Development of Conceptual Framework for Adaptive State for Energy Resilience Assessment of Clean Energy Systems

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Abstract: Climate adaptation underlines protection of people and infrastructure by making them less vulnerable to impacts of climate change. This includes adaptation of clean energy systems which confront a new and unusual set of vulnerabilities compared to conventional energy systems. Energy resilience has emerged as a concept to help energy systems cope with disruptive events, in which recoverability and adaptability play a key role in sustaining their functionality. A delivery function was proposed to evaluate transition of system functionality due to disruptive events and resilience actions, consisting of three key components including distinct states, state transitions, and state triggers. Although recovery could be quantified, adaptability towards disruptions cannot be captured by the function. Built upon the delivery function for transitions in resilience, this study aims to conceptualize an adaptive state by integrating key components of promising concepts including global catastrophic risks (GCR), beyond design basis accidents (BDBA), and foresight, and to construct a resilience curve to quantify the adaptability of clean energy systems. GCR enlarges the scope of consideration of the resilience curve, covering system-wise and human-wise characteristics. A set of actions suggested in BDBA is incorporated to reduce severity of impacts, period of disruptive state, and frequency of occurrence of disruptions. Foresight is utilized to depict how state transitions occur and determine effective resilience actions. The resilience curve is conceptually established by integrating the abovementioned concepts, and the adaptive state is introduced where the system functionality possibly goes beyond the stable recovered state. The proposed adaptive resilience curve will be adopted in the ASEAN Energy Resilience Assessment Guideline to potentially enhance the adaptability of the clean energy systems in Southeast Asia.

Keywords: adaptive state, resilience curve, global catastrophic risk, beyond design basis accident, foresight.

1. INTRODUCTION

Climate adaptation plays a significant role in reducing vulnerability to the current and expected impacts of climate change. While climate mitigation contributes to fulfillment of global commitments through sustainably utilizing clean energy sources to transition away from convention fossil energy sources, climate adaptation protects people and infrastructure by making them less vulnerable to the impacts, in which a new and unusual set of vulnerabilities harms is experienced in clean energy systems. A variety of vulnerabilities related to climate change ranging from rising temperature, fire, landslide, sea level rise, drought, windstorm, flood, and lightning were identified [1] and expected to interrupt and halt the effort of climate mitigation. Energy resilience has emerged as a concept to address the climate impacts in energy systems and cope with increasing severity of disruptive events. According to Roege, et al. [2], the concept refers to the abilities to prepare, absorb, recover, and adapt to impacts from disruptive events and becomes preferable system conditions against climate change. The above set of characteristics of resilience is perceived important through reviews of resilience research to identify recommended actions attributed to various aspects of resilience response in energy systems. While the ability to prepare attempts to strengthen system capabilities to ensure service functionality during a disruptive event, the ability to absorb maintains critical function and service availability during the course of disruption. The abilities to recover and adapt are highlighted as the crucial elements to sustain functionality of energy systems in the respect that the ability to recover bounce back the function and service availability to original pre-event state, and the ability to adapt utilizes knowledge and experience in the past events to adapt to future undesired impacts.

A previous study [3] attempted to quantitatively evaluate recoverability in systems through demonstrating a time dependent quantifiable metric. A deliver function transition was illustrated with key complements of three distinct states, two state transitions, and two state triggers. It was stated that although there are various kinds of systems, ranging from small to large scale, built, operated, and managed by engineers, the proposed resilience metric applies equally to the entire range of systems. This indicates the wide range of its applications. The study also suggested that further figures-of-merit should be identified variously to study system resilience. In addition, the recovery transition towards stable recovered state will be assigned by capabilities of systems and pre-determined options. Given all of these, the resilience metric only assists in computing the system resilience and the time for resilience, and yet considers adaptability of systems. In organizational resilience, tangible measures on organization performance are considered stated objectives to resilience. When changes in key performance indicators occur, time to cope with the occurred change denotes the adaptive capability of systems. Yet, the ability to adapt to future impact and changes is not fully understood by the existing approaches. In the face of disruptions, system resilience involves the ability to respond appropriately to the impact and to adapt to changing conditions [4, 5] which are essential for future events. Although the transition is possible quantified by the study, adaptability towards disruptions cannot be seen. This calls for an approach to integrate resilience abilities into the resilience metric and to evaluate adaptability. Built upon the delivery function for transitions in resilience, this study aims to conceptualize an adaptive state by integrating key components of promising concepts including global catastrophic risks (GCR), beyond design basis accidents (BDBA), and foresight, and to construct a resilience curve to quantify the adaptability of clean energy systems.

2. METHODOLOGY

This section describes how the adaptive state is conceptualized and incorporated into the delivery function for transitions in resilience. Firstly, the function transition is studied and sorted into details in order to understand its important key components. As a result, additional key components must be included to form the adaptive state. Secondly, the three promising concepts are explored and studied to extract key elements and adopt to conceptualize the adaptive state. The key elements are essential to construct the adaptive state.

2.1. Breakdown of delivery function transition in resilience

According to Henry and Ramirez-Marquez [3], a time dependent quantifiable metric for resilience was illustrated (Figure 1). The metric is shown to imply that resilience can be mathematically quantified, and a standard can be existed and developed. The concept of delivery function for transitions in resilience is developed to assist computation of resilience of system, time for resilience and total cost for resilience. The recovery of a system from its disrupted state depends on system design, pre-considered policies and factors, existing directives for repair and recovery. Two tasks are required to compute the resilience of a system: recognizing the system of interest, where system boundary must be drawn to clearly identify scopes of system, and determining figure-of-merit, where a parameter for the resilience of a system should be defined. It is not trivial that a system exhibits resilience for more than one figure-of-merit. However, the parameter must always be with a time dependent attribute.

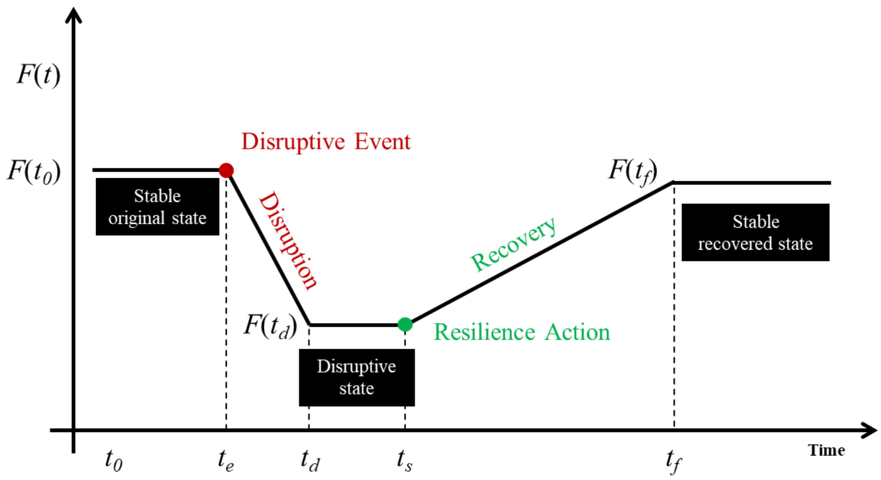

Figure 1. Illustration of delivery function for transitions in resilience

The concept of time dependent quantifiable metric in resilience is comprised of three key components including **distinct states**, **state transitions**, and **state triggers**. When considering the resilience of a system, function transitions travel through **distinct states**: stable original state, disruptive state, and stable recovered state. Two **states transitions**: system disruption (from stable original state to disruptive state), and system recovery (from disruptive state to stable recovered state) are incurred by **state triggers**: a disruptive event and a resilience action, respectively. It is noted that a disruptive event that incurs and triggers system disruption involves internal and/or external factors. A resilience action is taken place in response to trigger system recovery and the system bounces back from disruptive stat to stable recovered state.

2.2. Promising concepts for adaptive state conceptualization

To construct the adaptive state, three promising concepts including global catastrophic risk (GCR), beyond design basis accident (BDBA), and foresight are explored and studied. Key elements of each concept are extracted and utilized to support the conceptualization of the adaptive state. Regarding relevance of the three promising concepts towards the time dependent quantifiable metric, the concept of GCR is limited in literature without a sharp definition yet known to investigate risks and challenges that are not subjected to usual and existing standards of scientific understanding. This benefits that a figure-of-merit to compute the resilience of a system can be defined with unexplored risks and challenges. The concept of BDBA is well-studied in nuclear safety, attempting to discuss possible accident sequences that are not fully considered in the design process. Generally, a system is designed and built to withstand events with scopes of design basis accidents. The concept of BDBA introduces a set of actions to address impact derived from a BDBA. In this sense, the resilience action to trigger system recovery should incorporate the set of actions to the impact occurred to the system. The concept of foresight is adopted to support the concept of GCR in investigating risks and challenges that are known to occur in the future. Foresight anticipates scenarios of an event and studies options for actions towards the event using systematically translated and interpreted insights from available sources of information.

According to Bostrom and Cirkovic [6], GCR is loosely referred to as "a risk that might have the potential to inflict serious damage to human well-being on a global scale". In a taxonomy [6], a catastrophe that causes fatalities of 10,000 or economic loss of 10-billion-dollar worth is not considered as a GCR, even if the affected region suffers serious damages, leaving some regions unscathed. A catastrophe that causes over 10 million fatalities or economic loss of 10-trillion-dollar worth is quantified to be a global catastrophe. While global catastrophes with a result of more than 10 million facilities have occurred many times in history (for example, world wars and flu pandemics), catastrophes on a global scale regarding infrastructure are still limited in literature. Bostrom and Cirkovic [6] qualitatively characterize severity of risks using three variables including scope, intensity, and probability. Using the first two of the variables, a diagram (as shown in Figure 2) to present categories of risks was constructed, while the probability remains as a challenge to discuss. In the taxonomy, the scope of risks is labelled as personal (affecting one person), local, global (affecting a large part of population), and trans-generation (affecting the current population and future generations), while the intensity of risks is categorized as imperceptible (causing a barely noticeable impact), endurable (causing severe damage or harm yet not destroying quality of life), and terminal (causing a fatality or dramatic reduction on quality of life). Until this, it is perceived that the established taxonomy of risks is irrelevant to infrastructure and particularly a system. However, if the scope of risks is taken into account, figures-of-merit can be redesigned according to the nature of resilience.

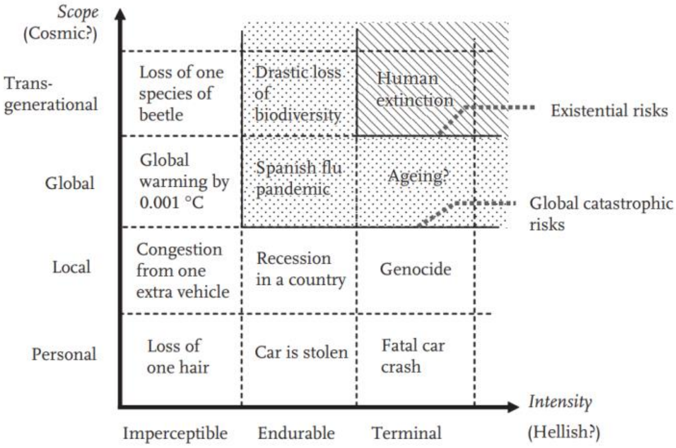

Figure 2. Qualitative categories of risk [6]

According to International Atomic Energy Agency [7-8], BDBA is a technical term used to discuss possible accidents that are not understood and considered in the design process. BDBA involves an accident that is outside the scope of design process is expected since it has never occurred or have an extremely low probability of occurrence yet emphasized to generate significant consequences. Consideration of a BDBA in the field of nuclear safety is an essential component to ensure safety. The events that are characterized as BDBA are difficult to predict with existing available sources of information and tools. The nature of extreme rarity can lead a system to an inability to operate safely. Opposed the BDBA, design basis accident (DBA) refers to an accident that a system must be designed and built according to established design criteria to withstand an event without significant loss to the system, structures, and components and to ensure public health and safety. Consideration of a DBA is enhanced by regulatory requirements, where regulatory criteria governing DBA is comprehensively and hierarchically created with rules to address safe concerns. A transient is defined as an event where a system changes from a normal state to an abnormal state, resulted by human negligence or inadequate training and preparation to operate the system [9]. Consideration to eliminate transients in a timely manner during the system operation is believed to enhance safety and achieve greater economic benefits. Figure 3 conceptualizes correlation between BDBA, DBA and transients in which it is perceived that BDBA shows a greater potential to generate consequences, comparing to the other two accidents. Thus, a set of actions: preventing the escalation of an event into a severe accident, mitigating consequences of a severe accident, and achieving a long-term safe stable state, is proposed to address a BDBA. The second action of mitigating consequences of a severe accident is also expressed in terms of severe accident management, which is considered an important part to ensure safety in the system.

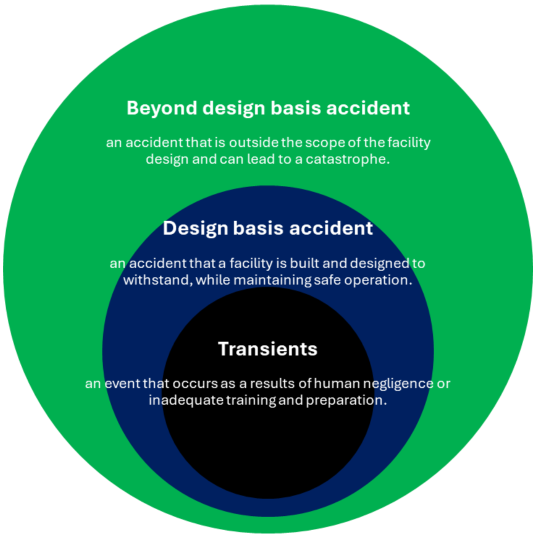

Figure 3. Conceptual correlation between beyond design basis accident, design basis accident, and transient

According to Kuosa [10], foresight is defined as "a process that attempts to broaden the boundaries of perception in ways". Slaughter [11] depicts the perceptions into four approaches including assessing implications of actions, detecting and avoiding consequences before existing, considering present implications for possible futures, and envisioning aspects of desired futures. On the other hand, the entire foresight was descriptively illustrated by a study of Horton in 1999 [12]. Based on the viewpoint of Horton, the highest value of foresight is realized at the very end of the process, where each phase including input, foresight, and output, offers a greater value than the previous one. Figure 4 summarizes Horton's foresight process. The first phase of foresight process relates to input and covers the following parts: collection, collation, and summarization of available information. The idea of input phase is to gather and organize relevant information regarding alternative futures to be predicted. Characteristic of the gathered information is large in volume and broad in scope in which it can cover a wide range of raw information on themes, trends, ideas, early signs from various sources of information such as experts, universities, networks, academic literature, government report, survey, and research. Horizontal scanning, Delphi, schematic reading and discussion sessions are often employed. The second phase of foresight relates to translation and interpretation of the processed information earlier in the first phase. The aim of translation and interpretation is to create and produce emerging or existing understanding and implications of alternative futures. This step is considered the most crucial part of the foresight since it answers what can and cannot do for the future, however, there is only a few theoretical techniques, supported in the translation and interpretation, which poorly understood by scientific community. The third phase refers to output of the foresight process, where actions and commitments to be taken for alternative futures are posed. Assimilation and evaluation of the understanding and implications from earlier phase are necessary.

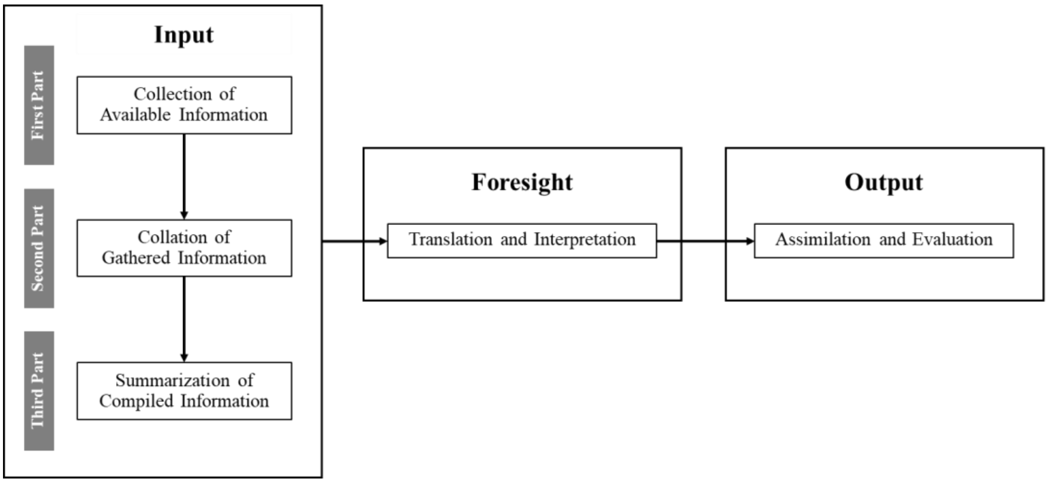

Figure 4. Foresight Process of Horton (1999)

3. INTEGRATION OF CONCEPTS INTO DELIVERY FUNCTION FOR TRANSITIONS IN RESILIENCE

The delivery function for transitions in resilience includes distinct states, state transitions, and state triggers. Resilience curve is established through integration of concepts including GCR, BDBA, and foresight. Sections below describe how each concept plays a role in establishing resilience curve.

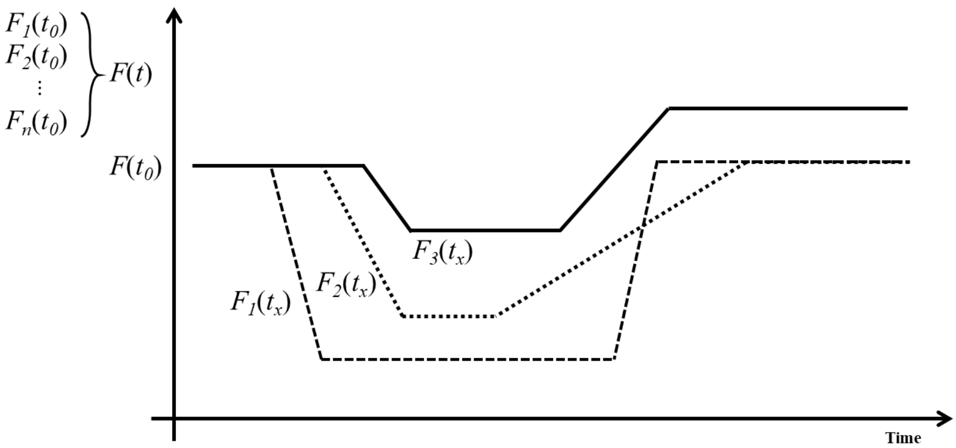

Figure 5. Function variation derived from scopes of risk

Borrowing from the concept of GCR, the key element is the scopes of risk which can be utilized to represent Y-axis. Built upon the delivery function for transitions in resilience illustrated by Henry and Ramirez-Marquez [3], *F(t)* can represent not only for capacity or revenue, but also for other functions. Impact from a disruptive event at different levels can be visualized by distinct functions (as shown in Figure 5). It is important to note that the function, represented by *F(t)* in the Figure, is determined depending on which aspect the system is assessed to investigate the transition. Thus, the functions to be determined in addition to the conventional revenue and generation capacity can consider system-wise and human-wise characteristics of the energy system since the core concept of resilience does not only cover systems and infrastructures, but also links to level of resilience in cities and communities towards disruptions [13]. Differences in impacts lead to specific resilience actions to bounce the functionality back to the stable original state in which it sometimes goes beyond the stable original state of the resilience curve. It is worth discussing that decoupling between system-wise and human-wise functionalities and recoveries are academically discussed and contributes to resilience in systems and communities.

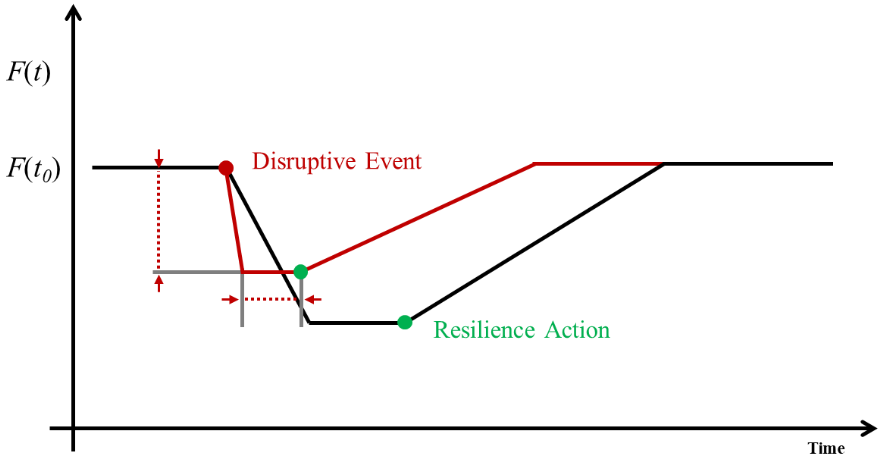

Figure 6. Function transition with applied set of resilience actions

Adopted from the concept of DBA, the design of systems and infrastructures should incorporate capabilities, according to established design criteria, to handle impacts from an accident without significant losses. In terms of BDBA, where an accident progresses outside of the scope of design, the set of actions to prevent the escalation of an event into a severe accident, mitigate consequences of the accident, and achieve a long-term safe stable state must be taken in order to address the accident and keep the systems in operational state. In the establishment of resilience curve, *F(t)* also involves human factors. With various aspects to be determined, the function does not only refer to operationality of systems, but also capabilities of people, or local communities to handle impacts derived from an accident or an event. Thus, *F(t)* can be determined variously to represent the aspect that the system is aimed to be assessed to investigate the transitions. The crucial point is that one of the core abilities of resilience to absorb impacts occurred to systems or humans should be incorporated into the set of actions. According to Figure 6, the set of actions can be taken to reduce severity of impact (as *F(t)* is minimized), reduce period of remaining at disruptive state (as time of disruptive state is reduced), and reduce frequency of occurrences. It is important to note that the set of actions is assigned variously according to the determined functions.

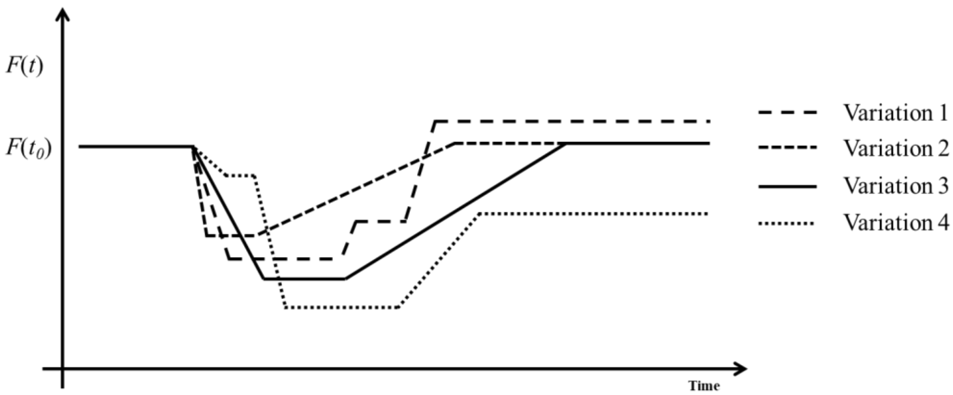

Figure 7. Alternative scenarios of a function transition depicted by Foresight

According to the concept of foresight, the systematic approach to translate and interpret information of alternative scenarios and futures are essential for depicting possible disruptions and resilience actions. Thus, foresight plays a key role in depicting state transitions and state triggers. According to Figure 7, the transition of *F(t)* is possible in various ways according to the aspect of *F(t)* determined, disruptive events occurred to the system, and resilience actions taken to bounce back the transition. When *F(t)* is determined either as functions in relevance to system-wise or human-wise characteristics, foresight helps understand alternative scenarios on how a *F(t)* is transitioned after disruptive events, and what resilience actions should be taken to formulate the pathways to bounce back the function from disruptive state to stable recovered state or even further to adaptive state. It is common that transitions of *F(t)* vary because impacts from the state trigger occur unsystematically at uncertain times and places and cannot be assumed or predicted accurately. Possible transitions involve a range of small to high severity of impacts, the second or third cascading impacts, and short to long time of disruptions (remaining at disruptive state). This is where foresight plays the crucial role in predicting alternative transitions. In terms of recovery, the system is also recovered in possibly various ways depending on applied resilience actions. The transition of *F(t)* requires resilience actions which generally aim to respond to disruptive events and characteristics of the recovery vary with speed and target of transition. The role of foresight is to determine resilience actions in response to disruptive events, capturing, characterizing, and deviating various transitions, both disruption and recovery, of *F(t)*.

4. CONCLUSION

This study builds upon the concept of delivery function for transitions in resilience to conceptualize the resilience curve by integrating an adaptive state. The three promising concepts including GCR, BDBA, and foresight are explored to develop the adaptive state. The resilience curve is equipped with key features of the three concepts to introduce adaptability to systems. Components of each promising concept were refined with the core concept of resilience and adopted to build the resilience curve.

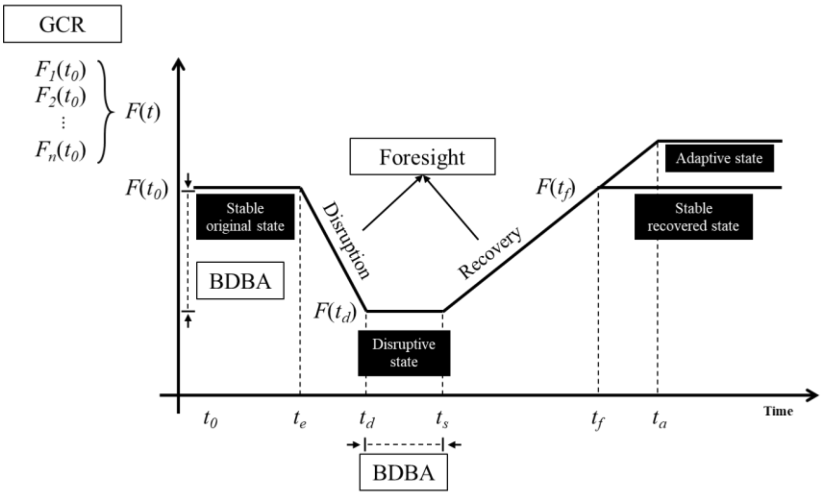

Figure 8. Illustration of resilience curve

Figure 8 represents the adaptive resilience curve established by integrating the abovementioned three key concepts, namely, GCR, BDBA, and foresight. The resilience curve introduces a new state, adaptive state, where *F(t)* possibly goes beyond the stable recovered state due to applied resilience actions. GCR enlarges scope of consideration to indicate *F(t)*, which varies upon system-wise and human-wise characteristics, BDBA offers the set of actions to reduce severity of impact, period of remaining at disruptive state, and frequency of occurrences. Lastly, foresight helps understand how a *F(t)* is transitioned and bounced back by disruptions and resilience actions, capturing, characterizing, and deviating the various transitions of *F(t)*. In the light of enhancing resilience through resilience actions, promising measures to be considered should emphasize actions to reduce severity of impact, period of remaining at disruptive state, and frequency of occurrences.

To demonstrate adaptability of systems, the adaptive resilience curve can be utilized along with existing resilience assessments. ASEAN Energy Resilience Guideline developed by National Energy Technology Center (ENTEC) is considered as one of the potential outlets for the adoption of the proposed adaptive resilience curve as the Guideline was developed with details, a clear standard operating procedure, and practiced with case studies of various clean energy systems. The adaptive disruptive curve will be reflected in the Guideline to seek opportunity to enhance adaptability of systems.

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