A NOVEL AND GENERIC METHOD FOR EXAMINING THE RELATIONSHIP BETWEEN ENERGY SECURITY AND DIVERSITY OF AN ENERGY SYSTEM

by

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DEDICATION

I dedicate this thesis in the memory of my beloved late father Sri. Rajendra Prasad Agrawal, who always been an inspiration and motivation to my work and life. I also dedicate this thesis to my loving mother and sisters, who continuously supported and encourages me in each step of my life and especially for the completion of this research work.

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ABSTRACT

In an energy system, diversity of supply—that is, reliance on a variety of mutually disparate energy suppliers and their energy supplies—is seen by many researchers and policymakers as an important component of energy security.

This thesis describes a novel and generic method for examining the relationship between energy security (as represented by an energy-security index derived from a set of energy security indicators) and diversity (as defined by the Shannon-Wiener diversity index) of an energy system, its entities, and flows. While diversity is often presented by policy makers as being essential to maintaining or improving the energy security of an energy system, the thesis employs the equations associated with the two indices to show that a diverse supply need not be secure and a secure supply need not be diverse. Several examples of the relationship and the events that can affect it are also provided.

LIST OF ABBREVIATIONS AND SYMBOLS USED

AHP	Analytic Hierarchy Process
APERC	Asia Pacific Energy Research Centre
ASEAN	Association of South-East Asian Nations
CP	Current Policy
EI	Energy Intensity
ESI	Energy-Security Index
ESMI	Energy Security Import Index
ESPI	Energy Security Price Index
EU	European Union
HEG & LC	High Economic Growth and Least Cost
HHI	Hirschman–Herfindahl Index
IEA	International Energy Agency
LCS	Low Carbon Society
MOSES	Model of Short-Term Energy Security
NEW	North-East-West
OECD	Organization for Economic Co-operation and Development
SPR	Strategic Petroleum Reserve
UK	United Kingdom

U.S.	United States
VB	Visual Basic

1°	Primary Energy
2°	Secondary Energy
3°	Tertiary Energy
$	Dollar
CO_2	Carbon Dioxide
D	Diversity
$Demand_{\mathrm{IN}}$	Demand Input
$Demand_{\mathrm{OUT}}$	Demand Output
e.g.	Example
$Energy_{\mathrm{IN}}$	Energy Input
$Energy_{\mathrm{OUT}}$	Energy Output
$Environment_{\mathrm{IN}}$	Environment Input
$Environment_{\mathrm{OUT}}$	Environment Output
e_i	Individual Population or Individual Input Energy ($Energy_{\mathrm{IN}}$)
$\mathrm{ESI}_{\mathrm{ACC}}$	Acceptability Energy-Security Index
$\mathrm{ESI}_{\mathrm{AFF}}$	Affordability Energy-Security Index

$\mathrm{ESI}_{\mathrm{AVA}}$	Availability Energy-Security Index
H	Shannon Index
i.e.	That Is
P	Total Population or Total Input Energy ($Energy_{\mathrm{IN}}$)
p_i	Relative Contribution of Individual Input Energy ($Energy_{\mathrm{IN}}$)
$Policy_{\mathrm{IN}}$	Policy Input
MMbbl	Million Barrels
TWh	Terawatt-hour
MW	Megawatt

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CHAPTER 1 INTRODUCTION

Energy plays an essential role in any jurisdiction, affecting its society, economy, and environment. All jurisdictions are associated with an energy system which is responsible for meeting the energy demands of its different energy services such as heating and cooling, electricity, and transportation (1). Energy systems evolve over time with respect to changes in the availability, affordability, and acceptability of the energy they convert and transport for the ultimate consumption by the energy services. Not surprisingly, energy systems differ from jurisdiction to jurisdiction, with a wide-range of entities and energy flows all contributing to the improvement or deterioration of its energy security (2).

Diversity is seen as essential for the long-term existence of many systems. In recent years, the concept of diversity has expanded into the fields of management, science, public policy, and politics. It can improve system stability which means that a diversified system comprising multiple species returns to the steady state faster after disturbances than a single species system (3). A diverse forest ecosystem is typically considered healthier and more viable than, for example, a monoculture (4). Similarly, a communications system that supports multiple communication channels is more likely to continue functioning in the presence of failures (5). Diversity is also regarded by many stakeholders, including policy makers, as important to anthropogenic energy systems (6; 7).

One of the earliest references to energy diversity is attributed to first Lord of the Admiralty Winston Churchill in 1910, when, after overseeing the conversion of the Royal Navy ships from coal to potentially insecure sources of Persian oil, stated, “Safety and certainty in oil lie in variety and variety alone” (8). This reflects the view that diversification is the key to maintaining and improving energy security. The diversification and localization of energy sources and systems is considered as the best future energy systems to provide energy security for the supply and distribution to the energy consumers, rather than the dominance of a single energy system that leads to the health and environmental risks (9). Another example of diversification occurred after the oil embargos of the 1970s, when the United States reduced its oil imports from the Middle East, replacing them with supplies from Mexico, Canada, Venezuela, and Nigeria (10).

Energy diversity, thus defined as the reliance on a variety of mutually disparate suppliers and their energy supplies, is often treated as a proxy for energy security (11). Stirling has identified the three general, necessary but individually insufficient, properties of energy diversity (i.e., variety, balance, and disparity), and developed a general framework to quantify the diversity of an energy system (11).

Diversity is often discussed as the mix of different energy sources such as oil, coal, natural gas, solar, wind, hydro, geothermal, biomass and biofuels, wave and tidal energy required to meet the end-use energy demands (12; 13; 14; 15; 16; 17). The diversity of the energy mix and the supply sources in an energy system can be measured by using different diversity indices such as Shannon–Wiener, Simpson, Hirschman–Herfindahl, and integrated multi-criteria diversity index (11; 3; 18; 6; 19).

The impact of diversity considered by most research is on the energy security of an energy system that employs the Shannon-Wiener diversity index, which 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.

While the diversity is important, focusing on suppliers and their energy supplies and neglecting the internal structure of the system and its energy services is a limited view of energy diversity. For example, replacement of oil with coal is not possible in all situations, because the energy chain associated with the source flow is not considered (2).[1] The multiple input energy flows to an entity give the impression of diversity (2; 9; 11), but it is necessary to measure the energy security of each input energy flow in addition to its contribution in order to know how secure the entity is. Thus, examining the relationship between energy security and diversity of an energy system along-with its other entities (i.e., energy chains with processes and its flows and energy services) seems to be important. While the Shannon diversity index is used to determine the diversity of an energy system, it gives no indication of the relationship between energy security and diversity. Hence, there is a need for developing a generic framework and approach to examine the relationship between energy security and diversity of an energy system, its entities, and flows, to provide a clear understanding of the issues facing a jurisdiction's energy system by its stakeholders (notably the public, policymakers, and politicians).

The need for diversification has been considered as the key to energy security (8). A diversity approach tries to reduce the risk and uncertainties associated with an energy system, while enhancing its energy security, and can act as (20):

- A key in promoting the favourable effects of innovation and growth.
- A guard against uncertainty in the decision-making process.

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[1] An energy chain consists of processes and their flows, responsible for meeting the energy demands of one or more energy services (2).

- A means to extenuate the unfavourable effects of momentum and lock-in in long-term technological paths.
- A way to accommodate the different types of interests and values in a pluralistic society.

A definition of energy security which captures the sentiment of most is that developed by the International Energy Agency (IEA), ‘‘the uninterrupted physical availability at a price which is affordable, while respecting environment concerns’’ (21). In various other methods and techniques, energy security is often dealt in an ad hoc fashion, according to the specific jurisdiction, its energy system, and multiple indicators, often unique to the application (22; 23; 24; 25; 26; 27; 28). From the IEA's definition of energy security, three generic energy security indicators can be obtained: availability (“uninterrupted physical availability”), affordability (“a price which is affordable”), and acceptability (“respecting environment concerns”) (2).

The jurisdiction's energy security can be affected when the system and its sources, internal structure, and services are subject to events, such as extreme weather events, grid failures, and new energy sources. An event is any external or internal action or activity that causes an entity (i.e., a source, process, or service) to deliver a measurable change to at least one of its flows. Events and event handling can offer further insight into the functioning of the jurisdiction's energy system and the conditions under which the supplies, prices, and environmental impacts of the energy used to meet the demands of its services—that is, its energy security—can improve, deteriorate, or be maintained (29).

The thesis presents a novel and generic approach to analyse the relationship between an energy-security index and the Shannon-Wiener diversity index as applied to a systems-based energy-security framework. The framework allows the indices to be applied to both the system and the entities that make up the system; in the latter case, offering insight into how the events that can change the state of energy security in an individual entity can affect—or be affected by—diversity. The findings can prove useful to policy makers when developing transition strategies to improve their jurisdiction's energy security.

1.1 Thesis Objectives

The primary objective of this thesis is to examine the relationship between energy security and diversity of an energy system, its entities, and flows.

The utility of the objective is demonstrated in the following ways:

1. Event-related stresses are defined in conjunction with systems analysis to specify methods for explaining the states through which an entity, energy chain, or system affects the energy security and can be measured in terms of the three dimensions derived from the IEA—availability, affordability, and acceptability—giving rise to the various energy-security indices (ESI).
2. The relationship between the three dimensions of energy security (represented as an ESI derived from a set of energy security indicators) and diversity (as defined by the Shannon-Wiener diversity index) is examined using a novel and generic method.
3. The examples of the relationship and the events that can affect it are provided.

This research presents a set of methods to define, measure and explain how event-related stresses affects a system's energy security, thereby giving rise to the ESI. Energy systems change over time due to occurrence of an event resulting in stresses in three different states (Normal, Tension, and Disruption) causing an entity—and possibly the chain and system—to reach a tipping point, and change from one state to another. This often affects the system's energy security as whether it is improving, deteriorating, or being maintained. The system's energy security can be measured in terms of the three indicators—availability, affordability, and acceptability—derived from the IEA's definition of energy security, thereby forming three different ESI (i.e., ESI availability, ESI affordability, ESI acceptability).

This research further examines the relationship between the three dimensions of energy security and diversity using a novel and generic method. An energy system and its internal entities (i.e., energy sources, processes, or services) can be analysed and discussed in terms of its energy security and diversity. Energy security is determined using the ESI derived from a set of IEA's energy security indicators (i.e., availability, affordability, and acceptability) affected by the event-related stress and diversity is obtained using the Shannon-Wiener diversity index. The relationship between energy security and diversity is examined using examples of conditions such as changing diversity with a constant ESI and changing ESI with a constant diversity to show that a diverse energy flow need not be secure and a secure energy flow need not be diverse. The application of the method is demonstrated with an example and implemented using Microsoft Office Excel and Visual Basic (VB).

The research also includes examples of the relationship between energy security and diversity and of the events that can affect this relationship along-with the discussion of their results. The energy security and diversity affected by events within the system and disparity is also discussed.

1.2 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 2 introduces a generic framework of energy systems and its functions, followed by energy security and its indicators. It also reviews the existing event-related stress, energy-security index (ESI), and energy diversity research.

A method for examining the relationship between the three indicators of energy security and diversity of an energy system, its entities, and flows is described in Chapter 3. This chapter also includes the application and implementation of the method.

Chapter 4 presents the discussion with the examples that illustrate the relationship and of the events that can affect it. The disparity of flows is also discussed.

Chapter 5 concludes the thesis, recapping the finds, listing some of its limitations, recommending future research, and publications.

CHAPTER 2 LITERATURE REVIEW

The focus of this chapter is to examine the background work related to energy-security diversity research. The chapter begins with an introduction to the generic framework of energy systems and its functions. An overview of energy security and its indicators, along-with existing event-related stress research and their impact on system's energy security are then presented. The chapter concludes by discussing the various methods for the formation of an energy-security index, followed by the review of existing energy diversity approaches.

2.1 Energy Systems

All jurisdictions are associated with an energy system which is responsible for meeting the energy demands of its various energy services by supplying them with energy. The system itself is only responsible for converting and transporting energy from its external sources in order to meet the needs of its energy services. Moreover, the system must meet certain regulations, specified by regulators, to minimize its impact on the environment. The relationship between the system and its external entities is shown in Figure 1 (2).

The internal structure of an energy system is composed of one or more energy chains consisting of conversion and distribution processes, linking source to a service. An entity is an energy source, process or energy service in an energy chain. The length and complexity of a chain is determined by its energy inputs and the intended demand. When a primary energy source is an energy input, it usually requires conversion into a secondary energy which can be distributed to energy services for further conversion into tertiary energy. Shorter chains are possible; for example, importing a secondary, rather than a primary, energy source (2).

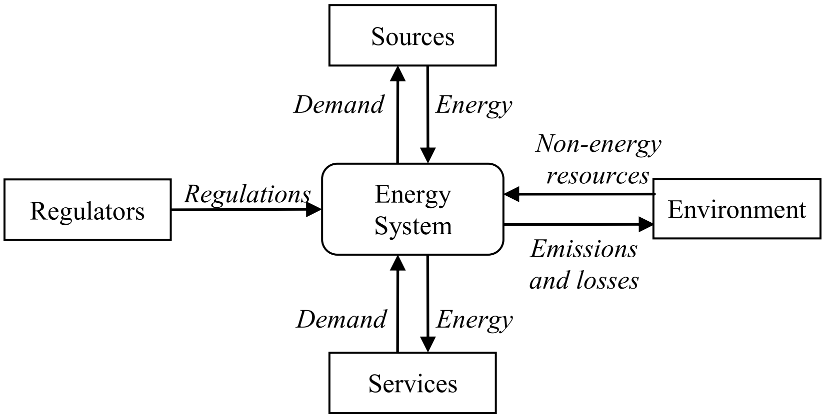

Figure 1: An energy system and its external entities (from (2))

Although the internal structures and actions of the energy system and its sources, processes, and services are typically quite different, their interactions can be described in terms of a generic entity, such as shown in Figure 2. A flow is a logical connection between entities, describing the components passing between them such as demand, cost, energy, or emissions; it gives no indication about how the component is actually moved. An entity is associated with seven flows, which are defined as follows (2):

1. The $Demand_{\mathrm{IN}}$ flow is from a downstream entity (either a process or a service) requesting energy from the entity; it indicates the quantity of energy required.
2. An entity attempts to meet the $Demand_{\mathrm{IN}}$ flow's demand with the quantity of energy requested; this is indicated by the $Energy_{\mathrm{OUT}}$ flow.
3. The $Demand_{\mathrm{OUT}}$ request should be met with a flow of energy, $Energy_{\mathrm{IN}}$, supplied by an upstream entity (either a process or an energy source).
4. All entities (conversion or distribution) exhibit a degree of inefficiency and as a result release emissions or losses, or both to the environment; these are specified by the

entity's $\textit{Environment}_{\text{OUT}}$ flow. Regardless of the entity, these inefficiencies mean $\textit{Energy}_{\text{IN}}$ is always greater than $\textit{Energy}_{\text{OUT}}$.

5. In addition to the $\textit{Environment}_{\text{OUT}}$ flow, an entity can also require non-energy resources from the environment; indicated by the $\textit{Environment}_{\text{IN}}$ flow.
6. Finally, most jurisdictions (or organizations responsible for the entity) have regulations intended to control the actions of the entity; these regulations are specified in the $\textit{Policy}_{\text{IN}}$ flow.

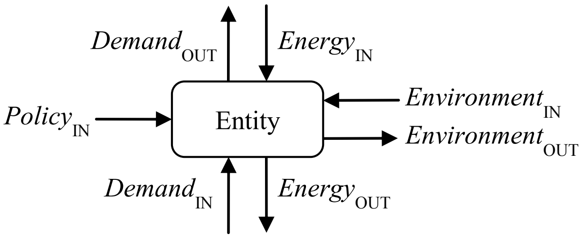

Figure 2: A generic entity and its associated flows (from (2))

An energy chain is composed of interconnected conversion and transportation entities (i.e., processes). The first $\textit{Energy}_{\text{IN}}$ is supplied by an upstream entity, while the last $\textit{Energy}_{\text{OUT}}$ is intended to meet the $\textit{Demand}_{\text{IN}}$ of a downstream entity. In most, if not all, cases, the output of a conversion entity feeds into a distribution entity, which in turn feeds into another conversion entity. A linear energy chain taking primary energy (1°) to meet tertiary energy (3°) demand is shown in Figure 3. More complex chains can have entities that accept multiple $\textit{Energy}_{\text{IN}}$ flows from more than one upstream entity or produce multiple $\textit{Energy}_{\text{OUT}}$ flows, with potentially different types of $\textit{Energy}_{\text{OUT}}$ to various downstream entities, or do both. In a similar fashion, an entity can be subject to multiple $\textit{Policy}_{\text{IN}}$ flows and have a variety of $\textit{Environment}_{\text{IN}}$ and $\textit{Environment}_{\text{OUT}}$ flows

(2).

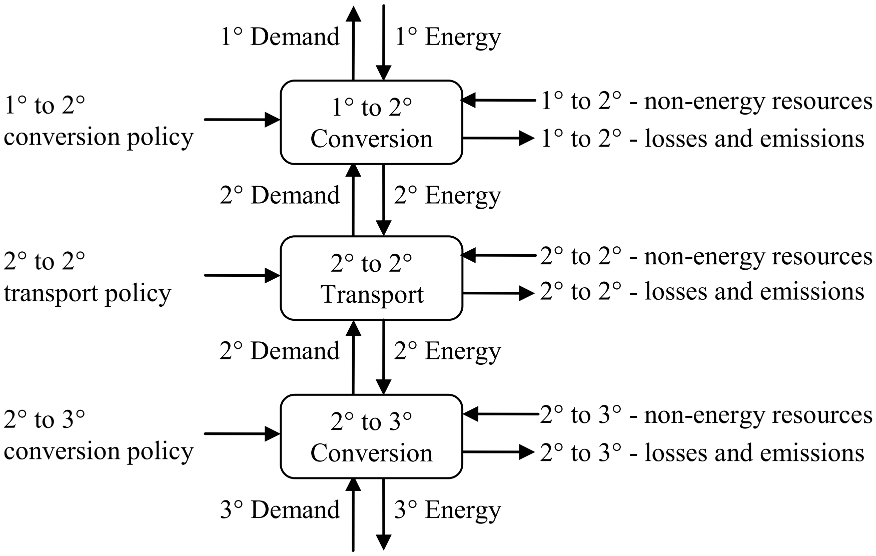

Figure 3: A linear energy chain (from (2))
(1°, 2°, 3° denote primary, secondary, and tertiary, respectively)

The energy system, its chains, and supplies are intended to meet the energy demands of the jurisdiction's energy services. Ideally, they do; however, the loss of an energy supply or the failure of an entity within a chain can lead to a deterioration of the jurisdiction's energy security (2).

2.2 Energy Security

Energy security is defined by the International Energy Agency (IEA) from the perspective of an energy consumer as, "the uninterrupted physical availability [of energy] at a price which is affordable, while respecting environment concerns" (21). Most jurisdictions in the world are increasingly dependent on three primary energy sources (i.e., crude oil, coal, and natural gas) to meet their energy security needs over the past 50 years (1); however, supply disruption, price instability, and environmental degradation can lead to a decline in energy security and an increase in social and economic difficulties. Thus, maintaining and improving energy security due to these problems and the global economic downturn will be one of the major challenges facing stakeholders (notably the public, policymakers, and politicians) in the 21st century (1).

Energy security has for the most part focused on the development of indicators or dimensions and their application to nation-states or specific energy chains within an energy system (29). At the national level, recent examples of this include an analysis of energy security in the Asia-Pacific region using 11 dimensions, each associated with a number of attributes (30); an examination of 10 countries using 16 dimensions of energy security (some of which consider the underlying energy system of each jurisdiction) (31); an evaluation of energy security performance for 18 countries from 1990 to 2010 using five dimensions broken down into 20 components and 20 metrics (32); a synthesized list of 320 simple and 52 complex indicators of energy security based on surveys, a workshop, and research interviews (33); an assessment of the energy security of Thailand using nineteen indicators for a 45 year period (1986-2030), and applying three energy scenarios (i.e., high economic growth and least cost option (HEG & LC), low carbon society (LCS), and current policy (CP)) (34); an integrated energy strategy based on a conceptual system model to deal with energy challenges in China (35); and recommendations for the implementation of energy strategy for the Republic of Croatia (36). Examples examining specific energy chains include a study of three indicators of energy security as a part of social indicators of sustainability for the assessment of nuclear power in the UK (37); a detailed examination of natural gas and its contribution to energy security in the UK (38); a review of China's coal usage in light of carbon-emission constraints and its replacement with natural gas (39); projections of future oil development in China (40); a development of a broadened typology to describe an interconnection between energy and security (41); and a focus on supply relative to demand as the principal view of energy security (42).

From the IEA's definition of energy security, three generic energy security indicators can be derived: availability ("the uninterrupted physical availability"), affordability ("a price which is affordable"), and acceptability ("respecting environment concerns") (2). These indicators (or dimensions) can be associated with metrics for measuring changes to the flows between entities, and within a chain; this can indicate the improvement or deterioration of energy security (2):

Availability: When the energy input of an entity, $Energy_{\mathrm{IN}}$, matches its $Demand_{\mathrm{OUT}}$, the flow is available and can be considered secure; however, if $Energy_{\mathrm{IN}}$ is less than $Demand_{\mathrm{OUT}}$, there is a loss of availability resulting in deterioration of energy security. The problem could be due to the failure of, or the lack of $Energy_{\mathrm{IN}}$ to, the upstream entity.

Affordability: An entity's $Energy_{\mathrm{IN}}$ flow cost is determined by the initial $Energy_{\mathrm{IN}}$ cost from the supplier and the processing costs applied by the intervening upstream entities. The increase in costs can make the $Energy_{\mathrm{IN}}$ flow become less affordable and hence less secure; conversely, if the costs decline, it can become more affordable and potentially more secure. Subsidizing the cost of $Energy_{\mathrm{OUT}}$ can signal an improvement in affordability; however, the size and duration of the subsidy can adversely impact the jurisdiction.

Acceptability: The acceptability of an $\mathit{Energy}_{\mathrm{IN}}$ flow pertains to the flow’s environmental acceptability and is related to the technology used in the conversion and transportation of energy by upstream entities. For example, a flow’s security can be discussed in terms of the $\mathit{Environment}_{\mathrm{IN}}$ and $\mathit{Environment}_{\mathrm{OUT}}$ flows with standards or requirements specified by $\mathit{Policy}_{\mathrm{IN}}$ flows relating to ground, water, and air emissions. Policies dictate that acceptability also refer to the social or political acceptability of an energy flow or entity in some jurisdictions. Acceptability metrics can range from evidence-based research through ideological opinion.

An energy system and its entities (i.e., sources, processes, or services) are all potentially affected by the occurrence of expected and unexpected events such as weather events, and grid failures that results in affecting the system’s energy security which can improve, deteriorate, or be maintained (29). An event is any internal or external action that leads to a measureable change in at least one of the entity’s flows. An internal event occurs within an entity and if handled, the output flows are unchanged, or else one or more of the entity’s output flows are affected (i.e., $\mathit{Energy}_{\mathrm{OUT}}$, $\mathit{Demand}_{\mathrm{OUT}}$, or $\mathit{Environment}_{\mathrm{OUT}}$), whereas an external event causes a measureable change in entity’s input flow (i.e., $\mathit{Energy}_{\mathrm{IN}}$, $\mathit{Demand}_{\mathrm{IN}}$, $\mathit{Environment}_{\mathrm{IN}}$, and $\mathit{Policy}_{\mathrm{IN}}$); ideally, the entity handles the event; otherwise one or more of its output flows change. The understanding of events, their causes, and handling, can help a jurisdiction and its stakeholders create a better and evidence-based energy policy (29).

2.2.1 Defining the Events that can Affect Energy Security

Stirling has defined four dynamics of energy security to describe how events can change energy security in an energy system (43; 44). It enumerates the places where an event can occur (inside or outside the system) and its temporal characteristics (short-term or long-term); their classification is shown in Table 1. The temporal characteristics refer to the time taken for an event to occur which is captured over timescale: shock is a short-term event occurring very quickly or rapidly (e.g., a grid failure), whereas stress is a long-term event occurring gradually over a period (e.g., annual emissions reduction targets). External events occur outside the system and are not under its direct control, whereas internal events take place within the system and can be controlled by it. In either case, if the effects of the event are restrained from reaching its energy suppliers or services, or both, due to system's response, the system is said to be resilient (external-shocks), robust (external-stresses), stable (internal-shocks), or durable (internal-stresses). The energy security of those services using the system can be compromised, if the system is unable to handle the event (29; 43; 44).

Table 1: Stirling's four dynamics of energy security (29; 43)

	Short-term (Shock)	**Long-term (Stress)**
External to system	Resilience	Robustness
Internal to system	Stability	Durability

Rather than using vague terms such as "gradually" or "very quickly" as Stirling does and mix the terms shock and stress, a better understanding of an event's impact can be obtained by measuring the outcome of the event relative to a metric; moreover, such measurements allow the magnitude and long-term effects of the event to be considered (29).

An alternative approach to explaining events and event handling in an energy system is discussed using systems analysis techniques and the three indicators (i.e., availability, affordability, and acceptability) required to measure changes to the system. A systems model supports the definition of entities, their associated input and output flows and the creation of entity chains (29). From this, a generic set of methods that can define, measure, and explain the impact of events causing stresses, affecting a jurisdiction's system and its energy security has been developed. The resulting effect of events on a system's energy security is examined, that is, the stress conditions under which an event will cause an entity or possibly the entire system to reach a tipping point and change from one state to another (29).

When an event occurs, it causes stress to the entity. As the stress increases, the entity is put under increasing tension until it reaches its elastic limit or tipping point (i.e., the point at which the level of stress makes it impossible for the entity to meet its minimum operating requirements and its operation is disrupted) (29). The choice of metrics and tipping points is a central issue in energy security analysis. The definition of the metrics, the values of the tipping points, and the depth of analysis will be obtained from the resolution of the available data for the implementation. For example, many statistical agencies provide data for the sectoral level (i.e., residential, commercial, and industrial) such as energy balance statistics (45) and they also have disaggregated data (as in (46)). Some tipping points are self-evident, such as an electricity blackout, and others can be difficult since they changes within an entity such as a process or service. This means that the entity is divided into sub-entities to determine the specific tipping points; for example, in the residential sector the energy use could be divided into appliances, lighting, water heating, and space heating or cooling (29).

According to the definition developed by Hughes, an entity is in one of three states depending upon the level of stress and tipping point (29)**:**

Normal: is an entity’s secure state where the stress level is considered to be zero.

Tension: is defined as an entity’s less secure state between the Normal and Disruption states associated with non-zero stress level (i.e., the stress level is greater than zero but less than the tipping point associated with the indicator metric of the flow). The entity cannot meet the same level of service it had in the Normal state and operates in a degraded fashion.

Disruption: is an entity’s insecure state where the stress level exceeds the tipping point; the entity enters the Disruption state.

The state of an entity can be determined by using an indicator-specific level of stress and its associated tipping point. Table 2 summarizes the conditions under which an entity will change its state. For example, if the stress exceeds the tipping point, the entity will be in the Disruption state. Similarly, stress levels can also decline; depending upon the resulting value, the entity may enter a new state. A state change can signal an improvement or a deterioration of the jurisdiction’s energy security (29).

Table 2: States and their conditions (29)

State	Condition
Normal	Stress = 0
Tension	0 < Stress < Tipping Point
Disruption	Stress ≥ Tipping Point

The method is applicable to describe any jurisdiction's energy system and energy security in which entity energy flows are known and tipping points and metrics have been defined for each indicator (i.e., availability, affordability, and acceptability) of each flow leading to a consistent and evidence-based energy policy (29).

2.3 Energy-Security Index

An energy-security index is a qualitative or quantitative, or combination of both measure of a jurisdiction's energy security (32; 28; 25; 26). It can be used in the development of new energy policy or climate policy, or both and for evaluating energy security policies and performance of a jurisdiction (32; 47). Revisiting the energy-security index regularly allows the new state of energy security to be obtained, and can influence energy policy decisions, including energy and infrastructure choices for all energy services (25; 47).

Sovacool has outlined the novelty or the value of creating an energy-security index as (48):

1. A focus on multidimensional concept of energy security that includes innovation, sustainability, technology, efficiency, stewardship, regulation, and governance.
2. A measure of energy security performance that informs energy policy and builds institutional capacity.

3. A correlation of energy security performance with major events such as embargoes, military conflicts, or the introduction of new, transformational energy policies or technologies.
4. An identification of tradeoffs within the various dimensions of energy security and areas needed for improvement.

An energy-security index is produced using different methods and dimensions. Examples of this includes a method developed employing the multi-criteria decision analysis tool, analytic hierarchy process (AHP), to create an energy-security index for each energy source and ranking them based upon the opinions of energy analysts in a jurisdiction (49; 28); an energy-security index is produced for the different energy sources, infrastructure, and services used by a jurisdiction using decision matrix method based upon the Asia Pacific Energy Research Centre's (APERC) four 'A's (availability, accessibility, affordability, and acceptability) (25; 47); constituting a comprehensive energy-security index from five dimensions related to availability, affordability, technology development, sustainability, and regulation broken down into 20 components and correlated with 20 metrics for evaluating national energy security policies and performance among the United States, European Union, China, India, Japan, Australia, New Zealand, South Korea, and the ten countries comprising the Association of South-East Asian Nations (ASEAN) from 1990 to 2010 based upon surveys, a focused workshop, a literature review, and research interviews (32; 50); the creation of an energy-security index using ten indicators comprising social, economic, political, and environmental aspects of energy security for the analysis of energy conditions in 22 Organization for Economic Co-operation and Development (OECD) countries from 1970 to 2007 (51); the use of

International Energy Agency's two indicators for security of supply (i.e., supply and price) for the development of an energy-security index as an aggregated indicators for energy security (22); an establishment of the evaluation indicators of energy security for the development of the model of energy-security index for determining the China's energy supply security from 1996 to 2009 (52); and the creation of a composite energy-security index (ESI) from the three indicators of energy security (energy security price index (ESPI), energy security import index (ESMI), and energy intensity (EI)) for the quantitative impact assessment of the European Union (EU) Climate and Energy Package (53).

Although an energy-security index is described in an energy system using different methods and dimensions, it can also be applied to an entity having various or multiple $Energy_{\mathrm{IN}}$ flows, each contributing an amount of energy to the entity.

2.4 Energy Diversity

Diversity is the state or quality of being varied or different (54). Diversification is applicable to an energy system and considered as the key to system's energy security (8). Hughes has illustrated the different views of diversification: one such view is the use of similar form of energy to meet the demands of the energy service, but the supplier changes, signaling the replacement of a less secure source of energy with the one that is more secure. For example, after the oil embargos of the 1970s, the United States reduced its oil imports from the Middle East, by replacing them with supplies from Mexico, Canada, Venezuela, and Nigeria (10). In some conditions, introducing, or changing new infrastructure that permits alternative energy sources, thereby replacing existing ones is regarded as a form of diversification and generally applied to electrical generation; One such example occurred in late 1970s, when increasing costs of oil contributed to the first oil shock of the 1970s, the world-wide change of energy source takes place from oil to coal and nuclear for electrical generation (10).

In Stirling's studies of diversity and characteristics of diverse energy systems, diversity is described in different contexts, including social, cultural, economic, scientific and technological (55; 56; 57; 58; 20). The reliance on a variety of mutually disparate suppliers and their energy supplies is known as energy diversity, and is seen as an essential component for energy security (11). The uncertainties and risk associated with an energy system can be reduced by diversity, while enhancing its energy security (20). According to Stirling, three general, necessary but individually insufficient properties of energy diversity are (11):

Variety: "The number of diverse categories of 'option' into which an energy system may be apportioned". It refers to the number of different energy sources or portfolios available to an energy system.

Balance: "a function of the apportionment of the energy system across the identified options". It relates to the evenness or relative abundance of the different energy sources.

Disparity: "the manner and degree in which energy options may be distinguished". It refers to the way in which the various portfolios of an energy system are defined.

Some examples of diversity research include an analysis of energy diversity in four Asian countries (Japan, Korea, Taiwan, and Indonesia) in terms of fuel types based on the OECD data set from 1987 to 2006 (12); a qualitative conceptual framework established to show the relationship between sources of imported oil and energy security of oil-importing countries such as the United States, Japan, and China (15); the diversification and localization of energy sources and systems to provide energy security for the energy supply and distribution to the energy consumers (9); a critical discourse analysis is used to analyse the struggle within the climate change mitigation as a symptom of unsustainability and energy security as a lack of energy diversity in UK (59); a discussion of the extent of diversification in oil sources and natural gas supplies in OECD economies by analyzing the cross-country heterogeneity, and representing the change in the extent of diversification on the basis of political risk attached to the suppliers, transportation risk, and the size of the importing country (17); an assessment of Taiwan's energy policy using multi-dimensional energy security indicators, which can adequately reduce the Taiwan's dependence on imported energy and improve the diversification of energy supply (60); an evaluation of the long- and short-term security based on the diversity of Mexico's current generation mix (14); the diversity of fuel-source mix representing the long-term security of supply in UK electricity generation and the influence of low-carbon objectives (13); the evolution of Germany's energy mix and the long-term strategy for energy availability and cost-efficiency with the inclusion of significant shares of renewable energy (16); and the development of a novel linear diversity constraint for the production scheduling in microgrids, so as to maintain diversity in the generation of electricity from multiple resources (61).

2.4.1 Measurement of Diversity

Diversity indices have been developed to measure diversity in various scientific fields which include biology, ecological sciences, information theory, statistics, and economics

(19). In an energy system, the diversity of the energy mix and supply sources can be measured by using different diversity indices such as Shannon–Wiener, Simpson, Hirschman–Herfindahl, and integrated multi-criteria diversity index (11; 3; 18; 19; 6). Indices reflect the three necessary components of energy diversity (i.e., variety, balance, and disparity) to different degrees (11; 19). Based on these three dimensions, a general framework to quantify the diversity of an energy system has been developed (11).

Diversity indices provide necessary measures to differentiate between various energy supply structures within one country or across countries (16). Some recent examples of this include the development of the "diversity reliability index" and "co-vary diversity reliability index" based on the Hirschman–Herfindahl and Shannon–Wiener indices, determines the diversity of different energy sources to Taiwan's energy supply structure, and analyzes the co-variance between different energies and their effects on energy security to reduce the risk of energy supply shortages and cost fluctuations (3); the diversity indices and oil-independence rates have been used to analyze the energy security, diversification, efficiency, and carbon emissions of the Chinese industrial sector (62); the Shannon index (H) and an adapted biodiversity index (D) have been applied to the power results of the period 2013 to 2032 of the Spanish generating system obtained from a stochastic linear model to analyze the diversity of primary energy resources (63); and the degree of concentration in energy supply and demand is measured using the Hirschman–Herfindahl index (HHI) to evaluate the cost of energy security in terms of supply disruption and price volatility in the Korean electricity market (64).

Various quantitative indicators are designed using diversity indices to determine the energy security of an energy system such as diversification of primary energy demand, energy import dependency, energy supply diversity, and political stability (23; 65; 22; 13). The International Energy Agency (IEA) has developed a tool called the Model of Short-Term Energy Security (MOSES), to determine short-term security of energy supply in IEA countries in terms of risks and resilience by using energy systems approach and various energy security indicators which includes diversity of suppliers, and diversity of reactor models (66).

2.4.1.1 Shannon-Wiener Diversity Index

Shannon used the concept of entropy to discuss informational uncertainty and thereby defined the Shannon-Wiener index or the Shannon diversity index. The Shannon-Wiener index places a greater emphasis on rare species from the relative abundance perspective. It has been applied to determine diversity in the different fields such as biology, ecology, and economics (3).

In an ecosystem, the Shannon diversity index is used for calculating its diversity and depends upon the number of different types of entity and the evenness of the distribution of these entities (i.e., similarity in size) (67; 68). Here, the diversity of a system increases as the number of entities increases and the population of the entities converges; in an energy system, an increase in diversity is assumed to improve its energy security (2).

The diversity of a system using the Shannon diversity index is calculated as follows (67; 68; 69):

1. For a system of R objects, determine the system's total population from the individual population, e, of each object with respect to equation (2.1):

$$P = \sum_{i=1}^{R} e_i \tag{2.1}$$

2. For each object in the system, determine the relative contribution, p_i, of its population, e_i, to the total population from equation (2.2):

$$\forall e_i : p_i = \frac{e_i}{P} \tag{2.2}$$

3. The diversity (D) is the weighted geometric mean of the proportional contributions of each object; this is the system's diversity (the higher the value, the more diverse the system) and can be obtained from equation (2.3) :

$$D = -\sum_{i=1}^{R} p_i \times \ln p_i \tag{2.3}$$

The Shannon diversity index is predominantly used in the energy field for calculating the fuel diversity and serves as a tool to assess long-term energy security strategies (16; 23; 65; 12; 19). Stirling has described the index as a simple and robust because it retains rank ordering under variations of logarithm base and displays the property of additivity with respect to taxonomy (22; 20).

The Shannon-Wiener diversity index has been recently used by the UK government with a review of the energy indicators of 2011 for the purpose of energy diversity analysis in UK and stated the reason for using the index as: “it places weight on the contributions of smaller participants in various fuel markets as they provide the options for future fuel switching” (70; 13; 6).

Although the Shannon diversity index is described as a system with R objects, it can also be applied to an entity having *R* upstream entities each contributing an amount of energy ($Energy_{\text{IN}}$) to the entity. The total amount of $Energy_{\text{IN}}$ is the entity's population.

2.5 Summary

In this chapter, existing research related to energy systems, energy security, event-related stress and their effects on energy security were reviewed. Further, the overview of the approaches for the formation of an energy-security index has been presented, followed by the review of existing energy diversity research. This review has highlighted that while the energy security and diversity of supply are important, by focusing on suppliers and supplies alone—omitting the internal structure of the system and its energy services—is a limited view of both energy security and diversity. Also, it shows that multiple input energy flows to an entity represent its diversity; however, it is essential to measure the energy security of each input energy flow in order to know how secure the entity is. The following chapter presents the method to examine the relationship between energy security and diversity.

CHAPTER 3 METHOD AND IMPLEMENTATION

This chapter presents a method for examining the relationship between energy security and diversity of an energy system, its entities, and flows. The chapter begins with the description of various equations that are used in the method, followed by the discussion of the method in distinct steps and its application. The chapter concludes with the results of the analysis and a description of the software used for the implementation of the method.

3.1 Determine the Energy-Security Index and Diversity

This section describes how the energy-security indices (ESI) and diversity of an energy system, its entities, and flows can be determined. The equations obtained are used in the method for examining the relationship between energy security and diversity.

3.1.1 Energy-Security Index

Energy security can be measured using both qualitative and quantitative metrics, with the results expressed as one or more energy-security indices (29; 26). The energy-security index (ESI) of an entity in an energy chain is determined by employing three indicators (or dimensions) and their metrics to measure the availability, affordability, and acceptability of its $Energy_{\mathrm{IN}}$ flows affected by the event-related stress three different states—Normal, Tension, and Disruption—along with their conditions causing an entity and possibly the chain and system to reach a tipping point, and change from one state to another (29).

The ESI of an entity is determined separately for the three generic indicators, availability, affordability, and acceptability.

3.1.1.1 Availability Energy-Security Index

An entity's availability energy-security index, $\mathrm{ESI}_{\mathrm{AVA}}$, indicates the degree to which the $Energy_{\mathrm{IN}}$ flows meets the $Demand_{\mathrm{OUT}}$ flows; the $\mathrm{ESI}_{\mathrm{AVA}}$ for an entity's $Energy_{\mathrm{IN}}$ flows is shown in equation (3.4) (29):

$$ESI_{AVA} = \frac{\sum Energy_{IN}}{\sum Demand_{OUT}} \tag{3.4}$$

An $\mathrm{ESI}_{\mathrm{AVA}}$ of at least 1 means the $Energy_{\mathrm{IN}}$ flow is available and secure, while values less than 1 indicates that in terms of availability, the flow is insecure leading to deterioration in energy security (29).

3.1.1.2 Affordability Energy-Security Index

The affordability energy-security index, $\mathrm{ESI}_{\mathrm{AFF}}$, is the ratio of the entity's energy budget and the total cost of its $Energy_{\mathrm{IN}}$ flows, and is shown by equation (3.5) (29):

$$ESI_{AFF} = \frac{Budget}{\sum Energy_{IN\,i} \times Cost_i} \tag{3.5}$$

The affordability of the flows is considered to be secure when the $\mathrm{ESI}_{\mathrm{AFF}}$ ratio is at least 1; however, a value less than 1 indicates that the flow is not affordable and is therefore insecure resulting in deterioration of energy security (29).

3.1.1.3 Acceptability Energy-Security Index

The acceptability energy-security index, $\mathrm{ESI}_{\mathrm{ACC}}$, depends upon the metrics being employed to the $Energy_{\mathrm{IN}}$ flow and how the results are interpreted. Quantitative metrics, such as the level of emissions, may be treated differently than qualitative ones, such as public opinion (social or political) on a certain issue. In these conditions, $\mathrm{ESI}_{\mathrm{ACC}}$ can be discussed in terms of acceptability, tolerability, and unacceptability of the $Energy_{IN}$ flow (29).

3.1.2 Diversity

Although an entity is shown as having a single $Demand_{OUT}$ flow and a single $Energy_{IN}$ flow as shown in Figure 2, there is nothing to say that there may not be multiple $Demand_{OUT}$ flows leading to a number of upstream entities and that these entities may all respond with varying levels of $Energy_{IN}$.

Figure 4 shows the condition where an entity has its demand met from multiple upstream entities (entities 1 through N), where 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. The diversity of flows is determined using the Shannon-Wiener diversity index.

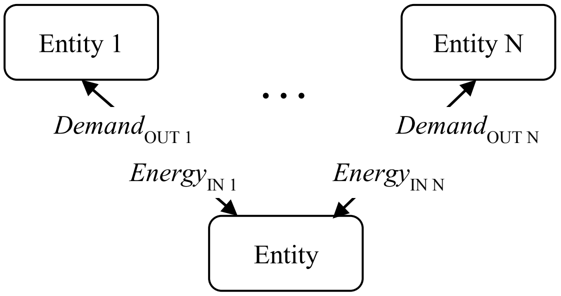

Figure 4: An entity with multiple $Demand_{OUT}$ and $Energy_{IN}$ flows

The steps associated with the Shannon-Wiener diversity index are as follows (67; 68; 69):

1. For an entity having (N) upstream entities contributing an amount of energy ($Energy_{IN}$) to it, determine the entity's total $Energy_{IN}$ flow (P) (total population) from

the individual $Energy_{\mathrm{IN}}$ flows (individual populations), e, of each upstream entity with respect to equation (3.6):

$$P = \sum_{i=1}^{N} e_i \tag{3.6}$$

2. For each upstream entity in the entity, determine the relative contribution, p_i, of its individual $Energy_{\mathrm{IN}}$ flow, e_i, to the total $Energy_{\mathrm{IN}}$ flow from equation (3.7):

$$\forall e_i : p_i = \frac{e_i}{P} \tag{3.7}$$

3. The diversity (D) is the weighted geometric mean of the proportional contributions of each upstream entity; this is the entity's diversity (the higher the value, the more diverse the entity) and can be obtained from equation (3.8) :

$$D = -\sum_{i=1}^{N} p_i \times \ln p_i \tag{3.8}$$

3.2 Method

The various $Energy_{\mathrm{IN}}$ flows forming combinations (i.e., single or multiple) of energy flows to an entity represent its diversity (11; 2). However, it is essential to measure the energy-security index of each of these energy flow combinations so as to know how secure the entity is. While the Shannon-Wiener diversity index is used to determine the diversity of an energy system, it gives no indication of the relationship between energy security and diversity. Moreover, while energy security and diversity are important, focusing on suppliers and their energy supplies and neglecting the internal structure of the system and its energy services is a narrow view of both energy security and diversity.

An analysis of the relationship between an energy security and diversity of an entity in an energy chain is now presented. It is dependent upon the multiple upstream entities supplying $Energy_{\mathrm{IN}}$, forming various combinations of $Energy_{\mathrm{IN}}$ flows, and is measured in terms of their energy-security index (ESI) and Shannon-Wiener diversity index. Energy security and diversity are obtained by considering what takes place within the system boundary or the energy services.

The method being proposed for examining the relationship between energy security and diversity of an energy system, its entities, and flows is described in the following steps:

1. Determine the number of $Energy_{\mathrm{IN}}$ flows of an entity.
2. Obtain the maximum (i.e., total $Energy_{\mathrm{IN}}$) flow requirements of the entity to meet its availability requirement (using total $Demand_{\mathrm{OUT}}$) and the maximum availability of each of the $Energy_{\mathrm{IN}}$ flow.
3. Determine all possible combinations of $Energy_{\mathrm{IN}}$ flows by changing their values from a maximum to a minimum (zero) in integer steps (i.e., for obtaining finite number of values). By changing the value of the flows, the resulting effects (i.e., improvement or deterioration) on energy security and diversity of an entity can be shown.
4. Calculate the sum of each combination of $Energy_{\mathrm{IN}}$ flows, obtaining the total flow in each case.
5. Determine the energy-security index ($\mathrm{ESI}_{\mathrm{AVA}}$) of each combination of flows (from step 4), by taking the ratio of the total flow to the entity's availability requirement ($Demand_{\mathrm{OUT}}$) using equation (3.4).

6. Determine the diversity of each combination of $Energy_{IN}$ flows (from step 4) using the Shannon-Wiener diversity index (equations (3.6), (3.7), and (3.8)).

7. The results are analyzed and explained by applying two necessary conditions of analysis such as changing diversity with a constant ESI_{AVA} and changing ESI_{AVA} with a constant diversity to show that a diverse energy flow need not be secure and a secure energy flow need not be diverse.

8. Generate the graph of the relationship between energy security and diversity for each of the condition by plotting the values of the total flow (considered as a proxy for ESI_{AVA}) and diversity against each other on an X-Y axis. The graphical representation of the values shows the resulting effects of changing flows as an improvement or deterioration in energy security and diversity of an entity. Hence, the comparison of the two values is shown in order to know how secure the entity is in addition to its diversity.

These eight steps allow the relationship between energy security and diversity to be examined.

3.3 Application of the Method

An entity with four $Energy_{IN}$ flows from upstream entities (F1 to F4) is considered as an example. The flows attempt to meet the entity's $Demand_{OUT}$ of 100 units; the maximum availability of each the flow is shown in Table 3.

Table 3: The maximum availability of each of the four $Energy_{IN}$ flows

F1	F2	F3	F4
100	100	100	100

3.3.1 Changing Diversity with a Constant Energy-Security Index

If the total $Energy_{IN}$ flow of an entity remains equal to its $Demand_{OUT}$ flow, its availability energy-security index (ESI_{AVA}) can be kept constant. This can be obtained if one or more of the entity's $Energy_{IN}$ flows can be increased to compensate the decline of its other $Energy_{IN}$ flows. The diversity index of the total $Energy_{IN}$ flow will also change by changing the number and evenness of the flows, regardless keeping the ESI_{AVA} constant.

The diversity and ESI_{AVA} values for an entity with a $Demand_{OUT}$ of 100 units supplied from up to four $Energy_{IN}$ flows (F1 through F4) is shown in Table 4. The different $Energy_{IN}$ flows change in each case, all together having 100 units in total, keeping the ESI_{AVA} constant at 1.0. The diversity also changes with the changing number and size of the flows.

The results in Table 4 show that changing an entity's number and size of the $Energy_{IN}$ flows while maintaining a constant ESI_{AVA} can affect the diversity and that a low diversity does not necessarily mean the entity is insecure.

Table 4: Changing diversity and maintaining a constant ESI_{AVA}

F1	F2	F3	F4	Total Flow	ESI_{AVA}	Diversity
20	40	20	20	100	1.0	1.332
40	40	20	0	100	1.0	1.054
20	20	0	60	100	1.0	0.950
0	0	60	40	100	1.0	0.673
0	80	20	0	100	1.0	0.500
100	0	0	0	100	1.0	0.000

Figure 5 is a graph of the relationship of the total flow (considered as a proxy for ESI_{AVA}) values and the diversity of the various $Energy_{IN}$ flows taken from Table 4. The figure shows that for the combination of $Energy_{IN}$ flows of the entity, if the number and size (evenness) of the $Energy_{IN}$ flows change and the total flow is kept constant (in this case, 100 or that the ESI_{AVA} is constant at 1.0), the diversity changes. This also shows that a low diversity does not necessarily mean that the entity is insecure, such as in the case where diversity is zero but the total flow is 100 (means ESI_{AVA} is 1.0).

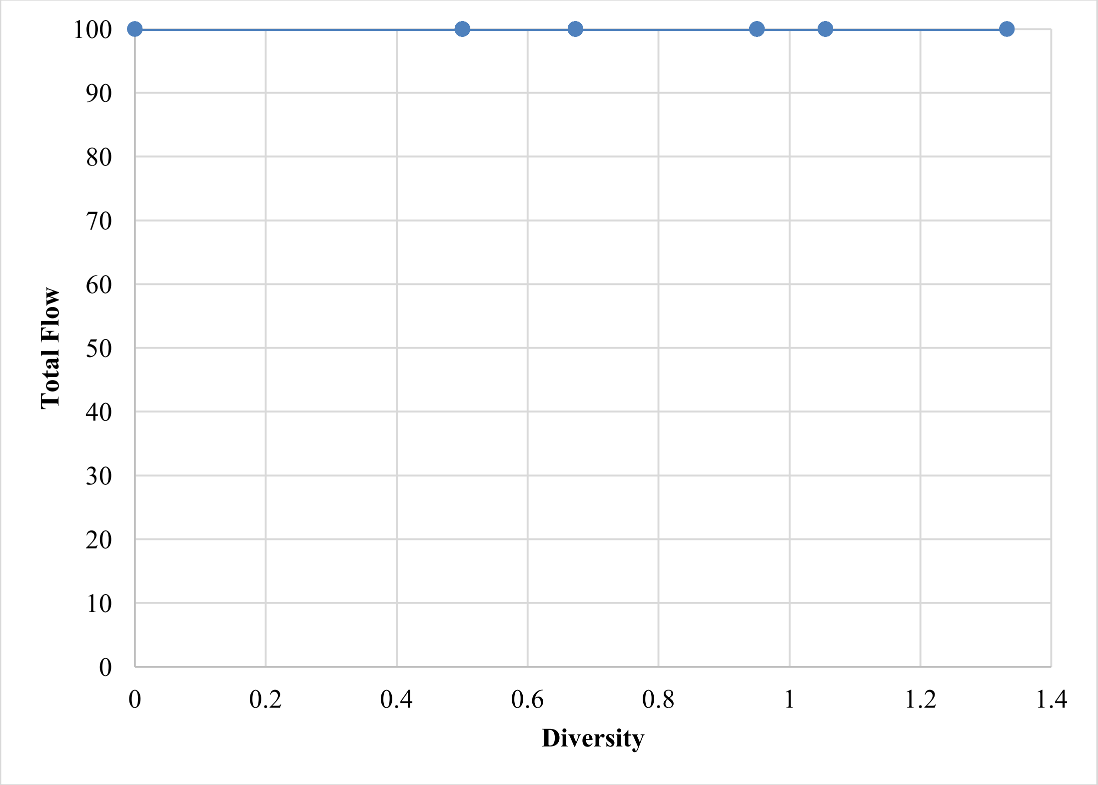

Figure 5: Changing diversity with a constant ESI_{AVA}

3.3.2 Changing Energy-Security Index with a Constant Diversity

If an entity's total $Energy_{IN}$ is less than its total $Demand_{OUT}$, its availability energy-security index (ESI_{AVA}) will decline. However, this does not necessarily mean that its diversity will change. The Shannon-Wiener diversity index is determined using the proportional contributions of each entity (rather than the actual contribution); this will lead to the same value of diversity, despite of the total *Energy*$_{\mathrm{IN}}$ flow (total population), as long as the proportions remain constant. Thus, the diversity of two or more sets of flows will be equal, despite of the total flow of each, if the number of flows and the ratio of the sum of the individual flows to the total flow remain constant.

An entity with four *Energy*$_{\mathrm{IN}}$ flows with a *Demand*$_{\mathrm{OUT}}$ of 100 units is considered as an example. The results in Table 5 show that the diversity will remain constant (at 1.386), as long as the ratio of the individual flows to the total flow remains constant (at 0.25). However, since the total of the *Energy*$_{\mathrm{IN}}$ flows is decreasing, the ESI$_{\mathrm{AVA}}$ also decreases.

Table 5 shows that changing the *Energy*$_{\mathrm{IN}}$ flows of an entity while maintaining a constant diversity can affect the ESI$_{\mathrm{AVA}}$ and that a high diversity does not necessarily mean the entity is secure.

Table 5: Changing ESI$_{\mathrm{AVA}}$ and maintaining a constant diversity

F1	**F2**	**F3**	**F4**	**Total Flow**	**ESI$_{\mathrm{AVA}}$**	**Diversity**
25	25	25	25	100	1.0	1.386
20	20	20	20	80	0.8	1.386
15	15	15	15	60	0.6	1.386
10	10	10	10	40	0.4	1.386
5	5	5	5	20	0.2	1.386
1	1	1	1	4	0.04	1.386

Figure 6 is a graph of the relationship of the total flow (considered as a proxy for ESI_{AVA}) and diversity values of the combination of $Energy_{IN}$ flows obtained from Table 5. The figure shows that for the different combinations of $Energy_{IN}$ flows, if the evenness of the flows is equal and their relative contributions are constant, the diversity is maintained at constant level, in this case, 1.386, despite changing total flow (in this case, a declining ESI_{AVA}) value. Furthermore, a high diversity does not necessarily mean the entity is secure such as in the case where diversity is 1.386 and its corresponding total flow is 4.0 (means ESI_{AVA} is 0.04).

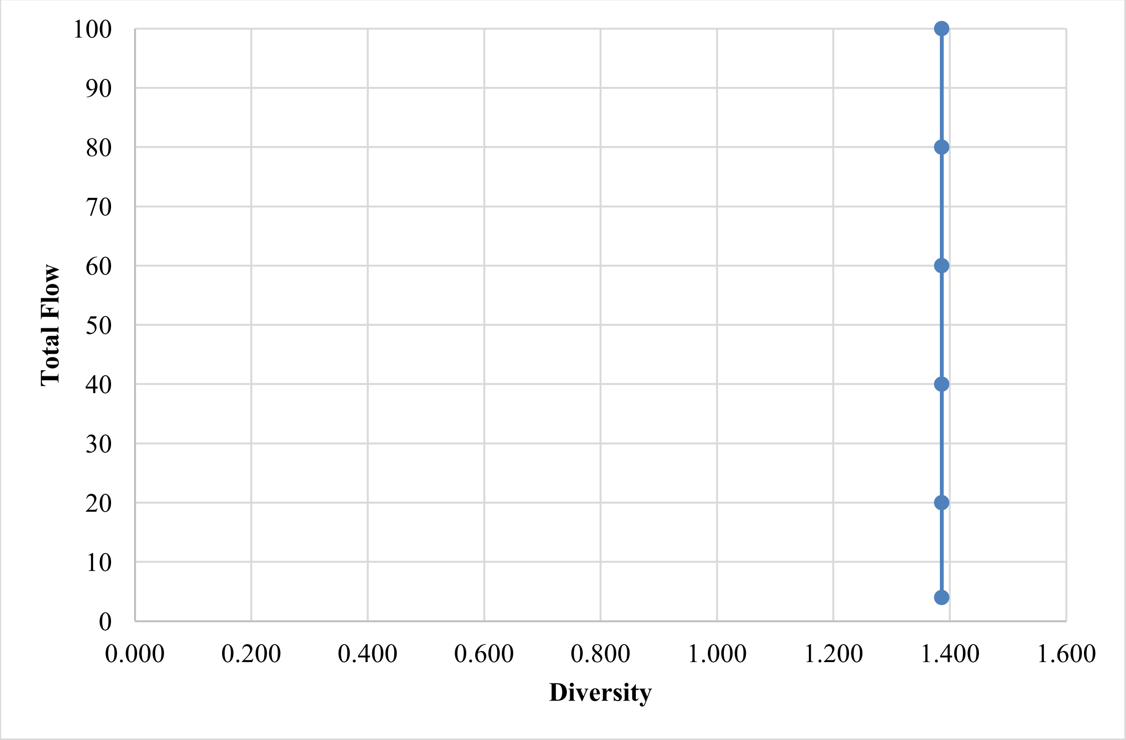

Figure 6: Changing ESI_{AVA} with a constant diversity

3.4 Diversity and its Effects on the Affordability and Acceptability Indicators

In the method discussed above, the energy security and diversity indices were determined for the availability of an entity's $Energy_{\mathrm{IN}}$ flows. The diversity equations are applied to the affordability and acceptability indicators using two methods.

In the first method, the value of the indicator's metric (for affordability, e.g., the unit cost of an $Energy_{\mathrm{IN}}$ flow such as cents per kilowatt hour and for acceptability, e.g., the emissions associated with the flow, such as CO_2 per kilogram) is used alone when determining the diversity index. The value determined from the diversity equations is the diversity of the metric and has no relationship to its usage by the entity. For example, in affordability, it shows whether there is a similarity in the costs (high diversity) and how evenly the individual costs are distributed (low diversity), while in acceptability, the result shows whether the flows are associated with similar emissions (high diversity) or have a range of different emissions (low diversity).

The second method is determined by using the metric (e.g., dollars per barrel in case of affordability, and for acceptability, e.g., CO_2 per tonne) as a weight which is applied to the value of each $Energy_{\mathrm{IN}}$ flow and results in the form of total affordability or acceptability of the flows. In this approach, the individual population of each entity is obtained from the flow and the value of its metric; for example, for entity i shown by equation (3.9):

$$e_i = Energy_{IN\,i} \times Metric_i \tag{3.9}$$

From this, the entity's total population (equation (3.6)), the relative contribution of the metric and its associated flow (equation (3.7)), and the diversity (equation (3.8)) can all be obtained.

The same metric value of the flows leads to the determination of diversity of availability with the flow scaled by the value of the affordability or acceptability metric. For example, the purchase of fuel for an automobile having similar prices in case of affordability or using a variety of fuels with the same emissions intensity for acceptability. However, if the flows have different metric values, the diversity shows the similarity of the combined costs for affordability or total emissions in case of acceptability; this can be useful for acceptability, since single energy sources are related with health and environmental risks (9).

Some acceptability metrics do not contribute to diversity calculations, for example the political or social acceptability of $Energy_{\mathrm{IN}}$ flows from an individual or group of entities, such as the United States refusing to purchase crude oil from Iran. On the other side, diversity could be applied to polling results, signifying the diversity of responses.

3.5 Implementation

For the implementation of the method a programming application is used in a spreadsheet software tool.

Microsoft Office Excel is an electronic spreadsheet that can be used to create tables, handle large data sets, calculate and analyse data, and develop charts or graphs to display the results (71; 72).

Visual Basic (VB) is an object oriented programming language that allows programs or procedures to be written to perform operations and calculations on an Excel spreadsheet. It has a specific library of objects that relates to Excel (73).

A program is written in VB programming language using Microsoft Office Excel following the steps of the method as developed in section 3.2. The results shown in section 3.3 were obtained from the software.

3.6 Summary

This chapter presented a novel and generic method for examining the relationship between the energy security and diversity of an energy system, its entities, and flows. The equations for the determination of the energy-security indices (ESI) and energy diversity of the entity are obtained. Further, the equations are used in the method for examining the relationship between energy security and diversity of an energy system, its entities, and flows. The application of the method and its results are discussed in terms of two necessary conditions of analysis. Finally, the description of software using Excel and Visual Basic for the implementation of the method is provided. More examples of the method are discussed along with their results in the following chapter.

CHAPTER 4 EXAMPLES AND DISCUSSION

This chapter discusses the examples of the relationship between energy security and diversity and the events that can affect it with their results. The chapter concludes with the discussion of disparity of flows in an energy system, and its entities.

4.1 Events and Diversity

An occurrence of an event can affect the system's entities and their flows leading to the change in energy security of an entity and, potentially, that of its system. Diversity is often applied as a means to handle such events that can affect the flows in a detrimental fashion, as the following examples illustrate.

4.1.1 Diversity within the System

Energy diversity is usually discussed in terms of the primary energy resources such as fuel mixes available to meet the energy demands of an energy system (26; 18; 11; 13; 22). Although each entity within the system is associated with one or more $Energy_{\mathrm{IN}}$ flows, consideration is rarely given to the possibility of events affecting these flows and the resulting effects on energy security and diversity.

An entity 'N' that depends upon various $Energy_{\mathrm{IN}}$ flows from neighbouring, upstream entities may be regarded as both secure and diverse. However, if the energy chains associated with these entities ultimately rely on a single entity 'M', any event causing 'M' to become unable to meet its $Demand_{\mathrm{IN}}$ flows may lead to an event that causes entity 'N' to fail to meet its $Demand_{\mathrm{IN}}$. Entity 'M' is considered to be a single point of failure (74). Thus, while determining the energy security and diversity of an entity within the system, it is necessary to consider the energy chains leading upstream from it.

An example of an event that affected an entity causing all its downstream entities to fail was the 2012 blackout in northern India where the NEW (North-East-West) grid (the upstream entity) that interconnects India's northern, eastern, north-eastern, and western grids collapsed due to load encroachment and power swings caused by internal faults, the loss of critical transmission links, and the tripping of distance relay. This resulted in the failure of the northern, eastern, and north-eastern grids. The western grid isolated automatically and avoided the failure by rapidly reducing demand and managing its existing supply (75; 76; 77).

Table 6 shows the power generated by the grids in northern India before the failure occurred (76); the diversity of the grids at the time of the NEW grid collapse is determined to be 1.10. Both the energy security and diversity were affected by the collapse of the NEW grid resulting in a blackout in northern India. The availability energy-security index (ESI_{AVA}) and the diversity value declined during the blackout because of the failure of the electrical power supply.

Table 6: Power generation and the diversity of the grids in northern India (76)

Grid	**Total MW generated**	p_i	$\ln p_i$	$p_i \times \ln p_i$
Northern	56058	0.36854	-0.9982	-0.3679
Western	66757	0.43888	-0.8235	-0.3614
Eastern	26838	0.17644	-1.7348	-0.3061
North-Eastern	2454.94	0.01614	-4.1265	-0.0666
Total Power Generated	152107.94		**Diversity**	1.10199

Other examples of such events include the 2003 blackout across eastern North America where the grid (the upstream entity) that distributes electricity to the eastern United States became overloaded causing circuit breakers to fail at generating stations from New York to Michigan and into Canada (78; 79); the 1998 severe ice-storm that hits the southwestern Quebec (the upstream entity) first resulted in causing freezing rain and power outages at eastern Ontario, New Brunswick, and bordering areas from northern New York to central Maine in the United States (80; 81); and the 2007 fire at Imperial Oil Limited's refinery (the upstream entity) in Nanticoke, Ontario which caused fuel shortages in various parts of southwestern Ontario (82; 83).

4.1.2 Eastern Canadian Crude Oil Supply

In 2012, refineries in the eastern Canadian province of Quebec and those in Atlantic Canada (New Brunswick, Nova Scotia, and Newfoundland and Labrador) received over 90% and 83% of their crude oil supply from non-Canadian sources, respectively (84). Table 7 shows the suppliers and the volumes (i.e., 127.9 million barrels) of crude oil supply to Quebec's refineries for 2012 (85); the diversity value of 1.48 is obtained.

Table 7: Quebec's crude oil suppliers, volume, and diversity of availability (85)

Suppliers	**Supply (MMbbl)**	**p_i**	**$\ln p_i$**	**$p_i \times \ln p_i$**
United Kingdom	4.62	0.0361	-3.3214	-0.1199
Norway	5.04	0.0394	-3.2337	-0.1274
Angola	5.08	0.0398	-3.2248	-0.1282
Mexico	8.15	0.0637	-2.7529	-0.1755
Canada	10.05	0.0786	-2.5430	-0.2000
Other countries	42.81	0.3348	-1.0943	-0.3663
Algeria	52.12	0.4076	-0.8975	-0.3658

Total Supply	127.87		**Diversity**	1.4832

The region's suppliers, the diversity and the availability of supply (ESI_{AVA}) until recently have not been an issue in either eastern Canada or Canada (84). However, since the protests in 2011 against the construction of the Keystone XL pipeline from Alberta to the United States (U.S.) Gulf coast refineries, various political and corporate groups in Canada have been arguing that western Canadian crude oil should be made available to the eastern parts of Canada, that is, to Quebec and other eastern Canadian provinces by pipeline (for example, see (86; 87; 88; 89; 90; 91)).

The construction of the pipeline will be a policy-driven event intended to improve Canadian energy security by ensuring that most of eastern Canada's refineries will no longer depend on foreign sources (i.e., acceptability) of crude oil that are more expensive than the currently landlocked western-Canadian crude (i.e., affordability) (92).

This means that any refinery in Quebec or Atlantic Canada, similar to those in the provinces to the west, depending entirely on western Canadian crude, may improve its energy security, but its diversity would be zero. Moreover, if the federal government and the proponents of the project proceed with the development as expected, the crude would be supplied by a single pipeline from western Canada which means that the diversity of the physical transportation of the crude would also be zero.

4.1.3 Hurricane Katrina and the IEA's Response

On 29 August 2005, Hurricane Katrina made landfall in Louisiana on the United States (U.S.) Gulf Coast and it was anticipated that about 90% of the crude oil production in the

U.S. Gulf of Mexico (about one-quarter of total U.S. production at the time) was shut-in (93). By 9 September 2005, six refineries in Louisiana and Mississippi (representing more than 5% of total U.S. capacity) were shutdown for an extended period (94).

On 2 September 2005, the International Energy Agency member countries agreed to take collective action, in response to the loss of the availability of domestic crude oil from the Gulf of Mexico and refined product from Gulf coast refineries, leading to the release of two million barrels of crude oil and refined product for thirty days to compensate the removal of oil supply from the market (95). Out of the 60 million barrels of crude authorized to be released, 30 million barrels were to come from the U.S. Strategic Petroleum Reserve (SPR) (i.e., the largest emergency fuel storage of oil maintained by the U.S. Department of Energy) (96; 97), with the rest coming from other IEA members (18 MMbbl from Europe and 10.8 MMbbl from the Pacific region) (98).

There is a great deal of data available on the impact of Hurricane Katrina on U.S. oil production and the IEA's response. Much of it is non-specific or too general to allow for nothing more than a "best-guess" at the values of the energy security and diversity indices. For example, the absence of specific data on crude oil production and refining capacity in the U.S. in the wake of the hurricane would suggest that both energy security and diversity declined. In a similar way, the response from the IEA members would appear to have improved both indices; however, to what extent is not clear.

4.1.4 The Fukushima Accident

In some cases, events are so extreme that they result in a loss of diversity. One such example was the aftermath of the earthquake and tsunami that damaged the Fukushima Daiichi nuclear reactor complex (Fukushima) in Japan in March 2011. The impact on

Japanese energy security and diversity would have been considerably less, if the event been limited to the tsunami and Fukushima accident; however, the policy decision to shut all of Japan's reactors was the event that leads to a deterioration of the country's energy security and a loss of the diversity of electricity supply (99). The month before the accident, nuclear power supplied about 31% of Japan's electricity, but after the shutdown of all the country's reactors, in August 2011, the rates of dependency on nuclear power declined to 12.4% and finally zero in May 2012. In June 2010, Japan revised its *Strategic Energy Plan of Japan* and decided to increase its dependency on nuclear power for electricity to about 53% by 2030 by constructing 14 new nuclear reactors, but abandoned these plans due to the accident (99).

Japan depends on a secure, diverse electricity supply prior to the accident, but after it, there is a loss of nuclear electricity which contributed to the deterioration of the country's energy security and resulted in a reduction of the electricity supply (availability) from 78.8 million TWh in December 2010 to 75.8 million TWh in December 2011, electricity suppliers experienced a net-loss in sales of $20.5 billion and additional fuel costs of $29.5 billion in fiscal 2011 (i.e., affordability), and a marked decline in public acceptance of nuclear power, with 57.3% of respondents favouring the withdrawal of nuclear power in September 2011, compared to 16.2% in 2009 (i.e., acceptability) (99).

Table 8 illustrates how diversity was affected: in December 2010, the diversity of Japan's electricity supply was 0.8538; by December 2011, it had fallen to 0.5084. The energy security was also affected as the availability energy-security index (ESI_{AVA}) which was secure in December 2010, declined marginally in December 2011 after the accident with respect to December 2010 demand.

Table 8: Changes in the diversity and availability of Japan's electricity supply (99)

	December 2010				**December 2011**			
Source	**Total TWh generated**	**p_i**	**$\ln p_i$**	**$p_i \times \ln p_i$**	**Total TWh generated**	**p_i**	**$\ln p_i$**	**$p_i \times \ln p_i$**
Nuclear	24,673,973	0.3133	-1.1606	-0.3636	5,549,686	0.0732	-2.6141	-0.1914
Thermal (coal, oil, LNG)	48,793,963	0.6196	-0.4787	-0.2966	65,367,650	0.8626	-0.1478	-0.1275
Hydroelectricity	5,045,776	0.0641	-2.7478	-0.1761	4,605,428	0.0608	-2.8006	-0.1702
Renewables (geothermal, solar, wind)	238,292	0.003	-5.8006	-0.0176	256,867	0.0034	-5.687	-0.0193
Total Electricity Generation	78,752,004		**Diversity**	0.8538	75,779,631		**Diversity**	0.5084

4.2 Different Types of *Energy*$_{\text{IN}}$ Flow: Disparity

The energy supplied in each *Energy*$_{\text{IN}}$ flow is usually regarded to be of the same type (e.g., all crude oil, all electricity), when Shannon's Wiener diversity index is applied to energy security; however, this is not universally true as some entities can utilize different types of energy (e.g., a dual-fuel furnace burning both biomass and fuel oil or a hybrid-electric vehicle using a petroleum product and electricity).

Stirling introduced a new metric, disparity, to distinguish between the differences in the types of *Energy*$_{\text{IN}}$ flows (this is in addition to variety and balance, which correspond to type and evenness in Shannon's diversity index), since Shannon's diversity index does not clearly distinguish between types of energy (11). Neither the energy-security index nor the diversity index refers to disparity, but its use can be traced to research into the fuel mixes used in energy systems in general and electricity supply in particular:

- Examples dealing with disparity of fuel mixes include an analysis of energy diversity in four Asian countries (Japan, Korea, Taiwan, and Indonesia) in terms of fuel types based on the OECD data set from 1987 to 2006 (12); a critical-discourse analysis of climate change mitigation as a symptom of unsustainability and energy security as a lack of energy diversity in UK (59); a qualitative conceptual-framework established to show the relationship between sources of imported oil and energy security of oil-importing countries such as the United States, Japan, and China (15); the extent of diversification of oil sources and natural gas supplies in OECD economies (17); and an assessment of Taiwan’s energy policy using multi-dimensional energy security indicators, which can adequately reduce the Taiwan’s dependence on imported energy and improve the diversification of energy supply (60).
- Examples of disparity with respect to electricity supply (i.e., availability) and diversity include an evaluation of the long- and short-term security based on the diversity of Mexico’s current electricity generation mix (14); the evolution of Germany’s energy mix and the long-term strategy for energy availability and cost-efficiency with the inclusion of significant shares of renewable energy (16); the diversity of renewables in UK electricity supply (6); and the development of a novel linear diversity constraint for the production scheduling in microgrids, so as to maintain diversity in the generation of electricity from multiple resources (61).

In many cases, the apparent disparity in the types of a number of $Energy_{\mathrm{IN}}$ flows is the outcome of the level of detail of the energy system being examined and the definition of the entity utilizing the flows. For example, if an electricity supplier is shown as a single entity, it has a disparity of primary energy flows (Figure 7); on the other hand, if the supplier is described in terms of its generating facilities and other parts of the chain that flows from source to service (part of which is shown in Figure 8), the need for disparity disappears.

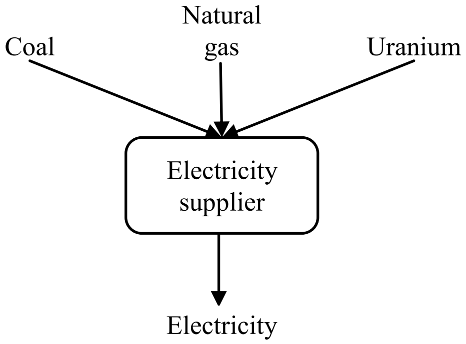

Figure 7: An electricity supplier with a disparity of *Energy*$_{\text{IN}}$ flows

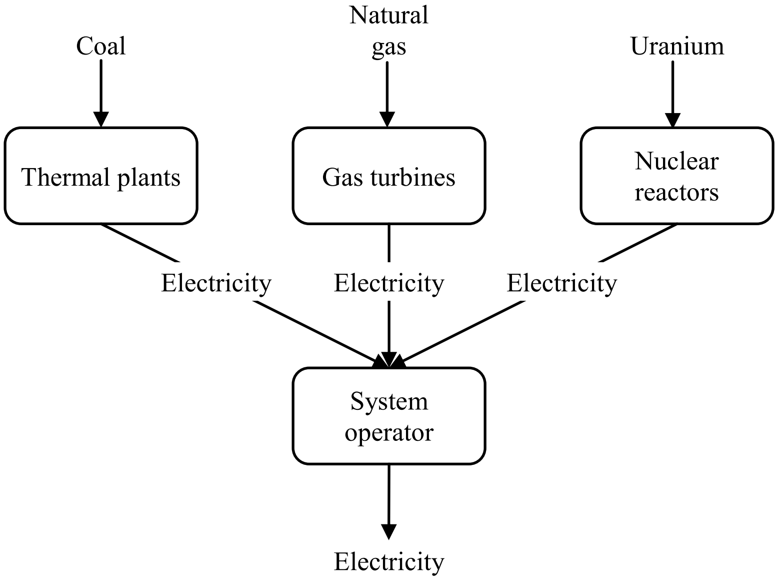

Figure 8: An electricity supplier separated into its generating facilities

Some entities can be described as having a disparity of flows if the entity can handle each of them; for example, a multi-fuel space-heating furnace (e.g., oil/wood or natural gas/wood) with a single, shared firebox (for example, see (100)). In such conditions, the two *Energy*$_{\mathrm{IN}}$ flows could be discussed in terms of their availability without regard to type.

4.3 Summary

This chapter presented the examples that illustrate the relationship between energy security and diversity and the events that can affect it with the discussion of their results. A discussion of the disparity of flows in an energy system, and its entities was also provided.

CHAPTER 5 CONCLUDING REMARKS

Energy diversity is essential for the long-term existence of an energy system and considered as the key to maintaining and improving system's energy security. Diversity can be determined from the various $Energy_{\mathrm{IN}}$ flows forming combinations of energy flows to an entity; however it is necessary to measure the energy-security index of each of these combinations of energy flow in order to know the entity's security. The focus of energy security and diversity is on suppliers and their energy supplies, while the internal structure of the system is neglected representing a limited view of both energy security and diversity.

Given the need to address energy security and diversity, the contribution of this thesis is the development of a novel and generic method to examine the relationship between energy security and diversity of an energy system, its entities, and flows that can be used to address the above two issues. An energy system and its internal entities can be analysed and discussed in terms of its energy security and diversity using the energy-security index and the Shannon-Wiener diversity index, respectively. Both indices employ an entity's $Energy_{\mathrm{IN}}$ flows to determine their respective values. The diversity index determines the diversity by measuring the proportional abundances of the combination of $Energy_{\mathrm{IN}}$ flows while the energy-security index is obtained from the ratio of total of the combination of $Energy_{\mathrm{IN}}$ flows to the $Demand_{\mathrm{OUT}}$ flow. The application of the method was described and demonstrated with an example and the results were produced by a program written in Visual Basic using Microsoft Office Excel.

By using proportional abundances, the diversity obtained by the Shannon-Wiener diversity index means that a high diversity index need not result in a high energy-security index as:

- A group of $Energy_{IN}$ flows (i.e., the combination of $Energy_{IN}$ flows) with a high diversity index can have a low energy-security index.
- A group of $Energy_{IN}$ flows with a low diversity index can have a high energy-security index.

Considering diversity alone does not mean that the availability of an entity's energy flows is necessarily secure. In a similar way, the value of the energy-security index is not an indication of the diversity of the availability of flows to an entity. Thus, if the diversity of an energy system's energy flows is being measured, the energy-security index of the flows should be as well. Any application of these two indices need access to a fine granularity of data otherwise the results will be of limited value. As with all energy calculations, the quality of the data will determine the usefulness of the resulting energy security and diversity indices.

An $Energy_{IN}$ flow can be associated with any of the three energy security indicators: availability, affordability, and acceptability. While the energy-security index can be applied to any of the indicators, the Shannon-Wiener diversity index is essentially limited to availability as:

- The diversity of the affordability or acceptability of a group of $Energy_{IN}$ flows (i.e., the combination of $Energy_{IN}$ flows) reflects the degree of similarity of the different metric values.

- The diversity obtained by applying the affordability or acceptability metric to the availability of each $Energy_{\mathrm{IN}}$ flow (i.e., the metric acts as a weight) is essentially a scaling of the diversity of availability.

The analysis of the relationship between energy security and diversity of an energy system also provides a better appreciation of the relationship between the events and the components of the system leading to a more systematic, transparent, and complete way to articulate the energy security and diversity perspectives and approaches to the stakeholders of any jurisdiction’s energy system.

The importance of understanding the relationship between energy security and diversity cannot be over-emphasized when developing energy policy. It is important for policy makers to understand this, since the push for more small-scale, localized energy production may be regarded as an increase in a jurisdiction’s diversity; however, if its long-term security is to be improved, it will also be necessary to prepare for those events which can affect energy flows and hence both energy security and diversity. If policy makers can understand their jurisdiction’s energy system and the events that can affect its entities, both its energy security and diversity can be improved.

5.1 Limitations

The limitation which needs to be considered when using the proposed method is that the measurement of the diversity of an energy flow’s affordability or acceptability is problematic.

5.2 Future Work

This thesis examines the relationship between energy security (represented as an energy-security index derived from a set of energy security indicators) and diversity (as defined by the Shannon-Wiener diversity index) of an energy system, its entities, and flows using a novel and generic method. Further research work can be carried out using the method where:

- Energy-security indices can be developed using different methods such as the analytic hierarchy process (AHP) or the decision matrix method.
- Diversity can be determined from other diversity indices such as Simpson, Hirschman–Herfindahl, and integrated multi-criteria diversity index.
- A web-based tool could be developed to examine the relationship between energy security and diversity.

5.3 Publications

The part of the work presented in this thesis is based on a research paper "Event-related stresses in energy systems and their effects on energy security" published in the journal *Energy* in September 2013 by Dr. Larry Hughes (Dalhousie University) and the author which is used for the determination of the energy-security indices.

Research from this thesis has been submitted as a research paper "Energy security and diversity" to the journal *Energy* in October 2013; with Ashish Ranjan as the first author and Dr. Hughes as the second.

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