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The effects of event occurrence and duration on resilience and adaptation in energy systems

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ABSTRACT

Energy security exists in an energy system until an event occurs which increases the stress on one or more of its entities. A resilient entity, designed to recover quickly from an event, will return the system (and, by extension, the affected entity) to its previous secure state. However, if the event occurs repeatedly or the time to recover is deemed too slow, or both, the system may remain in a high-stress, insecure state. In these situations, if the stress is to be reduced, the entity must be adapted to handle the event and put the system into a new, secure state.

This paper applies research from a variety of disciplines to analyze the temporal effects of events on entities, and shows how resilience and adaptation contribute to the existence of energy security in energy systems. It underscores the importance of time when discussing the impact of events on an energy system and employs methods associated with reliability, notably mean time between failures (MTBF), mean time to recover (MTTR), and tolerance, to describe resilience and adaptation. The analysis is presented and discussed with examples using three common energy security indicators.

1. Introduction

Any jurisdiction, regardless of its size or complexity, has an energy system responsible for taking flows of primary or secondary energy, or both, and converting and transporting them to meet the tertiary energy demands of its energy services [1]. Energy security exists when the energy flows that pass through the energy system are available to meet the jurisdiction's tertiary energy demands affordably and acceptably [2]. Moreover, there is no incentive for the jurisdiction to change its energy system as long as the flows remain available, affordable, and acceptable.

Energy flows in anthropogenic energy systems are not immune to change caused by events, both external (e.g., supply disruptions, price rises, weather, and cyber-attacks) and internal (e.g., equipment failure, labour disputes, and emissions) to the system [3]. When an event occurs, the energy services relying on the energy flows affected by the event may experience an increase in stress caused by some combination of a decline in supply, an increase in cost, or a decrease in acceptability. Those responsible for the operation of the various entities that comprise the energy system must deal with the energy trilemma and attempt to maintain the availability, affordability, and acceptability of the energy flows [4].

To reduce the stress associated with an event, entities in an energy system can be designed to be resilient [5]. A resilient entity is one that, when an event occurs, returns its flows to the pre-event (or Normal) state in as short a time as possible. The entity itself does not change; if the event occurs again, the entity is expected to repeat the actions required to return to the Normal state.

The need for resilience in critical energy infrastructure has become of paramount importance in many countries with the increased risks of natural disasters and cyber-threats [6,7]. Resilience has been examined in electricity use in OECD countries [8], pipelines and other energy infrastructure in the EU [9], district heating networks in Latvia [10], and renewables and nuclear power [11]. The increasing use of ICT (Information and Communication Technologies) in modern energy systems requires resilience in both physical and virtual infrastructures [12].

Although resilience is a characteristic of an entity or an energy system, it has its limitations [13]. In some cases, entities may not be resilient to certain events because, for example, they were not considered likely or the cost of making the entity resilient outweighed the benefits [14]. In others, the entity may be resilient but the flow is not considered secure because an event occurs repeatedly or the time taken by the flow to return to the Normal state is

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considered unreasonably long. Such events can result in a high-stress “new Normal” state for the entity [3].

An entity in its new Normal state can either operate in a degraded fashion, unable to handle the event, or be adapted to handle the event. The process of adaptation is dictated by policies, regulations, or operational requirements that change the entity, its flows, or both. An entity that has been adapted to its new Normal state is considered to be resilient to the event.

With few exceptions, limited research appears to have been published on the relationship between resilience, adaptation, and events and how this affects entities in an energy system [13]. In this paper, the temporal effects of events on an energy system are explained using concepts associated with reliability, notably the rate of occurrence of an event and the time taken to recover from it. These concepts are employed to describe resilience and stress, the effect of tolerance (or lack thereof) as an impetus for change in an energy system that is no longer resilient, and adaptation, the transformation of the system to its new Normal state.

The paper builds upon existing research on systems, events and stress in energy systems, and systems reliability to analyze the effects of events on entities and shows how resilience and adaptation contribute to the existence of energy security in an energy system. It employs state diagrams to explain stress in resilient entities and shows how the tolerance of events determines whether an entity will adapt to a new Normal state. The paper demonstrates how the occurrence and duration of events affects resilience and adaptation in an energy system. Examples are presented of the utilization of the terminology and some potential, unexpected consequences of adaptation.

2. Background

2.1. Systems and entities

A jurisdiction's energy system can be described in terms of a hierarchy of external and internal entities [15]. An external entity is either an energy supplier providing the system with primary and secondary energy or an energy service with tertiary energy demands [16]. Internally, the system consists of entities organized into energy chains which convert and transport the primary and secondary energy from energy suppliers to energy services [1].

Regardless of its task, an entity can be described in terms of the flows between it and its neighbouring entities, those members of the jurisdiction responsible for its operation, and the environment. Fig. 1 shows a generic entity with its seven flows: $Demand_{IN}$ (a request from a downstream entity for a quantity of energy), $Energy_{OUT}$ (the energy supplied by the entity), $Demand_{OUT}$ (a request for a quantity of energy to an upstream entity from the entity), $Energy_{IN}$ (the energy supplied by the upstream entity),$Environment_{IN}$ (non-energy inputs from the environment needed by the entity), $Environment_{OUT}$ (emissions and losses from the entity to the environment), and $Policy_{IN}$ (regulations dictating the operation of the entity set by government agencies or the organization responsible for it).

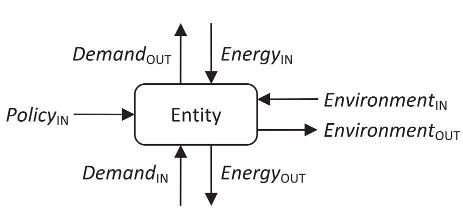

Fig. 1. A generic energy entity [1].

An entity can be associated with multiple input flows (fan-in) and output flows (fan-out); for example, a coal-fired thermal-power station can purchase fuel from different suppliers ($Demand_{IN}$), a refinery can produce different refined oil products ($Energy_{OUT}$), and a district heating station can supply a city with both electricity and hot water ($Energy_{OUT}$) [1]. Some entities attempt to improve their energy security with a diversity of $Energy_{IN}$ flows [17].

In an energy chain, the $Demand_{OUT}$ and $Energy_{OUT}$ flows from an entity become the $Demand_{IN}$ and $Energy_{IN}$ flows of its upstream and downstream neighbours, respectively. Similarly, an entity's $Demand_{IN}$ and $Energy_{IN}$ flows correspond to the $Demand_{OUT}$ and $Energy_{OUT}$ flows from its downstream and upstream neighbours, respectively. $Policy_{IN}$ flows are usually associated with a single entity. A flow is simply a description of what passes from one entity to another, such as a request for a number of MWh ($Demand_{IN}$), a volume of petroleum ($Energy_{OUT}$), or the particulate emissions limits from a thermal power station ($Policy_{IN}$).

There are two special cases associated with the external entities: at the start of a chain, the $Demand_{OUT}$ and $Energy_{IN}$ flows of the energy source or supply entities are not considered, while at the end of chain, the $Demand_{IN}$ and $Energy_{OUT}$ of the energy service entities are not considered.

An entity's energy security is determined by three indicators that refer to the state of the flow (the indicators and their associated metrics are shown in Table 1):

Availability: The available supply of energy in the entity's $Energy_{IN}$ flows meets or exceeds the energy requirements of its $Demand_{OUT}$ flows. If the ratio of the availability metric is at least 1, demand is met and the entity is secure in terms of its supply, otherwise demand is not met and supply is not secure.

Affordability: The budget for the $Demand_{OUT}$ flows equals or exceeds the cost of the $Energy_{IN}$ flows. The ratio of the affordability metric must be at least 1 for the entity to be secure; if the ratio falls below 1, the entity cannot afford the cost the $Energy_{IN}$ flows and is in an insecure state.

Acceptability: The $Energy_{IN}$ flows are required to meet certain standards (such as environmental, social, or political); if they are met, the $Energy_{IN}$ is acceptable, otherwise it is unacceptable. The acceptability of the $Energy_{IN}$ flows are determined by an indicator-specific function, $f()$; the result can be less than a lower-limit (LL) or acceptable, greater than an upper-limit (UL) or unacceptable, or between the two or tolerable [3]. The value of LL and UL are typically standards or regulations targeting flows or entities [3].

The feedback obtained from monitoring changes to the indicators and their metrics can be used to maintain or improve energy security.

2.2. Events

An event is any action, either internal (such as equipment failure or labour disputes) or external (an incoming flow that the entity cannot handle adequately); it is detected when one or more of an

Table 1
Energy security indicators and metrics.

Indicator	Metric
Availability	$\frac{Energy_{IN}}{Demand_{OUT}}$
Affordability	$\frac{Budget\ for\ Demand_{OUT}}{Cost\ of\ Energy_{IN}}$
Acceptability	$\frac{f(Energy_{IN})}{LL}$

From Refs. [16,4,3].