Electrical Power and Energy Systems 132 (2021) 107137

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Optimal and economic operation of microgrids to leverage resilience benefits during grid outages

Hasan Masrur [a,*], Ayyoob Sharifi [b,c], Md. Rabiul Islam [d], Md. Alamgir Hossain [e], Tomonobu Senjyu [a]

[a] Faculty of Engineering, University of the Ryukyus, 1 Senbaru, Okinawa 903-0213, Japan
[b] Graduate School of Humanities and Social Sciences & Network for Education and Research on Peace and Sustainability, Hiroshima University, Japan
[c] Graduate School of Advanced Science and Engineering, Hiroshima University, Japan
[d] School of Electrical, Computer and Telecommunication Engineering, University of Wollongong, NSW 2522, Australia
[e] Queensland Micro- and Nanotechnology Centre, Griffith University, Nathan 4111, Australia

ARTICLE INFO

Keywords:
Power resilience
Grid outages
Solar photovoltaics
Microgrids
Batteries
Simulation and optimization

ABSTRACT

With the rapid proliferation of power supply via the national grid, energy resiliency in unforeseen outages has to be ensured. However, the resilience advantages of microgrids concerning power failure endurance, which also result in financial disbursements, are little explored in available academic research. Hence, this study proposes an airport microgrid tied with the grid, which increases a host critical facility's resiliency under different circumstances, using an optimized dispatch of renewable energy technology (Photovoltaics) with energy storage and diesel generator. First, the proposed system's superiority is established in terms of technical and economic values by comparing with other feasible hybrid and standalone configurations feeding critical loads. Then, the resilience benefits from the microgrid during blackout occurrences are examined through a case study under four different scenarios. Finally, the microgrids' survival probability during a significant outage over any time in a year has been carried out. Results show that the critical facility subject to the proposed system's deployment, can save more than 73 thousand US dollars on average, over 25 years of the life cycle, and withstand 718 hours of grid outage.

1. Introduction

Power resilience has become a crucial issue due to the concerns over blackouts and brownouts occurring worldwide [1,2]. While people now have access to electricity more than ever, grid interruptions are still an acute problem due to various factors such as increasing demand, vandalism, and the climate change-induced increase in the intensity and frequency of extreme events. The resilience of the power system focuses on avoiding power loss and restoring electricity supply as soon as possible when an outage occurs while minimizing the effects of the outage [3]. Traditionally, diesel-fired generators have been providing backup power in case of such emergencies. However, renewable energy (RE) based microgrids are gradually replacing them and contributing to the energy resiliency worldwide [4–7].

A microgrid (consisting of small-scale emerging generators, loads, energy storage elements and control units) is an autonomous and controlled small-scale power system that can be operated both in a grid-isolated or grid-connected mode in a defined area to facilitate the provision of supplementary power and/or maintain a standard service [8]. Unlike conventional backup generators, RE based microgrid serves the load demand during normal conditions pairing with the utility grid. The diesel generators are usually unused for a long period, making them aged and unreliable during an emergency. Besides, lack of fueling options and fuel supply interventions in these types of generators have caused inefficiency over the years [9]. While traditional stand-alone diesel-fired generators provide power during minor outages of low impact, it may not be a reasonable choice to solely rely on them without other on-site power sources (such as batteries and renewables) in the event of major power outages caused by high-impact natural disasters [10]. At the same time, the world is encountering heavy magnitude and frequent weather-related damages. For instance, in the United States (US), a recent study has pointed out that grid outages could have adversely affected at least 15 million critical infrastructure facilities across seven sectors. These facilities represent around 570 terawatt-hours of load and an outage could cost more than $700 billion [11].

* Corresponding author.
E-mail addresses: k198676@eve.u-ryukyu.ac.jp, hmasrur@gmail.com (H. Masrur).

https://doi.org/10.1016/j.ijepes.2021.107137
Received 25 November 2020; Received in revised form 20 February 2021; Accepted 19 April 2021
Available online 24 May 2021
0142-0615/

Nomenclature

Indices and sets

$t \in \mathscr{T}$	set of energy technologies (solar PV = PV and G = grid and Dg = Diesel Genset)
$l \in \mathscr{L}$	set of loads; l^S for site load, l^B for Battery load, l^{Ex} for export
$h \in \mathscr{H}$	set of time steps
$r \in \mathscr{R}$	set of all ratchets
$s \in \mathscr{S}$	set of all locations
$v \in \mathscr{V}$	set of net metering levels
$m \in \mathscr{M}$	set of all months

Parameters

F_{dths}	hourly capacity factor for demand d for energy technology t in time step h at locations s (unitless)
F_t^{dgr}	degradation factor for technology t (unitless)
F_{tlh}^{pd}	production factor for technology t, serving load l, in timestep h (unitless)
c_t	capital cost for technology t ($/kW)
c_t^{om}	O&M cost per unit size of the system for technology t ($/kW)
c_h^e	electricity cost in time step h ($/kW)
c_r^d	demand cost for ratchet r
c_m^d	demand cost for month m
c_{kWh}^b	capital cost of battery per kWh ($/kWh)
c_{kW}^b	capital cost of storage inverter per kW ($/kW)
L_{lh}	production size restriction for load l in time step h(kW)
L_{sv}^{NEM}	capacity of net metering level v at location s
B_{max}^{kWh}	maximum storage capacity of the battery (kWh)
B_{max}^{kW}	maximum size of the battery (kW)
$B^{SOC_{min}}$	minimum state of charge of battery (%)
η_B	battery (round trip inverter) efficiency

Variables

X_t	system size for energy technology t (kW)
P_{tlh}	Rated production of technology t, serving load l. in timestep h (kW)
d_r	peak demand in ratchet r (kW)
d_m	monthly peak demand for month m (kW)
$Z_h^{B^+}$	1 if battery is being charged in h time step, 0 otherwise
$Z_h^{B^-}$	1 if battery is being discharged in h time step, 0 otherwise
Y_{sv}	1 if operated at Net metering level v for location s, 0 otherwise
B^{kWh}	The battery capacity (kWh)
B^{kW}	Battery system size (kW)
B_h^+	power delivered to the battery in time step h (kW)
B_h^-	power delivered to the battery in time step h (kW)
B_h^{SOC}	Energy stored in battery in time step h (kWh)

The US, like the rest of the world, has been experiencing power outages because of severe weather conditions followed by fuel supply emergency, intentional attack (vandalism), public appeal made by utility (for a reduction in the use of electricity to safeguard the continuity of the electric grid), equipment failure, system operability disruption and faulty islanding [12]. Over the last one and half decades, the US has endured around 161,462 hours of power cut affecting approximately 157 million customers with 445 gigawatt (GW) demand loss [13] which makes the federal agencies and governments betting on microgrids.

In this context, microgrids are playing a vital role in providing continuous backup power during a grid outage. Microgrids can tackle or limit outages to critical loads by unplugging from the utility grid subject to a fault (islanding), and by detaching dispatchable or controllable loads, where necessary. Most often, after a system-wide shutdown, they provide *black start* and *cold load* pick up support over the restoration phase, which may be longer than 12 hours considering the aging electric network [14]. Moreover, they have become more cost-effective due to the significant decline in prices of RE technologies in recent years. Therefore, microgrids have drawn enormous attention, specially to the critical infrastructures to survive the prolonged outages by receiving reliable as well as economic power supply and already have proven their worthiness [15]. Again, RE based microgrid offers clean energy, which makes it more appealing for adoption. Some utilities support grid-tied microgrids because of the increased reliability of microgrids, especially in times of disaster [16] despite having regulatory and monetary issues [17].

Since the critical infrastructures, including airports, can not afford a power cut, microgrids' support goes beyond the monetary value and is considered a 'lifesaving' service. Governments are providing incentives and soft loans to both on-grid and off-grid RE systems, i.e. microgrids [18,19]. Microgrids can operate on a number of 'behind the meter energy assets' renewables, typical diesel generators, battery storage devices, microturbines powered by natural gas, or even evolving technologies like fuel cells. However, to leverage maximum resilience benefits, particularly during bulk grid disruption, these power sources must be optimized and dispatched accordingly for a specific site and time-frame.

Most of the previous works have implemented multi-objective optimization model for optimal sizing and dispatching of microgrids disregarding the resilience value. They have mainly focused on techno-economic-environmental performance enhancement of microgrids from demand response [20,21], energy arbitrage [21], load flexibility [22,23], lowering the loss of load probability (LOLP) [24], peak shaving [25,26] minimum capital and operating cost [23,27,28], maximum use of renewables and reduced greenhouse gas (GHG) emission [27,28]. Very little work has been done to quantify grid-connected microgrids' resilience value, specially during grid disruption. Zhou et al., [24] proposed an optimization model that shows the significance of battery capacity and price to affect the system cost and LOLP. Tsianikas et al. adopted the same approach focusing on the value of lost load (VoLL) and battery price to quantify and monetize the resilience value [29]. However, outage simulation was disregarded for both cases. Laws et al. [30] designed a techno-economic optimization model comprising Photovoltaics (PV) and Battery for different commercial buildings in three cities of USA and found out the resilience benefits worth $50,000 with a $5,317/hr 'value of resilience'. The cost of islanding of the microgrid along with outage cost sensitivity were discussed broadly; however, they did not discuss the dispatch strategy of the microgrid in case the grid fails. The added techno-economic advantage of PV-Battery based hospital microgrid is described in [31]. Although it achieved 4 h of extended survivability and saved $112,410 because of the adopted resilience measures, scenario analysis during blackouts was overlooked. Anderson et al., [32] presented a methodology to increase the resiliency of a building microgrid system in New York, which survives the outage with a substantial economic gain but did not describe the dispatch strategy and sensitivity of the system in various scenarios. Wu et al. formulated a stochastic two-stage optimization model that found the optimal size of the distributed energy resources (DER) in a military base, but the cost of resiliency increases with the elevated outage survivability [33]. In [34], Ashraf et al. optimized a PV/Diesel/Battery system in Gobi Desert of

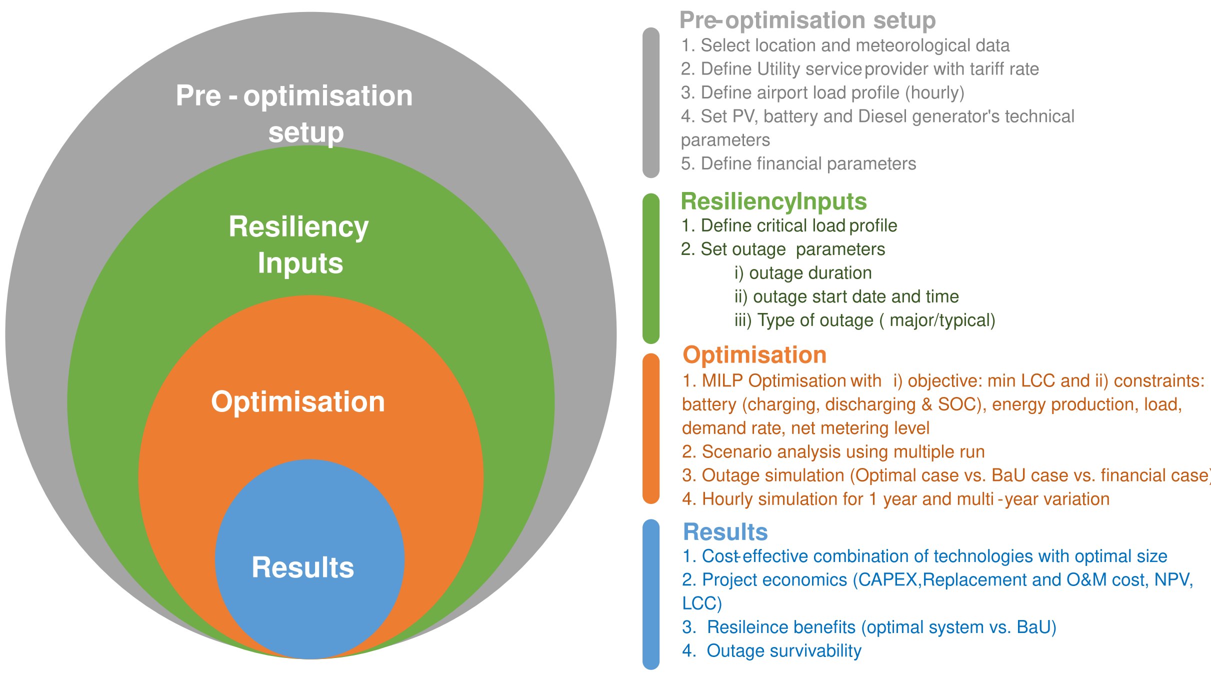

Fig. 1. Steps for overall research methodology.

China using Particle Swarm Optimisation (PSO) based algorithm to assess the optimal cost and environmental impact of their proposed system without considering any resiliency analysis. It is the same for the proposed Kenyan Marsabit county microgrid by Kiptoo et al. [20] although they considered demand response as mentioned earlier.

The work presented in this paper optimizes a grid-tied microgrid system to provide backup power during grid interruptions at a minimum life cycle cost (LCC) within a critical infrastructure. To fill the inadequacy of literature in terms of dispatch strategy during different operational and climatic situations, this work describes the energy dispatch scheme of the proposed microgrid system while grasping the maximum resilience benefits. Our approach includes outage simulation as well. Hence, the contribution of this study is threefold: (a) assessment of the economic viability of a grid-connected microgrid consisting of PV and battery storage with diesel genset for a particular site which can be translated to other locations as well, (b) estimation of the optimal energy mix and dispatch strategies to lower energy costs and most importantly, (c) evaluation of the probability of surviving outages compared to business as usual case.

Resiliency tests a system's (or device) ability to withstand and heal from significant destructive events, such as natural hazards, intentional incursions, or accidents. Typically, resilience measures are implemented within different stages- planning, absorption, recovery and adaptation [35]. In the point of view of power grids, the resilience emphasis is on preserving the supply of energy before, during, and after these destructive events. Power Resilience is itself a complicated and broad process [36–38], however, this study does not account for 'infrastructure' resilience, instead focuses on enhancing 'operational' resilience. While we acknowledge the significance of planning and adaptation stages, in this study our main focus is on the absorption, and to some extent the recovery capacity. In other words, the emphasis is on the ability to maintain energy supply during and after the shock and also ensure rapid recovery in case the system loses some of its functionality.

Although the proposed system's resilience benefits can be realized within the regular operation connecting to the main grid, this work particularly conceived the idea of resilience under blackout conditions. It is worth noting that the net present value (NPV), PV/battery capacity and the overall dispatch strategy would vary under different net metering rates, time of use (ToU), peak period starting hour and demand charge regardless of outage duration and condition [39]. This is, however, not the scope of the current study. The microgrid system, under investigation, can sell power to the utility grid and exchange other services during regular grid operations outside of the blackout hours.

The remainder of this study is categorized as follows; Section 2 describes the adopted materials and methodology, Section 3 describes the results, and the last section contains the concluding remarks with recommended future works.

2. Materials and methods

This section describes the selected case study and explains the research methodology which involves the optimisation framework. Further, it provides a comprehensive discussion on the model inputs and their characteristics. The steps for the overall study approach and followed procedure are shown in Fig. 1.

2.1. Case study

In the US, airports are accountable for around 2.3% of energy consumption of the total critical infrastructure consumption. Amongst the transportation sector, they have the third-largest load demand followed by sea ports and gas stations [11]. Since the past few years, Massachusetts (MA) has been encountering grid outages mainly because of the system operability disruptions and extreme weather. Logan International Airport, located in Boston, MA, US, is chosen as a case study. In 2017, the airport suffered from a power outage for nine long hours, which led to more than 900 Delta mainline and regional flights cancellations. Almost 50 flights were redirected to other airports [40]. Anyway, through this airport, more than 40 airlines operate non-stop flights to over 100 domestic and international destinations. It covers an area of 2,384 acres (9,502,019 square meters). As of January 2020, 33,001 flights have operated with 2,940,985 number of passengers excluding the cargo and mail flights. More information can be found at [41]. Even if it can lead to a particular case study, its attributes and applicability make it possible to deduce and emulate the findings to other related critical infrastructures worldwide and, specifically, in the US.

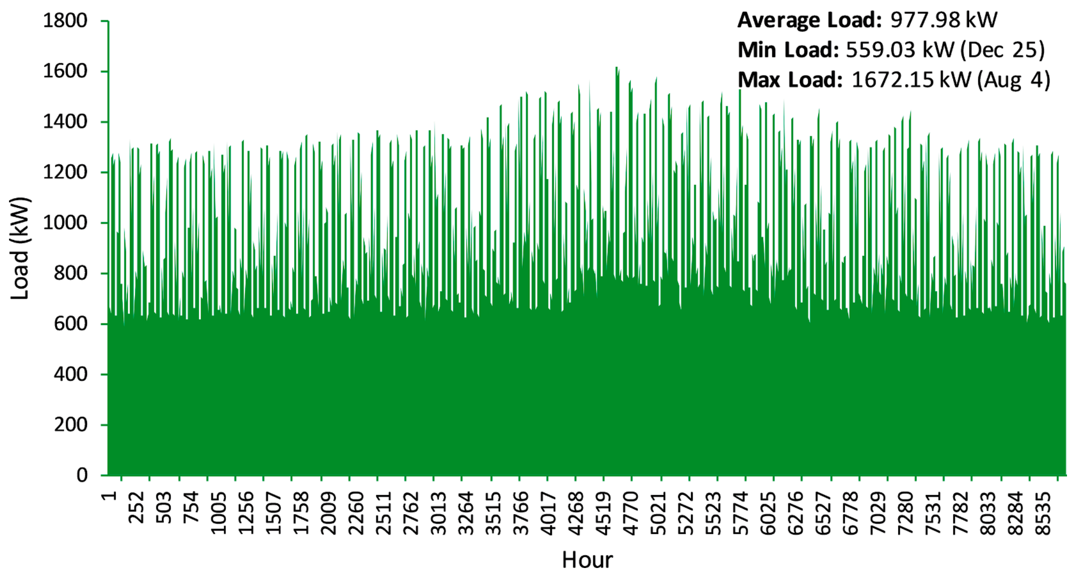

Fig. 2. Annual load demand of the airport.

2.2. Optimization problem formulation

This study have used a modified mixed-integer linear program (MILP) to solve the optimization problem via REopt tool [42]. It derives the optimal selection, sizing, and dispatch scheme of power generators for a specific site while assuring the minimum life cycle cost (LCC) over project lifetime. The objective function of this optimisation problem can be formulated as:

$$\min LCC = \min\left(C_{Eg} + C_{Dn} + C_{BDgPV} + C_{OM}\right) \quad (1)$$

where, C_{Eg} represents the energy costs, C_{Dn} refers to the demand cost, C_{BDgPV} denotes the capital cost of PV, battery and Diesel generator and finally, C_{OM} is the cost of operation & maintenance of the airport microgrid.

$$C_{Eg} = \sum_{l\,\in\,\mathcal{L},\; h\,\in\,\mathcal{H}} \left(F^{pd}_{tlh} * P_{tlh} * c^{e}_{h}\right) \quad (2)$$

$$C_{BDgPV} = \sum_{t\,\in\,\mathcal{T}} (X_t * c_t) + (B^{kWh} * c^{b}_{kWh}) + (B^{kW} * c^{b}_{kW}) \quad (3)$$

$$C_{Dn} = \sum_{r\,\in\,\mathcal{R}} (d_r * c^{d}_{r}) + \sum_{m\,\in\,\mathcal{M}} (d_m * c^{d}_{m}) \quad (4)$$

$$C_{OM} = \sum_{t\,\in\,\mathcal{T}} (X_t * c^{om}_{t}) \quad (5)$$

The life cycle cost is minimized subject to the following constraints:

$$\sum_{t\,\in\,\mathcal{T}} \left(F^{pd}_{tl^{Ex}h} * P_{tl^{Ex}h} * F^{dgr}_{t}\right) \leqslant L_{lh}, \qquad \forall\, h \in \mathcal{H} \quad (6)$$

$$\sum_{t\,\in\,\mathcal{T}} F^{pd}_{tl^{B}h} * P_{tl^{Ex}h} * F^{dgr}_{t} \; + \; B^{-}_{h} \leqslant L_{lh}, \qquad \forall\, h \in \mathcal{H} \quad (7)$$

$$\sum_{h\,\in\,\mathcal{H}} F^{pd}_{PVDglh} * P_{PVDglh} * F^{dgr}_{PVDg} \leqslant \sum_{h\,\in\,\mathcal{H}} L_{l^{S}h}, \qquad \forall\, l \in \mathcal{L} \quad (8)$$

Eq. 6 to Eq. 8 define the load constraints. Eq. 6 requires the sum of the energy on-site demand to be less than or equal to the maximum load for each phase of all energy sources. The next equation demands a certain mix of sources of power (PV, DG and grid) and battery to meet the site load each time. Eq. 8 allows the amount of all PV- and DG-produced electricity to be lower or equal to the annual load at the airport.

Eq. 9 states the production constraint that the rated power provided by the PV system has to be equivalent to the system size selected in each phase over all loads.

$$\sum_{l\,\in\,\mathcal{L}} P_{tlh} \leqslant X_{th}, \qquad \forall\, h \in \mathcal{H} \quad (9)$$

The subsequent equations (Eq. 10- Eq. 13) refers to the constraints regarding to the storage i.e., battery charging and discharging considering degradation and battery state of charge over each time step.

$$B^{+}_{h} = \sum_{t\,\in\,\mathcal{T}} \left(F^{pd}_{tl^{B}h} * X_t * F^{dgr}_{t} * \eta_B\right), \qquad \forall\, h \in \mathcal{H} \quad (10)$$

$$B^{SOC}_{h} = B^{SOC}_{h-1} + B^{+}_{h} - B^{-}_{h}, \qquad \forall\, h \in \mathcal{H} \quad (11)$$

$$B^{-}_{h} \leqslant B^{SOC}_{h-1}, \qquad \forall\, h \in \mathcal{H} \quad (12)$$

$$Z^{B^{+}}_{h} + Z^{B^{-}}_{h} \leq 1, \qquad \forall\, h \in \mathcal{H} \quad (13)$$

The next two equations describes the demand rate constraints. For each demand period or month, the demand must be greater than or equal to the utilized grid power for that particular period or month.

$$\sum_{h\,\in\mathcal{H}_r,\; l\,\in\,\mathcal{L}} P_{Glh} \leqslant d_r, \quad \forall\, r \in \mathcal{R} \quad (14)$$

$$\sum_{h\,\in\mathcal{H}_m,\; l\,\in\,\mathcal{L}} P_{Glh} \leqslant d_m, \quad \forall\, m \in \mathcal{M} \quad (15)$$

Eq. 16 forces the size all technologies (PV system) to be less than or equal to the net metering level, if operating in that level, and zero otherwise.

$$\sum_{t\,\in\,\mathcal{T}} X_t \leqslant L^{NEM}_{sv} * Y_{sv}, \qquad \forall\, v \in \mathcal{V}, s \in \mathcal{S} \quad (16)$$

It is worth noting that we have only considered relevant constraints stated in [42] in our work. For example, except PV, battery and diesel generator, the constraint formulations for other power sources are excluded but NEM's constraint is taken into account. Anyway, apart from reduced cost and energy use, resiliency benefits of the microgrid can be realized via this model when the grid becomes de-energized. To analyse resilience impact from the selected candidate pool of technologies, critical load information must be set up, such as percentage of critical load, outage starting date and time, outage duration and type of outage. Note that, instead of percentage value, one can input the actual critical loads into the model as well.

Table 1
Utility Tariff rate structure.

Greater Boston General Service G-2 (B2)			
Rate parameter	Value	Max Usage	Designated Months
Fixed Charge Units	18 [$/month]	–	All
Seasonal/Monthly Demand Charge Structure			
Period 1 (Tier 1)	17.19 [$/kW]	10 [kW]	January-May; October-December
Period 2 (Tier 1)	40.61[$/kW]	10 [kW]	June-September
Tiered Energy Usage Charge Structure			
Period 1 (Tier 1)	0.04252 [$/kWh]	2000 [kW]	January-May; October-December
Period 1 (Tier 2)	0.03735 [$/kWh]	150 [kW]	
- Period 1(Tier 3)	0.03544 [$/kWh]	-	
Period 2 (Tier 1)	0.05266 [$/kWh]	2000 [kW]	June-September
Period 2 (Tier 2)	0.03912 [$/kWh]	150 [kW]	
Period 2 (Tier 3)	0.3594 [$/kWh]	–	

2.3. Model inputs

The detailed model inputs along with techno-economic assumptions are mentioned in Appendix A. The following subsections describe most of the input in details.

2.3.1. Load profile

The simulated load profile (using USA-DOE's commercial reference building [43]) of Boston Logan Airport is shown in Fig. 2. A small part of the airport is considered for this work that contains critical loads. The estimated energy consumption is 8,567 MWh per year. The average daily load, including critical loads, is 977.98 kW, with a maximum demand in August and a minimum in December. More details on hourly load demand can be found in the *supplementary materials*. According to average load demand stated in Fig. 2. Primarily, it is assumed that 50% of the total load is 'critical'. All types of control systems such as airport traffic control, passenger arrival and departure control need continuous power supply. Like any other facility, an airport needs a complete online network; several airports have also implemented internet of things (IoT) and artificial intelligence (AI) that require a dedicated server and cannot afford a power cut either. However, for this work, a large office building of the airport is assumed to have typical common critical loads such as elevator, main lights, air-conditioning, security checking system, and so on.

2.3.2. Electricity tariff

The electricity utility company Eversource energy is mainly responsible for powering Boston city. According to the characteristics and amount of electricity load demand of the said airport, 'Greater Boston General Service G-2 (B2)' rate is applied for this study. It offers delivery plus standard service to the commercial facilities. Under this tariff, the service voltage should be less than 10 kilo Volts and the monthly demand is equivalent to or greater than 10 kilowatts for all use at a single location [44]. The detailed electric tariff applied in this study is presented in Table 1.

2.3.3. PV module

The PV module uses a bi-directional interface allowing the PV system's AC power to either supply electrical loads on site or back feed the grid when the PV power production is greater than the on-site load requirement. NREL's PVWatts tool is used to model the PV module by Dobos [45]. Since the module loses its effectiveness over time, a 0.5%/year degradation rate and 14% of derating factor is considered. The derating factor includes all types of losses due to soiling (dust, dirt, snow, bird droppings, bio-films of bacteria, pollen, and other particles that cover the PV module surface), Shading, Mismatch, Wiring Connection, Light induced degradation, Nameplate rating and so on [46]. The expected lifetime of the module is 25 years. REopt uses the TMY2 dataset for solar radiation which is available at PVWatts repository [47]. Fig. 3 demonstrates the yearly solar radiation of Boston, US.

2.3.4. Energy storage

Given the intermittent nature of renewables, the importance of batteries in RE based microgrids is paramount due to its energy security i.e., storing capability [48]. Design and dispatch approaches of the battery storage vary based on the test-case and the value sources being exploited. This study considers the minimum state of charge (SoC) of the battery unit as 20% whereas the initial SoC is taken as 50%. In principle, the battery is allowed to get charged from any technology, including the main grid, if required. REopt normally estimates a functional 10-year battery life, based on annual depletion; the dispatch is then post-processed utilizing a rain-flow algorithm to validate the assertion [42,49].

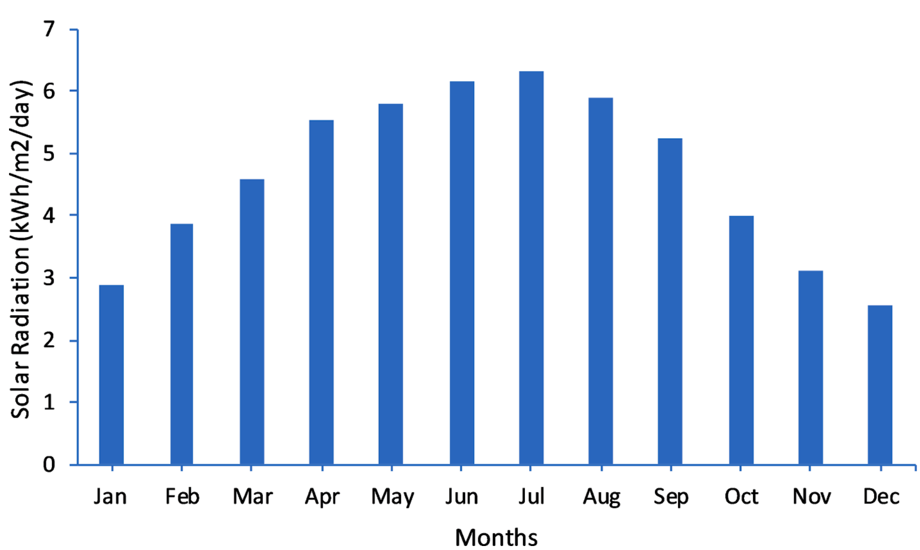

Fig. 3. Solar Radiation in Boston, USA.

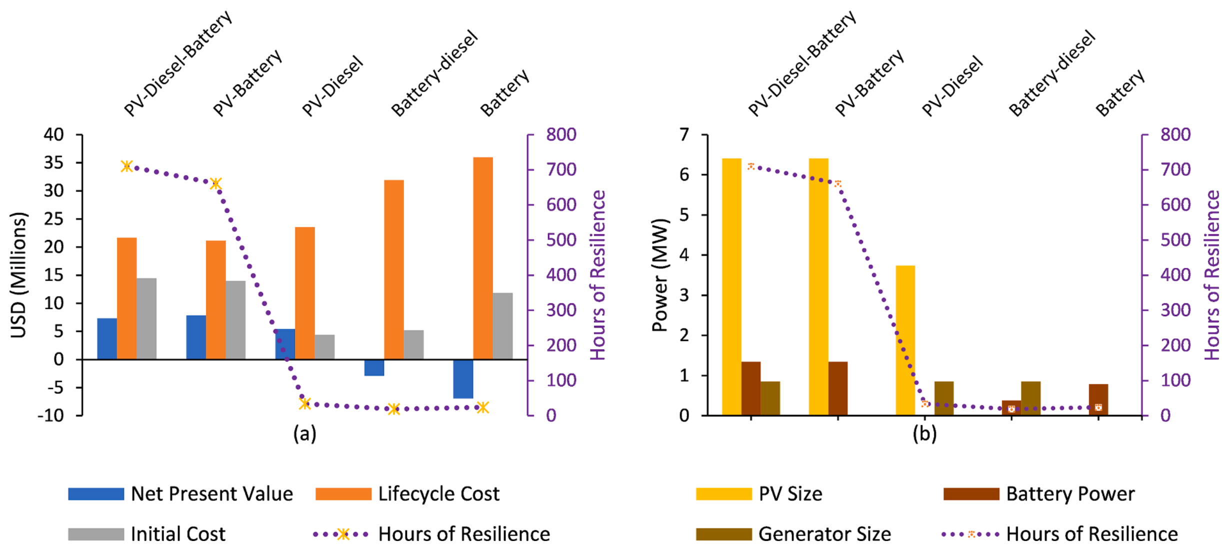

Fig. 4. Technical and economic performance of different configuration in terms of resilience hours.

2.3.5. *Existing diesel generator*

Traditional generators choose a reciprocating engine design and typically rely on the user to input manufacturer data to obtain generator output. For this study, it is assumed that the airport possesses a 850 kW diesel fired conventional generator. A specific amount (660 gallons) of fuel is available to the existing generator. Standardized fuel consumptions against load profiles are used to develop a linear model of the diesel generator with calibrated fuel consumption [50].

3. Results

To find out the resilience hours of different power supply units considering both hybrid and standalone options, multiple simulations are performed when the main grid has been disconnected for a certain date and period considering the 70% critical airport load. Out of seven options (excluding wind technology), standalone PV and Diesel generator are found out to be infeasible. The inability of the standalone PV system is apparent - due to the incapability of supplying power at nighttime. Although the autonomous diesel generator (850 kW) can support critical load (unable if it exceeds 50% of total load) during shutdown, it cannot support the implied high load demand (average load 977.98 kW) in normal operating conditions because the microgrid model considers both normal and blackout periods. This choice is therefore untenable in the simulation result. The rest of the options i.e., PV-diesel-battery, PV-Battery, PV-diesel, Battery-diesel and Battery have appeared to be feasible and provide resilience to the host critical facility. Fig. 4 shows a comparative picture of those options in terms of resilience hours. The financial and technical (system size) parameters for different options are compared in Fig.4(a) and Fig.4(b), respectively. Evidently, the PV-diesel-battery hybrid scheme provides the maximum resilience value and the Battery-diesel option has the minimum resiliency and even negative NPV. Hence, the micorgrid comprising of PV, battery and diesel generator is selected to perform the further analysis. The complete dataset related to the case studies can be found in the *supplementary materials*.

3.1. *Normal grid operation*

During the regular operation, the grid-tied microgrid serves the airport smoothly as shown in Fig. 5. In July and August, the microgrid shows almost same behaviour. However, during July, it needs to supply more power with longer service hours compared to August. Most of the time the load demand for airport is met by PV and Battery. In the winter season, on the other hand, the main grid has the largest contribution to the load profile. The grid does not appear to be active in charging the energy storage during the entire year. In principle, the main grid is assumed to be an infinite source of power supply with the prospect of power failure. In addition, the operating and maintenance costs of the grid are not factored as a first approach, but rather the financial and technical value of the energy flow is considered.

Fig. 5 would act as a reference for conducting the analysis of following dispatch schemes during grid interruptions.

3.2. *Scenario 1: Outages in peak load period*

According to the load profile data (available in supplementary materials), the airport observes the peak load on August 4. It is crucial to investigate whether the microgrid sustains outages during such hours when the critical load demand is the highest because it indicates the system's reliability. We have selected four outages with six hours of each duration on the said date. For this scenario, the critical load is kept constant at 50% of the total load.

The four consecutive optimization results suggest a microgrid system consisting of 6,498 kW PV, 1,389 kW storage unit with 10,195 kWh capacity accompanying the backup 850 kW diesel generator to address any six-hour blackout within the day. Note that the PV is assumed to be ground-mounted as rooftop PV is not a viable option. It provides resilience benefits compared to business as usual (BaU) and financial case, as seen in Table 2. The optimal system secures a whopping net present value (NPV) over its lifetime compared to BaU, since it survives the 50% critical load throughout the 6-h outage period. However, even though the outages happen on the same day, during optimization, they are treated as outages occurring 'once' in project lifetime, resulting in slight differences in NPVs for each outage period. Since PV can export all extra energy, if not curtailed, after the 12 am–6 am outage, the NPV becomes higher, and for the 12 pm–6 pm outage case, it has the reverse impact. The NPV is the lifecycle energy cost savings when compared to the base case of purchasing all energy from the gird, and primarily comes from the grid-connected savings. The PV and battery provide in reducing utility energy and demand charges. Note that the 'financial' approach can obtain higher NPV than the resilience case, but it fails to offset the specified grid outage (refer to Fig. 6). Besides, the optimal resilient system sustains the outage an additional 52 hour compared to the financial case.

Fig. 7 presents the results of the simulation. The power dispatch strategy differs depending on the outage starting time. When the

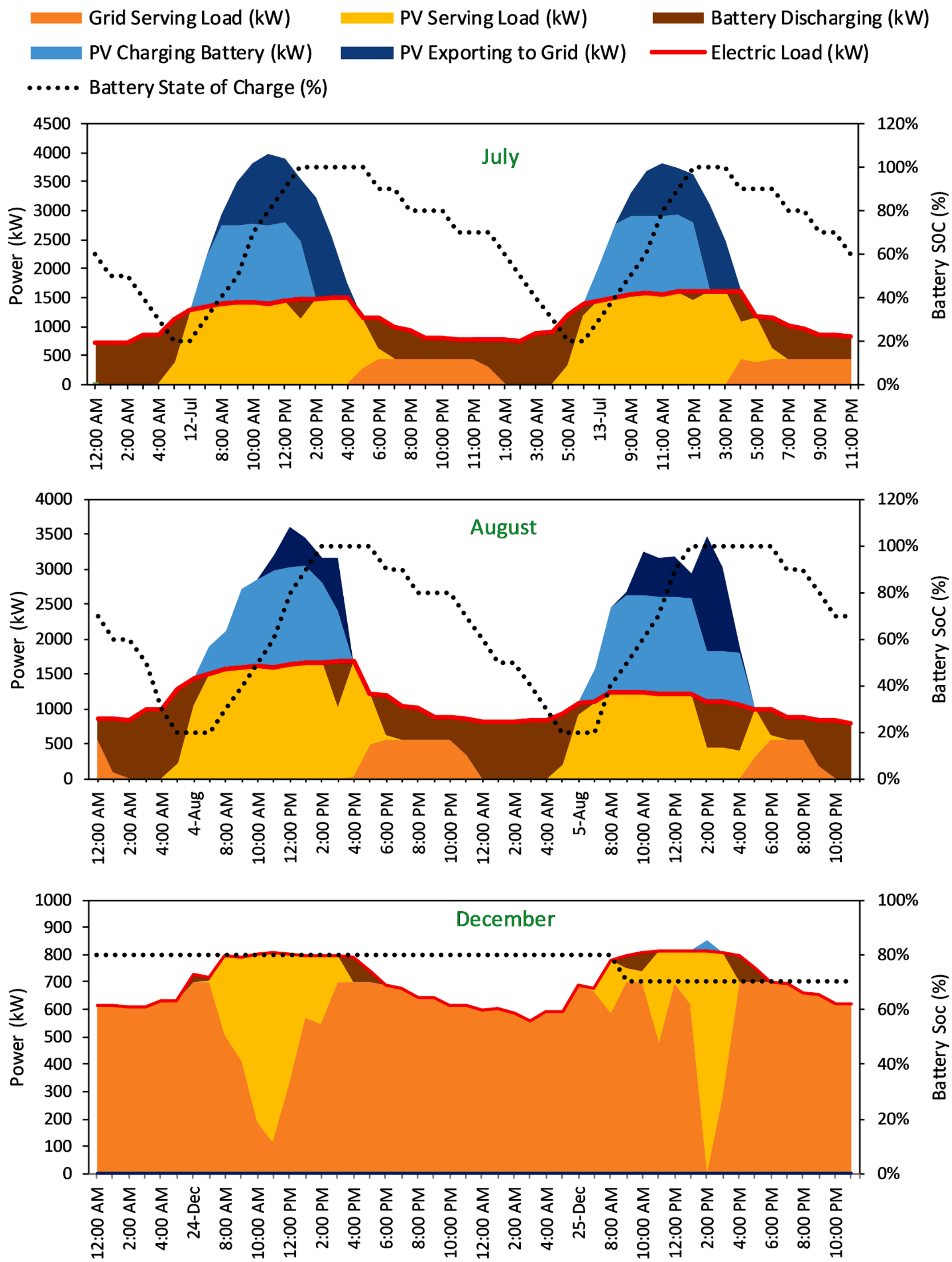

Fig. 5. Microgrid operation during normal grid tied mode without outages.

blackout starts at midnight (12am-6am), the diesel generator and battery act jointly and serve the load until the PV starts to produce electricity. The generator only supplies power when there is an outage and the battery is about to reach its threshold. The battery was only at 40% state of charge going into the outage, and thus required more diesel generation that it would have had the battery been fully charged (Fig. 7a). In the presence of sunlight in the daytime, the diesel generator is absent from dispatching energy to make the microgrid economically viable. Even in the night time, the generator has the least contribution given its capacity (850 kW). Hence, as seen in Fig. 7a and 7d, the generator only provides totaling around 1,567 kWh and 638 kWh during the blackout for five and two hours, respectively. Generally, at night without an outage, the energy storage unit pairs with the utility grid and serves the required load. Noticeably, during the simulation time, the main grid does not engage in charging the battery as it would be less cost-effective for the airport. Daytime outages have little to zero requirements for battery usage because the PV power satisfies almost all load demand (Fig. 7b-c). The PV even charges battery while the excess energy is curtailed as the simulation period falls on the summer solstice and thus, abundant solar energy is available. At normal operating conditions, the battery SoC tails off to its initial stage (20%) at 6 am and starts to get charged through PV from 7 am until it reaches 100% capacity. However, this is not the case in the winter solstice, as explained in the latter section.

Table 2
Comparison of resilience benefits with 'business as usual' and 'financial' case in different outage durations for the same day.

Parameter	Business as usual	Resilience			Financial
		12 am-6am outage	6 am-12 pm outage	6 pm-12 am outage	
System	None	850 kW Diesel, 6,498 kW PV, 1,389 kW Battery with 10,195 kWh capacity			0 kW Diesel, 6,498 kW PV, 1,389 kW Battery with 10,195 kWh capacity
NPV ($)	$0	7,421,732	7,403,239	7,420,957	7,937,100
Survives specified outage	No	Yes			No
Average time (hrs)	0	718			666
Diesel used (gal)	0	119	0	49	0

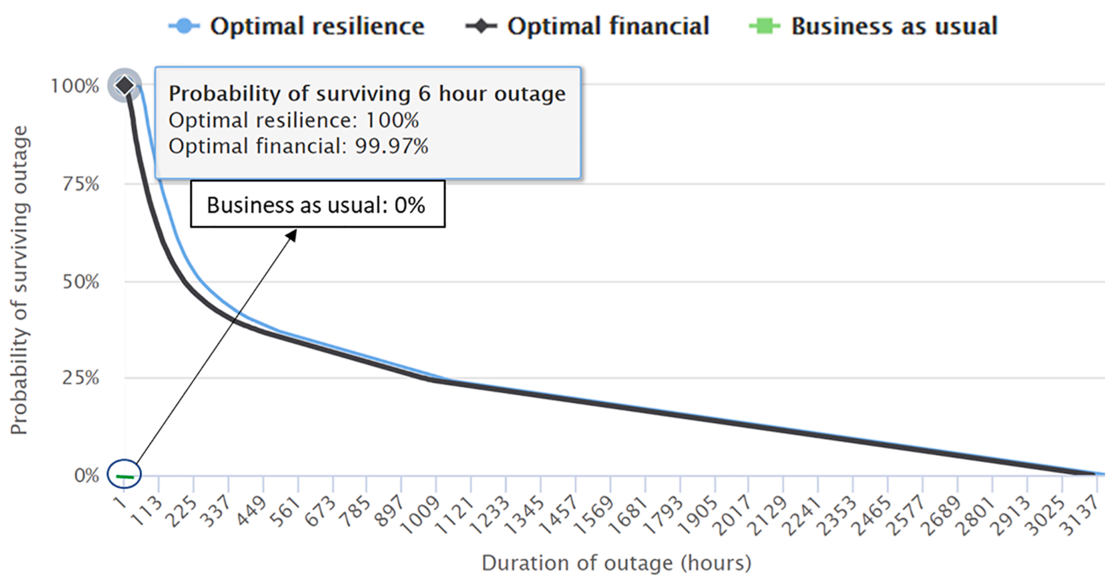

Fig. 6. Probability of surviving outage of the microgrid over time.

3.3. Scenario 2: Outages in variable load demand situation

The level of critical load in the airport may change depending on the situation. For example, unscheduled commercial and cargo airplanes can land at the airport in case of an emergency or simply the number of passengers can go up due to occasions, vacations and so on. All these circumstances would lead to the increase in critical loads as well. For this particular scenario, the base case (50% critical load) is being compared to an escalated 70% critical load and another 'hypothetical' 100% critical demand for a 12-h outage period in August. The system size for this scenario is depicted in Table 3. This scenario also withstands the assigned grid outage as seen in Fig. 8.

A closer look at Fig. 8 indicates that energy storage unit mainly supports the airport during the blackout because PV does not produce electricity due to lack of solar energy, specially in late afternoon. When the critical load demand elevates, the generator is forced to dispatch energy and thus, serve the required demand (Fig. 8a-b). Clearly, generator's share is higher when the critical demand is higher and vice versa. Normally, after a blackout the grid is supposed to supply electricity during night hours, but for this particular scenario it is not doing so. The reason the battery continues to power the load, rather than the grid, is because there is a lot of excess PV being generated at this time of year, and the battery wants to drain as much as possible before the sun comes up again, so it has room to store as much excess PV as possible.

3.4. Scenario 3: Outages in summer and winter

We introduce this scenario to investigate the impact of extensive changes in solar resources, e.g., PV power during an outage. According to Fig. 3, Boston receives the highest solar radiation in July (summer) and the lowest in December (winter). Hence, a 24 hour outage is assigned to both months starting from the mid day for 50% critical load. This scenario, as well, can successfully meet all load demand during the grid interruption (refer to Fig. 9 and Fig. 10) although the probability of sustaining outage in December is smaller than July due to the shortage of solar energy in the winter solstice. Table 3 shows the system size for this scenario.

At summer, PV charges the battery and serves the loads with battery preventing the backup generator to run (Fig. 10a). But generator's partaking is a must in winter due to the lack of solar resource during the outage (Fig. 10b). Fig. 10 shows that a significant amount of PV energy is utilized to charge the battery. To be exact, the generator is providing 88.36% of the total load whereas PV is supplying only 11.64%. Again, PV spends 42.9% of its power to charge the battery out of 1702.6 kW of total produced energy. In December, on the contrary, PV only charges the battery for 1–2 h at the beginning of the outage (Fig. 10b). Although it seems that the generator is producing excess power from 12 pm–3 pm due to the constrained stacking area in Fig. 10b, actually it is providing exact power with PV output to meet the load demand. PV may be charging the battery instead of serving the load because the generator has a minimum turndown constraint, and must be dispatched at a minimum level when it runs. Note that the energy storage remains

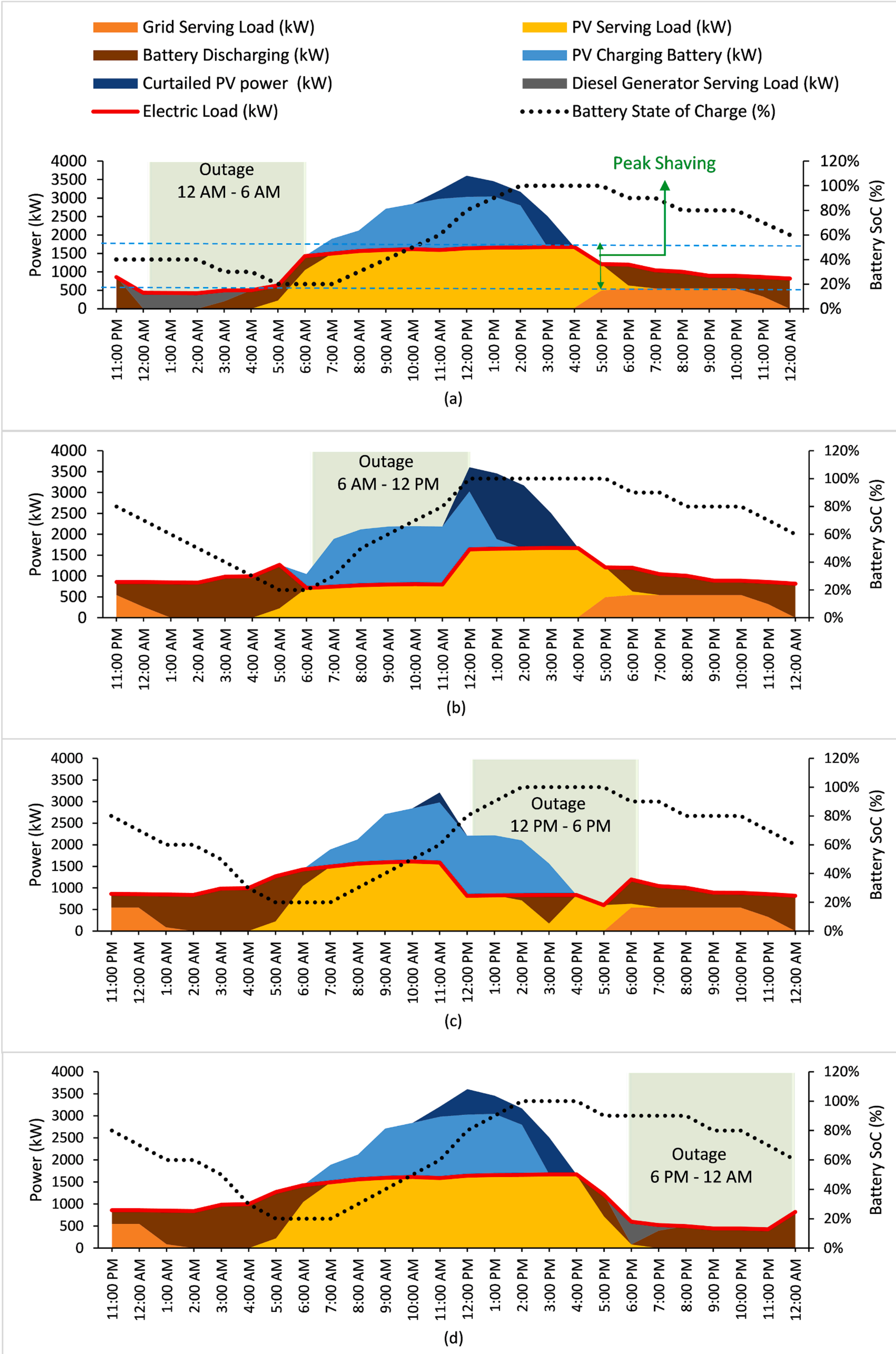

Fig. 7. Energy Dispatch strategy of microgrid components during outages between: a) 12 am–6 am, b) 6 am–12 pm, c) 12 pm–6 pm and d) 6 pm–12 am, at maximum load demand on August 04.

Table 3
System size for Scenario 2 and 3.

Scenario	Critical load (%)	PV (kW)	Battery Power (kW)	Battery Power Capacity (kWh)	Diesel Generator (kW)
Scenario 2 (August)	100	6,498	1,389	10,195	850
	70	6,494	1,387	10,183	850
	50	6,405	1,347	9,770	850
Scenario 3 (December)	50	6,498	1,389	10,195	850
Scenario 3 (July)	50	6,407	1,346	9,770	850

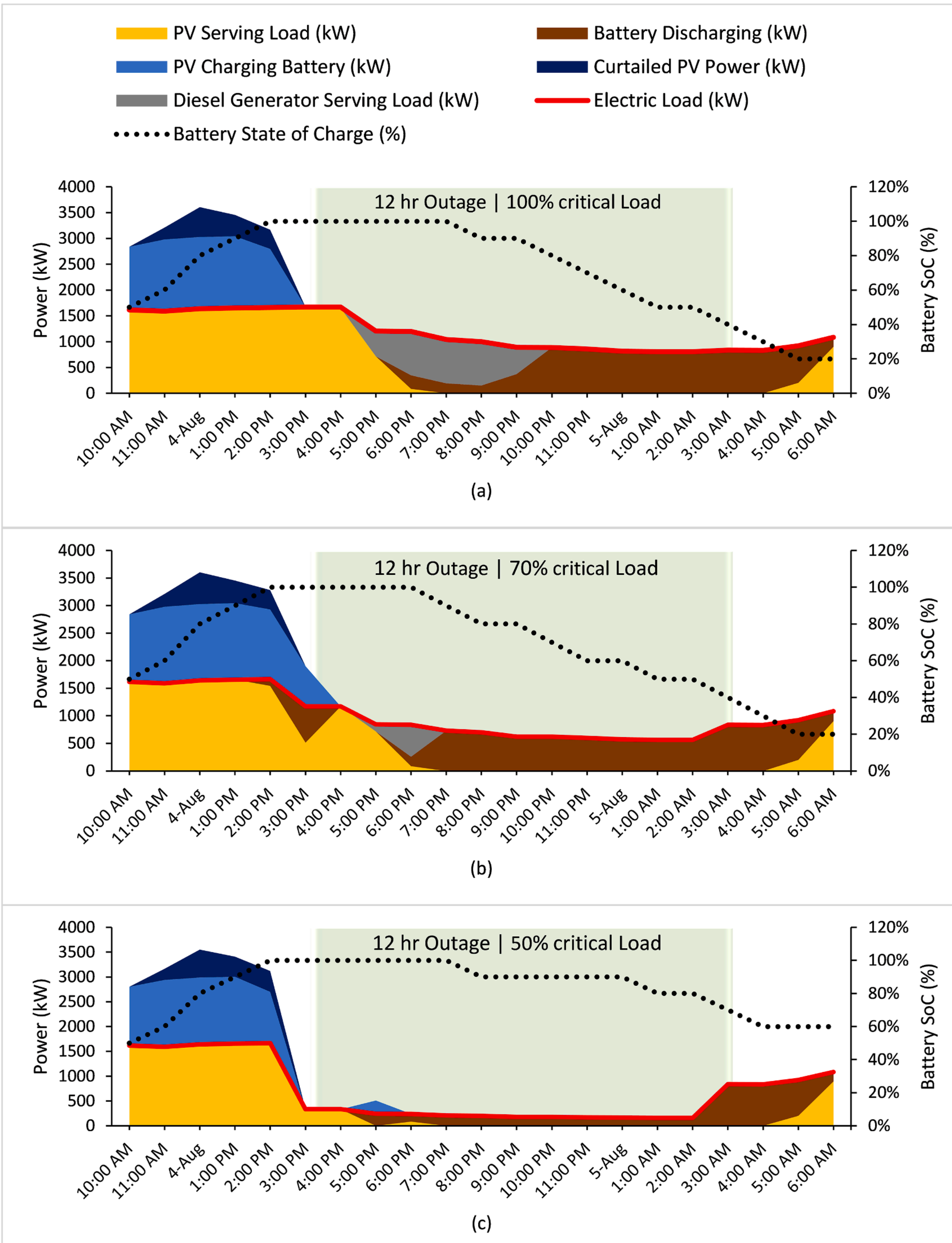

Fig. 8. 12 h outage scenario under different level of critical load: a) 100%, b) 70%, and c) 50%.

unused during the whole blackout period and even in normal condition, there is not so much discharging. This is because the system would be

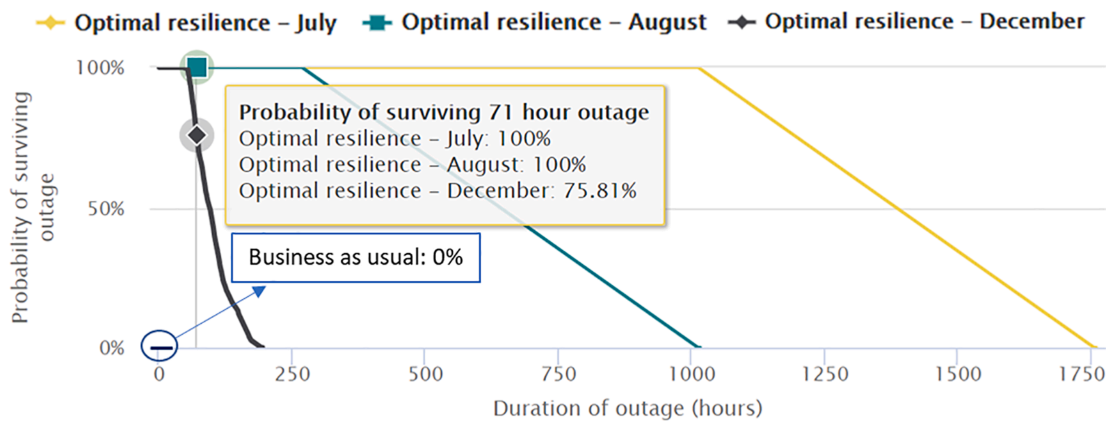

Fig. 9. Probability of surviving outage for the optimal resilience case in different months.

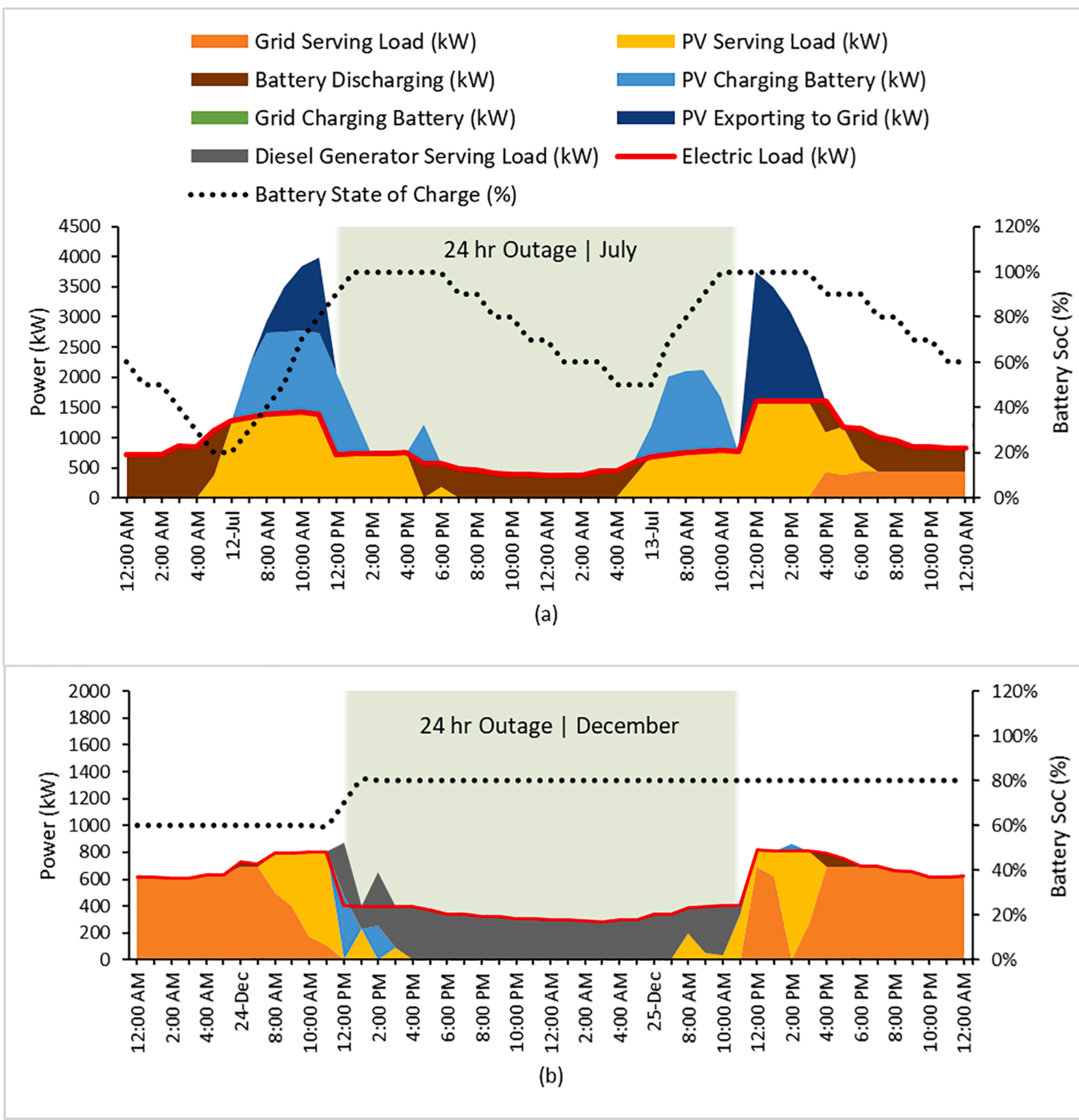

Fig. 10. Power dispatch scheme of microgrid under: (a) Summer and (b) winter solstices.

more profitable to receive electricity from the grid and generator than the energy storage devices.

3.5. Scenario 4: outages when net metering is adopted

Net Energy Metering (NEM) denotes to the scheme of offsetting customers' energy use and sending back the excess energy to their

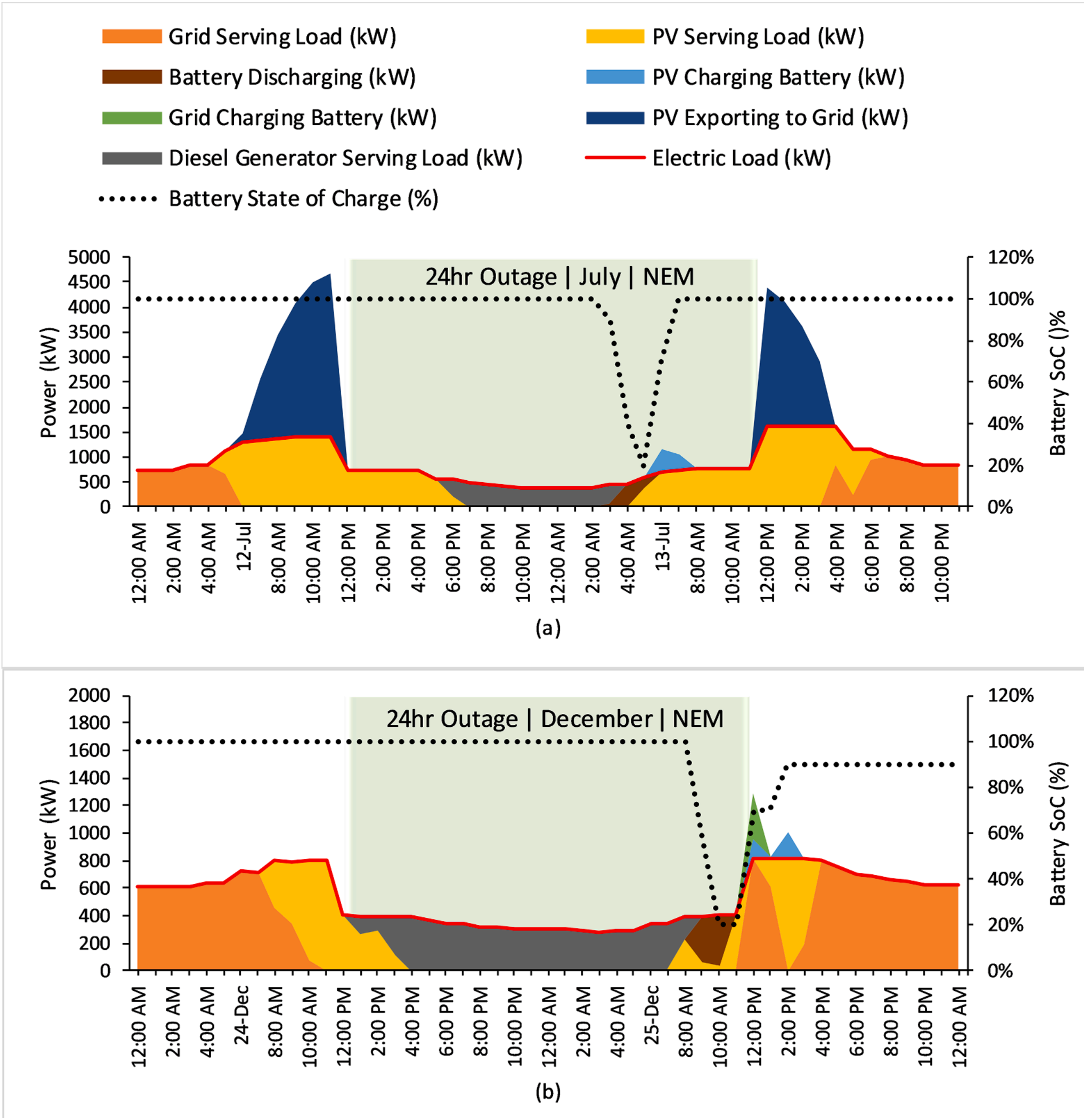

Fig. 11. Operation strategy of microgrid under net metering scheme during 24 h outage in: a) July and b) December.

electric companies for credit. According to the regulation of Massachusetts government policy, Eversource West is allowed to net meter a maximum of 10 MW of energy for a government owned facility [51]. So, we set up the same amount as the highest limit of NEM for this particular scenario. Similar to the previous case, July and December are selected for this case as well, so that one can quickly assess the impact of NEM during a 24-h prolonged blackout. The critical load is 50% of the total load demand.

There are notable differences between before (Fig. 10) and after (Fig. 11) implementing the 'fixed' NEM scenarios. First of all, the battery discharging is much lower relative to without NEM scenarios. Secondly, the PV is exporting more power to the grid, avoiding battery charging. Both of these occurrences expedite the profitability of the system by exporting energy back to the utility with the existing electricity tariff scheme. Therefore, neither PV nor the grid is charging the energy storage during the outage (except in summer for 2 h); consequently, the PV can export most of its produced energy. The battery performs a quick discharging (only for three hours) to supply the load for both in December and July in the event of grid disturbance and then attempts to regain its full as well as constant SoC. Hence, the backup generator fills the role of the battery, supplying 4,025 kW power in July and 5,828 kW power in December, which are 28% and 70% of the total critical load, respectively (Fig. 12).

3.6. General discussion

In the light of the above figures and discussions, it is fairly obvious that the airport microgrid can handle the grid failures stated for all scenarios.Three outage durations- 6, 12 and 24 (all in hours) are chosen to emphasize this claim that is associated with specific conditions. Undoubtedly, it experiences the highest chance of surviving any outage in July and the lowest in December (refer to Fig. 9). In terms of energy dispatch strategy, the system is significantly dependent on the outage starting time and duration. Availability of solar resources plays a crucial role as well. In general, PV leads the energy contribution followed by battery and backup generator during an outage (Fig. 12). The most obvious finding to emerge from all four cases of this study is that PV does not, to be more accurate- *cannot* sell any electricity to the grid under any power cut, but rather charges the battery if there is a surplus. Normally, storage unit supports PV in *peak shaving* by curtailing the load demand. For example, Fig. 7a displays a 460 kW of reduction in demand of around 1 hour because of battery-solar PV combined energy dispatch. Electrochemical units are typically charged when they hit the lower limit (20% SoC), except when the PV module generates either maximum

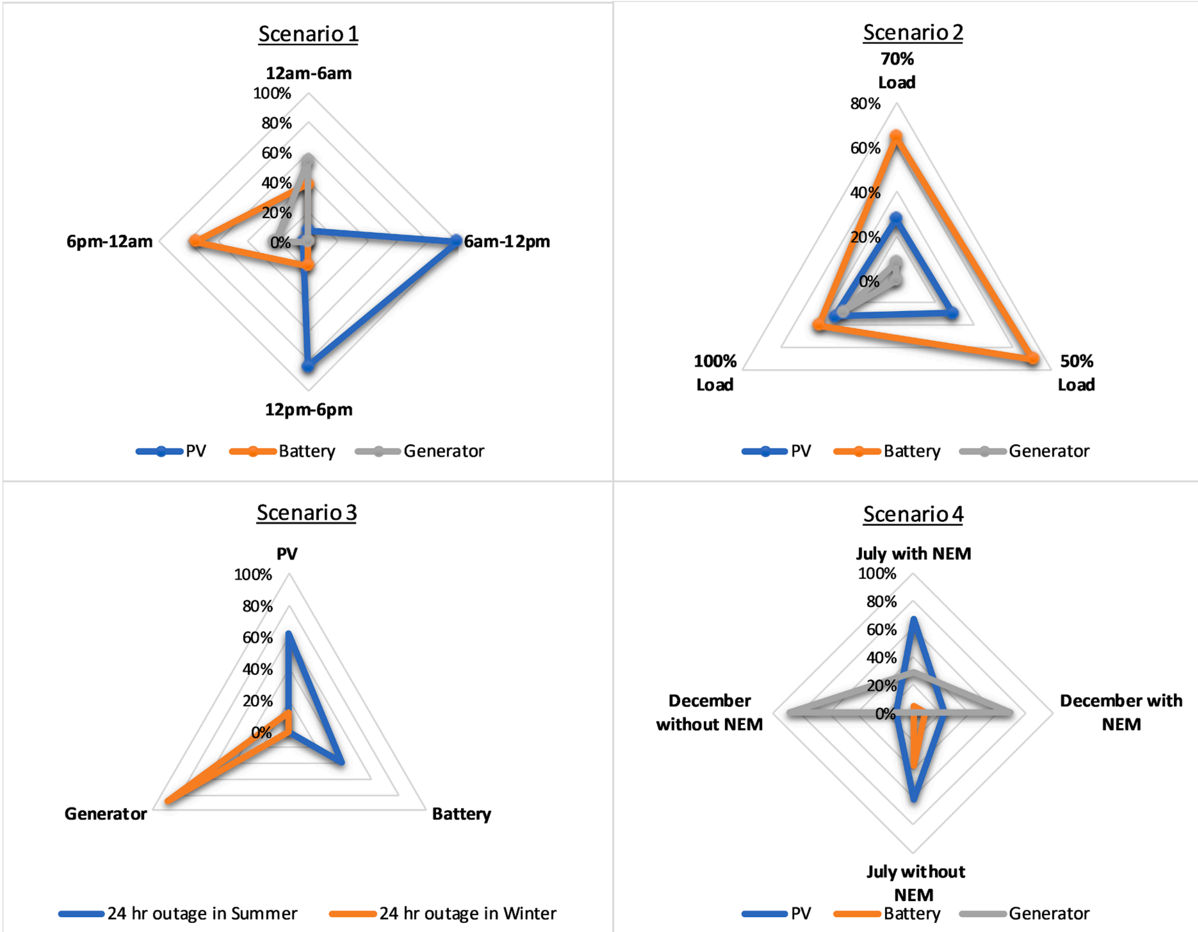

Fig. 12. Share of power supply of microgrid elements for different scenarios during grid outages.

(Fig. 10a) or zero (Fig. 10b) excess energy after meeting the airport load requirement. This finding is consistent with that of Lagrange et al. [9] who found out that, in extreme cases, batteries are charged when the SoC is around 60 to 80%. During the normal operating hours, it is observed that in all scenarios except scenario 4, the microgrid system curtails huge sum of PV power due to the absence of net energy metering. Had the scheme been properly implemented, it would be profitable for all situations.

Interestingly, out of all scenarios, the system encounters grid participation in charging the battery for the first time (Fig. 11b) right after the end of the blackout in December due to the unavailability of solar energy at 12 pm and the urgency of energy storage's sharp charging as mentioned earlier. In Fig. 12, PV has the largest share of power supply when there is adequate solar irradiation (refer to scenario 1 and 3) while battery supplies most of the energy when there is lack of solar generation during nighttime (scenario 2). The diesel generator, on the contrary, contributes more during the winter solstice (scenario 3 and 4). Taking a closer look at scenario 4, both July and December have 7% and 10% more PV power consumption because of the adoption of NEM compared to the very same months without NEM.

In this study, every simulation is carried out considering the resiliency of the airport. So, the LCC has always been lower for the optimal resilient case compared to the business as usual approach. NPV can be positive or negative, however, for this research, all optimized and simulated (via REopt) cases are outage resistant, reflective of positive NPVs. As a reference, Table 4 summarizes and compares the techno-economics of the optimal case with the BaU case considering net metering scheme. The optimal system required around 5.8 GWh less electricity from the utility, enabling lower LCC (after tax) that made its

Table 4
Techno-economic comparison between the BaU and Optimal case for a 24-h outage starting from 12 pm, July 12 (scenario 4, Fig. 10a).

Parameter	BaU	Optimal case with resiliency	Difference
System Size, Energy Production, and System Cost			
PV Size	0 kW	6,407 kW	6,407 kW
Annualized PV Energy Production	0 kWh	7,297,845 kWh	7,297,845 kWh
Battery Power	0 kW	1,346 kW	1,346 kW
Battery Capacity	0 kWh	9,770 kWh	9,770 kWh
Generator Size	0 kW	850 kW	850 kW
Net CAPEX + Replacement + O&M	$0	$14,478,333	$14,478,333
Energy Supplied From Grid in Year 1	8,538,819 kWh	2,747,609 kWh	5,791,210 kWh
Year 1 Utility Cost (Before Tax)			
Utility Energy Cost	$2,579,919	$830,163	$1,749,756
Utility Demand Cost	$450,037	$182,645	$267,392
Utility Fixed Cost	$216	$216	$0
Utility Minimum Cost Adder	$0	$0	$0
Life Cycle Utility Cost (After Tax)			
Utility Energy Cost	$24,721,206	$7,954,755	16,766,451
Utility Demand Cost	$4,312,325	$1,750,138	2,562,187
Utility Fixed Cost	$2,070	$2,070	$0
Utility Minimum Cost Adder	$0	$0	$0
Total System and Life Cycle Utility Cost (After Tax)			
Total Life Cycle Costs (LCC)	$29,035,600	$21,679,326	$7,356,274
Net Present Value (NPV)	$0	$7,356,274	$7,356,274

NPV worth $7,356,274. Note that this NPV is calculated before microgrid investment. The recommended optimal microgrid system can be installed subject to upgradation cost. It might involve additional installation costs such as distribution system facilities, controllers, and networking updates. Typically, NPV or the net difference between the benefits and costs of a project determines the cumulative economic benefits [30]. The economic benefit is perceived when the proper value of avoiding the costs of an outage (VACO) is examined and then taken into account. VACO, also referred to value of lost load, may be defined as the amount of money the customer is willing to pay in order to avoid a specified outage [29]. But it is somewhat very challenging to identify the true VACO due to insufficient data and governmental policy [52]. Anyway, the optimization results do not consider the microgrid modernization costs and prevented failure costs. Hence, the net NPV after microgrid investment would be significantly higher, taking account of VACO.

Limitations: Practically, the real savings can be less on the grounds of the capability to reliably forecast solar irradiance and estimate the load and the battery management technique used in the system. The MILP model used one year solar data and load profile, but accurate demand charges and savings can differ from year to year, as loads and resources differ. Again The load profile for the airport is simulated because the actual one is unavailable. No demand target is set; instead, the extent of demand is measured by the optimisation model. The hourly model does not reflect the PV resource's inter-hour variance. Therefore, the estimated savings from the reduction in demand can be overstated. The results imply the ideal prediction of the imminent power outages, which allows the battery system to charge prior to the failure. Added attributes, like subsidiary services or capability fees, internal rate of return, simple payback period, which are not discussed in this study, can be further investigated.

4. Conclusion and future work

This study assesses the techno-economic performance of the grid-connected microgrid in the event of grid disruption. A MILP-based optimisation model is presented that minimizes the life cycle cost subject to certain constraints and detects the outage survivability over the year. Taking an international airport as a case study, the modelling methodology considers renewable energy source- PV and conventional energy sources- battery and diesel generators with several technical and financial assumptions as input. Despite some limitations, the scenario-based analysis has proved the resiliency of the optimal microgrid that enables the airport to have a continuous power supply with substantial monetary value compared to business as usual and financial approach during every power outage. For each case, the model garners and optimizes the best possible generation capacity to address critical electrical load. The microgrid explores the following parameters- grid export and import, PV serving load and charging the battery storage, battery discharging and state of charge, and finally, generator serving load while dispatching energy. Thanks to Boston's reasonable solar radiation, the PV module works well with the energy storage device by providing energy arbitrage and peak shaving. During winter, the diesel generator takes over in the absence of the sun and ensures the continuity of electric supply. The results suggest that a regulated and suitable net metering scheme should be adopted to avoid the PV power curtailment as much as possible and export the power to the grid. This research also shows the techno-economic viability of such systems (PV-Battery) despite slightly lowered resilience hours, both in regular and interrupted grid service periods. The study is expected to assist vulnerable infrastructures worldwide, prone to grid failures, to adopt microgrid as a resilience measure.

This study has focused on an airport, but as a future work, the findings may be used for other critical infrastructures like hospitals, schools, data centers, water treatment plants and emergency service centers (fire service, police department) to implement such renewable energy-based resilient microgrids. A scenario can be generated using only renewable energy technologies with an appropriate energy storage unit to explore the resiliency and techno-economic performance of the microgrid model. Furthermore, it is recommended to compare the resilience benefits of these facilities using actual critical load data and accurate weather profile as a part of the integrated microgrid solution. Thermal loads should also be included in the future model, alongside electrical loads.

CRediT authorship contribution statement

Hasan Masrur: Conceptualization, Methodology, Software, Data curation, Validation, Writing - original draft. **Ayyoob Sharifi:** Writing - review & editing, Conceptualization, Visualization. **Md. Rabiul Islam:** Writing - review & editing, Investigation. **Md. Alamgir Hossain:** Writing - review & editing, Visualization. **Tomonobu Senjyu:** Supervision.

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.

Acknowledgement

The authors would like to acknowledge the inputs from the two anonymous reviewers which have enhanced the paper's quality to a great extent. We also recognize the National Renewable Energy Laboratory (NREL), USA for the open source code, software and related white papers.

Appendix A. Model inputs

Table A.1.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ijepes.2021.107137.

References

[1] Hussain A, Bui V-H, Kim H-M. Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience. Appl Energy 2019;240:56–72. https://doi.org/10.1016/j.apenergy.2019.02.055.
[2] Gholami A, Aminifar F, Shahidehpour M. Front lines against the darkness: Enhancing the resilience of the electricity grid through microgrid facilities. IEEE Electrif Mag 2016;4:18–24.
[3] Anderson KH, DiOrio NA, Cutler DS, Butt RS. Increasing resiliency through renewable energy microgrids. J Energy Manage 2017;2.
[4] Wang R, Lam C-M, Hsu S-C, Chen J-H. Life cycle assessment and energy payback time of a standalone hybrid renewable energy commercial microgrid: A case study of Town Island in Hong Kong. Appl Energy 2019;250:760–75. https://doi.org/10.1016/j.apenergy.2019.04.183.
[5] Das I, Cañizares CA. Renewable Energy Integration in Diesel-Based Microgrids at the Canadian Arctic. Proc IEEE 2019;107:1838–56. https://doi.org/10.1109/JPROC.2019.2932743.
[6] Masrur H, Howlader HOR, Elsayed Lotfy M, Khan KR, Guerrero JM, Senjyu T. Analysis of Techno-Economic-Environmental Suitability of an Isolated Microgrid

Table A.1
Outline of the system input parameters [43].

SITE AND UTILITY	
Site location	Boston, MA, USA
Latitude	42.3600825
Longitude	−71.0588801
Land available (acres)	Unlimited
Roof space available (sq. ft)	Unlimited
Building type	Large airport office
Load profile	Simulated
Annual energy consumption (kWh)	8,567,087
URDB rate	
Eversource (NSTAR)-	
Greater Boston General Service G-2 (B2)	
SOLAR PV MODULE	
System capital cost ($/kW)	$ 1,600
O&M cost ($/kW per year)	$ 16
Minimum size desired (kW DC)	0
Maximum size desired (kW DC)	Unlimited
Module type	Standard
Array type	Ground mount, Fixed
Array azimuth (deg)	180
Array tilt (deg)	10.0
DC to AC size ratio	1.2
System losses (%)	14%
Net metering system size limit (kW)	0 (4th Scenario- 68.32 MW)
Federal percentage-based incentive (%)	26%
Federal maximum incentive ($)	Unlimited
Federal rebate ($/kW$)	0
Federal maximum rebate ($)	Unlimited
State percentage-based incentive (%)	0%
State maximum incentive ($)	Unlimited
State rebate ($/kW)	$ 0
State maximum rebate ($)	Unlimited
Utility percentage-based incentive (%)	0%
Utility maximum incentive ($)	Unlimited
Utility rebate ($/kW)	$ 0
Utility maximum rebate ($)	Unlimited
Production incentive ($/kWh)	$ 0
Incentive duration (years)	1
Maximum incentive ($)	Unlimited
System size limit (kW)	Unlimited
MACRS schedule	5 years
MACRS Bonus Depreciation	100%
ENERGY STORAGE	
Energy capacity cost ($/kWh)	$ 420
Power capacity cost ($/kW)	$ 840
Energy capacity replacement cost ($/kWh)	$ 200
Energy capacity replacement year	10
Power capacity replacement cost ($/kW)	$ 410
Power capacity replacement year	10
Minimum energy capacity (kWh)	0
Maximum energy capacity (kWh)	Unlimited
Minimum power capacity (kW)	0
Maximum power capacity (kW)	Unlimited
Rectifier efficiency (%)	96%
Round trip efficiency (%)	97.5%
Inverter efficiency (%)	96%
Minimum state of charge (%)	20%
Initial state of charge (%)	50%
Allow grid to charge battery	yes
Total percentage-based incentive (%)	0%
Total rebate ($/kW)	$ 0
MACRS schedule	7 years
MACRS Bonus Depreciation	100%
GENERATOR	
Existing diesel generator size (kW)	850 kW
Fuel availability (gallons)	660
Install cost ($/kW)	$500
Fixed O&M cost ($/kW per year)	$10
Variable O&M cost ($/kWh)	$0
Diesel cost ($/gal)	$3
Fuel burn rate (gallons/kWh)	Capacity-based default value
Fuel consumption curve y-intercept (gallons/hour)	Capacity-based default value
FINANCIAL PARAMETERS	
Analysis period (years)	25
Host discount rate, nominal (%)	8.3%
Host effective tax rate (%)	26%
Electricity cost escalation rate, nominal (%)	2.3%
O&M cost escalation rate (%)	2.5%

System Located in a Remote Island of Bangladesh. Sustainability 2020;12:2880. https://doi.org/10.3390/su12072880.

[7] Hossain E, Kabalci E, Bayindir R, Perez R. Microgrid testbeds around the world: State of art. Energy Convers Manage 2014;86:132–53. https://doi.org/10.1016/j.enconman.2014.05.012.

[8] Hossain MA, Pota HR, Hossain MJ, Blaabjerg F. Evolution of microgrids with converter-interfaced generations: Challenges and opportunities. Int J Electr Power Energy Syst 2019;109:160–86. https://doi.org/10.1016/j.ijepes.2019.01.038.

[9] Lagrange A, de Simón-Martín M, González-Martínez A, Bracco S, Rosales-Asensio E. Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital. Int J Electr Power Energy Syst 2020;119:105865. https://doi.org/10.1016/j.ijepes.2020.105865.

[10] Rosales-Asensio E, de Simón-Martín M, Rosales A-E, Colmenar-Santos A. Solar-plus-storage benefits for end-users placed at radial and meshed grids: An economic and resiliency analysis. Int J Electr Power Energy Syst 2021;128:106675. https://doi.org/10.1016/j.ijepes.2020.106675.

[11] Cook JJ, Volpi CM, Nobler EM, Flanegin RK. Check the Stack: An Enabling Framework for Resilient Microgrids. Technical Report. Golden, CO (United States): National Renewable Energy Lab.(NREL); 2018.

[12] Electric Disturbance Events (OE-417) Annual Summaries: DOE, USA; 2020. https://www.oe.netl.doe.gov/OE417_annual_summary.aspx [Online; accessed 10. Oct. 2020].

[13] Major Power Outage Risks in the U.S.; 2020. https://engineering.purdue.edu/LASCI/research-data/outages/outagerisks [Online; accessed 3. Aug. 2020].

[14] Microgrids 1 Engineering, Economics, & Experience; 2015. https://e-cigre.org/publication/635-microgrids-1-engineering-economics-experience [Online; accessed 22. Jul. 2020].

[15] Galvan E, Mandal P, Sang Y. Networked microgrids with roof-top solar PV and battery energy storage to improve distribution grids resilience to natural disasters. Int J Electr Power Energy Syst 2020;123:106239. https://doi.org/10.1016/j.ijepes.2020.106239.

[16] Microgrid Effects and Opportunities for Utilities; 2020. URL https://www.burnsmcd.com/insightsnews/tech/techbriefs/2013-issue-4/microgrid-effects-and-opportunities-for-utilities [Online; accessed 10. Oct. 2020].

[17] Hirsch A, Parag Y, Guerrero J. Microgrids: A review of technologies, key drivers, and outstanding issues. Renew Sustain Energy Rev 2018;90:402–11. https://doi.org/10.1016/j.rser.2018.03.040.

[18] Ali A, Li W, Hussain R, He X, Williams BW, Memon AH. Overview of Current Microgrid Policies, Incentives and Barriers in the European Union, United States and China. Sustainability 2017;9:1146. https://doi.org/10.3390/su9071146.

[19] Terrado E, Cabraal A, Mukherjee I. Operational guidance for World Bank Group staff: designing sustainable off-grid rural electrification projects-principles and practices. Technical Report. The World Bank; 2008.

[20] Kiptoo MK, Lotfy ME, Adewuyi OB, Conteh A, Howlader AM, Senjyu T. Integrated approach for optimal techno-economic planning for high renewable energy-based isolated microgrid considering cost of energy storage and demand response strategies. Energy Convers Manage 2020;215:112917. https://doi.org/10.1016/j.enconman.2020.112917.

[21] Nwulu NI, Xia X. Optimal dispatch for a microgrid incorporating renewables and demand response. Renew Energy 2017;101:16–28. https://doi.org/10.1016/j.renene.2016.08.026.

[22] Atia R, Yamada N. Sizing and Analysis of Renewable Energy and Battery Systems in Residential Microgrids. IEEE Trans Smart Grid 2016;7:1204–13. https://ieeexplore.ieee.org/document/7399422.

[23] Swaminathan S, Pavlak GS, Freihaut J. Sizing and dispatch of an islanded microgrid with energy flexible buildings. Appl Energy 2020;276:115355. https://doi.org/10.1016/j.apenergy.2020.115355.

[24] Zhou J, Tsianikas S, Birnie DP, Coit DW. Economic and resilience benefit analysis of incorporating battery storage to photovoltaic array generation. Renew Energy 2019;135:652–62. https://doi.org/10.1016/j.renene.2018.12.013.

[25] Garmabdari R, Moghimi M, Yang F, Gray E, Lu J. Multi-objective energy storage capacity optimisation considering Microgrid generation uncertainties. Int J Electr Power Energy Syst 2020;119:105908. https://doi.org/10.1016/j.ijepes.2020.105908.

[26] Li Y, Gao W, Ruan Y. Performance investigation of grid-connected residential PV-battery system focusing on enhancing self-consumption and peak shaving in Kyushu, Japan. Renew Energy 2018;127:514–23. https://doi.org/10.1016/j.renene.2018.04.074.

[27] Ahmadi M, Lotfy ME, Shigenobu R, Howlader AM, Senjyu T. Optimal sizing of multiple renewable energy resources and pv inverter reactive power control encompassing environmental, technical, and economic issues. IEEE Syst J 2019;13:3026–37.

[28] Nagapurkar P, Smith JD. Techno-economic optimization and environmental Life Cycle Assessment (LCA) of microgrids located in the US using genetic algorithm. Energy Convers Manage 2019;181:272–91. https://doi.org/10.1016/j.enconman.2018.11.072.

[29] Tsianikas S, Zhou J, Birnie DP, Coit DW. Economic trends and comparisons for optimizing grid-outage resilient photovoltaic and battery systems. Appl Energy 2019;256:113892. https://doi.org/10.1016/j.apenergy.2019.113892.

[30] Laws ND, Anderson K, DiOrio NA, Li X, McLaren J. Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings. Renew Energy 2018;127:896–909. https://doi.org/10.1016/j.renene.2018.05.011.

[31] Rosales-Asensio E, de Simón-Martín M, Borge-Diez D, Blanes-Peiró JJ, Colmenar-Santos A. Microgrids with energy storage systems as a means to increase power resilience: An application to office buildings. Energy 2019;172:1005–15. https://doi.org/10.1016/j.energy.2019.02.043.

[32] Anderson K, Laws ND, Marr S, Lisell L, Jimenez T, Case T, et al. Quantifying and Monetizing Renewable Energy Resiliency. Sustainability 2018;10:933. https://doi.org/10.3390/su10040933.

[33] Wu D, Ma X, Huang S, Fu T, Balducci P. Stochastic optimal sizing of distributed energy resources for a cost-effective and resilient Microgrid. Energy 2020;198:117284. https://doi.org/10.1016/j.energy.2020.117284.

[34] Ashraf MA, Liu Z, Alizadeh A, Nojavan S, Jermsittiparsert K, Zhang D. Designing an optimized configuration for a hybrid PV/Diesel/Battery Energy System based on metaheuristics: A case study on Gobi Desert. J Cleaner Prod 2020;270:122467. https://doi.org/10.1016/j.jclepro.2020.122467.

[35] Sharifi A, Yamagata Y. Principles and criteria for assessing urban energy resilience: A literature review. Renew Sustain Energy Rev 2016;60:1654–77. https://doi.org/10.1016/j.rser.2016.03.028.

[36] Panteli M, Mancarella P. The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience. IEEE Power Energy Mag 2015;13:58–66. https://doi.org/10.1109/MPE.2015.2397334.

[37] Bajwa AA, Mokhlis H, Mekhilef S, Mubin M. Enhancing power system resilience leveraging microgrids: A review. J Renew Sustain Energy 2019;11:035503. https://doi.org/10.1063/1.5066264.

[38] Mishra S, Anderson K, Miller B, Boyer K, Warren A. Microgrid resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies. Appl Energy 2020;264:114726. https://doi.org/10.1016/j.apenergy.2020.114726.

[39] O`Shaughnessy E, Cutler D, Ardani K, Margolis R. Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings. Appl Energy 2018;213:11–21. https://doi.org/10.1016/j.apenergy.2017.12.118.

[40] Dozens of flights at Boston Logan affected by power outage; 2017. https://www.boston25news.com/news/dozens-of-flights-at-boston-logan-affected-by-power-outage-at-atlanta-airport/665412840 [Online; accessed 14. Aug. 2020].

[41] Boston Logan International Airport; 2020. http://www.massport.com/logan-airport/about-logan [Online; accessed 14. Aug. 2020].

[42] REopt_Lite_API, NREL; 2021. https://github.com/NREL/REopt_Lite_API/wiki/REopt-Mathematical-Model-Documentation [Online; accessed 19. Jan. 2021].

[43] REopt Lite User Guides, NREL; 2021. https://reopt.nrel.gov/user-guides.html [Online; accessed 19. Jan. 2021].

[44] International Utility Rate Database; 2017. https://openei.org/apps/IURDB/rate/view/5cd34bf95457a30e7954e9d6 [Online; accessed 14. Aug. 2020].

[45] Dobos AP. PVWatts version 5 manual. Technical Report. Golden, CO (United States): National Renewable Energy Lab.(NREL); 2014.

[46] Masrur H. Techno-economic-environmental impact of derating factors on the optimally tilted pv system; 2020. https://doi.org/10.36227/techrxiv.12369305.v1.

[47] PVWatts Calculator; 2020. https://pvwatts.nrel.gov [Online; accessed 13. Aug. 2020].

[48] Kosai S. Dynamic vulnerability in standalone hybrid renewable energy system. Energy Convers Manage 2019;180:258–68. https://doi.org/10.1016/j.enconman.2018.10.087.

[49] Hossain MA, Pota HR, Squartini S, Zaman F, Guerrero JM. Energy scheduling of community microgrid with battery cost using particle swarm optimisation. Appl Energy 2019;254:113723. https://doi.org/10.1016/j.apenergy.2019.113723.

[50] Cutler D, Olis D, Elgqvist E, Li X, Laws N, DiOrio N, et al. Reopt: A platform for energy system integration and optimization. National Renewable Energy Laboratory, Tech. Rep. NREL/TP-7A40-70022; 2017.

[51] Net Metering Guide, MA, USA; 2020. https://www.mass.gov/guides/net-metering-guide [Online; accessed 29. Jun. 2020].

[52] Küfeoğlu S, Lehtonen M. Interruption costs of service sector electricity customers, a hybrid approach. Int J Electr Power Energy Syst 2015;64:588–95. https://doi.org/10.1016/j.ijepes.2014.07.046.