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Research paper

Estimation of air pollutant emissions from captive diesel generators and its mitigation potential through microgrid and solar energy

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ABSTRACT

The grid power supply in many developing countries is insufficient and irregular resulting in many commercial users relying on inefficient and air pollution intensive off-grid captive diesel generators (DGs) as a backup power supply. This study investigates the fuel consumption and emission level of such DGs and explores the possibility of reducing them through the formation of a microgrid of DGs and solar PV in a commercial area in Kathmandu, Nepal. An optimized microgrid system has been designed using the HOMER framework for both DGs and solar PV based systems. The optimized DG based microgrid results reduction in specific fuel consumption by 19% and cost by 5%. It also mitigates emissions of key air pollutants ($PM_{2.5}$, PM_{10}, CO, and VOCs) by 21% to 92% as compared to the baseline. If the solar PV based microgrid is used, the emissions can be reduced by 100% but cost increases by 27%. However, the overall economic benefit to the country could be quite significant due to the reduction of external costs of imported fossil fuel and generators, air pollution, adverse health outcomes, investment locking in grey power generation, and energy security issues. The approach used here can be emulated in many other developing countries with similar conditions.

1. Introduction

One of the most challenging issues for economic development in the 21st century is the unsustainable growth of urban areas with infrastructure development unable to maintain the pace of expansion, particularly in developing countries. Sustainable supply of electricity is a major requirement for economic activities in urban areas, but the power supply in many countries is both insufficient and unreliable, forcing commercial and industrial enterprises to rely on captive power generation, such as diesel power generators (DGs), to ensure their power supply during grid power outages. It has been reported that about 1.5 billion people around the world live day-to-day with power blackouts for hundreds and sometimes thousands of hours a year (Lam et al., 2019). The DGs can be a major source of emissions of ambient air pollutants (AAP) in those areas (Lam et al., 2019; World Bank, 2014). Poor air quality, often exceeding the national and the WHO guidelines, is a major cause of premature death in developing countries, notably in South Asia, besides its adverse impacts on crops, ecosystems, and climate in the region. Reducing these emissions can be an important component in clean air strategies, particularly in urban areas.

In Nepal, there was a persistent power shortage, as in several other developing countries, with regularly scheduled power cuts spreading across the country for up to 14–18 h a day particularly during the dry season for a long period until recently, and therefore a huge number of captive DGs were used in industrial, commercial, and even in the residential sectors as a backup power supply during load-shedding. Nepal's captive DGs had a total installed capacity of 600 MW in 2010 (NPC, 2013), with 200 MW in the Kathmandu Valley alone in 2014 (World Bank, 2014). These DGs accounted for two-thirds of diesel sales, provided 28% of electricity consumption in the valley, and emitted 383 tonnes of PM_{10} (aggregate mass of particles with diameter $\leq$ 10 μm) and 221 tonnes of black carbon (World Bank, 2014).

Emissions of air pollutants are a major contributor to premature death across the world with 6.67 million every year, mostly in the developing countries, and in the case of Nepal, it is ca. 42 thousand a year (Health Effects Institute, 2020). The emissions

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Fig. 1. Map of the commercial area selected for the study.
Source: Google Earth Map.

from captive DGs contribute significantly to the poor air quality, indicating an urgent need to manage these DGs to reduce fuel consumption and mitigate emissions while still providing power backup during load shedding hours (Majumder et al., 2012; Pradhan et al., 2012; World Bank, 2014). Furthermore, fossil fuel imports make a serious dent in Nepal's trade balance. Almost all petroleum products are imported from the neighboring country India, accounting for 23% of imports from India and 14% of overall imports in 2014/15 (NRB, 2016). Nepal's total export earnings are not enough to pay for the imports of petroleum products (NRB, 2016). Therefore, it is extremely important to reduce its petroleum consumption.

The DGs, which are mostly operated at a low load factor in an isolated mode leading to inefficient operation with high emissions and high unit costs, can be potentially operated more efficiently, with reduced emissions by developing a microgrid system to improve the load factor. This approach has been investigated as a means of supplying electricity in remote areas without a grid connection in various places around the world - Colombia (Haghighat Mamaghani et al., 2016), India (Chaurey and Kandpal, 2010; Hiremath et al., 2009; Kobayakawa and Kandpal, 2016; Nouni et al., 2008), Nepal (Sovacool et al., 2011), and Philippines (Agua et al., 2020). However, there are very few studies on the potential of microgrid systems in urban areas which are grid-connected but receive only intermittent supplies (Arshad and Ali, 2017; Murphy et al., 2014) but non of them measured and analyzed the effects on the emission of ambient air pollutants and other cobenefits. In addition, UN Sustainable Development Goal (SDG) 7 emphasizes the use of clean, renewable, and efficient energy to improve energy access (UNDP, 2021). In this context, the incorporation of solar PV in the microgrid can be a more sustainable solution in the long run. This study tries to fill some research gap related to the original data measurement related to the emission level of ambient air pollutants under different operating conditions and capacities of DGs, possibility of reducing the emissions and improving the efficiency of power production through DG based and solar PV based microgrid systems in a commercial area in a fast-growing area of the Kathmandu Metropolitan City (KMC), representing a typical urban area with intermittent grid power supply in the developing country. It also discusses the socio-economic benefits of the emission mitigation intervention measures in terms of public health, energy security, and investment locking on dirty technology.

2. Materials and methods

2.1. Site selection

The commercial sector – hotels, restaurants, financial institutions, communication service providers, and others – was the largest user of DGs in the Kathmandu Valley, about 54% of the total, followed by the manufacturing industries during the power load-shedding period (World Bank, 2014). Therefore, a representative commercial zone with significant use of isolated DGs during load-shedding hours and high levels of ambient air pollutants was selected. The study area chosen was the strip along the sides of the Madan Bhandari Road in New Baneshwar between the bridge at Bijuli Bazar and the Bagmati Bridge at Tinkune (Fig. 1). The road is an area designated as a commercial zone by the Kathmandu Metropolitan City and contains a wide range of commercial units including academic institutions, financial institutions, retailers, restaurants, a shopping complex, banks, company offices, and hospitals.

2.2. Field survey

A walk-through survey was carried out first to document the number and nature of commercial entities in the study area. The entities were categorized into three groups: small scale (operating in 1–2 rooms), medium scale (4 to 10 rooms), and large scale (occupying a whole building). A total of 219 commercial entities were identified: 120 small, 85 medium, and 11 large. The power backup types of equipment in use were as follows:

i. Small-scale: all 120 entities relied on battery storage for backup power (i.e., none of them had a DG). The small entities included small shops.
ii. Medium-scale: 20 entities (out of 85) had DG, and 19 used DG regularly during load-shedding. The remainder relied on battery storage for backup power. DG capacity ranged from 4 to 63 kVA. The medium-scale entities included restaurants, guesthouses, banks, a cooperative, a clinic, and a home decor company.
iii. Large-scale: 8 entities (out of 11) owned DGs (3 entities were damaged in the 2015 earthquake and were not operational during study period) with capacities ranging

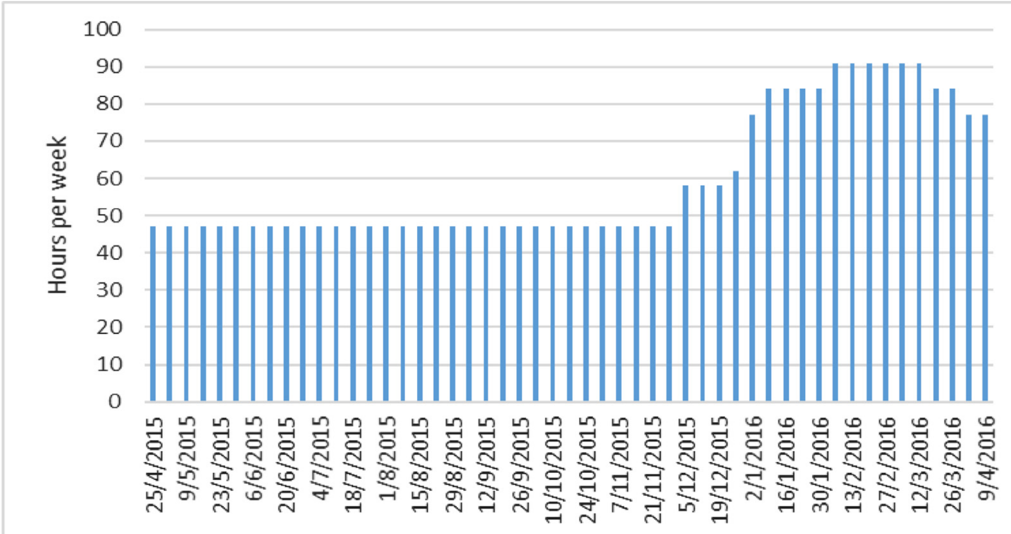


Fig. 2. Weekly load-shedding hours from mid-April 2015 to mid-April 2016 in the study area.

from 100 to 260 kVA. Some of them also had an additional backup DG (operated alternately). The large entities included a bank, hospitals, shopping complexes, and corporate offices.

All 28 entities that owned a DG were surveyed in detail gathering information on capacity, brand, model, efficiency, and age of the DG, average daily operating hours in the dry and wet season, fuel consumption rate (L/h), fuel usage (per day/month) in the dry and wet season, average loading, capital and maintenance costs, reasons for using a DG, and emission factor and ambient concentrations of air pollutants.

2.3. Load-shedding schedule

Electricity availability from the main grid is strongly affected by the amount of water flow in a river as most hydropower systems in Nepal are run-of-river hydropower systems. Thus, the schedule can be divided into two seasons with ca. April–November as the wet or high river flow season (rivers fed by glacier melts and monsoon rain) and December–March as the dry or low river flow season. Nepal Electricity Authority (NEA) used to publish the schedule of load-shedding for a given area of the country. The load-shedding schedule for the study area from mid-April 2015 to mid-April 2016 (i.e., for the Nepali year 2072 B.S.) was obtained from the NEA (NEA, 2016). The scheduled power cuts in hours per week are shown in Fig. 2. The daily load-shedding schedule is further divided into four time periods – morning (6:00 to 10:00 with 1 to 2 h power cut), day (10:00 to 17:00 with 2 to 3 h power cut), evening (17:00 to 22:00 with 1 to 2 h power cut), and night (22:00 to 6:00 with 2 to 4 h power cut) – which are used to create a rolling blackout with a weekly plan across adjacent districts.

2.4. Estimation of load profile and annual fuel consumption

The survey was used to establish a complete average daily load profile for the DGs in the study area in both wet season and dry season. The power demand of each commercial entity was added for each time period (morning, day, evening, night) to estimate the peak power demand for that period (Eq. (1)).

$$PDt = \sum_{t=0}^{n} \sum_{j=0}^{m} ED_{j,t} \tag{1}$$

where,

t = time of day

PD_t = power demand at time t

$ED_{j,\,t}$ = power rating of electrical device 'j' operating at time t

m = number of electrical devices operated by DG at commercial entity i

n = number of commercial entities

The peak power demand is the highest PD_t during the given time period. The number of load-shedding hours tends to vary with season and the PD_t may also have seasonal variation. In order to calculate the annual energy demand (AED), the power demand for each device was multiplied by the hours of operation in each time period of the day and season over a year (Eq. (2)).

$$AED = \sum_{t=1}^{p} PD_t \times H_t \tag{2}$$

where,

PD_t = power demand at time t

H_t = duration in hour of power demand PD_t

The annual fuel consumption (FC, in Liter) of the DG sets was estimated using Eq. (3).

$$FC = P \times T \tag{3}$$

where,

P = fuel consumption rate (L/hour)

T = annual operation hours of DG set (hours)

The values for fuel consumption rate and annual operating hours for each generator were taken from the survey.

2.5. On-site emission measurement

The ambient mixing ratios of volatile organic compounds (VOCs) and carbon monoxide (CO) (ppm) and mass concentrations of $PM_{2.5}$ and PM_{10} ($\mu g/m^3$) were measured on-site adjacent to the exhaust pipe of 15 randomly selected DGs. VOCs and CO were measured with a test meter (Gray Wolf Sensing Solutions IQ-610, USA) and $PM_{2.5}$ and PM_{10} with a PM monitor (AEROCET 831, USA). The carbon mass balance method was used to estimate the emission factor (EF) for each DG and was then normalized to estimate the emissions from all DG sets in the commercial zone.

2.6. Development of DG and solar PV based microgrid systems

The Hybrid Optimization of Multiple Energy Resources (HOMER) modeling framework (HOMER Energy, 2016) was used to develop an optimized microgrid system based on the existing DGs and solar PV. HOMER is a computer modeling and optimization tool developed by the National Renewable Energy Laboratory (NREL), USA. It can be used in designing and deploying microgrid, off-grid, and grid-connected supply systems consisting of hybrid energy sources. It has been used in many countries to design and optimize microgrid systems using conventional, renewable, and hybrid energy sources, for example in Somaliland (Abdilahi et al., 2014), Canada (Hafez and Bhattacharya, 2012), Saudi Arabia (Rehman et al., 2007; Shaahid and Elhadidy, 2008), and India (Kobayakawa and Kandpal, 2016). The input data for load demand and optimization of microgrid supply systems were mostly obtained from the primary survey (load profile in hours per year for the chosen area, annual operating hours of the DG sets, cost of components, and others).

The potential annual fuel consumption if the DGs were operated under a microgrid system and capacity of the solar PV system-based microgrid was estimated using the HOMER optimization tool (HOMER Energy, 2016) and compared with the existing consumption by the captive DGs. The reduction in emissions in the microgrid options was estimated based on the primary emission factors generated for the local context and the quantity of reduction in fuel consumption.

2.7. Financial and other analyses

A financial analysis was performed to check the financial viability of the alternative microgrid systems. The levelized cost of electricity (LCOE), which is a measure of the average net present cost of electricity generation for a power plant over its lifetime (Ouyang and Lin, 2014), was calculated for the existing systems, DG based microgrid and solar PV based microgrid. The fuel consumption per kWh, emissions of air pollutants per kWh, and LCOE of the existing system and proposed microgrid options were compared.

3. Results and discussion

3.1. Characteristics of the DGs

The age of the DGs ranged from a few months to 10 years with the capacity from 4 kVA to 260 kVA (Fig. 3a,b), and the hourly fuel consumption rate from 2 L to 33 L during the study period. The total installed capacity of operational DGs in the study zone was 1535 kW (1,696 kVA). Some large-scale users kept additional backup DGs with a total capacity of 538 kW (595 kVA). The fuel consumption rate increased by only 16 times for a 50-fold increase in the DG capacity, indicating increased fuel efficiency of the larger generators. However, even the larger generators were not operating under optimal conditions as they were oversized for the load, leading to lower energy efficiency and higher emissions of air pollutants compared to the operation at the standard rated capacity.

3.2. Impact of loading on emissions of air pollutants

Fig. 4 shows ambient mixing ratios of CO from two DGs of similar size but operated with different loading. The initial and final five minutes in each plot show the ambient background mixing ratios with the DG turned off. Table 1 shows the mean CO mixing ratios after correcting for the background mixing ratio per kW for the two DGs. The higher loading of 66% compared to15% resulted in a significant reduction in $PM_{2.5}$ by 48%, PM_{10} by 41%, and CO by 83% indicating increased combustion efficiency at higher load.

Table 1
Mean ambient mixing ratio of CO per kW (ppm/kW) and mass concentrations of $PM_{2.5}$ and PM_{10} per kW ($\mu g/m^3/kW$) were monitored adjacent to the DGs operated with different loading conditions.

DG	Loading	$PM_{2.5}$ ($\mu g/m^3/kW$)	PM_{10} ($\mu g/m^3/kW$)	CO (ppm/kW)
DG1	15%	0.63	0.75	0.230
DG2	66%	0.33	0.44	0.038

Table 2
Average duration of load-shedding in different seasons.

Time of day	Time period		Total load shedding (h)	
	Time	Total hours	Wet	Dry
Morning	06:00 to 10:00	4	1.1	1.8
Day	10:00 to 17:00	7	2.0	3.2
Evening	17:00 to 22:00	5	1.4	2.3
Night	22:00 to 6:00	8	2.2	3.6

3.3. Estimation of energy and power demand

The average duration of load-shedding at different times of day in each season is shown in Table 2.

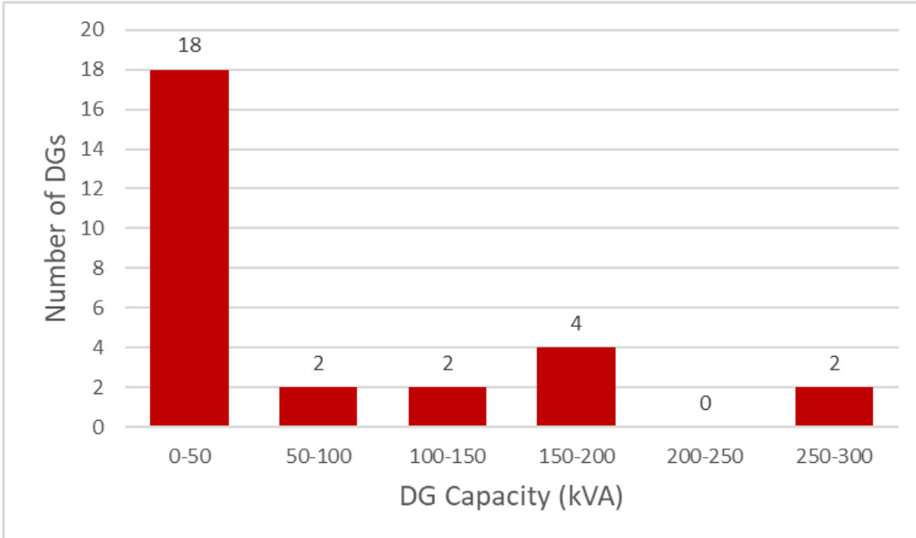
The survey showed that when power was supplied through DGs during load-shedding, the users made changes in the use of appliances to reduce the load in order to reduce fuel consumption. For example, medium-scale users turned off air conditioning and used fans for space cooling. Similarly, elevators were shut down in all except tall buildings. Thus, measurements were focused on the appliances that were used during load-shedding.

The total energy demand and hourly peak power demand (PD) from the DGs were estimated differently in the medium and large commercial entities. In the medium-sized entities, the power rating, and duration, and season of operation were recorded for each of the electrical appliances operated by DG power and used to estimate the peak power demand (Table 3).

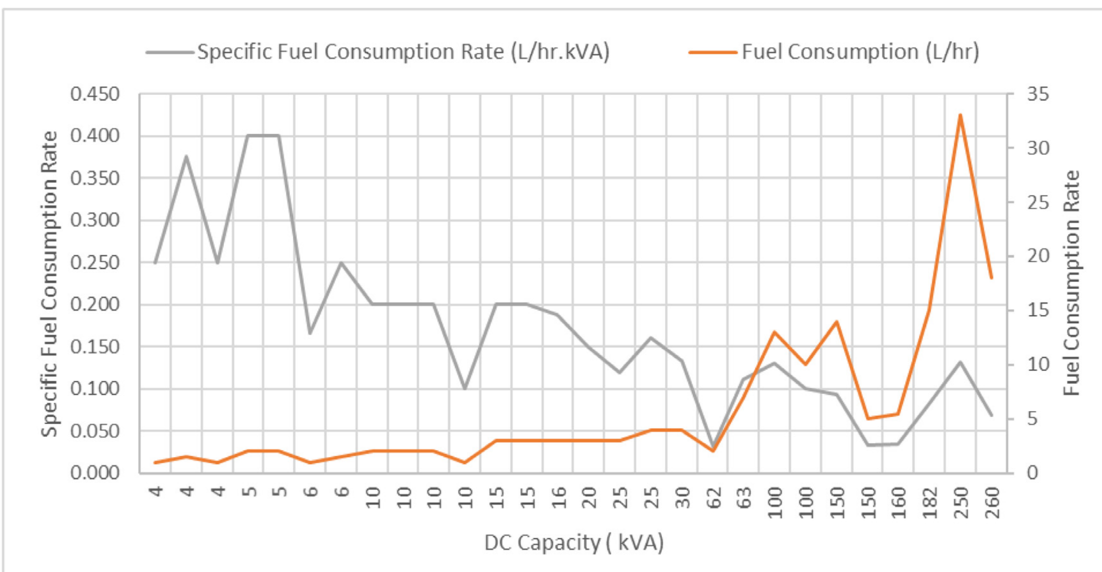
In large size commercial entities, it was not feasible to record the power rating and time of operation for each appliance and estimates (Table 4) were prepared as follows: (1) DG capacity and fuel consumption rate for each DG was noted in the field survey; (2) peak power demand was estimated to be 87% of installed DG capacity and only reached in the day time; (3) the peak power demand in morning, evening, and night was estimated from the peak demand in the daytime using the ratio in demand observed for medium size users as shown in Table 3; and (4) the energy demand was calculated on the basis that the DGs were operated at an average load factor of 60% in the daytime, 36% in the morning, 33% in the evening, and 10% at night, giving an overall average load factor of 40% (based on the average values in the sample surveyed).

The peak power demand for the whole study area during load-shedding hours is slightly higher during the day and evening than in mornings and nights in the wet season (Fig. 5), which is attributed to the use of fans for space cooling. It is slightly higher in the morning in the dry season (Fig. 5), which is attributed to the use of pumps to extract groundwater. The proportion of total energy demand in the whole study area in the morning, day, evening, and night was 16%, 55%, 20%, and 9%, respectively. Although the peak power demand is higher in the morning than in the evening, the energy demand is slightly higher in the evening because the duration of load utilization is longer in the evenings.

The annual energy demand from DGs was calculated by mapping the load-shedding schedule for 2015/16 (Fig. 2, Table 2) to the business operating hours of each entity, as the DGs were only operated during load-shedding in the business hours. The time and duration of operation of appliances were taken from the field survey. The total annual energy demand from the DGs for the



(a)



(b)

Fig. 3. (a) Number of operational DG systems in the study area, (b). Fuel consumption rate with a capacity of DG systems in the study area.

Table 3
Peak power demand (PD) profile in medium-sized entities.

Season	Peak power demand (kW)				Proportion of day peak demand			
	Morning	Day	Evening	Night	Morning	Day	Evening	Night
Dry	86	144	80	17	60%	100%	55%	16%
Wet	90	163	93	26	55%	100%	57%	16%

Table 4
Estimated peak power demand and average daily energy demand of large commercial entities in the study area in different seasons and at different time of day.

Season	Peak power demand (kW)				Average daily energy demand (kWh)			
	Morning	Day	Evening	Night	Morning	Day	Evening	Night
Dry	432	725	401	116	540	1,587	626	290
Wet	399	725	412	115	308	979	397	178

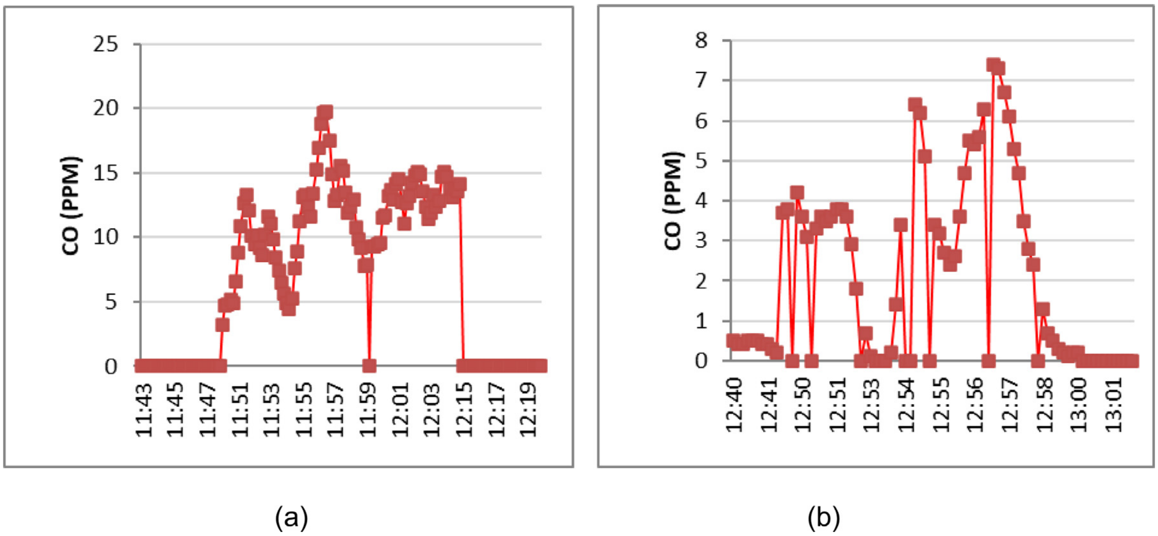


Fig. 4. Ambient mixing ratio of CO (after correcting for the background mixing ratio) measured adjacent to the DGs operated with different loading: (a) 15% load (of a 50 kW DG) (b) 66% load (of a 64 kW DG).

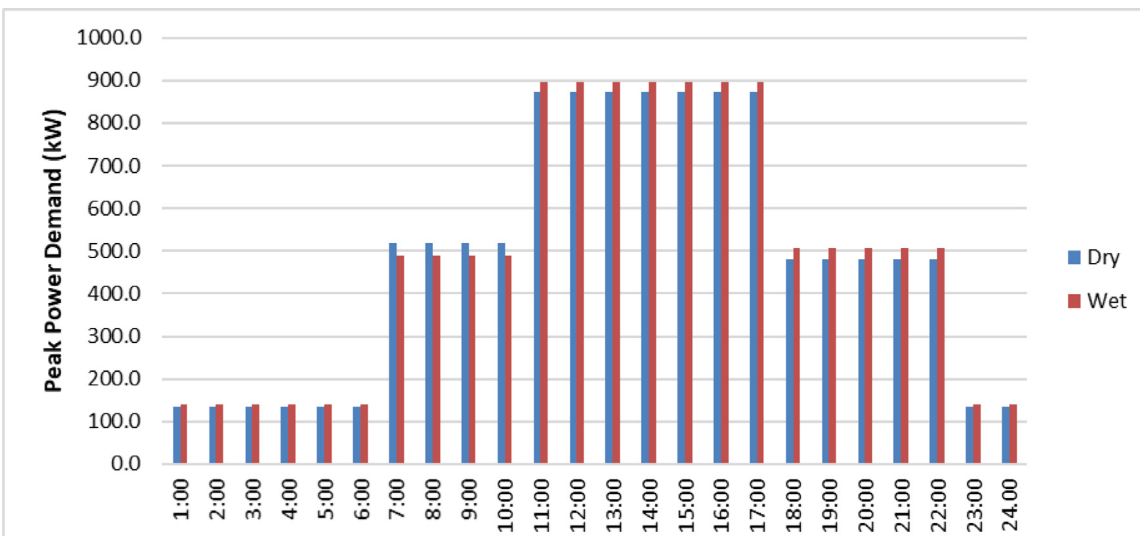


Fig. 5. Hourly peak power demand in the whole study area during different time of day in dry season and wet season.

study area was estimated to be 1177.43 MWh. The annual fuel consumption was calculated from the hourly fuel consumption rate and the annual number of hours of operation of each DG obtained from the survey. The days of the week in which commercial entities operated were taken into consideration when calculating the annual operating hours. The total annual diesel consumption for the study area was estimated to be 370 thousand liters.

3.4. Optimization of the DG based and solar PV based microgrid systems

A DG microgrid system was designed that could provide backup power more efficiently during load-shedding hours while meeting the peak power demand and energy demand fulfilled by the existing system. The input parameters for the HOMER model are summarized in Fig. 6. The seasonal load profile for the DGs in the study area was generated using the field survey data. The annual business operating hours for DGs were estimated by mapping the operating hours of the business entities to the load shedding hours for 2015/2016 as mentioned in Section 2.3. Cost information was taken from the literature and local market. The version of HOMER used for the study does not include parameters such as load-shedding or scheduled power outages. Hence, load-shedding hours were assigned in the system by setting a much higher grid electricity tariff (USD 1000 per unit) during load-shedding hours so that the system avoided taking electricity from the grid and instead operated DGs or solar PV system to minimize the system cost.

The fuel consumption of a generator varies with the generator capacity and load factor. Average fuel consumption charts were used in the HOMER system (Diesel Service & Supply, 2016). Fig. 7 shows a typical efficiency curve for a 150 kW capacity DG.

Various combinations of DGs were tested in the model. The optimum combination was provided by a group of three generators with capacities of 150 kW (DG1), 400 kW (DG2), and 500 kW (DG3). The system was designed to serve a peak load of 888 kW, with a load of around 135 kW during the night, 500 kW during morning and evening, and 900 kW during the day. DG1, DG2 or DG3 are used for loads of <150 kW, 150 to <400 kW, and 400 to <500 kW, respectively; DG1 and DG2 operate simultaneously for

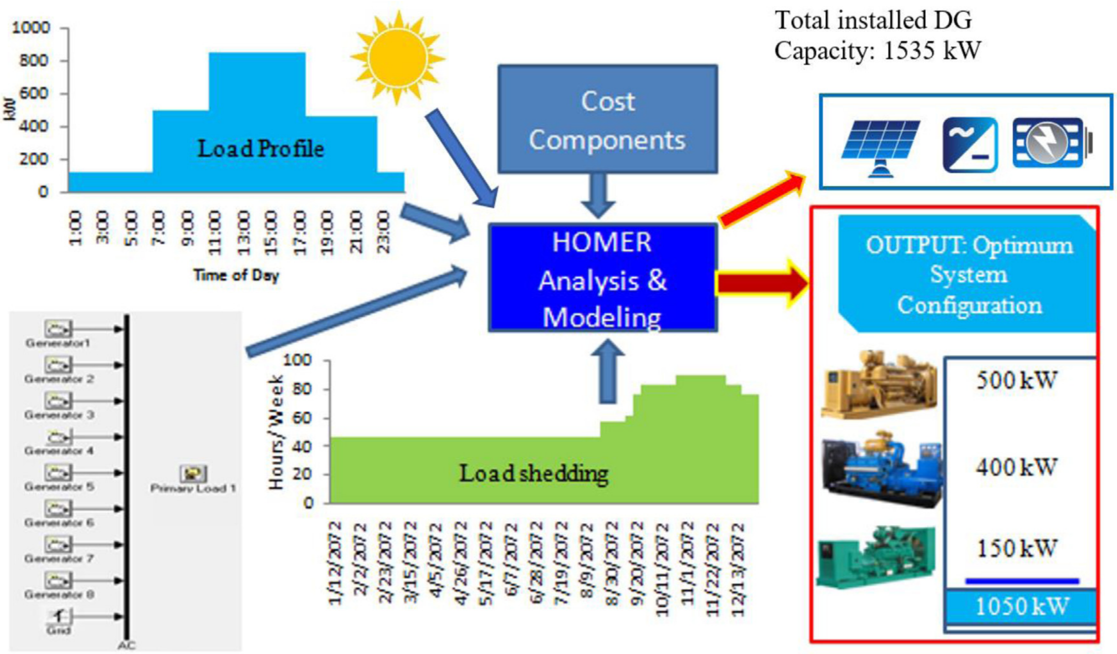


Fig. 6. HOMER optimization input parameters used in the analysis.

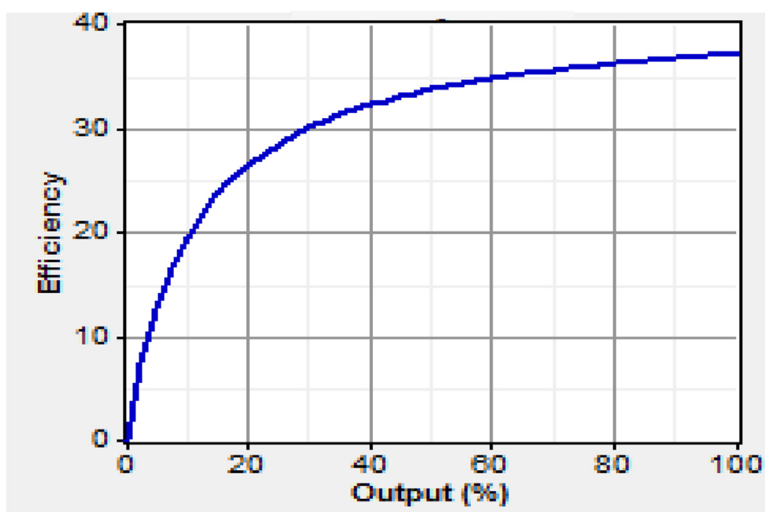


Fig. 7. Efficiency curve for a 150 kW generator (HOMER Energy, 2016).

loads of 500 to <650 kW with equal load-sharing; and DG2 and DG3 operate simultaneously for loads ≥650 kW. The generators are designed to operate at the highest loading possible to maximize fuel consumption efficiency. Fig. 8 shows the percentage loading of generators for different combinations during operation. Most of the time, the loading is greater than 70%, which results in lower emissions and reduced fuel consumption per unit of power produced.

Table 5 shows the consumption and emission values calculated for the existing system – with 28 separate captive DGs – and the HOMER optimized microgrid system. Both systems are designed to meet a peak power demand of 888 kW and annual energy demand of 1177 MWh, but the existing installed capacity of 1535 kW could be reduced to 1050 kW in the optimized system, providing ca. 32% reduction in installed capacity and a 19% reduction in specific fuel consumption indicating improvement in energy efficiency of electricity supply. This is equivalent to an annual saving of 80,700 L diesel, with a total value of USD 56,490 at a cost of USD 0.7 per liter. This indicates a potential for microgrids to both reduce emissions and help improve energy security and economic vulnerability by reducing the volume of imports (diesel, DGs etc.).

The optimal system design of solar PV power supply system consists of 602 kW of solar PV panels, 131 kW inverter, and 1330 kWh Lead Acid battery system. Altogether 1,278,296 kWh of electricity is required to supply from the system where solar PV contributes 75.9% and the rest by the grid for battery charging to supply electricity during the nighttime load-shedding period.

3.5. Emissions of air pollutants

The carbon mass balance method was used to calculate the emission factor (g/L) for CO, VOCs, $PM_{2.5,}$ and PM_{10} for the 15 DGs based on their concentrations measured at the site. The scatter diagrams were plotted against generator capacity for each emission factor. A representative curve of best fit was plotted on

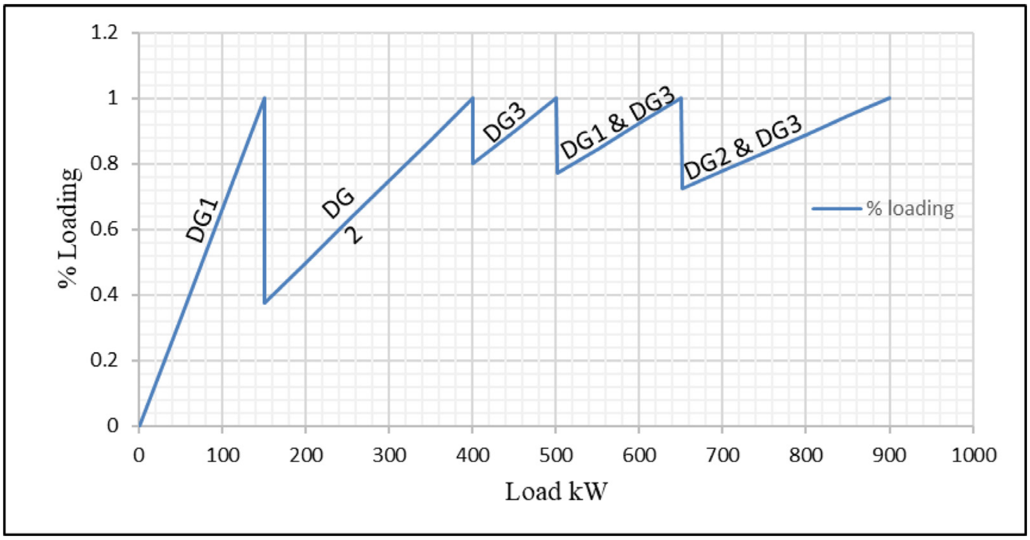


Fig. 8. Percentage loading of generators for operation at different total peak loads.

Table 5
Energy and fuel consumption under the existing system and the HOMER-optimized system.

Parameter	Existing system	DG microgrid system	Solar PV microgrid system
Capacity (kW)	1,535	1,050	602
Energy consumption (MWh/year)	1,177	1,177	1,177
Specific fuel consumption (L/kWh)	0.31	0.25	0

Table 6
Emission factors (EF) of selected pollutants.

Pollutant	EF equation[a]	Average EF[b] (g/L)
$PM_{2.5}$	$y_1 = 0.1089e^{-0.005x}$	0.08
PM_{10}	$y_2 = -0.10\ \ln(x) + 0.884$	0.55
CO	$y_3 = 29.276e^{-0.016x}$	16.78
VOCs	$y_4 = 9.7168e^{-0.008x}$	6.79

[a]x = DG capacity and y = emission factor (g/L).
[b]Average of all sampled DGs.

the scatter diagram to estimate the emission factors for the air pollutants (Fig. 9). The net annual emission of $PM_{2.5}$, VOCs, and CO from the captive DGs was estimated using the average emission factors obtained from fitting the curves (Table 6). The average emission factors were comparable to other previous studies (EEA, 2019; Sadavarte et al., 2019; Shrestha et al., 2013; Sothea and Kim Oanh, 2019; USEPA, 2000). The average AP emission factor was multiplied by the annual fuel consumption in the study area to obtain the net emission of each pollutant. Table 7 shows the emission intensity per kWh and calculated net annual emission of each pollutant.

The AP emissions from the optimized microgrid system were calculated using the HOMER optimization tool. The annual emissions per kWh and total emissions for the existing and microgrid system are summarized in Table 7. The estimated emissions from the optimized system were markedly lower than from the existing system, with significant reductions in total $PM_{2.5}$, PM_{10}, CO, and VOCs ranging from 21 to 92%. In case of the solar PV based microgrid, there is complete fuel switching from the emission-intensive diesel fuel to the clean source of solar energy thus contributing 100% reduction in emissions of air pollutants. In addition, the solar PV-based microgrid helps to avoid the use of 375,807 liters of diesel resulting in 976,275 kg of CO_2 emission reduction annually considering the average CO_2 emission factor of 2597.81 g/L measured (by using a test meter Gray Wolf Sensing Solutions IQ-610, USA) from the 13 DGs in the site thus supporting the efforts aimed at global climate change mitigation.

3.6. Financial analysis

A detailed financial analysis was made taking into account both the initial investment and various operating costs. The levelized cost of electricity (LCOE) was calculated for the different scenarios.

The capital costs for the microgrid project include the initial cost of the generators, solar PV with a storage system and the components required for a distribution system (see supplementary file for details of the distribution system). The capital cost was estimated to be USD 373,677, 85% of which is for the purchase of fixed assets (DGs: 41%; transformer: 22%; electrical accessories such as wires, poles, switching, and protection equipment: 22%), 9% for contingencies, and 6% for installation and labor. The running costs were calculated using a fuel cost of USD 0.66 (NPR 73) per liter for diesel as in the base year (NOC, 2016), a variable maintenance cost for the generators of USD 0.1 per hour of operation (Abdilahi et al., 2014), annual maintenance cost for the grid system of 1% of the initial cost, and maintenance overhaul of the generators every 6000 h of operation costing USD 9450. The fixed operating costs include debt payment, insurance, remuneration, and rental charges. DG life was assumed to be 15 years (Kumar et al., 2015). A discount rate of 6% was taken for estimating the LCOE following (Kumar et al., 2015).

The capital cost investment for the solar PV system including solar PV panels, battery bank, and inverter was estimated as USD 1,942,858. The battery replacement cost after ten years of operation is considered as USD 228,718.

When calculating the costs of the existing system, generator life was taken to be the average remaining life of the generators, fuel price was fixed at the level in the base year, and maintenance was assumed to be optimal. A further scenario was considered with redeployment of the existing DG sets which were purchased

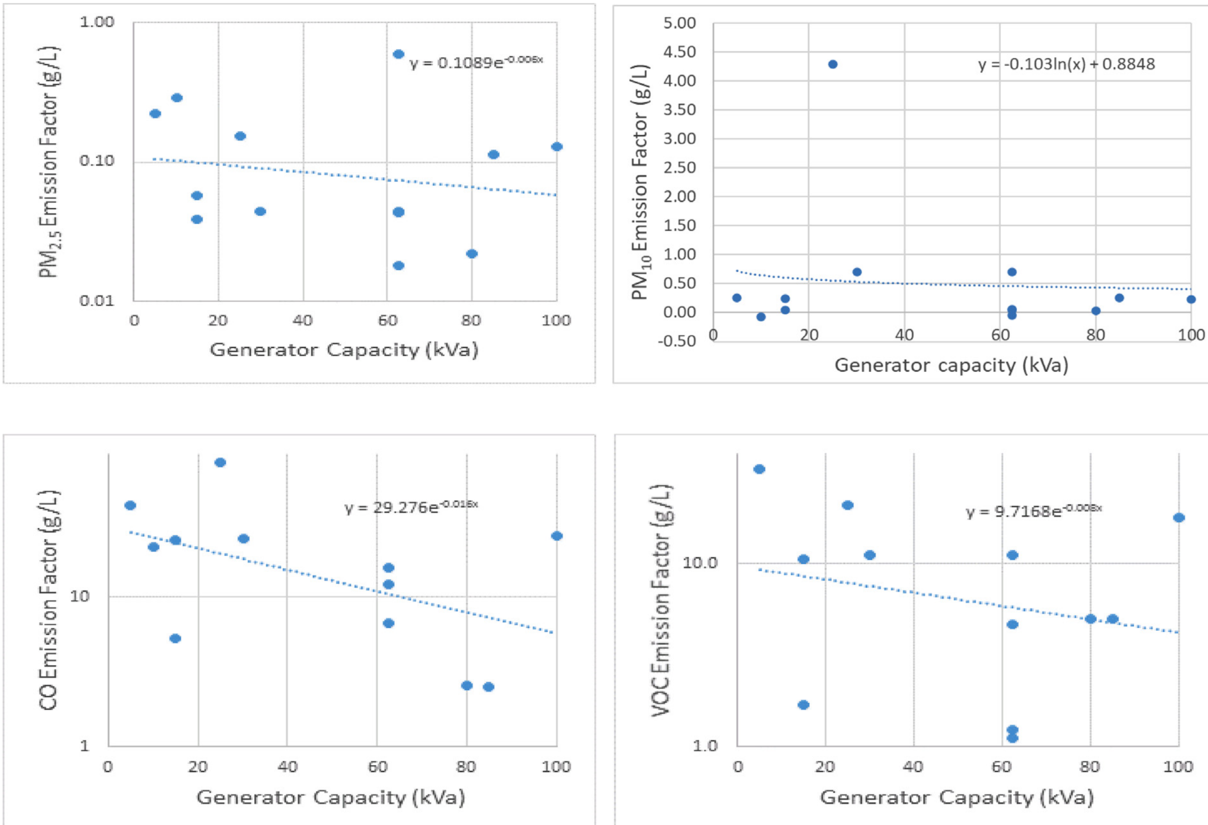


Fig. 9. DG capacity and emission factor for individual air pollutant.

Table 7
Annual emissions of air pollutants from the existing system and microgrid system.

	$PM_{2.5}$		PM_{10}		CO		VOCs	
	g/kWh	kg	g/kWh	kg	g/kWh	kg	g/kWh	kg
Existing system	0.031	31.8	0.204	206.3	6.24	6,305	2.52	2,553
Microgrid system	0.022[a]	23.0	0.161[b]	163.0	1.86[c]	1,879	0.21[d]	208
% reduction	27.7	27.7	21.0	21.0	70.2	70.2	91.9	91.9

[a] 1.89 g/kWh using 9.17 g/kg from Sadavarte et al. (2019); 0.07 g/kWh using 5.6 g/GJ from Shrestha et al. (2013); 1.4 g/kWh from Gilmore et al. (2010).
[b] 0.10 g/kWh using 7.7 g/GJ from Shrestha et al. (2013); 0.22 g/kWh using 1.05 g/kg from Sothea and Kim Oanh (2019).
[c] 5.84 g/kWh using 28.31 g/kg from Sadavarte et al. (2019); 0.19 g/kWh using 15 g/GJ from Shrestha et al. (2013); 2.05 g/kWh using 9.92 g/kg from Sothea and Kim Oanh (2019); 6.40 g/kWh from Gilmore et al. (2010).
[d] 0.54 g/kWh using 2.62 g/kg from Sadavarte et al. (2019); 0.062 g/kWh using 5 g/GJ from Shrestha et al. (2013).

at a depreciated value (25% cost reduction) rather than buying new DGs, with the remaining life taken to be 15 years. All other hardware and costs were the same as in the optimized system.

The average cost (LCOE) of existing distributed captive generation is found to be 0.35 USD/kWh and that for microgrid systems are estimated to be 0.33 USD/kWh and 0.31 USD/kWh for optimized and redeployment options, respectively. Similar costs have been reported in other countries for using backup generators with the range of 0.20 USD/kWh to 0.6 USD/kWh (Lam et al., 2019). The LCOE for the optimized microgrid system is only 4% lower than for the existing system, despite the saving in fuel and reduction in generator capacity. This is mainly because of the high capital costs of the new transformers, control system, and grid accessories, none of which are required under the existing system. Further, the optimized system requires a dedicated team for operation and maintenance. Redeployment of existing DG sets would result in 11% lower LCOE. Thus, introducing an optimized DG microgrid system is marginally cheaper than the existing captive DG generation.

If we introduced a solar PV integrated microgrid system, it will be slightly more expensive, by 27% (LCOE: 0.44 USD/kWh). But, if we considered other non-monetary benefits in terms of improvement in the local environment (due to mitigation of air pollution and sound pollution), reduction in a health hazard and improvement in energy supply security the PV integrated system could be beneficial in the multiple folds compared to the existing system (see Table 8).

3.7. Reaping the benefits — the need for a national policy

The study outlines the potential for improving energy efficiency and reducing emissions of air pollutants from DGs used during planned electricity outages by switching from individual captive use of DGs to a microgrid option. One of the key issues,

Table 8
Levelized cost of electricity (LCOE) for different scenarios.

Scenario	LCOE (USD/kWh)
Existing DG system	0.35
Optimized DG microgrid system	0.33
Re-deployment of existing DGs	0.31
Solar PV with battery storage microgrid system	0.44

however, is whether it would be feasible to develop a provision for microgrids in parallel to the central grid. The feasibility will differ according to specific conditions of the country as it depends on the national policy setting.

We looked at the feasibility of developing microgrids in the grid-connected urban area of Nepal with an irregular power supply; similar considerations are likely to apply elsewhere. There are three main policy issues or questions: would the government permit microgrids to be established to generate electricity? would it permit microgrids to set up their own transmission and distribution networks or use the existing networks for a fee?, and would it permit microgrids to sell electricity at a price commensurate with the generation cost? In principle, it seems that all three are possible. Nepal's Rural Energy Policy 2006 has provisions for building interconnections and then selling power to the central grid as and when this is extended to particular areas. However, the question is the extent to which this could also apply in urban areas where a central grid already exists. The Electricity Act 1992 (MoE, 1992) deals with supplying power in areas where there is a supply from the central grid, but it does not address the situation when there is no supply from the central grid due to planned power cuts, and it is not clear if its clauses allow the establishment of microgrids in urban areas. Further, it does not permit multiple licenses for distribution networks. So, in contrast to the situation in rural areas, urban microgrids would not be allowed to develop their own transmission and distribution networks. They would have to use the existing networks for a fee.

Recently Government of Nepal introduced the scheme to purchase electricity generated from renewable energy through a power purchase agreement and advocate the installation of rooftop solar PV systems in the urban areas to improve supply security through distributed generation and import fuel substitution. In line with this, it has been observed that after the partial lifting of load-shedding since 2015 nearly 500 MW of DGs have been staying in idle condition with huge capital investment locked in this sector. If the solar PV-based microgrid has been installed, the investor could have sold the excess electricity generated to the national utility.

Although the optimized microgrid system described here does not provide much financial benefit to consumers, the overall economic benefit to the country can be quite significant once the external costs of pollutant emissions, health hazards, and energy security are considered. Thus, the government should carefully consider developing policies that will enable or even support interested parties to install microgrids preferable with renewable energy to provide backup power where appropriate. The policies will need to be sufficiently comprehensive to cover different sources of electricity as well their hybrids.

The ideal solution for reliable electricity access would be to ensure a sufficient continuous supply from the central grid. Contrary to that, backup generators are a major source of electricity access in many developing regions, providing as high as 40% of the electricity consumed in western Africa, 9% in Sub-Saharan Africa, and 2% in South Asia (Lam et al., 2019). However, in many developing countries with fast urbanization and economic growth, electricity demand is likely to increase by many folds in the future, continuing to outstrip supply. The continued need for load-shedding in these countries is seen as a reality for some years though there is gradual improvement in the capacity of electrical power infrastructure (Lam et al., 2019; Murphy et al., 2014). Meantime, at least for a short to medium run, the development of microgrids with existing DG systems or solar PV systems could be a viable solution for electricity supply in these countries as well.

4. Conclusions and policy implications

Sustainable supply of electricity is a major requirement for economic activities, but it is both insufficient and unreliable in most developing countries, forcing them to rely on captive power generation, such as diesel power generators (DGs), to ensure their power supply during grid power outages. This has resulted in high levels of ambient air pollutants emissions causing the increase in premature death and adverse impacts on crops, ecosystems, and climate in the region. Reducing these emissions can be an important component in clean air strategies, particularly in urban areas. Besides, UN Sustainable Development Goal (SDG) 7 emphasizes the use of clean, renewable, and efficient energy to improve energy access. In this context, this study tries to fill some research gap related to the original data measurement related to the emission level of ambient air pollutants under different operating conditions and capacities of DGs, possibility of reducing the emissions and improving the efficiency of power production through DG based and solar PV based microgrid systems in a typical urban area with intermittent grid power supply.

The captive diesel generators operating in isolation in the Kathmandu Valley to provide backup power during load-shedding hours were not operating efficiently and are emitting high levels of air pollutants, as shown by a case study in a commercial area in Baneshwar, Kathmandu. The emissions are a major human health risk and contribute to degradation of local environment, while sub-optimal efficiency also increases the requirement for imports of diesel oil, further contributing to the trade imbalance and reduction in energy security.

Most of the captive DGs surveyed were oversized with an average loading of just 40%. The average loading can be increased to more than 70% and improve energy efficiency resulting 19% reduction in specific fuel consumption by introducing an optimized DGs based microgrid system. The microgrid can reduce emissions of key air pollutants: $PM_{2.5}$, PM_{10}, CO, and VOCs by 28%, 21%, 70%, and 92%, respectively, compared to the existing system with isolated DGs. The levelized cost of electricity (LCOE) of the existing isolated system (USD 0.35/kWh) was higher than the optimized microgrid system (USD 0.33/kWh). The cost was further reduced to USD 0.31/kWh if the existing DGs were redeployed. Furthermore, if solar PV based microgrid is used the emissions of air pollutants can be reduced by 100% but the cost of electricity generation would increase by 27%. However, although the direct economic benefit to the consumer is low, the overall economic benefit to the country can be quite significant once the external costs of air pollution, health hazards, and energy security are considered.

There is a need for an effective national policy to address issues related to the mitigation of air pollutants, harmful to public health and environment, from the inefficient use of fossil fuel-based captive DGs. Implementation of microgrid and use of renewable energy sources like solar PV could provide a short to medium-term contribution to addressing the problem of electricity shortages and load-shedding in the industrial and commercial sectors in Nepal, and in other developing countries, and can also deliver multiple co-benefits as mentioned above. Governments should carefully consider developing policies that will enable or even support interested parties to install microgrids preferably with renewable energy to provide backup power during scheduled power cuts in the supply constraint regions of Nepal and other developing countries which face a similar situation.

CRediT authorship contribution statement

Shree Raj Shakya: Conceptualization, Methodology, Software, Writing – original draft. **Iswor Bajracharya:** Data curation, Financial analysis. **Ramesh Ananda Vaidya:** Methodology, Policy analysis. **Prakash Bhave:** Data curation, Visualization, Emission factor. **Anzoo Sharma:** Data collection, Software. **Maheswar Rupakheti:** Writing – review & editing. **Tri Ratna Bajracharya:** Data collection facilitation and review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2022.02.084.

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