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Energy security and the diversity of energy flows in an energy system

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ABSTRACT

In order to maintain or improve a jurisdiction's energy security, its energy system needs to meet the demands of its energy services with affordable and preferably environmentally acceptable flows of energy. Since diversity can be a factor in the long-term survival of a system, having a diversity of energy flows is frequently treated as a proxy for energy security.

This paper examines the relationship between energy security and the diversity of an energy system's energy flows using a set of energy security indicators and the Shannon–Wiener diversity index. Although diversity may be considered necessary for maintaining and improving energy security, the quantitative analysis of the relationship shows that an energy flow considered diverse need not be secure and that a secure energy flow need not be considered diverse. Examples of this relationship are included. These findings can prove useful to policy makers and energy analysts when developing transition strategies for a jurisdiction's energy system.

1. Introduction

Regardless of its size or state of development, every jurisdiction is associated with an energy system responsible for meeting the energy demands of its different energy services, such as heating and cooling, electricity, and transportation [29]. A jurisdiction's social and economic well-being ultimately depends upon ensuring the availability, affordability, and environmental acceptability of the energy demanded by the users of the energy services [23]. Energy policies and technologies are needed to maintain and improve the system's energy security in the face of threats from external and internal events [24]. Diversity is regarded by many stakeholders, including policy makers and energy analysts, as essential to the energy security of an energy system [11,39]. In fact, diversity is often treated as a proxy for energy security [19,32,35,53].

One of the arguments for diversity is that it is necessary for a system's long-term survival. A diverse forest ecosystem is typically considered healthier and more viable than, for example, a monoculture. Similarly, a communications system that supports multiple communication channels is more likely to continue functioning in the presence of failures [21].

An early reference to diversity in energy systems is attributed to Winston Churchill, who, after overseeing the conversion of the Royal Navy from coal to potentially insecure sources of Persian oil in 1910, stated, "Safety and certainty in oil lie in variety and variety alone" [59]. Churchill's response to the Royal Navy's evolution from coal to oil reflects the widely held view that diversity is necessary for maintaining and improving energy security.

The diversity of an energy system can be described in different contexts, including social, cultural, economic, scientific, and technological [51,52]; for example, it has been presented as a way to reduce the risks and uncertainties associated with an energy system while enhancing its energy security and can act as [50]:

- A key in promoting the favourable effects of innovation and growth.
- A guard against uncertainty in the decision-making process.
- A means by which the unfavourable effects of momentum and locked-in long-term technological paths can be extenuated.
- A way to accommodate the different types of interests and values in a pluralistic society.

Diversity indices have been developed to measure diversity in various fields, including biology, ecological sciences, information theory, statistics, and economics [44]. Most research that considers the impact of diversity on an energy system employs the Shannon diversity index, sometimes referred to as the Shannon–Wiener index [1,19,32]. The index is commonly used to calculate the diversity of an ecosystem and depends upon the number of different types of species in the ecosystem and the evenness of their distribution.

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Although it is sometimes used as a proxy for energy security, it has been observed that, by itself, diversity is insufficient to determine the energy security of an energy system [53]. In order to gain further insight into the energy–security–diversity relationship, this paper presents a quantitative analysis of a set of energy–security indicators and the Shannon-diversity index as applied to the energy flows in an energy system.

The remainder of the paper is organized as follows. The next section shows how the energy security indicators and diversity index can be applied to a generic energy system. This is followed by an application of the methods to examine the relationship. Examples that illustrate the relationship are then discussed in detail.

2. Energy systems, security, and diversity

2.1. Energy systems and energy security

A jurisdiction's energy system consists of external and internal entities [23]. There are two types of external entity: sources of primary or secondary energy and end-use energy services which use tertiary energy to meet demands for, for example, transportation, heating and cooling, and electricity [29]. While internal entities are responsible for the conversion and transportation of energy between entities, both external and internal. The system supports energy chains connecting internal and external entities.

As Fig. 1 shows, an internal entity attempts to meet the energy demand of a downstream process ($Demand_{IN}$) with a supply of energy ($Energy_{OUT}$). Since internal entities only convert or transport energy, each internal entity must request energy from an upstream entity (with $Demand_{OUT}$) which should be met with a supply of energy ($Energy_{IN}$ from its upstream neighbour). Entities are subject to policies (such as government, corporate, or institutional) and can take from, or emit to, the environment. An entity can have multiple upstream entities or multiple downstream entities, or both.

Internal entities are upstream (as viewed from those below it) and downstream (as viewed by those above it). The "topmost" upstream entities in an energy chain are energy sources; these do not have $Demand_{OUT}$ or $Energy_{IN}$ flows. The "bottommost" downstream entities in an energy chain are energy services; they do not have $Demand_{IN}$ or $Energy_{OUT}$ flows.

Fig. 2 shows the situation where an entity has its $Demand_{OUT}$ met from multiple upstream entities (1 through N): each upstream entity receives a separate $Demand_{OUT}$ and is expected to meet this demand with an $Energy_{IN}$ flow. An entity with multiple $Demand_{OUT}$ and $Energy_{IN}$ flows is said to have a variety or diversity of energy flows.

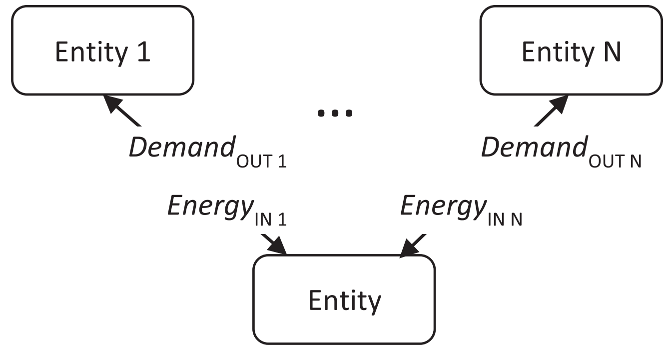

Fig. 2. An entity with multiple $Demand_{OUT}$ and $Energy_{IN}$ flows.

At a given point in time, the $Energy_{IN}$ flows an entity 'A' relies may be both secure and diverse. However, if the energy chains associated with the upstream entities eventually converge to a single entity 'B', any event that causes 'B' to become unable to meet its $Demand_{IN}$ flows may eventually result in an event that causes 'A' to fail to meet its $Demand_{IN}$. The entity 'B' is said to be a single point of failure [17]. When determining the energy security and diversity of an entity within a system, it is necessary to consider its upstream entities.

There are many definitions of energy security and methods or indicators to determine its state; these are often jurisdiction or system specific, can have numerous indicators (often unique to the application), and can deal with energy security in an apparent ad hoc fashion. Examples include a detailed examination of natural gas and its contribution to energy security in the UK [45]; an examination of 10 countries using 16 dimensions of energy security (some of which consider the underlying energy system of each jurisdiction) [46]; a review of China's coal usage in light of carbon-emission constraints and its replacement with natural gas [37]; and an analysis of energy security in the Asia-Pacific region using 11 dimensions, each associated with a number of attributes [54].

Some definitions of energy security limit the number of indicators to variations on whether an entity's energy flows are

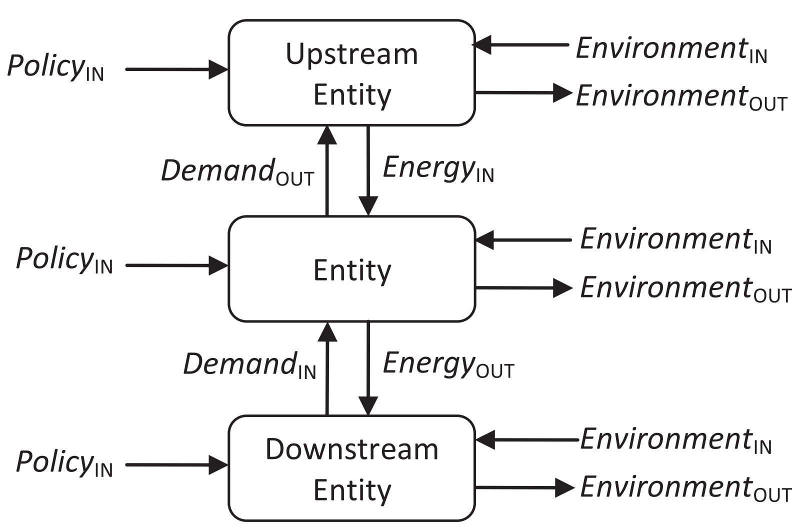

Fig. 1. An entity, its neighbours, and flows.