Estimating the Cost of Electricity in Case of Power Outages with and without a Hybrid Solar Rooftop System in an Industrial

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ARTICLE INFO

Article history:
Received: 5 March 2023
Revised: 26 February 2024
Accepted: 26 March 2024
Online: 31 March 2025

Keywords:
Cost of electricity
Power outage
Hybrid solar rooftop system
Industrial

ABSTRACT

This paper presents estimating the cost of electricity in case of power outages with and without a hybrid solar rooftop system in an industrial. The factory in Pathum Thani Province, Thailand needs to reduce the cost of electricity and improve power quality. A power outage in the factory damaged the cost of production. Therefore, the application of a hybrid solar rooftop system is selected to solve this problem. The objectives are to estimate the cost of electricity in case of power outages with and without a hybrid solar rooftop system and to estimate the cost of electricity from the compensated battery storage in a day. The analysis is divided into 2 sections as follows: section 1 the estimate of the cost of electricity in case of power outages with and without a hybrid solar rooftop system and section 2 the analysis of the cost of electricity from the compensated battery storage. The results found that hybrid solar rooftop system can reduce damage from power outages according to the conditions of this paper.

1. INTRODUCTION

Customer outage is a common problem in the distribution system. Therefore, consumers in the death-end distribution system find a solution by installing a distributed generation (DG). The DG is a small electricity generation unit located near the user. The main source of energy for DG is solar energy, hydropower, etc [1]-[2]. Application of solar energy, such as the integration of solar rooftops and battery storage, is called hybrid solar rooftops.

Hybrid solar rooftop system increases the duration scope and the efficiency of electricity generation. A hybrid solar rooftop consists of a photovoltaic system (PV) on the roof combined with battery energy storage system (BESS). DG is installed as a standby generator can enhance system in the situation of power quality issues, such as voltage sag or voltage swell, harmonic, and power outage. The battery storage compensates for energy in the situation of an emergency or power system failure.

DG is compensated active power at the installation bus. Power quality in industrial is an important problem. It is a direct effect of the product. As a result, the factory was damaged and at risk for voltage sag/swell or power outage.

Conceptual model of distribution system connects with battery storage and solar system as shown in Fig. 1.

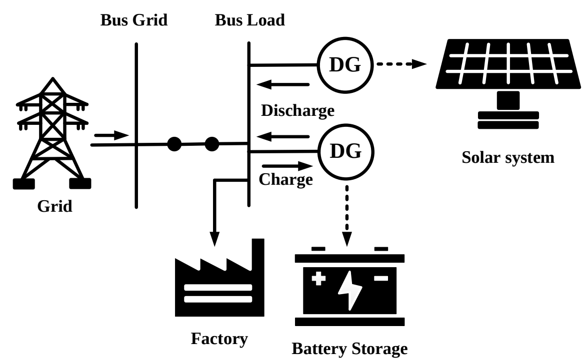

Fig. 1. Conceptual model of distribution system connects with battery storage and solar system.

In 2003, B.A. Carreras and others studied the estimation of reduced blackouts. The result found that minor interruption mitigation can increase the frequency of blackouts [3]. In 2015, Tan Zhang and others studied battery energy storage systems to solve outages. The result was found BESS available. However, the smart grid control was better than BESS [4]. In 2018, Said Mirza Tercan and others studied economic BESS to protect against outages in Turkey. Assess the economic impact of energy storage systems on substations covering outages [5]. In the same year, Hachidai Ito and others studied BESS to protect against outages. Power quality was improved with BESS

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and renewable energy [6]. In 2020, Hasan Masrur and others studied the operation of a microgrid during an outage. The results showed the PV system work with BS and minimizes the use of existing backup generator [7]. In 2021, Xuan Wu and others studied determining the best location to install BESS in a distribution system. The objective was to enhance reliability of a distribution network [8]. In 2022, Vignesh Gopalan, and A.K. Bakthavatsalam studied a cost analysis of BESS for industrial in Tamilnadu (India). The objective was to reduce the power fluctuations of the max load and protect a load from a power outage [9].

Therefore, this paper presents a comparison electricity cost of power outage in industrial with and without a hybrid solar rooftop system. The operation of battery storage combines with solar system as shown in Fig. 2.

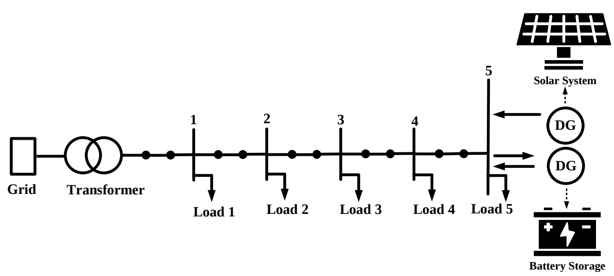

Fig. 2. The operation of battery storage combines with solar system.

Fig. 2. shows the operation of battery storage combine with solar system. Battery storage will release the stored electrical energy when the solar system cannot generate from an emergency.

2. LITERATURE REVIEW

2.1. Background of factory

The factory is located in Pathum Thani Province, Thailand. The factory consists of 3 sections. Each section receives power from a transformer capacity of 100 kVA, 400 kVA, and 800 kVA, respectively. The factory location is shown in Fig. 3.

Fig. 3. The factory location.

The factory daily load profile is shown in Table 1.

Table 1. The factory daily load profile

Time	Power (kW)
06:00	3.36
07:00	13.10
08:00	88.22
09:00	117.21
10:00	101.02
11:00	126.02
12:00	56.12
13:00	102.39
14:00	125.85
15:00	113.99
16:00	107.54
17:00	30.91
18:00	40.67
19:00	48.62
20:00	48.05
21:00	24.26
22:00	13.29
23:00	12.26
00:00	11.48
01:00	10.86
02:00	9.59
03:00	7.64
04:00	5.95
05:00	4.27
Total	**1,222.67**

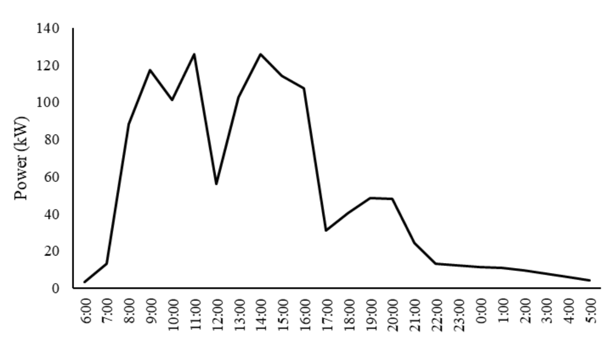

Fig. 4. Factory load curve.

Table 1. shows the factory daily load. The factory working time is 8:00-17:00. Overtime (OT) is 17:00-22:00. Factory load curve is shown in Fig. 4.

Fig. 4. shows the peak load from 9:00 to 22:00 (14 hours) and the off-peak load from 22:00 to 9:00 (11 hours).

Schematic diagram of hybrid solar rooftop system 149.80 kWp is shown in Fig. 5.

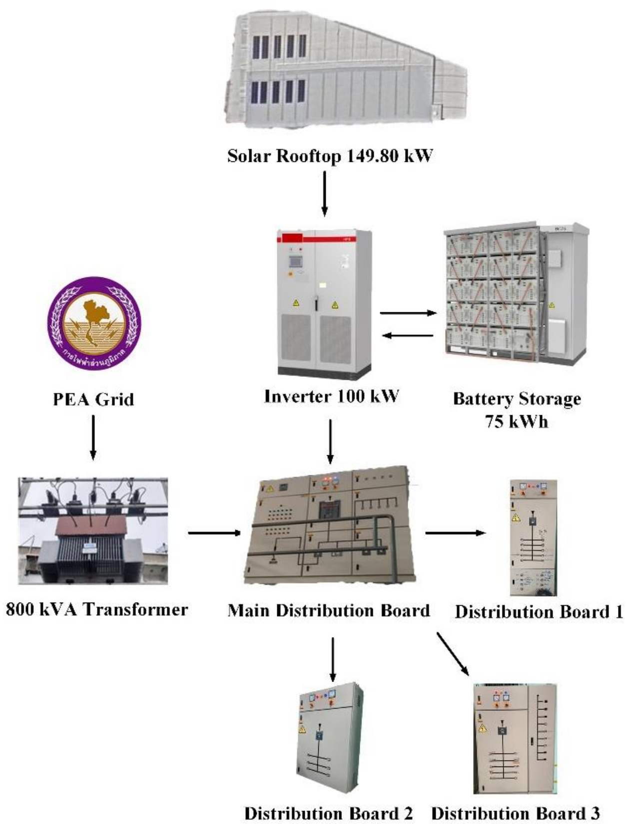

Fig. 5. Schematic diagram of a hybrid solar rooftop system 149.80 kWp.

Fig. 5. shows that a hybrid solar rooftop system consists of 280 solar panels. Each panel capacity is 535 W. Inverter capacity is 100 kW. Battery storage capacity is 75 kWh.

2.2. Power quality

Power quality problems consist of voltage quality and current quality [10]. Type of power quality is shown in Fig. 6.

The power outage can result from a variety of causes, including tripped breakers and failed circuit components. Power quality problems determined by IEEE 1159-1995 standard as shown in Fig. 7.

2.3. Power outage

Failure or blackout is a power outage problem. It is short-long loss electricity of grid. It may affect houses, buildings, and cities.

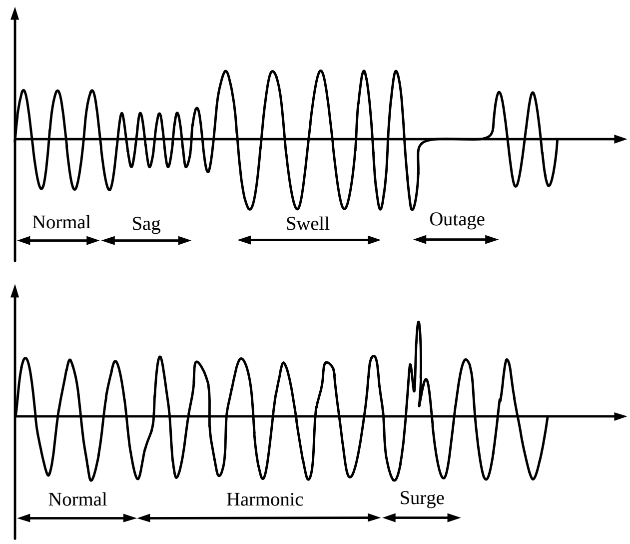

Fig. 6. Type of power quality.

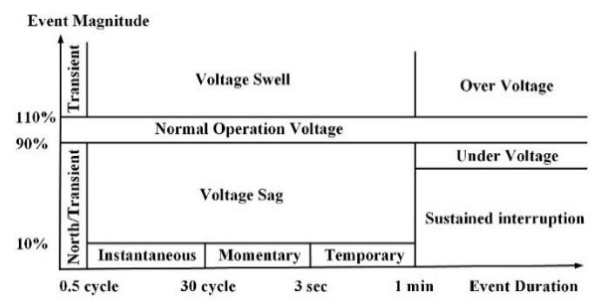

Fig. 7. Power quality problems determined by IEEE 1159-1995 Standard [11].

Table 2. Blackout classification

Blackout Classification	Causes
Natural disaster	- Earthquakes - Lightning
Transmission failure	- Transmission line tripping - Failure from protection device viz CT, VT - Transformer tripping - Fault by tree
Generation failure	- Loss of generation - Failure of substation - Voltage collapse - Frequency deviation and voltage deviation
Cyber issues	- Failure from communication - Failure from control system
Human/equipment/ unknown error	- Error from operator - Failure from mechanical - Animal misbehavior

The European Network of Transmission System Operators for Electric defines an outage as the interruption of four parts: the generating system, the power transmission system, the power distribution system, and the power consumer when the operation of the power transmission system or any part of it is interrupted [12]. The cause of blackout includes improper load shedding, voltage drop, and loss of stability [13]. Blackout classification is shown in Table 2.

Safety regulations (N-1) state that components remaining after a fault must be able to support new operating situations without compromising operational safety. Natural disaster events can cause the simultaneous failure of multiple components, resulting in a power outage [12].

2.4. Solar rooftop system

Solar rooftop system is an important technology in reversing global warming. Solar rooftop system produces clean energy in a form that doesn’t produce any pollutants or harmful gases. Solar rooftop system doesn’t use fuel to produce electricity, so there isn’t fuel transport or storage of radioactive materials. The maintenance requirements of solar system are low. Solar panels have no emissions. The efficiency of a solar power generation system depends on the amount and intensity of light. The lifespan of the solar power generation system is 25 years [14]-[15]. The method of generating electricity with solar cell is shown in Fig. 8.

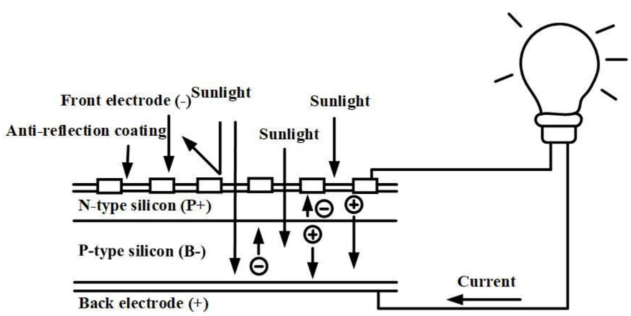

Fig. 8. The method of generating electricity with solar cells.

Another variable that affects the efficiency of a solar rooftop system is the azimuth angle and tilt angle of the module. Panel placement angle the module can be placed on a horizontal surface at an angle [16]. For Thailand, the most appropriate angle is 15 degrees south.

2.5. Effect of PV and BS reliability

Increasing the efficiency of photovoltaic system is important. Bad weather results in underdeveloped photovoltaic power generation. The energy storage system can help supply power in a shortage, thereby increasing the stability of the distribution system. The operation of battery storage on an island when an outage is shown in Fig. 9.

Fig. 9 shows that the operation of battery storage in the distribution system can enhance the reliability system through the in-island load supply, which is disconnected from the substation. After an emergency in the feeder section between bus 4, and bus 5, bus 5 became an island consisting of photovoltaic combined with battery storage. Electricity supply can still operate from the battery storage [17]-[18].

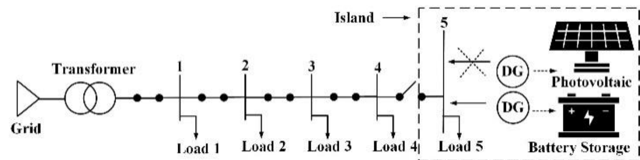

Fig. 9. The operation of battery storage in island when power outage.

2.6. Battery storage

Battery is a technology that charge energy for discharge energy later use. Electrochemical device that charges energy from a solar system or grid and discharge energy later to compensate for electrical power failures is a battery storage. Battery storage can be used for a variety of purposes such as improve power quality, balance the system.

State of charge (SOC) is the ratio of battery charge capacity to battery fully charged capacity [19]. State of charge can calculate in equation (1)

$$SOC = \frac{Q_{current}}{Q_{FC}} \tag{1}$$

where $Q_{current}$ is battery charge capacity.

Q_{FC} is battery fully charge capacity.

Depth of discharge (DOD) is the ratio of a battery discharge capacity ($Q_{release}$) to battery fully charge capacity (Q_{FC}). Depth of discharge can calculate in equation (2)

$$DOD = \frac{Q_{release}}{Q_{FC}} = 1 - \frac{Q_{current}}{Q_{FC}} \tag{2}$$

The capacity of battery storage is 75 kWh. Battery storage specification is shown in Table 3.

Table 3. Battery storage specification

Specification	Size
Rate capacity	200 Ah
Rate energy	76.8 kWh
Rate voltage	384 V
Voltage range	336-438 V
Normal charge/discharge	0.5 C
Max charge/discharge	1 C
Weight	<= 1060 kg
Protection degree	IP 54

2.7. Mathematical model

The battery has high energy density and regulated charge/discharge cycles that can provide constant voltage power. The terminal voltage of the battery was calculated in equation (3) [20].

$$V_{bat} = E - R \cdot i \tag{3}$$

The battery discharge was calculated in equation (4)

$$E = E_0 - K \frac{Q}{Q - it} \cdot it - K \frac{Q}{Q - it} \cdot i^* + Exp(t) \tag{4}$$

The battery charge was calculated in equation (5)

$$E = E_0 - K \frac{Q}{Q - it} \cdot it - K \frac{Q}{it - 0.1 \cdot Q} \cdot i^* + Exp(t) \tag{5}$$

where R is battery storage internal resistance (Ω)
E_0 is open circuit potential (V)
i is battery storage charging/discharging current (A)
K is polarization voltage (V)
Q is battery capacity (Ah)

3. RESULTS AND DISCUSSION

3.1. Case study

The case study divides two sections. Section 1 is about estimating the cost of electricity in case of power outages with and without a hybrid solar rooftop system. Section 2 is the analysis of electricity cost from compensated battery storage.

Section 1: Estimating cost of electricity in case of power outages with and without hybrid solar rooftop system.
Case study in section 1 as follows:

Case 1.1: Base case (no outage duration)
Case 1.2: Outage duration 0.50 hours (30 minutes)
Case 1.3: Outage duration 1.00 hours (60 minutes)
Case 1.4: Outage duration between 08:00 - 09:00 (08:00 - 08:05 (5 min.), 08:10 - 08:25 (15 min.), 08:30 - 09:00 (30 min.))
Case 1.5: Outage duration between 13:00 - 14:00 (13:00 - 13:05 (5 min.), 13:10 -13:25 (15 min.), 13:30 - 14:00 (30 min.))

Section 2: The analysis of electricity cost from compensated battery storage

The case study in section 1 as follows:
Case 2.1: Battery is discharging 2 sections.
Case 2.2: Battery is discharging 3 sections.
Case 2.3: Battery is discharging 4 sections.

In section 2, the battery analysis is discharged and converted to reduce electrical costs from battery storage.

3.2. Result

Section 1

Comparison results of electricity cost in case of power outages with and without a hybrid solar rooftop system are shown in Table 4.

Table 4. Comparison results of electricity cost in case of power outages with and without a hybrid solar rooftop system

Case	Outage duration (Min)	Power (kW)	Damage Cost (Baht)		
			Without hybrid solar rooftop	With hybrid solar rooftop	Compare damage cost
1	0	132.17	0.00	0.00	0.00
2	30	132.17	135.81	96.35	39.46
3	60	132.17	271.62	113.79	157.83
4	5	55.86	9.56	0.70	8.86
	15	88.84	45.64	8.94	36.70
	30	115.40	118.57	39.56	79.01
Total cost case 4			173.77	49.20	124.57
5	5	72.34	12.33	0.93	11.40
	15	112.08	57.58	11.92	45.66
	30	115.61	118.79	39.66	79.13
Total cost case 5			188.70	52.51	136.19

Damage cost of electricity in case of power outages with and without a hybrid solar rooftop system is shown in Fig. 10.

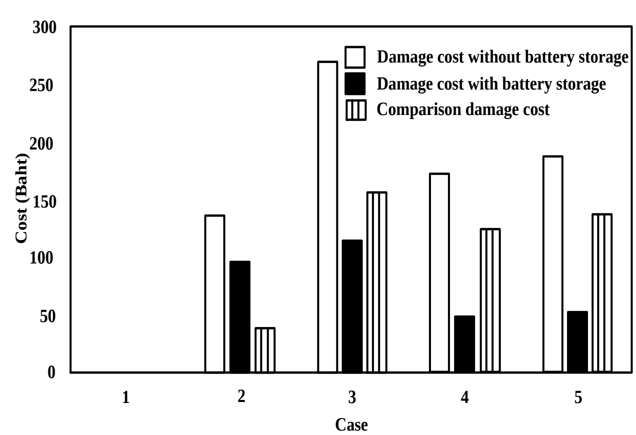

Fig. 10. Damage cost of electricity in case of power outages with and without a hybrid solar rooftop system.

Fig. 10. shows maximum energy was supported each duration by battery storage. After over 1 hour, battery storage cannot support the load because the battery can last

for 1 hour. The results found that battery storage is discharging in case of 76.8 kWh/hour outages. Therefore, the hybrid solar rooftop can reduce the damage outage. If there is not a hybrid solar rooftop, the damage is 299.09 baht/hour. The case study is outage 0, 30, 60, 60 (5, 10, 30 minutes at 8:00-9:00) and 60 (5, 10, 30 minutes at 13:00-14:00) respectively. The comparison damage cost is 0.00, 39.46, 157.83, 124.57, and 136.19 baht, respectively.

Section 2

The results of energy production and compensation for electricity costs from solar rooftop system are shown in Table. 5.

Table 5. The results of energy production and compensation for electricity costs from solar rooftop system

Month	Energy is produced (kWh)	Compensation for electricity costs from solar rooftop systems (Baht)
March (2023)	12,784.90	53,490.74
April (2023)	12,639.40	52,881.99
May (2023)	16,490.10	68,992.93
June (2023)	12,462.90	52,143.53
July (2023)	11,427.30	47,810.68
August (2023)	12,288.90	51,415.53
September (2023)	11,879.00	49,700.55
October (2023)	10,588.20	44,299.97
November (2023)	11,947.50	49,987.15
December (2023)	10,881.30	45,526.27
January (2024)	12,172.80	50,929.78
February (2024)	11,187.60	46,807.80
Total	146,749.90	613,986.91

Table 5. shows that the total energy from solar rooftop system is produced about 146,749.90 kWh. The total compensation for electricity costs from solar rooftop systems is 613,986.91 baht. The comparison results of energy production and compensation from solar rooftop systems are shown in Fig. 11.

Fig. 11. shows that the minimum month of energy is produced in October 2023 (10,588.20 kWh). In October solar system can cause the compensation for electricity costs around 44,299.97 baht. The maximum month of energy is produced in May 2023 (16,490.10 kWh). In May 2023, solar system can be compensated for electricity cost around 68,992.93 baht.

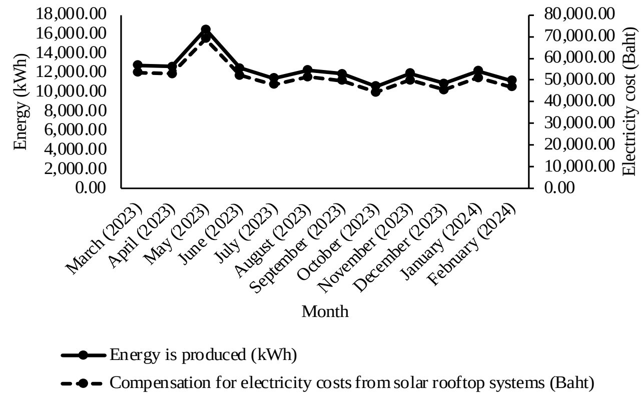

Fig. 11. The comparison results of energy production and compensation from solar rooftop system.

The next part is battery storage is operating. The results of charge, discharge, and compensation for electricity costs from battery storage are shown in Table 6.

Table 6. The results charge, discharge, and compensation for electricity costs from battery storage

Month	Battery is charging (kWh)	Battery is discharging (kWh)	Compensation for electricity costs from battery storage (Baht)
March (2023)	917.00	1,123.80	4,701.87
April (2023)	672.60	919.80	3,848.35
May (2023)	789.00	1,075.90	4,501.46
June (2023)	1,329.50	1,638.60	6,855.74
July (2023)	1,664.50	1,982.50	8,294.58
August (2023)	1,719.70	2,033.30	8,507.12
September (2023)	1,671.90	1,973.70	8,257.76
October (2023)	1,657.20	1,986.50	8,311.32
November (2023)	1,634.80	1,949.70	8,157.35
December (2023)	1,571.50	1,711.20	7,159.49
January (2024)	1,844.40	1,929.00	8,070.74
February (2024)	1,659.50	1,719.70	7,195.05
Total	17,131.60	20,043.70	83,860.84

Table 6 shows that the total battery storage is charging 17,131.60 kWh. The total battery storage is discharging 20,043.70 kWh. The total compensation for electricity cost from battery storage is 83,860.84 baht. The comparison results of charge, discharge, and compensation from battery storage are shown in Fig. 12.

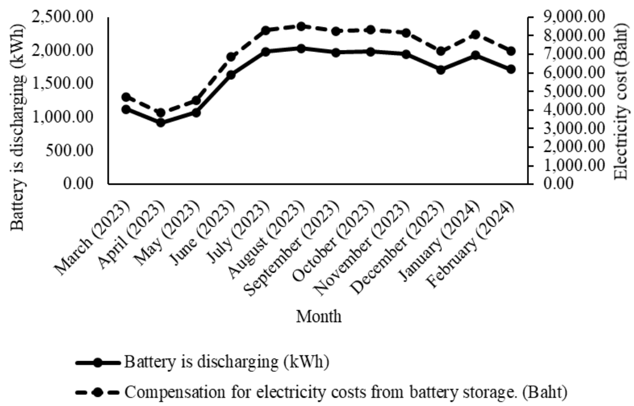

Fig. 12. The comparison results of charge, discharge, and compensation from battery storage.

Fig. 12. shows the minimum month of battery is charging in April, 2023 (672.60 kWh). The minimum month of battery storage is discharging in April, 2023 (919.80 kWh). In April 2023 battery storage can compensate electrical cost 3,848.35 baht. The maximum month of battery storage is charging in January, 2024 (1,719.70 kWh). The maximum month of battery storage is discharging in August 2023 (2,033.30 kWh). In August 2023, battery storage can be compensated for electricity costs by 8,507.12 baht.

Case study 2.1: Battery is discharging in 2 sections.

Discharged battery in 2 sections (2024-01-09) is shown in Fig. 13.

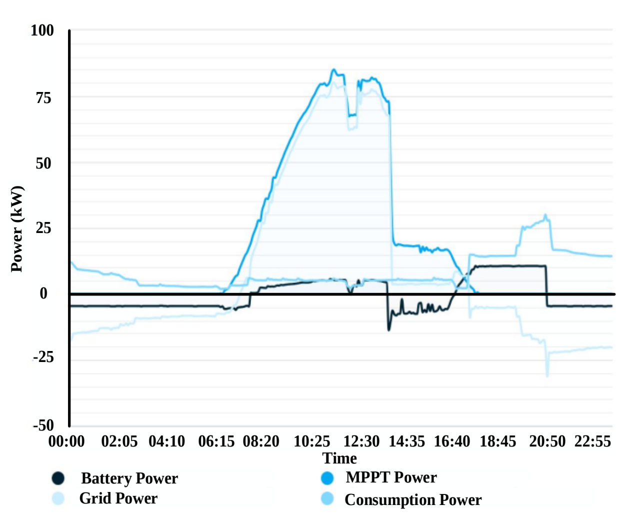

Fig. 13. Battery is discharging 2 sections.

Fig. 13. shows the battery storage is charging 68.6 kWh and discharging 61.5 kWh. The operating battery storage in 2 sections is shown in Fig. 14.

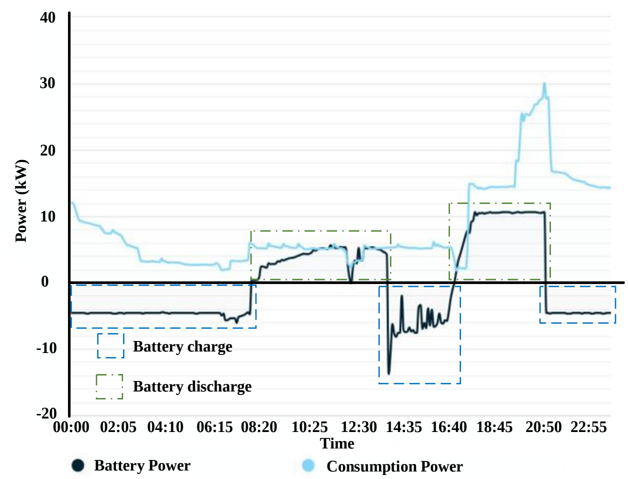

Fig. 14. The operating battery storage in 2 sections.

Fig. 14. shows that the battery storage is discharging. This case is divided into 2 sections viz after 8:30 and after 17:00. Section 1, the battery storage is discharging from 8:30 to 14:00. After that the battery storage is charging from 14:05 to 16:55. Section 2, the battery storage is discharging again from 17:00 to 21:00. SOC in 2 sections of battery storage is shown in Fig. 15.

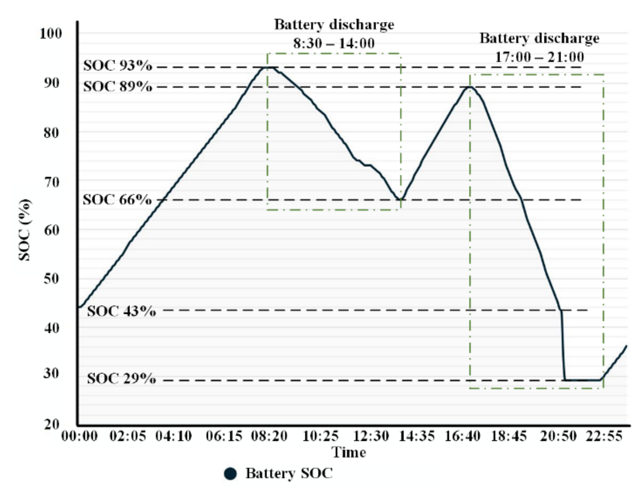

Fig. 15. SOC in 2 sections of battery storage.

Fig. 15. shows that from 8:30 to 14:00, the state of charge (SOC) is reduced by 27 % (93% - 66%). From 17:00 to 21:00, SOC is reduced by 46% (89% - 43%). The results of battery storage are discharging each period in case 2.1 is shown in Table. 7.

Table 7. The results of battery storage are discharging each period in case 2.1

Period	Battery storage is discharging (kWh)	Reduce electricity cost (Baht)
08:05 - 08:25	0.50	2.09
08:30 – 14:00	22.70	94.97
14:05 - 16:55	0.20	0.84
17:00 – 21:00	38.10	159.41
Total	**61.50**	**257.31**

Table 7. shows that from 8:30 to14:00, battery storage is discharging 22.70 kWh and can reduce electrical cost by 94.97 baht. From 17:00 to 21:00, battery storage is discharging 38.10 kWh and can reduce electrical cost by 159.41 baht. Therefore, the total battery storage is discharging in case 2.1 is 61.50 kWh, and the total reduced electrical cost in case 2.1 is 257.31 baht.

Case study 2.2: Battery is discharging in 3 sections.

Battery is discharging in 3 sections (2024-02-20) as shown in Fig. 16.

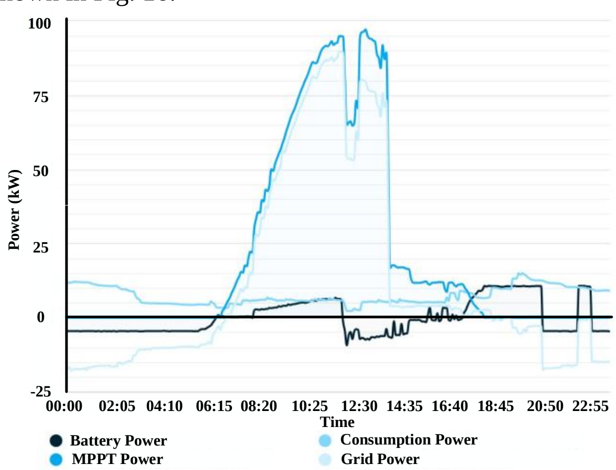

Fig. 16. Battery is discharging 3 sections.

Fig. 16. shows that the battery storage is charging 59.7 kWh, and it is discharging 62.1 kWh. The battery storage is operating in 3 sections is shown in Fig. 17.

Fig. 17 shows the battery storage is discharging. In this case is divided into 3 sections viz after 6:40, 17:30, and 22:35. Section 1, the battery storage is discharging from 6:40 to 12:00 after that it is charging from 12:05 to 17:25. Section 2, the battery storage is discharging from 17:30 to 20:55 after that it is charging from 21:00 to 22:30. Section 3, the battery storage is discharging from 22:35 to 23:05. SOC in 3 sections of battery storage is shown in Fig. 18.

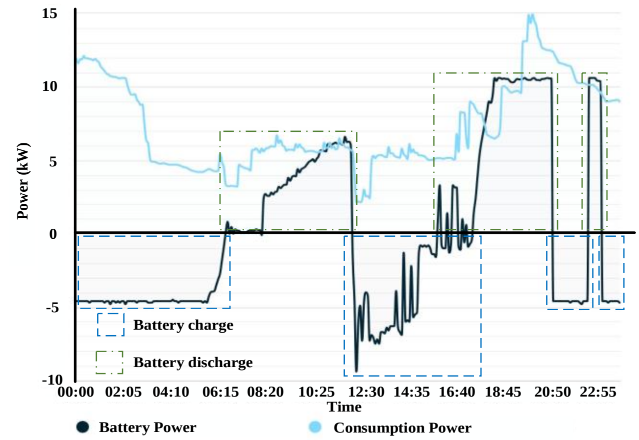

Fig. 17. The battery storage is operating in 3 sections.

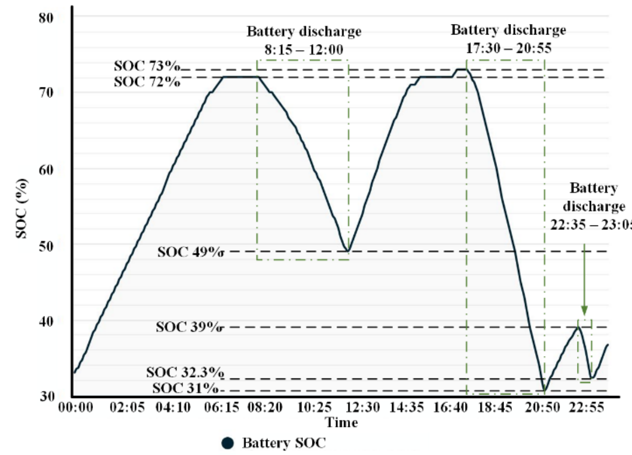

Fig. 18. SOC in 3 sections of battery storage.

Fig. 18 shows that from 8:15 to 12:00 SOC is reduced by 23% (72% - 49%), and from 17:30 to 20:55 SOC is reduced by 42.3% (73% - 30.7%), respectively. From 22:35 to 23:05 SOC is reduced by 6.7% (39% - 32.3%). The results of discharging battery storage each period in case 2.2 are shown in Table 8.

Table 8. The results of discharging battery storage each period in Case 2.2

Period	Battery discharge (kWh)	Reduce electricity cost (Baht)
06:45 - 08:10	1.20	5.02
08:15 – 12:00	18.70	78.24
12:05 - 17:25	1.90	7.95
17:30 – 20:55	34.20	143.09
21:00 – 22:30	0.00	0.00
22:35 – 23:05	6.10	25.52
Total	**62.10**	**259.82**

Table 8 shows that from 8:15 to 12:00, the battery storage discharges 18.70 kWh and reduces electrical costs to 78.24 baht. From 17:30 to 20:55, it discharges 34.20 kWh and reduces electrical costs by 143.09 baht. From 22:35 to 23:05, it discharges 6.10 kWh and reduces electrical costs by 25.52 baht. Therefore, the total discharging battery storage in case 2.2 is 62.10 kWh and the total reduced electrical cost in case 2.2 is 259.82 baht.

Case study 2.3: Battery is discharging in 3 sections.

Discharged battery in 4 sections (2023-11-25) is shown in Fig. 19.

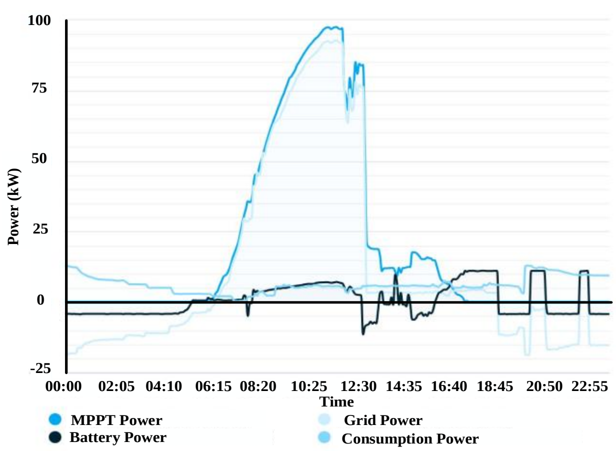

Fig. 19. Battery is discharging 4 sections.

Fig. 19 shows that the battery storage is charging 51.8 kWh and is discharging 65.1 kWh. The battery storage is operating in 4 sections as shown in Fig. 20.

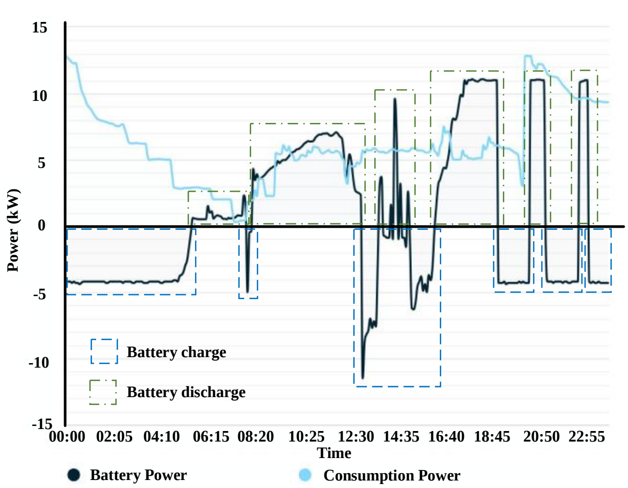

Fig. 20. The battery storage is operating in 4 sections.

Fig. 20 shows that the battery storage in this case is divided into 4 sections viz after 5:40, 16:20, 20:30 and 22:40, respectively. In section 1, the battery storage is discharging from 5:40 to 13:00. From 5:40 to 8:10, it is compensated 0.5 kW - 1.5 kW. After the battery storage is discharging from 8:15 to 13:00, it is charging from 13:05 to 16:15. In section 2, the battery storage is discharging from 16:20 to 19:00, and it is charging from 19:05 to 20:25. In section 3, the battery storage is discharging from 20:30 to 21:05, and it is charging from 21:10 to 22:35. In section 4, the battery storage is discharging from 22:40 to 23:00.

SOC in 4 sections of battery storage in 4 sections is shown in Fig. 21.

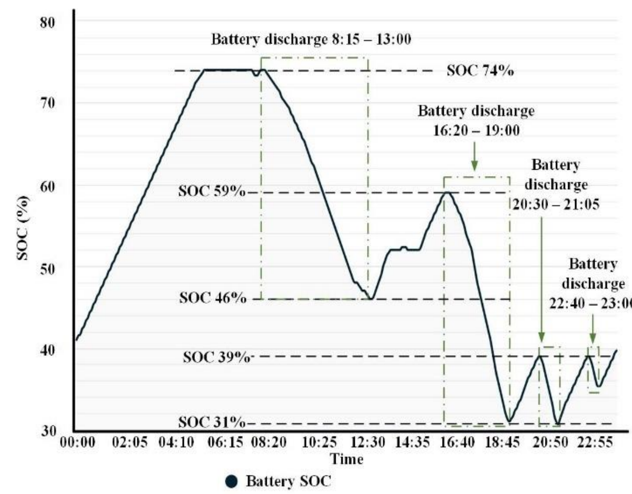

Fig. 21. SOC in 4 sections of battery storage.

Fig. 21 shows that from 8:15 to 13:00, SOC is reduced by 28% (74% - 46%). From 16:20 to 19:00, SOC is reduced by 28% (59% - 31%). From 20:30 to 21:05, SOC is reduced by 8.3% (39% - 30.7%). From 22:40 to 23:00, SOC is reduced by 3.7% (39% - 35.3%). The results of discharged battery storage each period in case 2.3 are shown in Table 9.

Table 9. The results of battery storage are discharging each period in Case 2.3

Period	Battery storage is discharging (kWh)	Reduced electricity cost (Baht)
05:40 - 08:10	2.30	9.62
08:15 - 13:00	24.70	103.34
13:05 - 16:15	2.50	10.46
16:20 – 19:00	24.00	100.41
19:05 – 20:25	0.10	0.42
20:30 – 21:05	7.50	31.38
21:10 – 22:35	0.00	0.00
22:40 - 23:00	4.00	16.74
Total	**65.10**	**272.37**

Table 9 shows that from 8:15 to 13:00, the battery storage is discharging 24.70 kWh, and it can reduce electrical cost by 103.34 baht. From 16:20 to 19:00, the battery storage is discharging 24.00 kWh, and it can reduce electrical cost by 100.41 baht. From 20:30 to 21:05, the battery storage is discharging 7.50 kWh, it can reduce electrical cost by 31.38 baht. From 22:40 to 23:00, the battery storage is discharging 4 kWh, and it can reduce electrical cost by 16.74 baht. Therefore, the total discharged battery storage in case 2.3 is 65.10 kWh and the total reduced electrical cost in case 2.3 is 272.37 baht.

4. CONCLUSIONS

This paper presents estimating the cost of electricity in case of power outages with and without a hybrid solar rooftop system in an industrial. The battery storage capacity is 75 kWh.

The case study is divided into two sections. In section 1, it is to estimate the electricity cost in case of power outages with and without a hybrid solar rooftop system. Five sub-cases were tested as follows: outage duration 0 minutes, 30 minutes, 60 minutes, 60 minutes (5, 10, and 30 minutes at 8:00-9:00), and 60 minutes (5, 10, and 30 minutes at 13:00-14:00). The results in section 1 found that the damage without hybrid solar rooftop system is 299.09 baht/hour. The outage battery storage can support a load of 76.80 kW. The comparison damage cost is 0.00 baht, 39.46 baht, 157.83 baht, 124.57 baht, and 136.19 baht, respectively.

Section 2 is the analysis of the electricity cost from compensated battery storage. Three sub- cases were tested as follows: battery storage is discharging in 2 sections, 3 sections, and 4 sections, respectively. The results in section 2 found that the battery storage can be compensated for energy in case study 2.1, 2.2, 2.3 by 61.5 kWh, 62.1 kWh, and 65.1 kWh, respectively, representing the reduction in electricity costs of 257.31 baht, 259.82 baht, and 272.37 baht, respectively.

Therefore, the hybrid solar rooftop system can reduce the cost of electricity in case of power outages from this paper's outage condition.

ACKNOWLEDGEMENTS

The authors would like to thank Rajamangala University of Technology Phra Nakhon (RMUTP), Thailand and Thai Carton (Rangsit) Service Co., Ltd.

REFERENCES

[1] N. Rugthaicharoencheep, and S. Sirisumrannukul, "Feeder Reconfiguration for Loss Reduction in Distribution System with Distributed Generators by Tabu Search," GMSARN International Journal, vol. 3, no. 2, pp. 47-54, 2009.

[2] N. Ruangsap, S. Nedphokaew, N. Rugthaicharoencheep, "Planning and Operation Enhanced Voltage Profile by Using Distributed Generators Installation in Distribution System with Feeder Reconfiguration," 2022 International Conference on Power, Energy and Innovations (ICPEI), 2022, doi: 10.1109/ICPEI55293.2022.9987013.

[3] B. A. Carreras, V. E. Lynch, D. E. Newman, and I. Dobson, "Blackout mitigation assessment in power transmission systems," 36th Annual Hawaii International Conference on System Sciences, 2003, doi: 10.1109/HICSS.2003.1173911.

[4] T. Zhang, S. Cialdea, J. A. Orr, and A. E. Emanuel, "Outage Avoidance and Amelioration Using Battery Energy Storage Systems," 2014 Clemson University Power Systems Conference, 2014, doi: 10.1109/PSC.2014.6808127.

[5] S. M. Tercan, E. Gökalp, and B. Kekezoğlu, "Economic Analysis of Energy Storage Preventing Energy Outages in Distribution Grid in Turkey," 2018 6th International Conference on Control Engineering & Information Technology (CEIT), 2018, doi: 10.1109/CEIT.2018.8751933.

[6] H. Ito, V. A. Kale, Y. Yokosawa, K. Yanagiuchi, K. Sasaki, and S. Kusagawa, "Study Results for Preventing Power Outages utilizing Battery Energy Storage Systems," 2018 IEEE 8th Power India International Conference (PIICON), 2018, doi: 10.1109/POWERI.2018.8704376.

[7] H. Masrur, T. Senjyu, M. R. Islam, A. Z. Kouzani, and M. A. P. Mahmud, "Optimal Operation of Resilient Microgrids During Grid Outages," 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2020, doi: 10.1109/ASEMD49065.2020.9276171.

[8] X. Wu, A. J. Conejo, and S. Mathew, "Optimal Siting of Batteries in Distribution Systems to Enhance Reliability," IEEE Transactions on Power Delivery, vol. 36, pp. 3118-3127, 2020, doi: 10.1109/TPWRD.2020.3034095.

[9] V. Gopalan, and A. K. Bakthavatsalam, "Cost Benefit analysis of Battery Energy Storage System for an Industry in Tamilnadu (India)," 2022 IEEE Delhi Section Conference (DELCON), 2022, doi: 10.1109/DELCON54057.2022.9753377 .

[10] K. K. Vanukuru, J. V. Rao, S. R. Davu, and A. Ramisetti, "Fuzzy control based APF with DG integration for power quality improvement in disribution system," 2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES), pp. 1410-1417, 2016, doi: 10.1109/SCOPES.2016.7955672.

[11] P. Ngamprasert, and N. Rugthaicharoencheep, "Optimization Technique for Voltage Sag with Integration of Photovoltaic Energy Distributed Generation," GMSARN International Journal. vol. 18, no. 4, pp. 414-420, 2024.

[12] N. C. Chakraborty, A. Banerji, and S. K. Biswas, "Survey on major blackouts analysis and prevention methodologies," Michael Faraday IET International Summit 2015, 2015, doi: 10.1049/cp.2015.1647.

[13] N. Sharma, A. Acharya, I. Jacob, S. Yamujala, V. Gupta, and R. Bhakar, "Major Blackouts of the Decade:

Underlying Causes, Recommendations and Arising Challenges," 2021 9th IEEE International Conference on Power Systems (ICPS), 2021, doi: 10.1109/ICPS52420.2021.9670166.

[14] N. Rugthaicharoencheep, P. Ngamprasert, N. Ruangsap, and N. Rodrueang, "Minimize the Customer Outage for Improved Reliability in Distribution System with Photovoltaic Distributed Generation," 2022 57th International Universities Power Engineering Conference (UPEC), 2022, doi: 10.1109/UPEC55022.2022.9917881.

[15] S. Dalala, V. Jadhav, R. Raut, and S. Narkhede, "Analysis of 1KW Solar Rooftop System by Using PYSyst," 2nd International Conference on Communication & Information Processing (ICCIP) 2020, 2020.

[16] J. Waewsak, R. Khamharnphol, S. Khunpetch, I. Kamdar, S. Chiwamongkhonkarn, C. Kongruang, and Y. Gagnon, "Techno-Economic Assessment of a 1 MW Solar PV Rooftop System at Thaksin University (Phatthalung Campus), Thailand," ASEAN Journal of Scientific and Technological Reports (AJSTR), vol. 26, no. 1, pp. 59-75, 2023, doi: https://doi.org/10.55164/ajstr.v26i1.248159.

[17] S. X. Wang, W. Zhao, Y. Y. Chen, "Distribution system reliability evaluation considering DG impacts," 2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, 2008, doi: 10.1109/DRPT.2008.4523850.

[18] H. Falaghi, and M.-R. Haghifam, "Distributed Generation Impacts on Electric Distribution Systems Reliability: Sensitivity Analysis," EUROCON 2005 - The International Conference on "Computer as a Tool", pp. 1465-1468, 2006, doi: 10.1109/EURCON.2005.1630240.

[19] A. Bavand, "Li-ion Battery State of Charge (SOC) and State of Health (SOH) Online Estimations Using Partial Charge or Discharge Data," Master of Science in Software Engineering and Intelligent Systems, Department of Electrical and Computer Engineering, University of Alberta, 2021.

[20] P. Shaw, P. K. Sahu, S. Maity, P. Kumar, "Modeling and control of a battery connected standalone photovoltaic system," 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), 2016, doi: 10.1109/ICPEICES.2016.7853123.