finding the most feasible solution to electrical energy-related issues. For this purpose, HOMER (Hybrid Optimisation of Multiple Energy Resources) Pro software has been used to present reliable results and findings. The study benchmarked and standardised the analysis procedures to evaluate MG deployment.

One of the key motives to perform this analysis is to present the case for the democratisation of the power sector in Pakistan. Every citizen of Pakistan has the right to receive electrical energy from the seller or opt for electrical energy-related services of his choice, i.e., a utility, service provider, independent MG system, own means, etc. The study explored initiatives to start the journey, as a nation, towards the democratisation of the power sector. It may be highlighted that the recent decision to incentivise ordinary customers by allowing net metering of up to 25 kW without any formal license is an initial step towards the democratisation of the power sector in Pakistan. One of the benefits of providing consumers with a choice for opting for MG solution will be the promotion of competition in the electricity market in Pakistan.

1.2. Research Questions

The following research questions are derived for this study:

(1) Can MG be a possible solution to resolve the issues of unelectrified areas and expensive electricity rates? What are the possible application scenarios for MG development in Pakistan?
(2) How to evaluate the feasibility of MG development in a particular area in Pakistan? What are the general technicalities involved in MG development in Pakistan?
(3) What are the possible advantages/disadvantages of MGs in the context of Pakistan's electrical power sector? How can the policy and regulatory framework be utilised for the successful widespread deployment of MGs in Pakistan?
(4) What are the possible business models, in broader terms, for MGs deployment in Pakistan? What are the recommendations to decision-makers to promote MGs in Pakistan?

1.3. Objectives of the Study

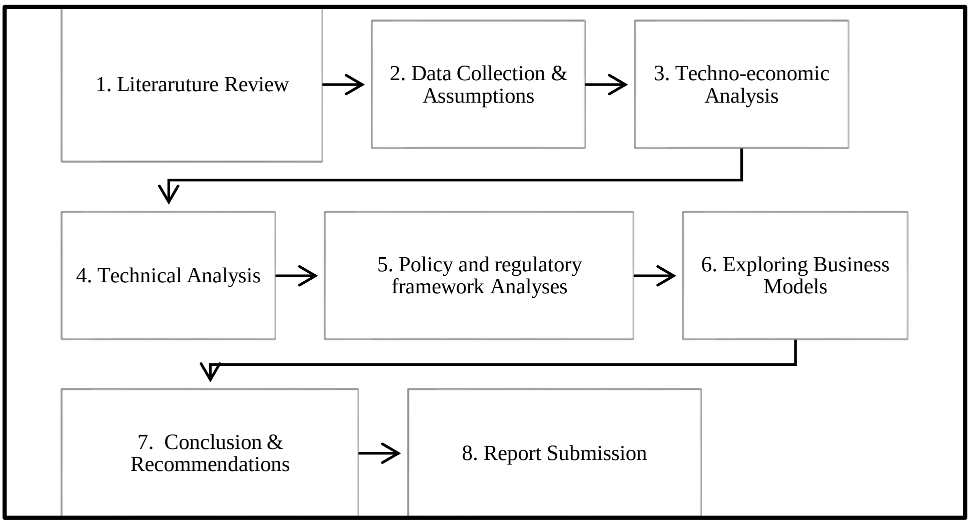
The objective of the study is to present a comprehensive analysis of the widespread deployment of MG systems in Pakistan. The study has been carried out keeping in view the techno-economic and policy perspectives; its results will facilitate the policy makers in taking necessary initiatives for MGs development in Pakistan.

The power sector of Pakistan is already following the path of major restructuring in line with the globally well-established 3D reforms, i.e., decarbonise, decentralise, and democratise. The current reforms related to 'decarbonise' and 'decentralise' include the important steps of the electric vehicle policy, the implementation of the CTBCM, and the Alternative and Renewable Energy (ARE) Policy 2019. This research work will pave the way for the very next step, which is the 'democratisation' of the power sector through the deployment of MGs in the electrical power network of Pakistan.

1.4. Methodology

The flowchart shown in Figure 1 describes in totality the research methodology followed during the study.

Fig. 1. Research Methodology for the Study



2. MODELLING ANALYSIS, SIMULATION, AND RESULTS

2.1. Techno-economic Analysis

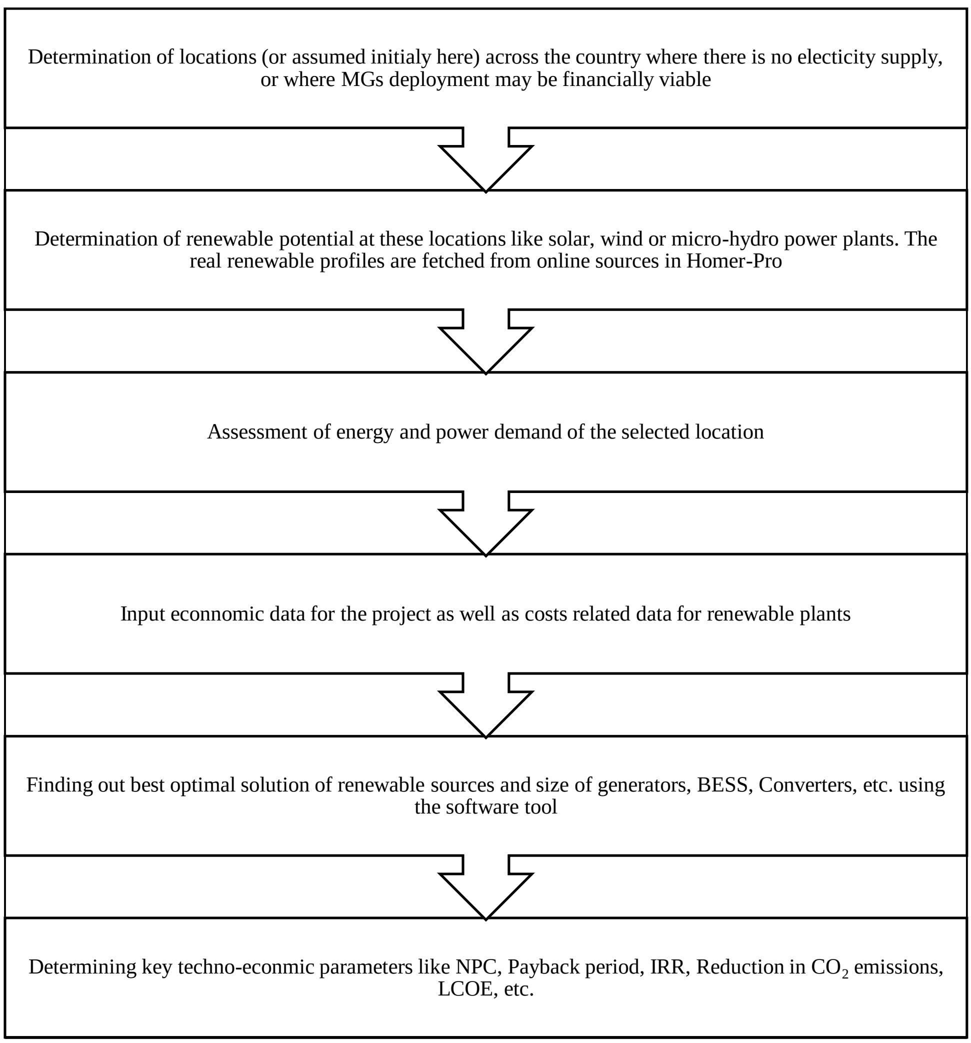
Out of various possible options for widespread MGs deployment in Pakistan, the following three most probable and feasible scenarios have been designed for the pre-feasibility analysis:

(1) Off-grid MGs application for rural villages/areas having solar PV and wind potential.
(2) Off-grid MGs application for rural villages/areas having solar PV and micro-hydro potential.
(3) Grid-connected MGs application for housing societies or commercial centres in urban areas having utility electricity access.

Each scenario is discussed in the following section along with results/findings. Here we are not going into details of mentioning the basic assumptions used for the study. It is important to mention here that considerations like the cost of distribution infrastructure, cost of land, profit margins, etc. have not been considered for this study, which need to be taken care of while evaluating the feasibility of a particular project, as it may vary significantly from one case to another.The following approach has been adopted for the techno-economic analysis:

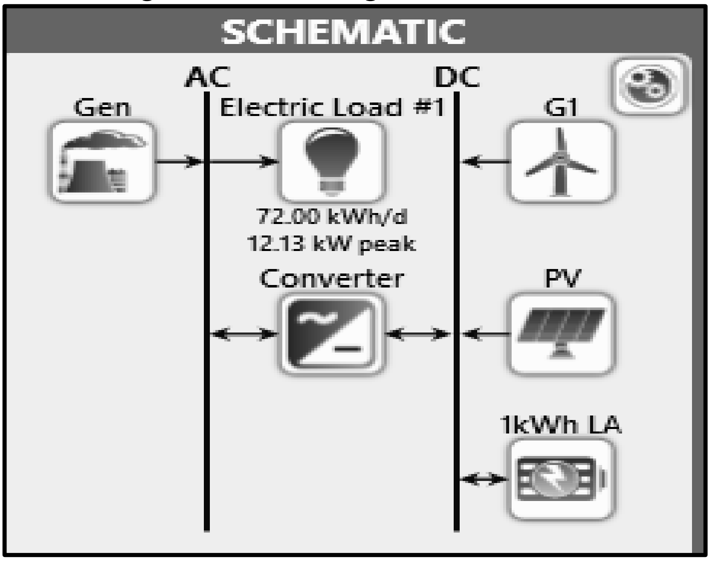
2.1.1. *Scenario 1. Off-Grid MGs Application for Rural Villages/Areas Having Solar PV and Wind Potential*

This scenario is particularly important to analyse the feasibility for remote rural populations having a significant distance from the utility grid connection. This situation is quite relevant in the scenario for Baluchistan, where many areas are still unelectrified and providing grid access to those areas is difficult and does not hold financial viability. A village near Panjgur with geographical coordinates of 26°58.2’N, 64°5.3’E has been considered. A load profile with a peak load of 12.13 kW and annual average energy of 72 kWh/day is considered.



In order to meet this demand profile of electricity, the schematic as shown in Figure 3 has been modelled in the software with the option to optimise the selection and size of the most feasible option considering the real solar and wind profiles from the NASA database.

Fig. 3. Schematic Diagram for Scenario 1



Different technology options (Various Combinations of PV, Wind, Storage and Diesel Generator) have been considered to determine the most feasible one for MG. From twelve different combinations, option with PV + Wind + Storage has been determined to be the most feasible one. It is important to mention here that we are not going into details of mentioning the optimised size/rating for each component along with their Net costs, as well as technical results related to load, storage, and generation from various resources.From the above different combinations, option with PV + Wind + Storage has been determined to be the most feasible one. The optimised size/rating for each component along with their Net costs, as well as technical results related to load, storage, and generation from various resources Comparing the base system (option 1) with the proposed optimised system, the IRR of the proposed system is found to be 79.5 percent, while discounted payback periods and simple payback periods are found to be 1.34 years and 1.32 years, respectively. A brief comparison of the base system and the proposed system is given in Table 1.

Table 1

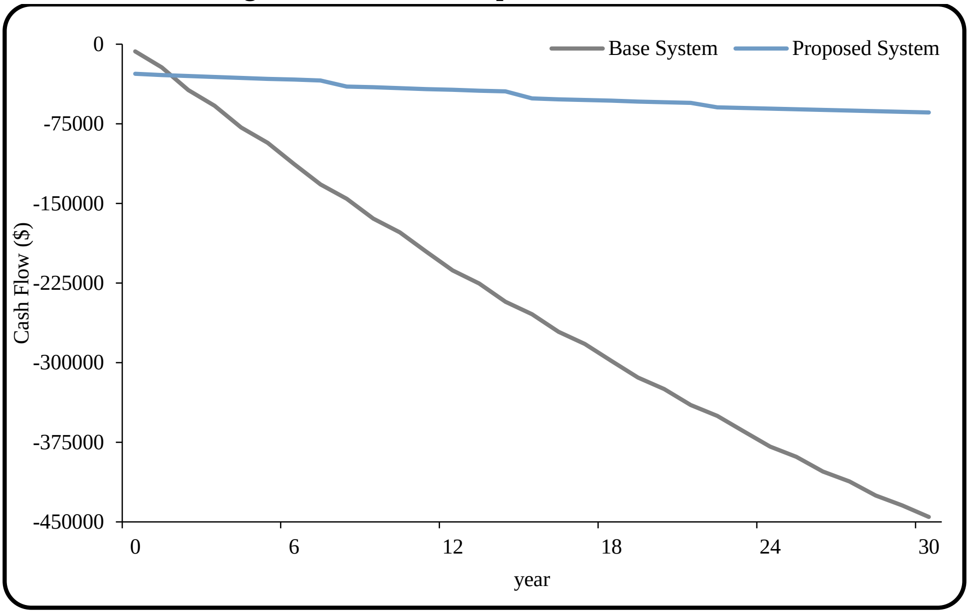
Comparison with Diesel Generator Option for Scenario 1

Parameter	Base System	Proposed System
Net Present Cost	$445,342	$64,120
CAPEX	$6,500	$27,836
OPEX	$19,197	$1,587
LCOE (per kWh)	$0.741	$0.111
CO_2 Emitted (Kg/Year)	39,831	0
Fuel Consumption (Litre/Year)	15,216	0

The Levelised Cost of energy (LCOE) came out to be $0.111/kWh, which is quite reasonable.

A graphical comparison of the base and the proposed system in terms of cash flows for the project lifetime is shown in Figure 4.

Fig. 4. Cash Flows Comparison for Scenario 1



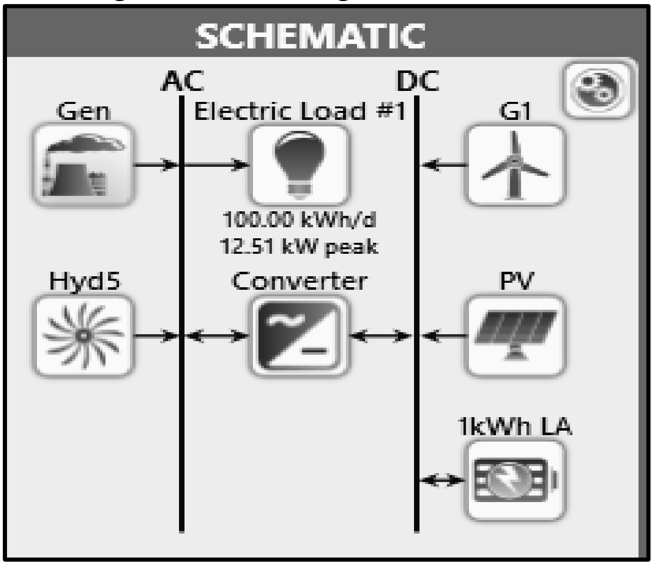
2.1.2. *Scenario 2: Off-Grid MGs Application for Rural Villages/ Areas Having Solar PV and Micro-Hydro Potential*

This scenario is particularly important to analyse the feasibility for remote rural populations having a significant distance from the utility grid connection. This situation is especially relevant for Gilgit Baltistan, AJK, and the northern areas of KPK where a large number of areas are unelectrified and providing grid access to those areas is difficult and is not financially viable. These areas possess large hydropower potential and lack of reliable electricity access especially for clean heating in these areas is a problem. Moreover, burning wood to meet the heating demand in these areas not only affects the environment but also affects the GoP target of promoting tourism in these areas. Hence, off-grid MGs deployment in these areas is a feasible option. The sample feasibility of off-grid MG deployment is discussed in the following section.

A village near Chitral, named Kiyar has been considered with geographical coordinates of 36°5.9'N, 71°51.0'E. A load profile with a peak load of 12.51 kW and annual average energy of 100 kWh/day is considered.

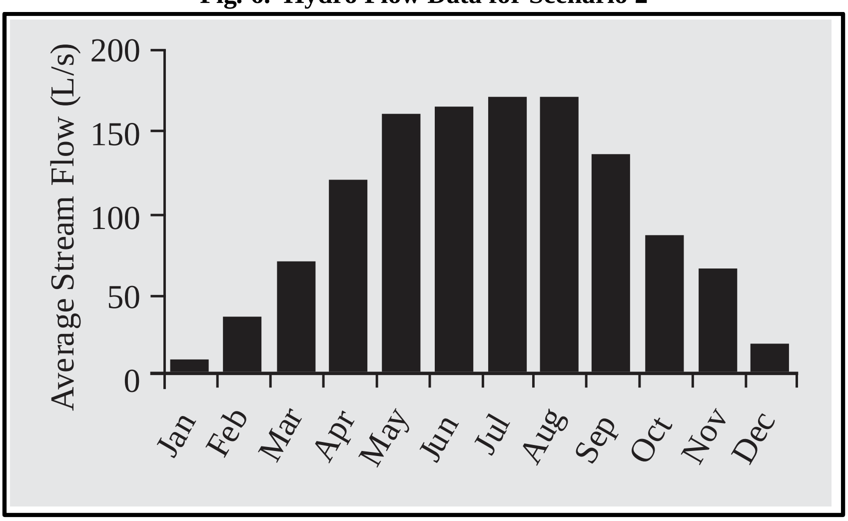
In order to meet this demand profile of electricity, the schematic as shown in Figure 5 has been modelled in the software with the option to optimise the selection and size of the most feasible option considering the real solar and wind profiles from the NASA database.

Fig. 5. Schematic Diagram for Scenario 2



The stream flows assumed for the micro-hydro plant are shown in Figure 6. Available head of 7 m and pipe head loss of 10 percent are also assumed.

Fig. 6. Hydro Flow Data for Scenario 2



Different technology options (Various Combinations of PV, Wind, Storage, Micro-Hydro and Diesel Generator) have been considered to determine the most feasible one for MG. From twenty-six different combinations, option with PV + Storage + Micro-Hydro has been determined to be the most feasible one. It is important to mention here that we are not going into details of mentioning the optimised size/rating for each component along with their Net costs, as well as technical results related to load, storage, and generation from various resources.

It is important to mention here that although per unit cost for micro-hydro is far less than PV and wind sources, the software guided us to choose only 5kW (39 percent) from the hydro source. This is because the hydro flow is almost negligible during winter months, therefore, other sources, such as solar PV, would be needed to meet the load demand ensuring supply reliability to the consumers.

Now, comparing Base System (option 1) with the proposed optimised system, the IRR of the proposed system came out to be 66.1 percent, while discounted payback period and simple payback periods are found to be 1.57 years and 1.53 years, respectively. A brief comparison of the base system and the proposed system is given in Table 2.

Table 2

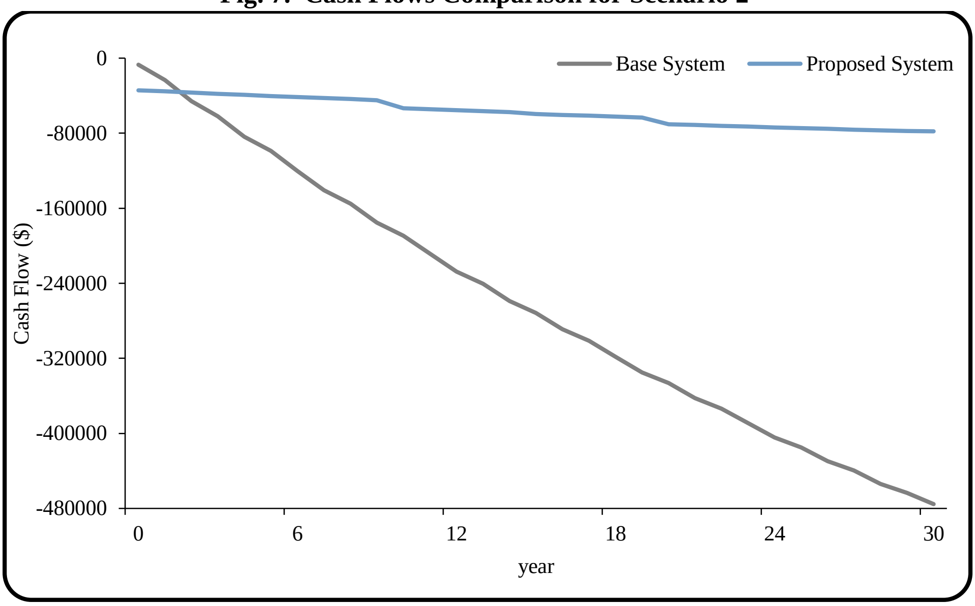
Comparison with Diesel Generator Option for Scenario 2

Component	Base System	Proposed System
Net Present Cost	$475,276	$78,068
CAPEX	$7,000	$34,213
OPEX	$20,485	$1,918
LCOE (per kWh)	$0.570	$0.0981
CO_2 Emitted (Kg/Year)	42,276	0
Fuel Consumption (Liter/Year)	16,151	0

The Levelised Cost of energy (LCOE) turned out to be $0.0981/kWh**,** which is quite reasonable.

A graphical comparison of the Base and the proposed system in terms of cash flows for the project's lifetime is shown in Figure 7.

Fig. 7. Cash Flows Comparison for Scenario 2



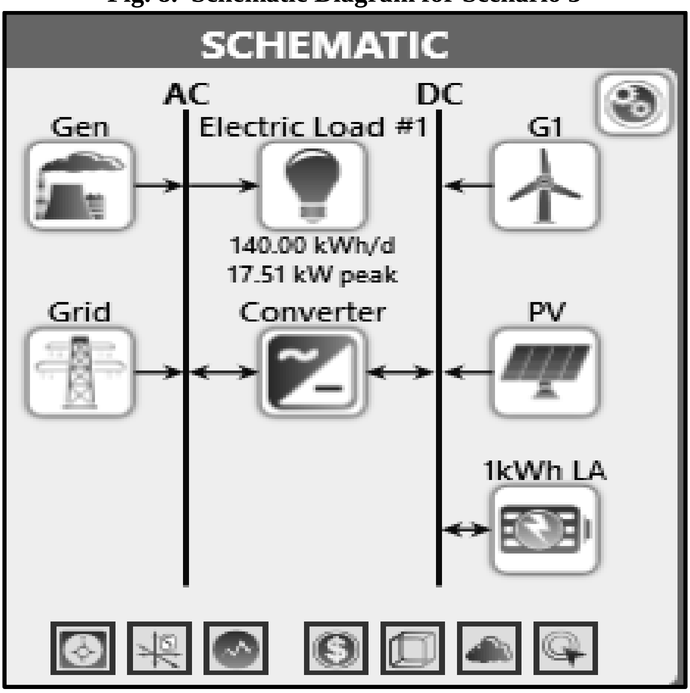
2.1.3. *Scenario 3: Grid-Connected MGs Application for Housing Societies or Commercial Centres in Urban Areas having Utility Electricity Access*

This scenario is particularly important to analyse the feasibility of housing societies or commercial centres situated in urban areas having utility electricity connections. This situation is relevant for large cities in Punjab, KPK, and Sindh, where a lot of private housing societies and large commercial centres already exist or will be developed in the near future. The rationale for considering this MG feasibility here is its ability to create a win-win situation for both the government as well as the private sector.

A small housing society in Lahore near Sunder Raiwind has been considered with geographical coordinates of 31°14.7’N, 74°12.8’E. A load profile with a peak load of 17.51 kW and annual average energy of 140 kWh/day is considered.

In order to meet this demand profile of electricity, the schematic as shown in Figure 8 has been modelled in the software with the option to optimise the selection and size of the most feasible option considering the real solar and wind profiles from the NASA database.

Fig. 8. Schematic Diagram for Scenario 3



Different technology options (Various Combinations of PV, Wind, Storage, Grid and Diesel Generator) have been considered to determine the most feasible one for MG. From twenty-six different combinations, option with PV + Grid has been determined to be the most feasible one. It is important to mention here that we are not going into details of mentioning the optimised size/rating for each component along with their Net costs, as well as technical results related to load, storage, and generation from various resources.

Now, comparing the Base System (option 1) with the proposed optimised system, the IRR of the proposed system turned out to be 20 percent, while discounted payback period and simple payback period are found to be 5.22 years and 4.93 years, respectively. A brief comparison of the Base System and the proposed system is given in Table 3.

Table 3

NPC for Scenario

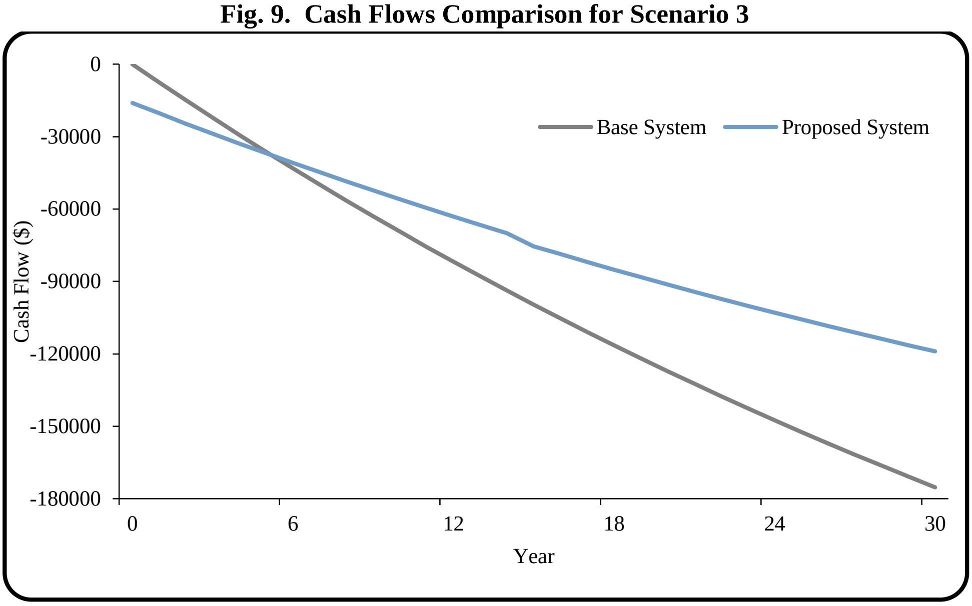
Component	Base System	Proposed System
Net Present Cost	$175,218	$118,903
CAPEX	$0.00	$16,048
OPEX	$7,665	$4,499
LCOE (per kWh)	$0.150	$0.0929
CO_2 Emitted (Kg/Year)	32,295	16,816
Fuel Consumption (Liter/Year)	0	0

The Levelised Cost of energy (LCOE) came out to be $0.0929/kWh, which is significantly lower than the existing grid-provided electricity tariff rate.

It is evident from the above analysis that the LCOE, which the end-consumer has to bear for only grid connection (0.15/kWh), would drop to $ 0.0929 $/kWh. Therefore, it holds substantial financial viability for end-consumers living in urban centres/housing societies.

Now, considering it from the perspective of the government, the need for investment planning for lesser energy/power, environment-friendly electricity generation, improving energy efficiency targets, and job creation in the private sector are some of its advantages. A graphical comparison of the base and proposed systems in terms of cash flows for the project lifetime is given in Figure 9.

Fig. 9. Cash Flows Comparison for Scenario 3



2.2. Further Insights into Modelling, Analysis, Simulation, and Results

It is important to highlight that the main purpose of the above-mentioned analyses is to present further insights and methodologies, which is why it has been performed only for a few of the selected cases and applications. The need of performing these analyses or even more advanced ones depends upon the exact application and model of a specific project, therefore, results may vary from one project to another.

2.2.1. *Sensitivity Analysis*

Sensitivity analysis is required to assess the impacts of changes in various input parameters on the results of the analysis. The most important input parameters for performing sensitivity analysis are:

- Permitted capacity shortage (%).
- Project lifetime (Years).
- Discount rate (%).

These parameters are allowed to vary over a range of values and the resulting impact on LCOE has been observed.
Based on the range of input parameters, a total number of 720 (12*6*10) scenarios/ sensitivities have been simulated through HOMER Pro for Case 1. Out of these 720 sensitivities, two are compared below as an example.

- Sensitivity A (Discount rate = 10, Project lifetime = 5 years, Capacity Shortage = 0 percent).
- Sensitivity B (Discount rate = 5, Project lifetime = 30 years, Capacity Shortage = 10 percent).

Table 4

Sensitivity A vs. Sensitivity B

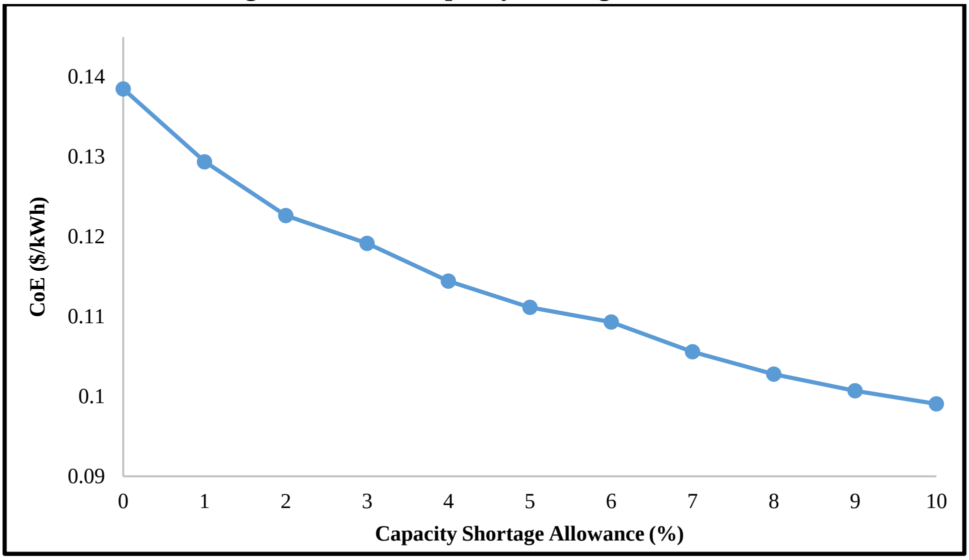
Component	Sensitivity A	Sensitivity B
Net Present Cost	$22,079	$83,957
CAPEX	$33,984	$25,841
LCOE (per kWh)	$0.177	$0.0729

It can be observed that the LCOE decreased either by increasing the project lifetime and the allowed capacity shortage or by decreasing the discount rate.

These sensitivities, along with other similar sensitivities, may be simulated for a specific project to identify the optimal solution as per the requirements. It is interesting to note that MGs' feasibility analysis is a multi-dimensional optimisation task where the project owner has to decide which energy mix will be installed to meet the electricity requirements of the consumers.

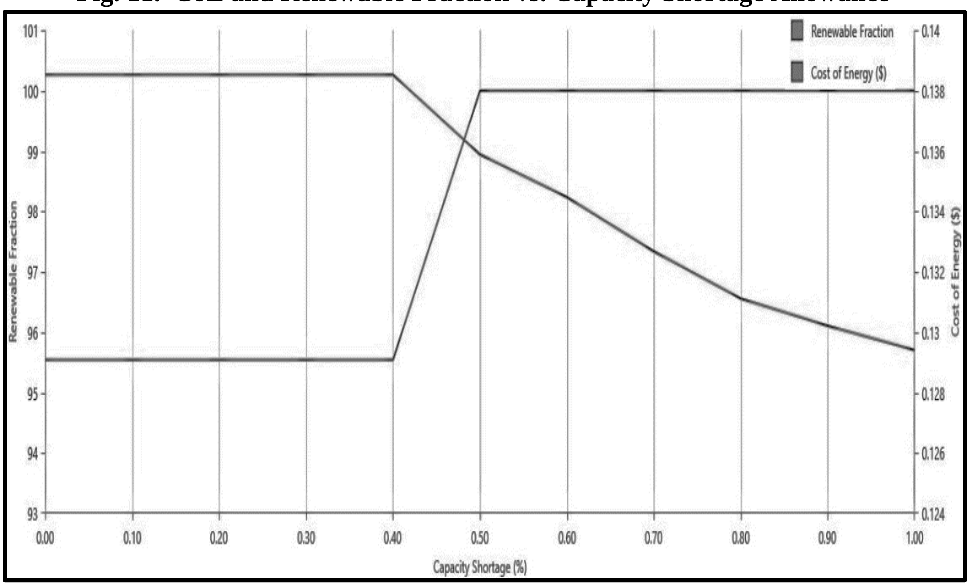
For example, let us consider the sensitivity of the cost of energy (CoE) with the capacity shortage allowance as shown in Figure 10. It is evident that the CoE decreased exponentially with the increase in the allowed capacity shortage.

Fig. 10. CoE vs. Capacity Shortage Allowance



An interesting behaviour has been observed concerning the renewable fraction in the energy mix for the MG. For a capacity shortage allowance of up to 0.4 percent, it is essential to include a conventional generator to determine the optimal resources for the MG, as shown in Figure 11. The corresponding graph for the CoE is also plotted below.

Fig. 11. CoE and Renewable Fraction vs. Capacity Shortage Allowance



Similarly, the relationship of CoE with discount rate and project lifetime can be easily observed as increasing linear and decreasing exponential respectively, as shown in Figure 12 and Figure 13.

Fig. 12. CoE vs. Discount Rate

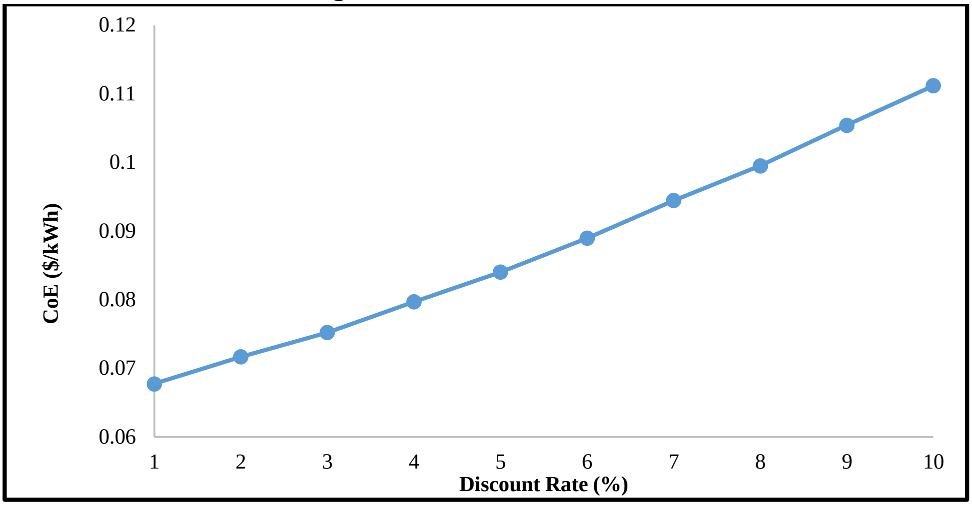
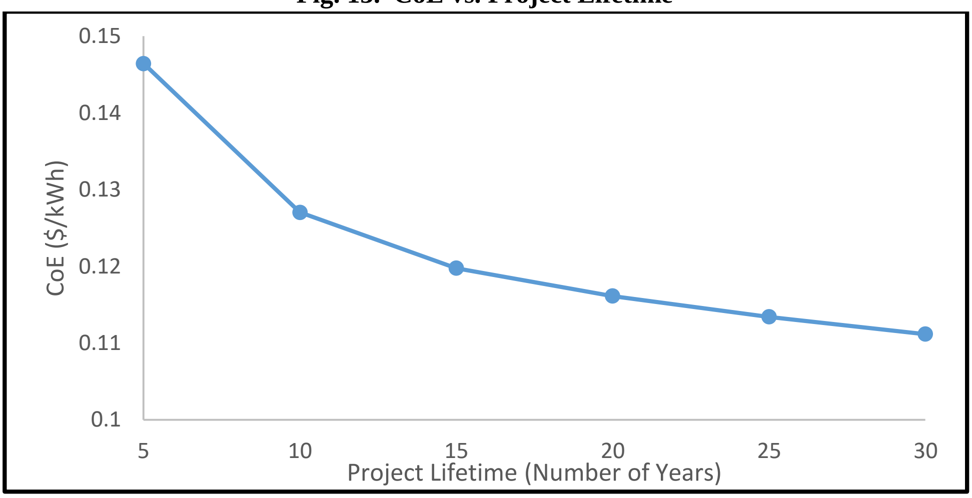


Fig. 13. CoE vs. Project Lifetime



The impact of these critical factors is an important insight for policymakers. For example, if the customers want the provision of supply 100 percent of the time, the price of per-unit electricity may increase by 200 percent as compared to the customers who want it 95 percent of the time. Again, this must be correlated with the consumer affordability index which varies significantly across the country. In line with the regulator's intent of deregulating this sector completely, it can be anticipated that it is the project owner who will conduct this sort of preliminary analysis to safeguard the investment, which would be depicted in the bilateral contracts between the project owner and the customers.

2.2.2. *Multiyear Analysis*

A multiyear analysis could be performed by inputting future cost projections of solar PV and wind to provide a more realistic insight for the future. It is important to highlight here that the results summarised in the previous modelling section will improve, i.e., LCOE will further decrease if a multiyear analysis is incorporated.

2.2.3. *Deferrable Load Analysis*

Deferrable load analysis has been performed to analyse a very practical application of irrigation in Pakistan's rural areas. Deferrable load is the load for which the exact timing of the electricity provision does not matter. However, it requires a certain amount of energy in a specific period. Loads are normally categorised as deferrable when they are linked with the availability of storage. Water pumping is a common example of deferrable load in rural areas of Pakistan. Thus, this special case has been analysed here with respect to MGs' widespread deployment in the country.

A cost comparison of scenario with normal load vs deferrable load is provided in Table 5.

Table 5

Comparison: Normal Load vs. Deferrable Load

Cost	Deferrable Load	Normal Load
Net Present Cost	$64,059	$78,095
CAPEX	$28,999	$33,289
OPEX	$1,534	$1,960
LCOE (per kWh)	$0.0976	$0.119

It is evident from the above comparison that MGs application to irrigation is a feasible case and has more economic viability.

2.2.4. *DC MG Analysis*

DC MGs have become a reality in recent years. We compare the already presented Scenario 1 with another scenario in which we replaced AC with DC MG. Here the AC Load is converted to DC load, which resulted in avoiding the requirement of the AC bus and the converter. Without going into technical details, a brief cost comparison of the two is given in Table 6.

Table 6

Comparison: Scenario 1 vs. DC MG

Cost	Scenario 1	Scenario 1 (DC MG)
Net Present Cost	$64,120	$56,579
CAPEX	$27,836	$22,949
OPEX	$1,587	$1,471
LCOE (per kWh)	$0.111	$0.098

The Levelised Cost of energy (LCOE) turned out to be $0.098/kWh in the case of DC MGs as compared to $0.111/kWh.

2.2.5. *MGs with Day-Only Load*

The load profile significantly affected the LCOE. For example, when the load profile is changed to a day-only load, LCOE turned out to be $0.0677/kWh as compared to $0.111/kWh (in Scenario 1).

3. POLICY OVERVIEW AND REGULATORY FRAMEWORK

3.1. Analysis of Existing Relevant Policies

3.1.1. *ARE Policy 2019*

As per the ARE Policy 2019, MGs are included in the targets, i.e., at least 20 percent on-grid RE generation by capacity by 2025 and at least 30 percent by 2030. However, all MG projects, under the ARE Policy 2019, developed with public sector funding will be undertaken through competitive bidding. However, this condition will not be applied to private sector projects. The ARE Policy 2019 mandates the AEDB to be the focal entity for developing and operating MGs in Pakistan.

3.1.2. *National Electricity Policy 2021*

The policy, approved in June 2021, is aimed to reform the power sector. However, its aim is also to promote electricity access in areas where grid expansion is financially unviable, through exploring off-grid and micro-grid solutions. The policy further includes the provision of integrated planning for rural electrification and the provision of electricity to unserved areas of the country.

3.2. GAP Analysis

The ARE Policy 2019 is aimed to create a conducive environment for the sustainable growth of the ARE sector in Pakistan and is not exclusively meant to focus on encouraging and pushing MG development in Pakistan. In order to target substantial upscaling of MG, Pakistan certainly requires dedicated policy intervention due to its distinctive nature and associated benefits as well as challenges.

In order to promote and secure the upscaling of MGs in the country, the Government of Pakistan (GoP) is certainly required to address the policy gaps described below. Furthermore, the AEDB is required to proactively pursue its mandate in this regard.

The inclusion of exploring MG solutions in the National Electricity Policy 2021 in a highly broad manner does not reflect the strong commitment and serious undertaking on the part of the GoP for MGs development in Pakistan. It is, therefore, expected that the GoP will manage a comprehensive and realistic coverage of MGs in the National Electricity Plan, which is expected to be launched for the implementation of the National Electricity Policy 2021, covering the aspects, which are not limited to the following:

(1) What will be the roles and responsibilities of different stakeholders? For example, who will build, operate, and maintain the distribution infrastructure? What will be the role of the NTDC, and DISCOs concerning MG interconnections? What will be the role of provincial/territorial government, if

any, in the context of the 18th amendment concerning autonomy in electricity generation? What will be the role of donors and IFIs in the MG deployment in Pakistan?

(2) Will the tariff of MGs be regulated or not? If yes, what would be the ceiling on non-regulated tariffs assuming that very small MG will not be regulated?
(3) Will grid-connected MG projects be allowed to become distributors of electricity purchased from the centralised grid?
(4) How simple regulatory framework will be? Will a license be required to become an MG operator? If yes, will the license be required for all or only for MGs above a certain kW capacity?
(5) What will be the legal and regulatory framework, and mechanism for the acquisition and the utilisation of public sector land for MGs development and operation?
(6) Will the MG sector be subsidised or not, e.g. through the allocation of 100 percent free or partly subsidised public sector land?
(7) Will the private housing societies be allowed to have their own MG setup? Will they be allowed net metering or not? Up to what capacity if yes? Will licensing be required or not?

3.3. MG Experience in Pakistan

It is important to mention here that the MG development has already been initiated in a few geographical areas of Pakistan. In order to facilitate new MG projects, there is a need of showcasing the MGs' feasibilities, projects, technologies, ready-made business plans, financing options, etc. Moreover, an integrated study may also be carried out for the whole country with respect to potential and opportunities related to MGs. Master database may be prepared and shared widely (data of all the existing microgrids, potential for new such options, investment opportunities, funding opportunities, etc.) among the potential sponsors and other stakeholders.

3.4. International Experience of MGs Deployment

Here we will review various dimensions including prerequisites and other implications that may be faced in MG deployment in Pakistan. These dimensions are analysed by studying various case studies of MG deployment in Asian and African regions having demographics and economic conditions similar to that of Pakistan.

Three tiers in MG development have been identified to deconstruct the challenges: (1) decision-makers or policy-makers, (2) investors, and (3) consumers. Each of these tiers has its own set of barriers/constraints, which are required to be overcome.

3.4.1. *Decision or Policy-makers*

This is the most critical tier in the upscaling of MGs in Pakistan. Policymakers, which include regulatory institutions, must design and provide a conducive environment for investors and consumers of MGs. One of the key considerations should be that the tailor-made, bottom-up expectations of the customer meet the top-down decisions of the policymakers (Bijker, et al. 1987). Two fundamental questions are expected to arise while designing this policy. The first is how the different tiers interact from the perspective of upcoming MG solutions. The second question is how different stakes associated with MGs, are managed by the local community and other stakeholders. (Bijker, et al. 1987 and Williams & Edge 1996).

In addition to considering the consumer side of the scenario, policymakers must address the investor side as well. They need to decide the level of participation from both the public sector and the private sector (Motjoadi, et al., 2020). The policy considerations for investors must include (1) long-term certainty in the market development; (2) addressing risks associated with the presence of a centralised grid; (3) meeting various regulatory requirements; and (4) providing sustainable operation and cost-recovery through tariff regulation and financial support schemes (Williams & Edge, 1996).

The international experience tells that it is important to have dedicated policies for MG deployment. The inclusion of MGs in the national electricity policy and plan may encourage the MG market. For example, Sierra Leone and Rwanda have dedicated policies for MGs deployment. Nigeria, Peru and Tanzania, have all included MG solutions in their plans.

Another critical policy-level issue is the MGs replacing conventional grids in their application areas and the strategies to deal with the stranded cost of transmission and distribution assets (Motjoadi, et al. 2020). The policymakers of Indonesia, Nigeria, Rwanda, and Tanzania, for example, have incentivised MGs operators to utilise net-metering provisions with the central grid at a fixed tariff, and to acquire distribution licenses, relocate assets or sell parts of their assets to the utility (IRENA, 2018).

3.4.2. *Investors*

Keeping in view a longer project life, a huge upfront investment is expected. The financial resources for setting up an MG system are presumably greater than the required investment for a diesel generator. Thus, for the implementation of MG systems, particularly in rural or remote communities, access to adequate capital is a major barrier.

There are two parts to this argument. Firstly, a sustainable investor-led MG business requires that the fixed and operational costs of the infrastructure and its operations be sufficiently recovered along with a decent return on the investment. Typical modes of revenue generation are connection fees and electricity sales. Secondly, the communities can pay the cost of services to the project owners.

Several ways are being exercised around the globe to ensure a smooth flow of capital from consumers to project owners, which include setting the right mechanism and the tariff for cost recovery, facilitation in project preparation, subsidising MG projects, and facilitation in access to finance and involvement of public sector in financing of community development projects.

In certain cases, policymakers allow project sponsors and the local community to set tariffs through mutual deliberation such that the tariffs are sufficient to cover costs but ensure that consumers are willing to pay. Increasingly, policymakers are taking a custom-built approach to set the tariff for MGs. For example, Nigeria, Rwanda, and Tanzania have allowed deregulated tariffs for MGs under an installed capacity ceiling. However, large MG systems require standardised tariffs, and such tariffs need to be approved by policymakers. Indonesia and Peru have prepared a methodology for standardising tariffs to encourage private sector involvement (IRENA, 2018).

The countries examined for this study show varying degrees of both public and private sector participation in MG development depending on the context. In Indonesia, the government has provided financial support in developing MG through subsidies and grants. The ownership remains with the public sector, while operation and maintenance are transferred to the community. In India, MG project sponsors are given a choice to opt for a pre-determined subsidy in exchange for other requirements including tariff restrictions, service quality, safety and security standards.

Investors, furthermore, fear that the presence of centralised grids may hamper MG development due to their superiority in ensuring a continuous supply of electricity.

3.4.3. *Consumers*

From the consumers' perspective, the need for energy may be of any type of end-use, such as for lighting, cooking, cooling, heating, irrigating, and charging. The need is to be decided by the consumer, which eventually drives the type of MG solution.

For the successful implementation of MG systems, a public-in-particular framework should be employed in which the communities have an identifiable stake. In such a framework, an issue, a controversy, or an internal difference can be solved or mitigated through technological endeavours. (Michael, 1998).

The consumer, whether the energy is clean or not, ultimately requires an uninterruptible supply of electricity. The case study of Bihar, India, clearly indicates that the hunger for more energy exists in the consumer, and they make an intended effort to go beyond the contracted energy needs. Such an increasing appetite for energy then drives consumers toward a centralised grid or the consumer may eventually claim their entitlement to the centralised grid (Sharma, 2020).

3.5. Policy Insights

Based on the existing policies, gap analysis carried out, and lessons learnt from the international experience of MG design, development, and implementation, the following are the certain policy insights that may be considered for the successful and large-scale deployment of MGs in Pakistan:

(a) A dedicated policy is critical to scaling up MG development addressing long-term certainty regarding market development, financial support schemes, and addressing risks associated with the presence of the centralised grid.

(b) Although MG deployment has already been initiated in a few areas, there is an urgent need for a regulatory framework to address various regulatory requirements, sustainable operation, and cost-recovery mechanisms.

(c) A meticulous identification of requirements becomes imperative in consultation with the local community to arrive at an MG solution. For example, in Balochistan or areas of Thar where there is currently zero access to electricity or any other form of energy, the requirement of energy from an MG system may, perhaps, be getting water from nearby wells, energy for cooling purposes, getting access to telecommunication services, or the internet for a significant part of the day. On the other hand, the requirements of energy use in Northern Areas of Pakistan are quite different as energy is mostly required for heating purposes where one cannot rely on a hydro resource, which becomes simply unavailable or highly unreliable in the winter.

(d) Extensive stakeholder engagement is vital for moving forward. Stakeholder engagement may be achieved through the involvement of community-based organisations (CBOs), technology demonstration and its effective use, and knowledge creation and institutionalisation.

(e) As a recent development in the power sector (August 2021), the GoP has approved the exemption of a license for small-scale RE-based systems up to 25 kW for net metering to facilitate the consumers who wish to install small-scale solar systems for their homes and businesses. Similarly, the GoP and NEPRA preferably may develop and implement a simple and encouraging regulatory framework for the development of MGs in Pakistan.

3.6. Regulatory Framework

As mentioned in the previous sections, MG regulations are one of the critical prerequisites in achieving widespread MG deployment in Pakistan. Fortunately, in December 2021, when the present study was in progress, NEPRA published the draft licensing regulations for MGs and sought comments from all the interested parties.

Accordingly, the study team interacted with NEPRA and subsequently submitted a comprehensive set of comments and observations via email (For reasons of conciseness, we will not mention our comments here). The finalisation of the regulations is under process. The regulations are expected to be approved and enforced in the coming months.

4. BUSINESS MODELS FOR MGs

4.1. Existing MG Activities in the Country

Although the MGs have started being recognised by the Government of Pakistan mainly through the recently enforced ARE Policy 2019, there are proactive interventions already in place at the provincial levels.

The Government of Khyber Pakhtunkhwa (KP) has a major focus on the social uplift of the deprived communities residing in far-flung areas of the province. In this regard, they have carried out three projects, i.e., (a) the development of mini/micro hydropower plants; (b) the Solarisation of schools and mosques; and (c) the installation of solar mini/micro energy systems. For all these three projects, the project sponsor is the Government of KP, the executing agency is PEDO, and the energy systems are managed by the local community. The objectives of these interventions are to increase economic activity in the region, create employment opportunities, utilise the local resources for the community optimally; and supply low-cost, locally managed, clean energy. Within the KP Province, 356 mini/micro hydropower projects, ranging from 15 kW to 500 kW, are located. The MG infrastructure comprises 175 kW solar PV, 250-300 kWh lithium-ion battery system, and an AC transmission system to connect with the consumers.

The Government of Punjab has also adopted a similar approach in the development and deployment of MGs in the province. The focus of Punjab is primarily on solar. PPDB has already managed to solarise 2,324 basic health units in Punjab and plan to expand it to schools in Southern Punjab. In a bid to reduce the carbon footprint, the Government of Punjab is the first to introduce a business model, Energy Service Companies (ESCOs), in the province. This initiative started with the solarisation of public universities in Punjab on the ESCO model. For this model, CAPEX and OPEX will be borne by the ESCO and the buyer will pay ESCO on a mutually agreed tariff. Major universities that are being benefited from this model include the University of Engineering and Technology, Lahore, and Islamia University Bahawalpur. The ESCO model has now been expanded to various commercial buildings as well as industrial facilities.

4.2. Potential Business Models

The MGs being installed or commissioned in the country are currently unregulated and unstandardised, and major interventions have been done by the government through International Financial Institutions (IFIs) with increasing CAPEX, but no plan to sustain the OPEX.

Any successful business model must possess three key features, namely scalability, interoperability, and sustainability. For this study and based on the ARE Policy 2019, National Electricity Policy 2021, and draft NEPRA Licensing (Microgrid) Regulations 2021, business models are envisaged that capture the future outlook of MG business activities in Pakistan.

Figure 14 provides a model where a government entity becomes the MG licensee and undertakes to plan, design, construct, operate, and maintain the MG infrastructure along with associated generation. This is the existing structure in which the government is investing in a bid to provide economic stimulus to the deprived communities. However, in this model, there is no room for scalability and sustainability of the MG deployments.

Figure 15 shows an investor-owned MG business model, which is based on the prevailing policy and the draft regulation. This is similar to the first model shown in Figure 14, but in this model, the private sector undertakes all the activities of planning, design, construction, operation, and maintenance. For this model, a major concern remains that the investor is deemed to have a monopoly on supply in the specified service territory.

Fig. 14. MG Business Model 1 – Utility Owned Model (Generation + Wire Business)

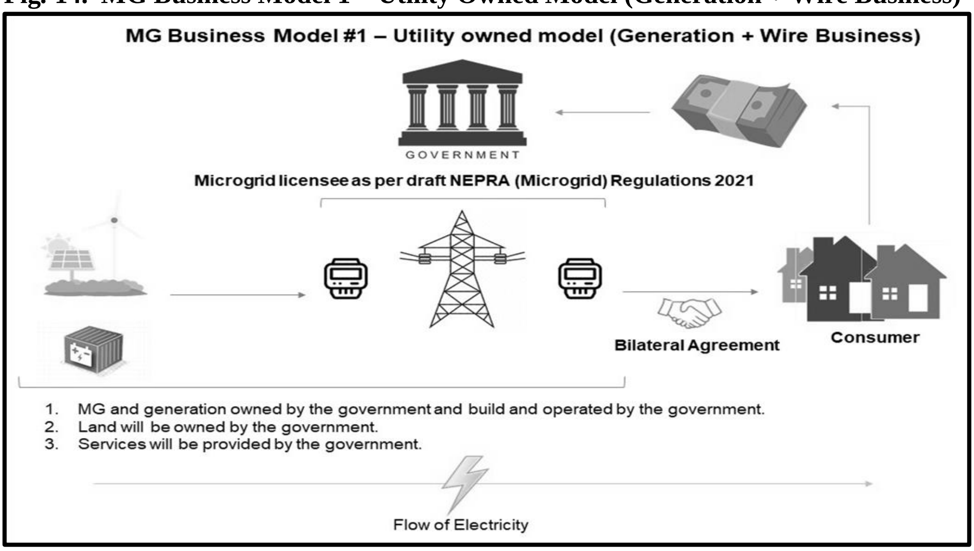
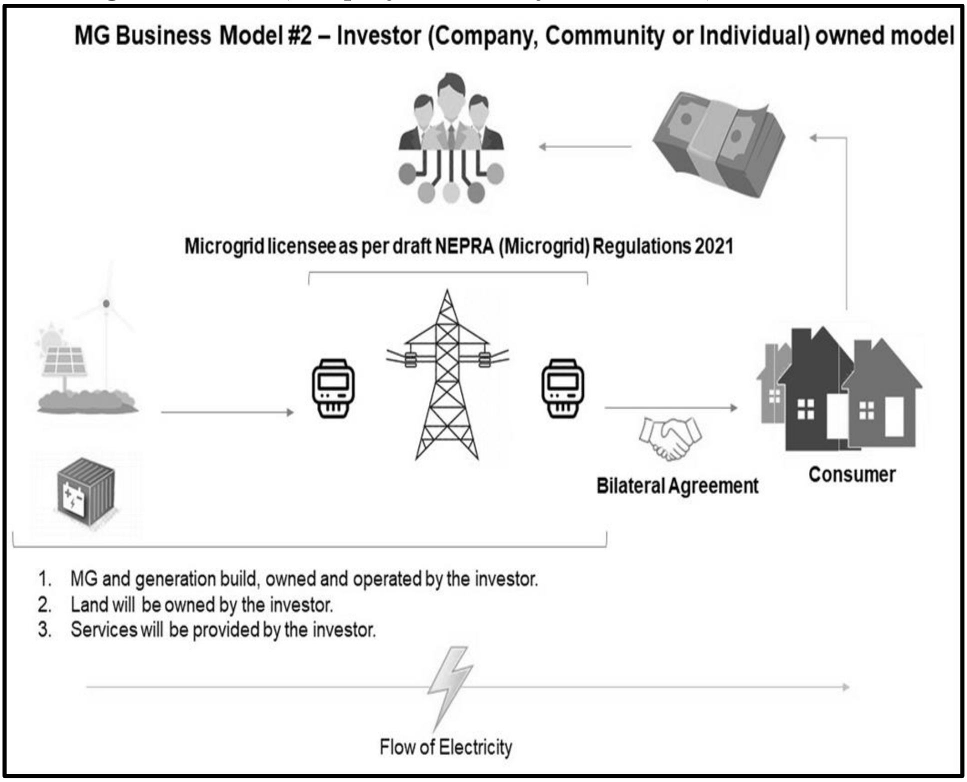


Fig. 15. Investor (Company, Community or Individual) Owned Model



The business models, as illustrated in Figure 16 and Figure 17, have been proposed for the upcoming MG enterprise, which will outperform the existing and unsustainable business frameworks, increase private sector participation, provide effective operation, and maintenance and ensure more transparency and sustainability in the energy system.

Figure 16 shows an investor-owned model, which is more decentralised allowing more competition and increased private sector participation. In this model, the MG licensee owns the wires and metring infrastructure. Generators in IPP mode supply electricity, which is contracted through Power Purchase Agreements (PPAs). This constitutes the CAPEX of the MG energy system infrastructure. The OPEX part of this model is undertaken and monitored by a Community Based Organisation (CBO), which manages the distribution network and the flow of power from the generator to the consumer. Furthermore, it manages metering infrastructure for the sale and purchase of electricity and provides authorised services to consumers through bilateral agreements. The CBO also acts as a power purchasing agency, which collects the payments from the consumers and disburses them to the wire business owners and the generators. This model manages the community's ownership, making the system more sustainable for a longer period. The CBO includes representation from generators, MG licensees, and the community itself.

Fig. 16. Investor-owned Model with Involvement of CBO

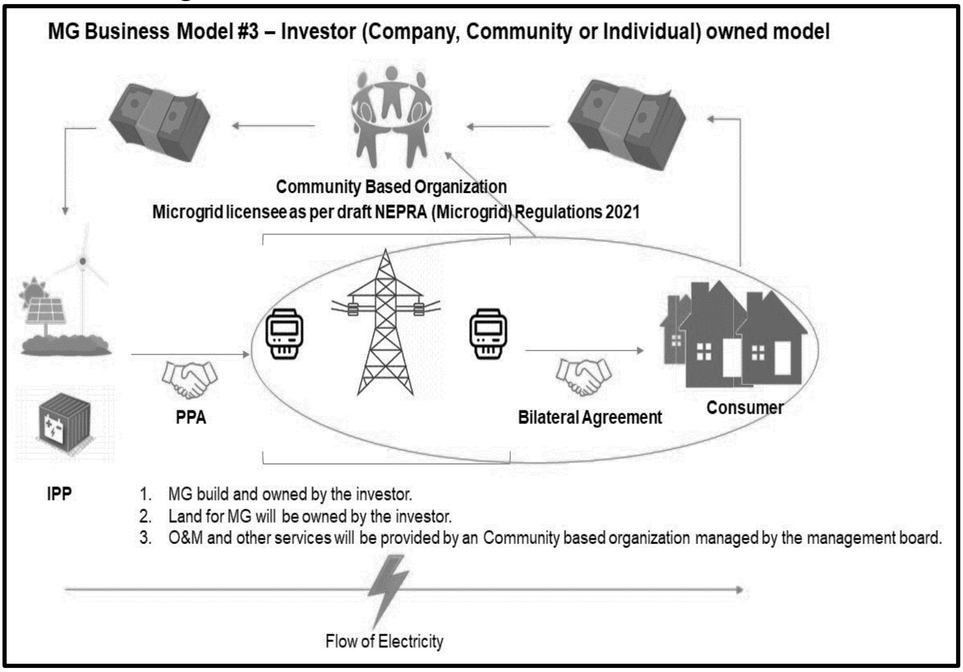
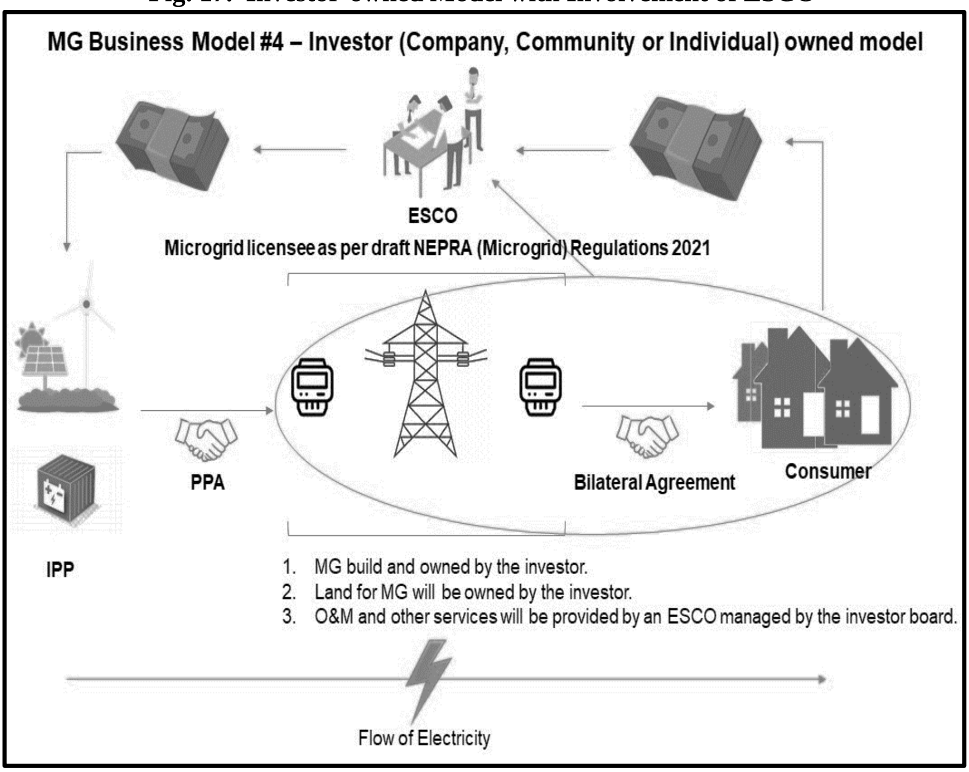


Fig. 17. Investor-owned Model with Involvement of ESCO



A similar approach is adopted in the business model displayed in Figure 17. However, the mandate to operate and maintain the MG infrastructure is transferred to an ESCO, which can be applied for more advanced network control and operations. The ESCO also acts as the power purchasing agency, which manages the sale and purchase of electricity. The ESCO is governed by an investor board, which includes participation from generators, MG licensees, and the community.

The success of any of the business models discussed above is subject to the underlying issues regarding the arrival of the host distribution licensee grid, the stringent regulations even for investors in the range of less than 100 kW, and SOPs on billing and metering to be made by the electricity regulator. These issues are potential impediments to the economic stimulus in the MG business growth in Pakistan.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

(1) The comparison of different applicable MG scenarios as discussed and analysed in Chapter 2 is provided in Table 7 below:

Table 7

Summarised Comparison of Scenarios

Parameter	Scenario 1	Scenario 2	Scenario 3
LCOE ($/kWh)	0.111	0.0981	0.0929
Net Present Cost ($)	64,120	78,068	118,903
CAPEX ($)	27,836	34,213	16,048
OPEX ($)	1,587	1,918	4,499
Fuel Consumption Savings as Compared to Diesel Generator (Litre/year)	15,216	16,151	–
CO_2 Emissions Savings as Compared to Diesel Generator (kg/Year)	39,831	42,276	15,479
IRR (%)	79.5	66.1	20
Payback Period (Year)	1.34	1.57	5.22

(2) The MG deployment has strong financial viability and presents a lucrative investment opportunity. The upscaling of MGs, therefore, needs to be acknowledged as a business opportunity by the private sector.

(3) Fuel-based MGs result in CO_2 emissions, which is detrimental to the environment. Renewable Energy (RE) based MGs save significant emissions and are, thus, environment-friendly.

(4) RE-dominated MGs present much more financial feasibility as compared to fossil-fuel-based MGs.

(5) Due to the increasing trend in electricity prices, the MG deployment has become a cost-effective solution as compared to the conventional integrated grid for particular scenarios/applications.

(6) The MG option is better than the conventional integrated grid for specific scenarios/applications discussed above. However, it is not an optimal solution in all situations. The feasibility will change significantly depending on various factors, such as no or lesser renewable energy (RE) potential, consumer requirement of 0 percent allowed capacity shortage, and change in cost trends of REs versus fossil fuels.

(7) Technical issues associated with the operations of MGs are stability, safety, protective relaying, harmonics, and voltage imbalance. Although MGs present a cost-effective solution for remote unelectrified areas of Pakistan, they may face technical issues if not properly designed.

(8) Keeping in view Pakistan's context, customised business models may be helpful for investors and other stakeholders.

(9) The existing policy and regulatory framework are insufficient to effectively upscale the MG deployment in Pakistan.

(10) DC MGs have become a reality in many countries in recent years. DC MGs show a promising 12 percent decrease in the cost of energy (from 0.111 $/kWh to 0.098 $/kWh) as compared to similar AC MGs.

(11) The application of MGs for irrigation purposes presents an interesting case. Hybrid MGs having an irrigation application has more economic viability as compared to similar normal rural MGs since it shows a promising 18 percent decrease in the cost of energy, i.e., from 0.119 $/kWh to 0.0976 $/kWh.

(12) Allowed capacity shortage is an important factor to be considered for MG development since the cost of energy decreases exponentially with the increase in the allowed percentage capacity shortage.

(13) Discount rate and project lifetime are important factors to be considered to evaluate the feasibility of MGs. The cost of energy (CoE) increases linearly with the discount rate and decreases exponentially with the project's lifetime.

(14) Allowed percentage capacity shortage significantly affects the energy mix decisions. With the consumer requirement of percentage allowed capacity shortage from 0 percent up to 0.4 percent, the inclusion of conventional generators in the optimal energy mix is essential, and cannot be achieved exclusively with renewables and storage systems.

(15) The demand profile significantly affects the CoE of an MG system. In case the demand profile is changed from 24 hours to 12 hours (day-only load), it shows a promising 40 percent decrease in CoE from 0.111 $/kWh to 0.0677 $/kWh.

5.2. Recommendations

(1) For the upscaling of MG development in Pakistan, a comprehensive policy is required for addressing the long-term uncertainty of market development, financial support schemes, and risks associated with the presence of the centralised grid. Furthermore, a regulatory framework is required to address various regulatory requirements, sustainable operation, and cost-recovery mechanisms.

(2) DC MGs should be included in the regulations on microgrids, to be launched by NEPRA. Similarly, MGs should also be allowed to operate in grid-

connected mode. For this purpose, the draft regulatory framework may be customised. Moreover, a mechanism for dealing with the technical issues, such as stability, safety, protective relaying, harmonics, and voltage imbalance associated with MGs should be addressed in the final regulations on microgrids.

(3) Coordinated efforts by the stakeholders are required for utilising the applicability of MGs for irrigation in remote rural areas.

(4) While assessing the electricity provision for remote unelectrified areas of Pakistan, the system planner must consider and evaluate the MG deployment before proposing huge investments for transmission and distribution infrastructure.

(5) Based on the study's findings, the optimal solution involving MGs includes a major share of renewable energy resources. Therefore, renewables-based MGs should be promoted in the upcoming policy and regulations. Further, CO2 emissions should be compensated through a carbon-credit mechanism for fossil fuel-based MGs to be provided in the upcoming regulatory framework.

(6) Given an inverse relationship between CoE and the allowed capacity shortage, the design of MGs should be aligned with the affordability for the customers in the specific geographical area, to create a win-win situation for all the stakeholders.

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