Resilient Energy Systems for Disaster Relief Operations in the Philippines

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Abstract

In the context of the increasing frequency and severity of disasters and associated power outages, a resilient energy system is needed to ensure smooth humanitarian operations and critical emergency responses such as preparing relief goods. The availability of electricity during the relief preparation is necessary to ensure that food items are packed efficiently and effectively. This study aims to design a resilient energy system for relief preparation. The objectives include assessing energy requirements during relief operations, determining the optimal energy system, and conducting sensitivity analysis to understand the effects concerning energy demand, component prices, and solar radiation. The sensitivity analysis reveals that the hybrid PV-diesel system is robust to varying parameters.

Keywords: disasters, resilient energy systems, humanitarian relief operations, optimization, sensitivity analysis

1. Introduction

Energy systems are vulnerable to power outages due to catastrophic disasters. Natural and man-made disasters can cause damage to power plants, transmission lines, and distribution facilities delivering electricity to the community, leading to large blackouts [1,2]. This is a growing threat, as according to U.S. National Oceanic and Atmospheric Administration (NOAA), there is a growing trend in the frequency and impact of weather disasters [3]. The Philippines, the world's third most susceptible country [4], struggles with power interruption during disasters. Typhoons such as Typhoon Kammuri and Typhoon Rai Odette destroyed many power lines in several regions leaving Filipinos without electricity [5, 6]. Earthquakes in Luzon and Mindanao closed down power stations, damaged transmission lines, and affected electricity distribution [7,8]. The bombing of a transmission tower in Lanao del Sur caused widespread power outages in the region [9]. With the constant threat of natural and man-made disasters, the country's electricity supply availability is at risk. This lack of energy supply during disasters could disrupt humanitarian disaster relief operations necessary for human survival.

Energy system resilience, as defined by the International Energy Agency (IEA), is "the capacity of the energy system and its components to cope with a hazardous event or trend, to respond in

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ways that maintain its essential functions, identity and structure as well as its capacity for adaptation, learning and transformation. It encompasses the concepts of robustness, resourcefulness, recovery" [10]. Resilience is a broad concept of "bouncing back" but has no precise definition [11]. Energy systems are exposed to numerous threats, such as extreme weather events [12], physical sabotage [13], changing demand [14], and high costs. These threats are present during disasters, making humanitarian operations vulnerable. Energy resilience is critical to reducing risks and maintaining relief work. With the increasing frequency and severity of natural disasters, there is an urgent need for energy systems to embrace the resilience concept to encompass relief and recovery efforts. A rise in the number of disasters escalates the demand for disaster relief operations. Electricity plays a vital role in humanitarian operations because it affects the speed of delivery of life-saving interventions in post-disaster situations. Therefore, a resilient energy system is vital in humanitarian response.

Humanitarian supply chain management (HSCM) is crucial in disaster relief operations as it delivers emergency items and critical information for human survival during disasters [15]. Most humanitarian supply chain studies in the literature tackle operations management such as storage, transportation, and distribution [16, 17]. In terms of supply chain infrastructures, existing studies focus more on information technology [18, 19] and transport [20, 21]. Studies on humanitarian supply chain management need to pay more attention to the energy system's resilience. The unreliable energy infrastructure may impede the delivery of emergency items in disaster situations [22]. It is challenging for the disaster responders to prepare, distribute, communicate, and monitor the relief operations during blackouts resulting in delayed delivery of necessary aid to the affected communities. A resilient energy system for humanitarian operations helps the process to be more efficient and effective.

This paper develops a resilient energy system for relief preparation. The objectives include assessing energy requirements during relief operations, determining the optimal energy system, and conducting sensitivity analysis to see the effects concerning energy demand, component prices, and inflation rate. This study contributes to the humanitarian supply chain management literature, specifically on energy infrastructures needed for humanitarian operations. Determining a resilient energy system supports Sustainable Development Goals, specifically Number 7 (Affordable and Clean Energy) and Number 13 (Climate Action). As such, this study promotes sustainable development in the Philippines by creating a culture of resiliency in the energy sector.

The rest of the article is structured as follows: Section 2 discusses the conceptual framework for a resilient energy system, Section 3 presents the optimal energy system, and Section 4 presents the sensitivity analysis. The final section concludes the article.

2. Resilience Energy System

With a multidisciplinary root, resilience is typically defined as the capability of a system to restore to its original state after experiencing disturbance [23]. Given the broad concept of energy system resilience, the qualitative and quantitative indicators for assessment could be more specific [24]. There are several themes in resilience conceptualization [25]. One theme of resilience is the ability to resist disruptions or supply chain risks [26]. In HSCM, these risks can be caused by increased prices, unstable demand, and other environmental factors.

In this study, a resilient energy system is defined as the ability of the energy structure to adapt to adversity caused by the varying inflation rate, component prices, electricity demand, and solar radiation. It presents how these parameters affect the net present cost, cost of energy, annual electrical production, greenhouse gas emissions, and renewable energy fraction. A resilient energy system must deliver an affordable and acceptable electricity supply during relief operations.

Affordability of energy can be measured in terms of net present cost and cost of energy. Availability is reflected in the annual electrical production. While acceptability can be measured using the Renewable Energy (RE) Fraction and pollutant emissions. Fig. 1 shows the conceptual framework of the study.

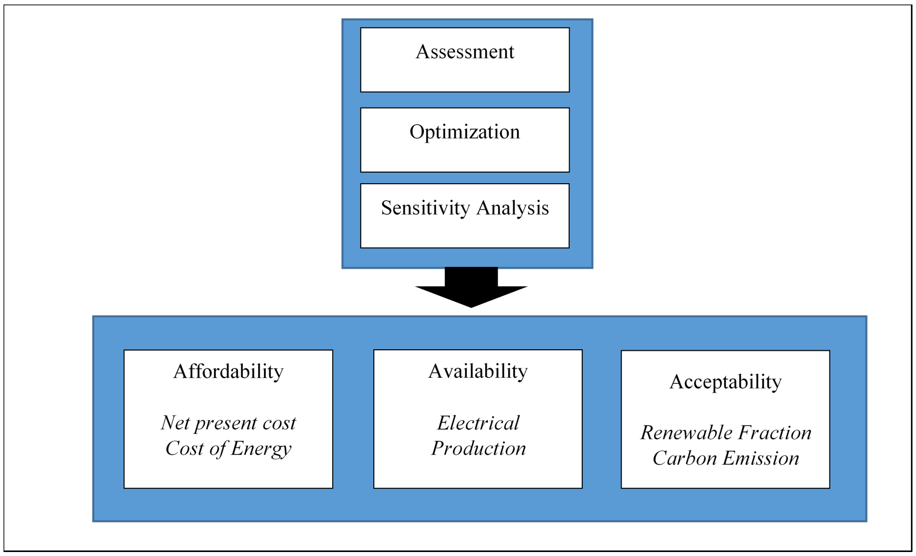

Figure 1: *Conceptual framework*

3. Optimal Energy System

This paper applied the Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software [27] to determine the optimal off-grid energy structure. An off-grid energy architecture is a system independent of the public grid. It is ideal during disasters where power lines are knocked down. The software simulates different energy system configurations for a micro power system, such as the relief preparation for a local community. HOMER's optimization and sensitivity analysis algorithms compare different design options based on five main inputs: resources data, energy load profile, component data, system economics, and constraints, as illustrated in Fig. 2. The resource data refers to the Global Horizontal Irradiation (GHI), which is used to calculate the panel PV array output. The energy load is a primary load that the system must supply to avoid unmet demand. Components are equipment integrated with the power system. This study considers the generator, PV, battery, and inverter. System economics comprises the discount rate, inflation rate, project lifetime, capital cost, and operating and maintenance cost. The software uses these input data to design the system architecture, calculate costs, and determine other system parameters such as renewable fraction and carbon emission.

An energy system is an assembly of components located within an environment. The system considered in the study consists of PV modules, a diesel generator, a converter, batteries, and a generator, as illustrated in Fig. 3.

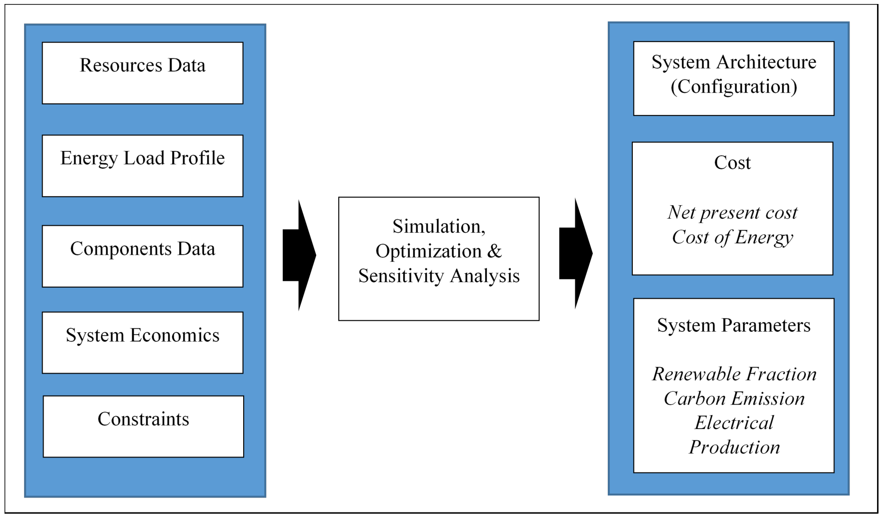

Figure 2: *Homer structure*

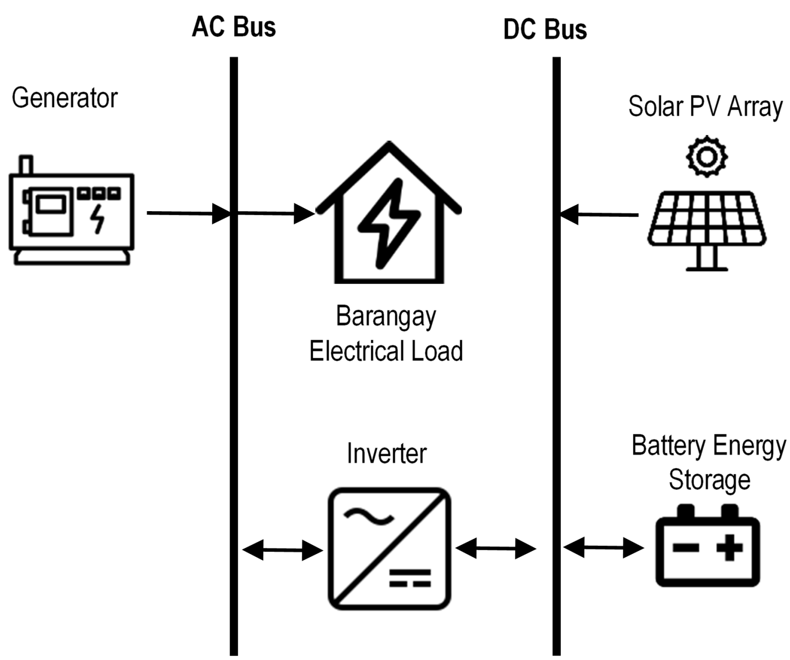

Figure 3: *Schematic diagram*

3.1. Resource data

The facility site for the relief goods preparation is situated at 6.75 North latitude and 124.75 East longitude. This location is chosen considering the volume requirement and distance to the distribution points of relief goods [28]. The solar radiation data were obtained from the NASA Prediction of Worldwide Energy Resource (POWER) database. The average daily solar radiation is 5.34 kWh/m2, as presented in Fig. 4.

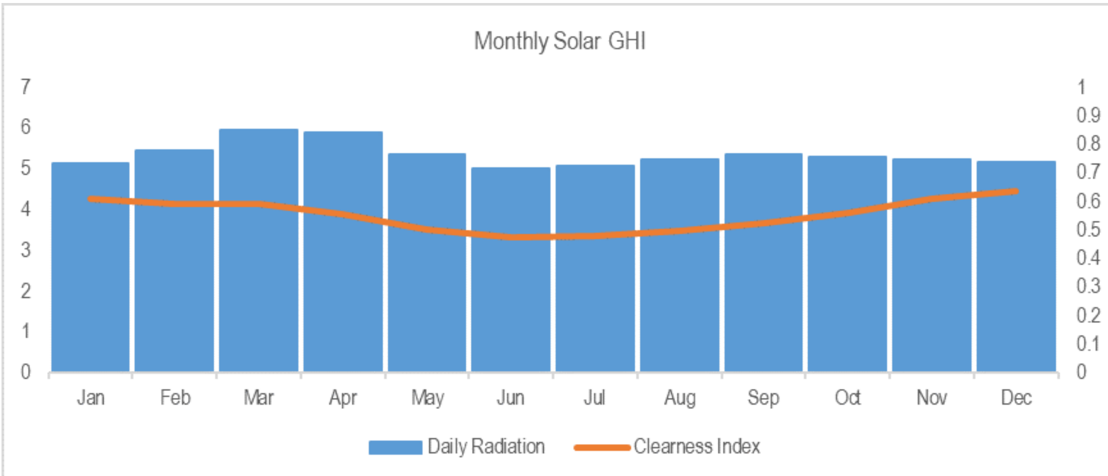

Figure 4: *Solar resource profile*

3.2. Energy consumption profile

The energy load profile for relief preparation was estimated by adopting the required number of packing machines and human resource requirements [28]. The electrical consumption for the repacking machine and communication charging considers the watts, time, and number of equipment and volunteers. The electrical consumption for the light and ventilation considers the space, light requirement, and ceiling height. This calculation reveals the facility's total daily load of 84.99 kWh, as illustrated in Table 1 and Fig. 5. The daily load profile, which shows the hourly demand, is presented in Fig. 6.

Table 1: *Energy consumption for relief operations*

Equipment	Quantity	Kwh per piece	Operating hours	Kwh
Machine	20	0.354	8	56.64
Lights	9	0.039	24	8.42
Ventilation	18	0.018	8	2.59
Communication	10	0.014	24	3.36
Others				13.97
Total				84.99

To address the accuracy limitations in calculating electricity load, this paper allows 10 percent daily and 20 percent hourly variations to change the load randomly. It is more realistic to allow variability in the load data because energy usages in relief operations are not constant.

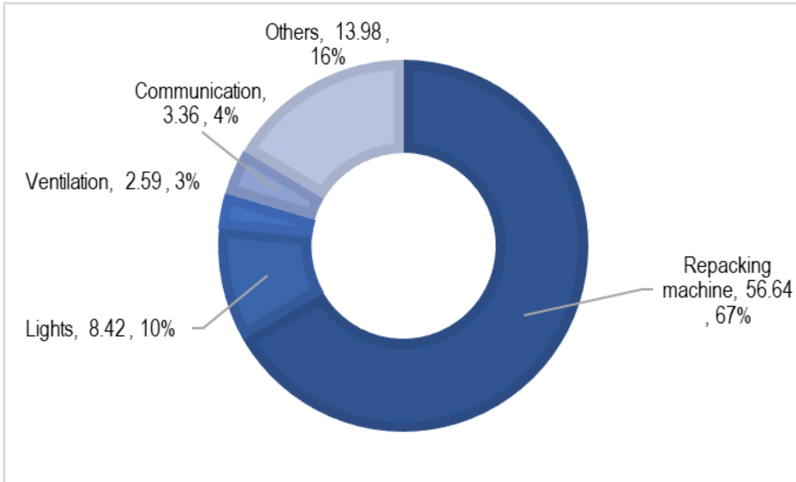

Figure 5: *Energy load profile*

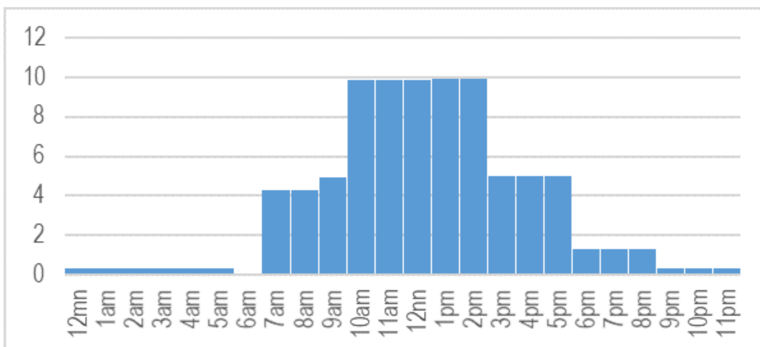

Figure 6: *Daily load profile*

3.3. System components

The components data, system economics, and constraints considered in this paper are summarized in Table 2. The valuation of the energy assets of the Philippines uses the Net Present Value Approach as recommended by SEEA-CF with a 10 percent discount rate [29,30]. The inflation rate in the simulation is 5.8 percent, which is the inflation rate in 2022 in the Philippines [31].

3.3.1 PV array

PV modules, called solar panels, are composed of numerous interconnected PV cells that convert solar energy into direct-current electricity. The PV panels used in the system simulation are generic flat plate PV with a lifetime assumed to be 25 years [32]. The derating factor from Asian Development Bank is 66 percent [33]. However, typical research in the Philippines uses a derating factor of 80 percent [34,35]. The estimated price of solar PV is $2400 per kWh in a study by the Department of Energy Philippines [36]. This study considered the average wholesale prices of PV panels and maintenance costs of $1740 and $15, respectively.

3.3.2 Batteries

Batteries are needed to store the PV output power, which can be used at night. The chosen battery has a 12-V, 83.4-Ah capacity, so the system can efficiently be decentralized if necessary. Its lifetime is considered to be 800 kWh of throughput per battery. The capital cost and replacement cost are the same at $370 per battery. The operating and maintenance cost is $10 per year for ten years [37].

3.3.3 Inverter

An inverter converts electric power from DC to alternating current (AC). Its efficiency is assumed to be 95 percent for all sizes considered. The estimated price is $290. The inverter converts the direct current generated by the PV system into an alternate current. It adapts to the typical voltage level of 230 V. Most inverters have a 10-year limited warranty [36].

3.3.4 Generator

A generator consumes fuel to produce electricity. A diesel-fueled generator is more efficient than other options and has a longer lifetime. The estimated generator price is $500 based on the average retail price. The fuel cost of $1.6 per liter is adopted from the average diesel price from May 2022 to November 2022 in the Philippines [38].

Table 2: *Summary of input parameters*

Components	Inputs	Values	Reference
	Discount rate	10%	[29,30]
	Inflation rate	5.8%	[31]
	Project lifetime	25 years	[32]
PV array	PV cost	$1740/kWh	
	Operating and maintenance cost	$15/kWh	
	Derating factor	80%	[34,35]
Battery	Battery cost	$370	
	Replacement cost	$370	
	Operating and maintenance cost	$10	[37]
	Life	10 years	[37]
Inverter	Inverter cost	$290	
	Replacement cost	$290	
	Life	10 years	[36]
Generator	Generator cost	$500	
	Replacement cost	$500	
	Fuel cost	$1.47 per litre	[38]

3.4. Optimization results

HOMER software simulates every system and ranks all the feasible system configurations according to Net Present Cost (NPC). The NPC of a system is the present value of all the costs it incurs over its lifetime minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, and fuel costs. As shown in Table 3, the optimal off-grid energy system or the least-cost system for relief preparation is 30.3kW PV, 19kW generator, 53kWh battery, and 16.2kW inverter. This configuration has the lowest NPC, amounting to $152,521, compared to other systems. Though the generator-only system has the least initial capital cost of $9,500, it has the highest NPC, cost of electricity, and operating cost. Hence, the hybrid system is the most feasible in the long run.

A PV-diesel hybrid energy system combines photovoltaic power generation with a generator set. This system ensures the availability of energy supply at any given time. The excess energy during the daytime is stored in batteries to use more solar power even at night. A hybrid system for an off-grid project is more viable than a diesel-only system, considering the cost of installing, operating and maintaining each system.

Table 3: *HOMER optimization results*

Architecture				Cost		
PV (kW)	Gen (kW)	Battery (kWh)	Converter (kW)	NPC ($)	COE ($)	Initial capital ($)
30.3	19.0	53	16.2	$152,521	0.314	$86,615
84.4		67	22.5	$238,275	0.490	$178,249
	19.0	22	3.79	$380,783	0.783	$ 18,740
9.57	19.0		6.97	$630,154	1.30	$28,180
	19.0			$666,762	1.37	$9,500

3.5. Sensitivity analysis

A sensitivity analysis is essential in building energy analysis. It identifies the key variables affecting the energy system. This study investigates the impacts of varying inflation cost, solar GHI, solar PV price, battery price, fuel price, and electric load on the project's net present cost, energy cost, annual electrical production, carbon emission, and RE Fraction. Table 4 presents the varying values of the set of parameters.

Table 4: *Set of parameters*

	Marginal change in base input								
Input parameters	-80%	-60%	-40%	-20%	Base	+20%	+40%	+60%	+80%
Inflation (%)	0.62	1.56	2.34	3.12	3.90	4.68	5.46	6.24	8.42
Solar GHI	0.85	2.13	3.20	4.27	5.34	6.41	7.48	8.54	11.53
Solar PV ($)	278	696	1044	1392	1740	2088	2436	2784	3758
Battery cost ($)	59	148	222	296	370	444	518	592	799
Fuel price ($/litre)	0.23	0.59	0.88	1.18	1.47	1.76	2.06	2.35	3.18
Electric load (kWh/day)	14	34	51	68	85	102	119	136	184

Regression is the most common technique for energy sensitivity analysis [39]. A correlation analysis is used to evaluate the relationship of input parameters to the project's NPC, cost of energy (COE), annual electrical production, carbon emission, and renewable energy fraction. The correlation (R^2) measures the strength of the linear relationship between two quantitative variables. Its values can range from -1 to 1. A correlation coefficient of -1 describes a perfect negative correlation, with values in one series rising as those in the other decline, and vice versa. A coefficient of 1 shows a perfect positive correlation or a direct relationship. A correlation coefficient of 0 means there is no linear relationship.

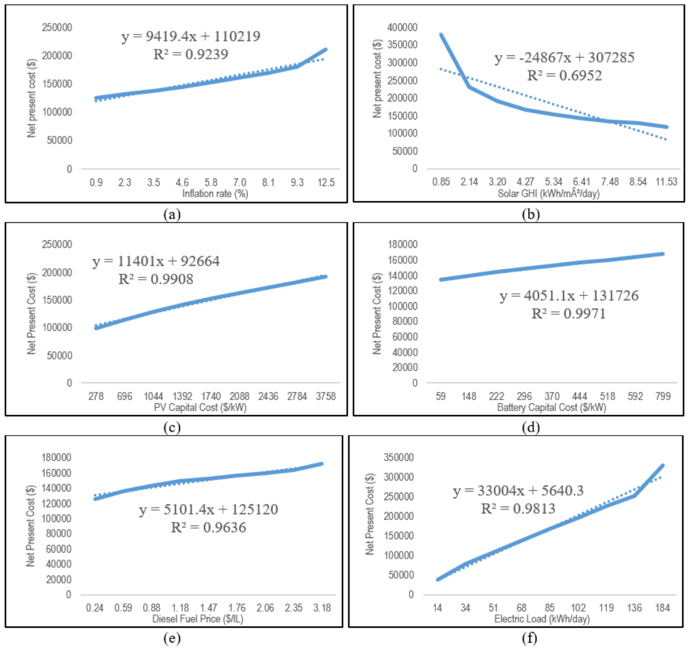

Figure 7: *NPC in relation to: (a) inflation rate; (b) solar GHI; (c) PV prices; (d) battery prices; (e) diesel price; (f) electrical load*

Fig. 7 shows that the inflation rate, PV cost, battery cost, fuel prices, and electrical load influence the NPC. The NPC increases when PV, battery, and fuel prices rise. The cost of installing and maintaining the energy infrastructure shoots up when the prices of these components increase. The surge in the inflation rate leads to an increase in component prices and the NPC. In addition, the increase in the demand for electrical load would require expansion of the energy system, thus, increasing its capital cost and NPC. Despite the price and inflation increase, a hybrid solar-diesel energy system still offers the most resilient configuration for relief operations.

The COE is the system's average cost per kWh of electrical energy production. A resilient energy system offers the least cost in constructing the project and minimal cost in operating and maintaining it over time. Fig. 8 presents that PV cost, battery cost, and fuel prices greatly influence COE. The components' prices have direct effects on the COE. However, the COE decreases as the electrical load increases because the system is maximized, resulting in lower excess electricity.

The total electrical production is the sum of the electrical energy produced by the PV and generator in one year. A resilient energy system must meet the demand of relief operations. The energy production of the optimal energy system has a positive relationship with the fuel prices and electrical load requirement, as shown in Fig. 9. An increase in the fuel prices would require a higher RE fraction because RE offers a lower cost. This increase in the RE fraction would boost the amount of energy produced. Moreover, electrical production grows when the electricity demand elevates because of the need to increase the energy configuration. On the other hand, too much solar GHI may reduce production due to increased temperature.

Carbon emissions are the total carbon pollutants produced annually by the power system in kg/yr. A resilient energy system responds to climate change. It minimizes the impacts of global warming and reduces greenhouse gas (GHG) emissions, which is necessary to address the challenges of a changing climate. The PV cost, battery cost, fuel prices, and electrical load

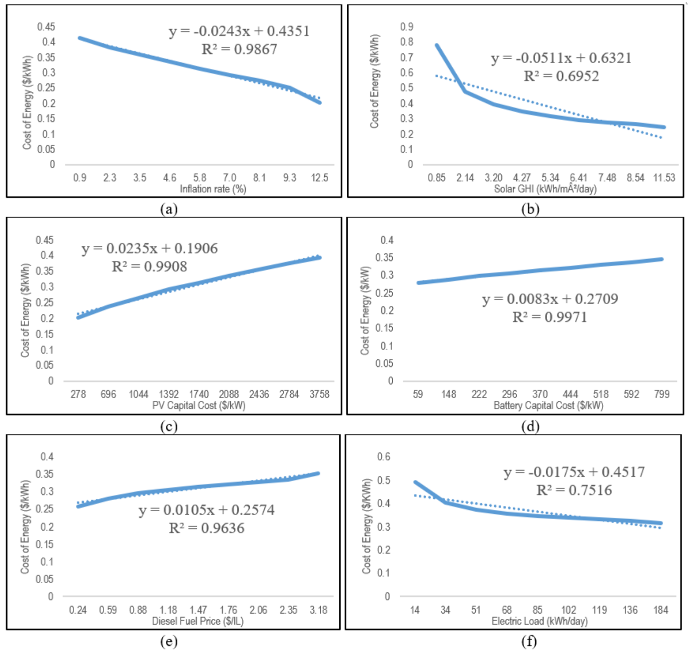

Figure 8: *COE in relation to: (a) inflation rate; (b) solar GHI; (c) PV prices; (d) battery prices; (e) diesel price; (f) electrical load*

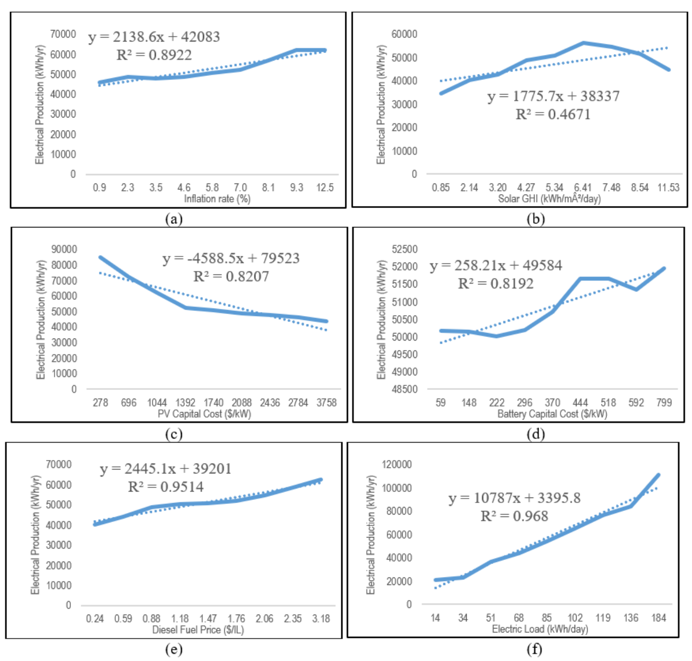

Figure 9: *Electrical production in relation to: (a) inflation rate; (b) solar GHI; (c) PV prices; (d) battery prices; (e) diesel price; (f) electrical load*

affect the amount of carbon emission, as presented in Fig. 10. The carbon emission is highly dependent on the RE fraction. The RE fraction determines the percentage of renewable energy usage. Suppose the system utilizes low renewable energy, and the carbon emission increases. This low RE fraction happens when the prices of PV and battery increase because the optimal energy system strengthens the use of diesel generators. The carbon emission declines when the fuel prices soar because the optimal energy system offers a high RE fraction. In addition, the increase in the electrical load requirement leads to an expansion in energy production, causing an increase in greenhouse gas emissions.

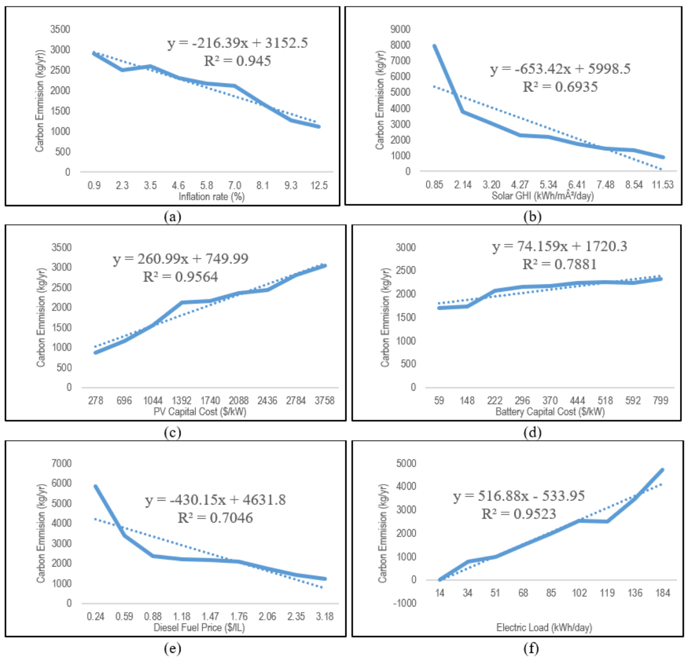

Figure 10: *Carbon emissions in relation to: (a) inflation rate; (b) solar GHI; (c) PV prices; (d) battery prices; (e) diesel price; (f) electrical load*

Renewable energy fraction is the proportion of energy delivered to the load that originated from renewable sources. Fig. 11 presents the effects of varying parameters on renewable fractions. The correlation coefficients for inflation, PV cost, battery cost, and fuel prices reveal that these parameters affect the RE fraction. As the inflation rate increases, the cost of fuel also rises. Therefore, it is ideal to increase the RE fraction when there is a surge in the inflation rate. On the other hand, the RE fraction declines when the PV and battery costs increase because the diesel generator offers the least energy cost. The output of the PV array depends on the GHI—a decline in the total solar radiation incident on the horizontal surface results in a lower RE fraction. The figures show that the PV-diesel energy system is resilient to changes in inflation cost, solar GHI, solar PV price, battery price, fuel price, and electric load.

4. Conclusion

The increasing frequency and severity of disasters demand a resilient energy system to ensure smooth humanitarian operations. One of the critical emergency responses is the preparation of relief goods. The availability of electricity during relief operations is necessary to ensure

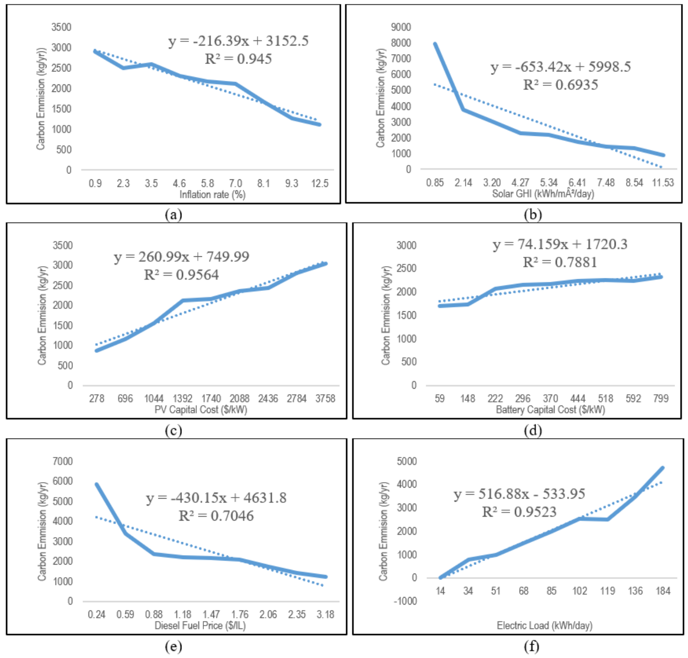

Figure 11: *RE fraction in relation to: (a) inflation rate; (b) solar GHI; (c) PV prices; (d) battery prices; (e) diesel price; (f) electrical load*

that food items are prepared and packed efficiently and effectively. This study assessed the energy requirement of relief operations, determined the optimal energy system, and conducted a sensitivity analysis. Using the HOMER software computer model, the most resilient energy system for relief operations with a daily load of 84.99 kWh comprises 30.3kW PV, 19kW generator, 53kWh battery, and 16kW inverter. The sensitivity analysis reveals that the hybrid PV-diesel system is robust to changing inflation cost, solar GHI, solar PV price, battery price, fuel price, and electric load. The increase in components cost and fuel prices influence NPC and COE. Electrical production is greatly affected by the growth in electrical demand and surge in fuel prices. An increase in PV prices, escalation of electrical demand, and reduction in fuel prices lead to high carbon emissions. There were no significant changes in both NPC, COE, and carbon emissions in the change in solar GHI. The renewable energy fraction is sensitive to component price hikes and inflation rates. Despite the changes in the parameters, a hybrid PV-diesel system remains the optimal configuration for relief operations.

Declaration of interest: None

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