Application of Resilience Curve for Evaluation of Change over Time of Risks in Clean Energy Systems

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Abstract: The number of clean energy systems is rapidly increasing to meet the global carbon neutrality commitment to tackle climate change. On the other hand, these power plants need to be able to cope with changing climate. In the past decade, energy resilience has emerged as a concept to enhance the adaptive capacity of energy systems towards climate change by equipping them with capacities to prepare, absorb, recover, and adapt. Energy resilience assessment consists of five steps including threat identification, impact assessment, vulnerability identification, assessment of risks and their change over time, and resilience measure identification. Evaluation of change over time is a crucial element providing information to strengthen recoverability. This study proposes the evaluation of change over time of the functionality of clean energy systems with and without resilience measures using the resilience curve with a case study at a commercial solar farm in peninsula Malaysia to demonstrate its application. Revenue from electricity sales is used to represent the functionality. In the case study, the risk pair of floods and lack of planning and standard procedure along with the resilience measure to reconsider the out-of-control action plan are used to demonstrate the method. As the resilience measure optimizes the response to the floods, the outage period can be shortened. The resilience measure would not significantly affect the size of impact or the occurrence frequency. The cost of the countermeasure is 40,000 USD/lifetime, and the savings vary from 19,636 to 1,656,000 USD/lifetime, resulting in a net benefit of -20,364 – 1,616,000 USD/lifetime. As the resilience curve helps visualize and quantify the recovery capacity of a system, it is expected to optimize investment on resilience measures and consequently contribute to resilience enhancement of future clean energy systems.

Keywords: change over time, resilience curve, recoverability, energy resilience assessment

1. INTRODUCTION

Climate change is one of the current global concerns that the public regard as humanitarian emergencies. At the 2021 United Nations Climate Change Conference (COP26), countries made pledges to achieve carbon neutrality by 2050 and reduce emissions enough to reach the Paris Agreement's goal. The Pact [1] resulted from COP26 urges countries to phase down coal and fossil fuel industries and support deployment of renewable energy. Installing new renewable energy systems can contribute to independence from fossil fuel sources, resulting in the reduction of greenhouse gas emissions. On the other hand, increasingly extreme climate can disrupt energy networks, stress these new energy systems, and pose significant risks in energy supply. This calls for actions to upgrade and protect the energy infrastructures from the impact of changing extreme weather.

The concept of energy resilience is used to describe an individual power plant's capacity to cope with adversity, stance towards changing weather conditions, and adaptability in response to environmental changes [2]. It is often seen as a risk management approach in the context of climate preparedness. Energy resilience is described as the ability to prepare, absorb, recover, and adapt to impacts from disruptive events and the ability to be in preferable conditions in response to increasing trends in disruption frequency and severity. Though energy resilience covers various types of ability, recoverability and adaptability were highlighted towards the future improvements of energy systems.

ASEAN Energy Resilience Assessment Guideline [3] developed by National Energy Technology Center (ENTEC) was introduced to facilitate the application of the concept of energy resilience to energy systems. With the endorsement by ASEAN Sub-Committee on Sustainable Energy Research (SCSER) and the approval from ASEAN Committee on Science, Technology and Innovation (COSTI), the Guideline was proved to have a comprehensive structure, and detailed information for conducting an energy resilience assessment of a renewable energy system. The Guideline presented the methodology for energy resilience assessment with a standard operation procedure (SOP) and supportive materials. The methodology was built upon the strengths of conventional risk assessments to identify threat, impact, and vulnerability in a system and importantly underlined key components for enhancing resilience in energy systems including recoverability and adaptability. A delivery function for transitions in resilience [4] was employed to visualize the transitions of functions when disruptive events and resilience actions take place. In the respect of determining resilience measures, evaluation of change over time not only depicts function transitions, but also visualizes changes in impacts before and after a resilience measure is implemented, which is an important piece of information to ensure recoverability. The objective of this study is to propose the evaluation of change over time of the functionality of clean energy systems with and without resilience measures using the resilience curve. A commercial solar power plant in peninsula Malaysia is used as the case study to demonstrate the applicability of the resilience curve to facilitate the evaluation of change over time.

2. METHODOLOGY

This section explains the methodology of energy resilience assessment adopted by ASEAN Energy Resilience Assessment Guideline, its differences from conventional risk assessment, along with the conceptual framework of evaluation of change over time, and how the evaluation is performed. Changes in the size of impacts, period of disruption, and frequency of occurrence when resilience measures are implemented are discussed.

2.1. Energy resilience assessment

The methodology of energy resilience assessment (referred to as the Assessment) was built upon the conventional risk assessment utilizing its strengths on identifying threats, impacts, and vulnerabilities. \ Capabilities to determine change over time and resilience measures were equipped to reflect the core concept of energy resilience. As shown in Figure 1, the Assessment contains five steps: Threat Identification, Impact Assessment, Vulnerability Identification, Risk Assessment and Change over Time, and Resilience Measure Identification. In Threat Identification, a list of observable threats is suggested to be created based on inputs from stakeholders and secondary data. Individual threat should be given by a score considering its frequency as high (9), medium-high (7), medium (5), low-medium (3), to low (1). The scores from all stakeholders were averaged to obtain the threat frequency score. Impact Assessment aims to determine impacts from the above individual threats on the system and their degree. The scope for impact consideration varies, while power sector and end users are recommended as default scopes. Vulnerability Identification aims to perceive weaknesses of the system that can be exposed to a threat. To complete this step, a list of vulnerabilities corresponding to multiple threats should be examined and given a score considering level of severity. The score can range from high (9), medium-high (7), medium (5), low-medium (3), to low (1). The scores are then averaged across different stakeholders to obtain the vulnerability severity score. In Assessment of Risks and Change over Time, a matrix of risks should be created using the list of threats and vulnerabilities, and their scores. As shown in Figure 2, the matrix of risks is obtained by simply multiplying frequency and severity scores, in which a higher score reflects higher risk. Discussion is held among stakeholders to select the priority

Figure 1. Energy resilience assessment flow

			Vulnerability				
			Vulnerability 1	Vulnerability 2	Vulnerability 3	Vulnerability 4	Vulnerability 5
			x	x	x	x	x
Threat	Threat 1	x					
	Threat 2	x					
	Threat 3	x					
	Threat 4	x					
	Threat 5	x					

Figure 2. Example matrix of risks

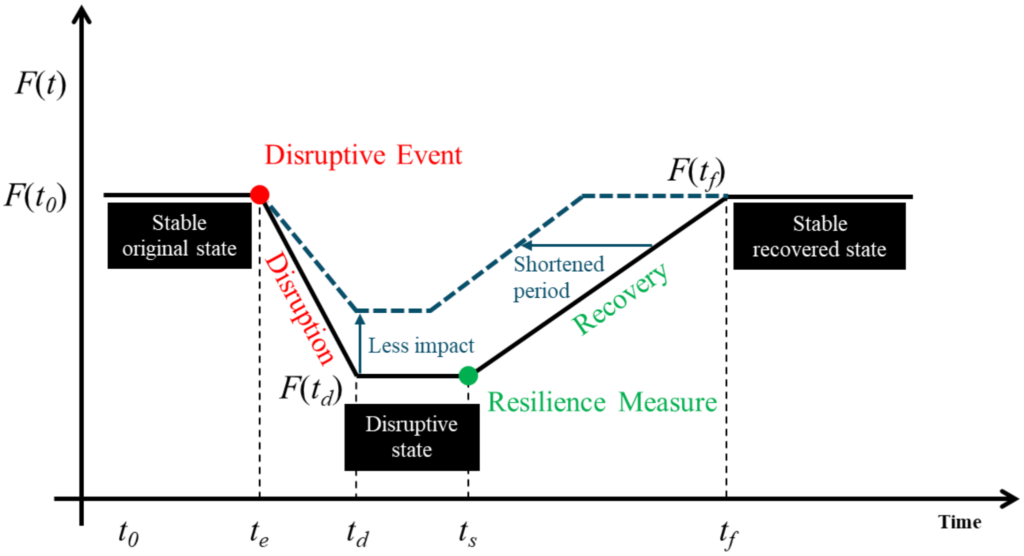

Figure 3. Schematic representation of change over time and effects of resilience measures [3]

risk pairs based on risk scores and evaluate change over time. Resilience Measure Identification aims to consider a resilience measure or solution to alleviate the impacts determined in Impact Assessment. A resilience measure should incorporate energy resilience features, especially recoverability and adaptability; and be determined with the consideration of current circumstances of the system. Generally, resilience measures are divided into two categories, including hardware resilience measures and software/managerial resilience measures.

As described earlier in the previous section, the Assessment built upon the conventional risk assessment to investigate threat, impact, and vulnerability of a system and was designed to incorporate recoverability and adaptability as key components of energy resilience. Evaluation of change over time is a crucial part to capture recoverability of the system which attempts to examine changes before and after a resilience measure is implemented. The evaluation is utilized not only to cope with the changes, but also to introduce appropriate and feasible resilience measures to the current circumstances of the system.

2.2. Evaluation of change over time

Figure 3 shows how the functionality (*F(t)*) of the power plants changes over time when a disruptive event occurs and a resilience measure is applied. Parameters to represent the functionality can be the power plant capacity, revenue from power sales, or any other parameters agreed upon by the assessors and the stakeholders. The power plant shifts from stable original state to disruptive state due to a disruptive event. The transition can be a gradual or a stepwise change depending on the type and severity of the disruptive event. The power plant may recover to the stable recovered state by itself or may require resilience measures to assist in bouncing back or shortening the disrupted period. Similar to the disruption, the recovery can be immediate or gradual.

In this study, evaluation of change over time should be conducted with and without resilience measures to assess the effectiveness of respective resilience measures in enhancing resilience of the power system. In the evaluation of change over time, there are three types of resilience enhancements to be considered, including change in the size of the impact, change in the disrupted period, and change in the frequency of the disruptive event. The first two items can be discussed in terms of functionality loss ($F(t_0)$-$F(t_d)$) and period of the disruptive state (t_s-t_d). The last item requires additional information on the occurrence frequency of the disruptive event.

3. CASE STUDY

3.1. Information about the power plant

A case study at a commercial solar power plant in peninsula Malaysia [5] is used to demonstrate the applicability of the resilience curve for the evaluation of change over time. Inputs and assumptions for the calculation are shown in Table 1. Revenue is used to represent the functionality as it can also capture the managerial elements of the power plant. To calculate the revenue, information on power generation capacity, power generation potential per day, electricity price per unit, and the lifetime of the power plant is needed.

3.2. Risk matrix and proposed resilience measures

Figure 4 shows the risk matrix which was developed based on the energy resilience assessment of the solar power plant. Six selected threats and five selected vulnerabilities along with their scores were used to develop the matrix. The risk score of each risk pair was obtained by multiplying the threat score to the vulnerability score. Pairs of threats and vulnerabilities that were irrelevant were crossed out. Five top risk pairs (of which the cells are painted grey) were chosen for the evaluation of change over time:

- Risk pair 1: East Coast Rail Link project future development and lack of planning and standard procedure;
- Risk pair 2: animals and lack of planning and standard procedure;
- Risk pair 3: future development and lack of physical protection;
- Risk pair 4: erosion and lack of planning and standard procedure;
- Risk pair 5: flood/flash flood lack of planning and standard procedure;

Based on the discussion with stakeholders, resilience measures were proposed for each selected risk pair as summarized in Table 2.

Table 1. Inputs and assumptions for the demonstration of evaluation of change over time

Input/assumption	Value	Unit
Total power (W_{ac})	50	MW
Power per module (W_{ac})	270	W
Number of modules	184,880	modules
Number of central inverters	21	inverters
Selling price	0.09	USD/kWh
Solar potential	4	hours/day
Lifetime of the power plant	20	years

			Vulnerability				
			Lack of planning and standard procedure	Lack of animal control	**Lack of physical protection**	Improper design	Location prone to disaster
			7.4	5.4	**5.4**	5	4.4
Threat	**Future development**	**8.1**	**60.26**	X	**43.97**	40.71	35.83
	Animals	**6.7**	**49.69**	36.26	X	33.57	29.54
	Erosion	**5.6**	**41.23**	X	30.09	27.86	24.51
	Flood/flash flood	**5.6**	**41.23**	X	30.09	27.86	24.51
	Lightning strikes	4.4	32.77	X	23.91	22.14	19.49
	Fire	3.3	24.31	X	X	16.43	14.46

Figure 4. Risk matrix for the demonstration of evaluation of change over time

Table 2. Selected risk pairs and proposed resilience measures

No.	Threat	Vulnerability	Countermeasure
1	Future development	Lack of planning and standard procedure	Clean panel more frequently
2	Animals		Set animal trap
			Cable protection
			Agrivoltaics
3	Future development	Lack of physical protection	Reconsideration of fence design
			Installation of signage
4	Erosion	Lack of planning and standard procedure	Additional installation of lighting/security (CCTV) system
			Cow grass turfing work
			Agrivoltaics
			Slope erosion control with Geoweb
5	Flood/flash flood	Lack of planning and standard procedure	Reconsideration of out-of-control action plan

Table 3. Assumptions for evaluation of change over time

Item	Value	Unit
Minimum outage	1	central inverter
Maximum outage	1	plant
Outage period (without countermeasure)	7-30	days
Outage period (with countermeasure)	1-7	days
Frequency of flood (without countermeasure)	0.2	times/year
Frequency of flood (with countermeasure)	0.2	times/year
Time for meeting and training	50	man-day/year
Salary of staff	800	USD/month/person

Table 4. Revenue loss per disruptive event

Revenue loss (USD/time)		
Outage scale	1 inverter	1 plant
Outage period		
1 day	818	18,000
1 week	5,727	126,000
1 month	24,545	540,000

Table 5. Results of evaluation of change over time

Item	**Value (USD/lifetime)**
Revenue loss without countermeasure	22,909 – 2,160,000
Revenue loss with countermeasure	3,273 – 504,000
Savings from countermeasure	19,636 – 1,656,000
Cost of countermeasure	40,000
Net benefit	-20,364 – 1,616,000

3.3. Evaluation of change over time

Risk pair 5: flood/flash flood lack of planning and standard procedure was used for the demonstration of evaluation of change over time, with reconsideration of out-of-control action plan as the selected resilience measure. Table 3 shows the assumptions of disruption size, disrupted period, occurrence frequency, and expenses needed for the resilience measure. These assumptions were obtained from literature, historical data of similar power plants, and consultation with the power plant’s stakeholders. Since the power plant is located on a flat plain, a large-scale flood can submerge areas covered by one central inverter up to the whole power plant. Reconsideration of the out-of-control action plan would most likely not reduce the size of the impact as it is determined by the severity of the flood itself. As for the disrupted period, the plant will need at least a week to recover from the flood with the current out-of-control action plan. The disrupted period may be extended to a month if there are damaged parts that are not spared. The reconsideration of the out-of-control action plan will include the line of command and the standard operating procedures (SOP) during and right after the flood, the parts that could be damaged by floods, the spare parts needed, and the procedure to request to the headquarters for damaged parts that are not spared. With the appropriate out-of-control action plan in place, the outage period would be reduced to a day up to a week as a one-week-long flood is not likely based on the historical floods in the area. The frequency of a flood that can potentially submerge the power plant is approximately once in five years, and the resilience measure is not expected to reduce this frequency. To develop, update, and keep the operators aware of the out-of-control action plan, approximately 50 man-day is needed for meeting and training per year.

Table 4 shows the estimation of revenue loss due to floods. The revenue loss is calculated taking into account the outage scale (disruption size), outage period (disrupted period), generation capacity per module, solar potential, and electricity unit price. To maintain the simplicity of the evaluation, the revenue at the stable recovered state is assumed to be the same as the stable original state, and a stepwise change in revenue is assumed for both disruption and recovery. Without the countermeasure, the outage period varies from a week to a month and the outage scale is from an inverter to the whole power plant, resulting in the revenue loss of 5,727 – 540,000 USD/time. Calculated in the same manner, the revenue loss with countermeasure will be 818 – 126,000 USD/time. Based on the assumption in Table 3, this kind of flood is expected to occur four times during the plant lifetime whether with or without countermeasure.

Table 5 summarizes the results of the evaluation of change over time of the revenue from the solar power sales when a flood disrupts the power plant with existing and updated out-of-control action plans. As the plant lifetime is 20 years and the occurrence frequency of a severe flood is assumed to be once in five years, numbers in Table 4 need to be multiplied by four to obtain the revenue loss for the plant lifetime. As a result, reconsideration of out-of-control action plan which costs 40,000 USD for the whole plant lifetime has the potential to reduce revenue loss by 19,636 – 1,656,000 USD, resulting in net benefit of -20,364 – 1,616,000 USD.

It can be seen from the case study that the resilience curve helps visualize and quantify the recovery capacity of the solar power system by capturing the change of the functionality of the system in terms of revenue. The flood decreases the generation capacity for a certain period, resulting in revenue loss which depends on the disrupted generation capacity and disrupted period. Reconsideration of out-of-control action plan decreases the outage period by optimizing the recovery procedures, though it does not reduce the size of the impact or the flood occurrence frequency. There are also other resilience measures that reduce the disruption size (e.g., more frequent panel cleaning which minimizes the efficiency decrease due to the Risk pair 1: future development and lack of planning and standard procedure) and the occurrence frequency (e.g., setting animal traps which reduces the frequency of wires bitten due to the Risk pair 2: animals and lack of planning and standard procedure). Since the disruption size and the disrupted period can alter according to the flood intensity, the net benefit of the resilience measure may vary significantly. In this case, the measure may result in net loss if the floods are not as intense as expected. In turn, the benefit can rise to over a million USD if the floods are very severe. Looking at the average net-benefit, it can be assumed that managerial resilience measures, such as reconsideration of out-of-control-plan, are likely to enhance the resilience of the power system, resulting in net benefits, if they are well-designed.

4. CONCLUSION

Resilience curve can be used to evaluate the change over time of the functionality of a clean energy system when a disruptive event occurs to estimate how the recovery capacity of the system would change when a resilience measure is applied. The power plant shifts from stable original state to disruptive state due to a disruptive event and bounces back to the to the stable recovered state by itself or with the assistance of resilience measures. A resilience measure can enhance resilience of the system by reducing the size of impact, the disrupted period, or the occurrence frequency. A case study at a commercial solar power plant in peninsula Malaysia was used to demonstrate the applicability of resilience curve in evaluate the change over time. Risk pair 5: flood/flash flood lack of planning and standard procedure was used for the demonstration, with reconsideration of out-of-control action plan as the selected resilience measure. Revenue is used to represent the solar system functionality. The managerial resilience measure can significantly mitigate the revenue loss by shortening the disrupted period, resulting in net benefit of -20,364 – 1,616,000 USD. The study showed that the resilience curve helps visualize and quantify the recovery capacity of clean energy systems and can aid in decision making whether or not to implement the proposed resilience measures. Decision makers can choose cost-effective resilience measures that result in net benefits to enhance resilience of clean energy systems with optimized investment on countermeasures.

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