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A generic framework for the description and analysis of energy security in an energy system

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Abstract

While many energy security indicators and models have been developed for specific jurisdictions or types of energy, few can be considered sufficiently generic to be applicable to any energy system. This paper presents a framework that attempts to meet this objective by combining the International Energy Agency's definition of energy security with structured systems analysis techniques to create three energy security indicators and a process-flow energy systems model. The framework is applicable to those energy systems which can be described in terms of processes converting or transporting flows of energy to meet the energy-demand flows from downstream processes. Each process affects the environment and is subject to jurisdictional policies.

The framework can be employed to capture the evolution of energy security in an energy system by analyzing the results of indicator-specific metrics applied to the energy, demand, and environment flows associated with the system's constituent processes. Energy security policies are treated as flows to processes and classified into one of three actions affecting the process's energy demand or the process or its energy input, or both; the outcome is determined by monitoring changes to the indicators.

The paper includes a detailed example of an application of the framework.

Keywords: Systems analysis, energy policy, indicators and metrics, energy chain

1 Introduction

Any jurisdiction, regardless of its level of development or size, has an energy system responsible for meeting its end-use energy demands. Energy systems are dynamic, they change over time responding to conditions such as the development of new energy technologies, higher energy costs, public concerns over the environmental impacts of energy production, evolving consumption patterns, and the ageing of existing infrastructure. When an energy system changes, it can have profound and far-reaching effects, potentially affecting the users of the system's services, the suppliers of energy to the system, and those responsible for operating the system. The policies or actions designed in response to—or in anticipation of—such changes should maintain or, ideally, improve the energy security of the system.

However, different jurisdictions will, not surprisingly, have different energy systems to meet their end-use energy demands. This means that the ways in which they attempt to address their energy security requirements may differ; for example, the approach in a developed, post-industrialized country will differ greatly from that of a sub-Saharan developing nation with virtually no access to electricity. Not only does this mean that attempting a direct comparison between different jurisdictions may not be possible, but using a method developed specifically for one may not be applicable to another. Furthermore, creating a method specific to the energy security problems that a jurisdiction faces today may mean that it is not applicable to those it may face in the future.

Various methods for the analysis of national and supranational energy systems have been proposed to assist in the development of energy security policy. Perhaps the simplest are Sankey diagrams which represent the various energy flows of an energy system graphically, although in themselves offering little in the way of analysis (for example, see Cullen and Allwood (2010)). More complex analysis methods have been proposed which aggregate various energy-related indicators to create a league-table ranking different jurisdictions such as the OECD in terms of their energy security (for example, see Brown and Sovacool (2007)). Rather than focusing on an aggregated ranking value, other approaches determine a jurisdiction's energy security using energy-related indicators that reflect the condition of the energy sources used by a jurisdiction's energy system (for example, see APERC (2007), Gnansounou (2008), Hughes and Sheth (2009), Hughes and Shupe (2011), Kruyt, van Vuuren, de Vries, and Groenenberg (2009), Jansen and Seebregts (2010) , and Streimikiene and Šivickas (2008)), although Sovacool's almost 200 energy security indicators is an extreme case (2010). A limited number of other methods consider the security of the components of an energy system, most often electricity (for example, see Grubb, Butler, and Twomey (2006)).

As Vivoda (2010) has observed, there is a need for a generic framework to discuss energy security. If such a framework is to be applicable to any jurisdiction it should not be ad hoc, meaning it will require both a common definition of energy security and a common energy system model.

This paper describes how systems analysis techniques for the definition of systems can be used in conjunction with the International Energy Agency's definition of energy security to derive a framework with a limited number of indicators for energy security analysis and energy policy creation. It explains how the indicators and their metrics can be applied to a jurisdiction's energy system and its constituent parts, thereby supporting a common set of methods for examining its condition or state. The paper also shows that the same methods can be used for determining the potential outcomes of energy policies; furthermore, a policy classification technique enables policymakers to consider the possible effects of potential changes, thus allowing competing initiatives to be compared and their potential for improving energy security estimated in advance.

The remainder of the paper is organized as follows. The next section is a brief introduction to structured systems analysis, showing how it can describe an energy system and, when combined with the IEA's definition of energy security, how it can be used to analyze the state of energy security in the system. The third section introduces additional systems analysis techniques that, when applied to the components of an energy system (i.e., its chains, processes, and flows), allow modeling of the system. The IEA's definition can be parsed to create a set of three indicators; the fourth section describes the indicators, sample metrics, and shows how each can be employed to analyze the changes to energy security. Energy security can be improved or a decline in security can be arrested by applying policy to a process; the next section classifies the possible policy actions and shows how they can affect the process or its flows, or both. This is followed by a detailed example of how a small jurisdiction is using the method to analyze two of its energy chains in order to improve its energy security. The final two sections are a discussion of the framework, which includes a comparison to other techniques as well as its limitations, and a summary of the work.

2 Structured systems analysis and energy security

A system, such as an energy system, can be defined as "a group of interacting, interrelated, or interdependent elements forming, or regarded as forming, a collective entity" (AHD, 2009). In structured systems analysis, a system is described in terms of two models (Yourdon, n.d.): the environmental model and the behavioural model.

In the environmental model, the system and the entities with which it interacts are represented graphically in a context diagram. A context diagram for a generic energy system is shown in Figure 1 and consists of terminators (shown as rectangles containing, in this case, energy sources, energy end-uses, the environment, and policymakers) and flows (drawn as arrows representing demands for energy and supplies of energy, both converted and unconverted, losses and emissions, and policy). The system (a labeled circle) responds to demands for energy from its end-uses (or energy services) with supplies of converted energy, obtained through processing sources of unconverted energy made available from the sources. The actions associated with converting and supplying the energy result in losses and emissions which are released to the environment, while policies are intended to influence or change the energy system, ultimately affecting one or more of the system's flows.

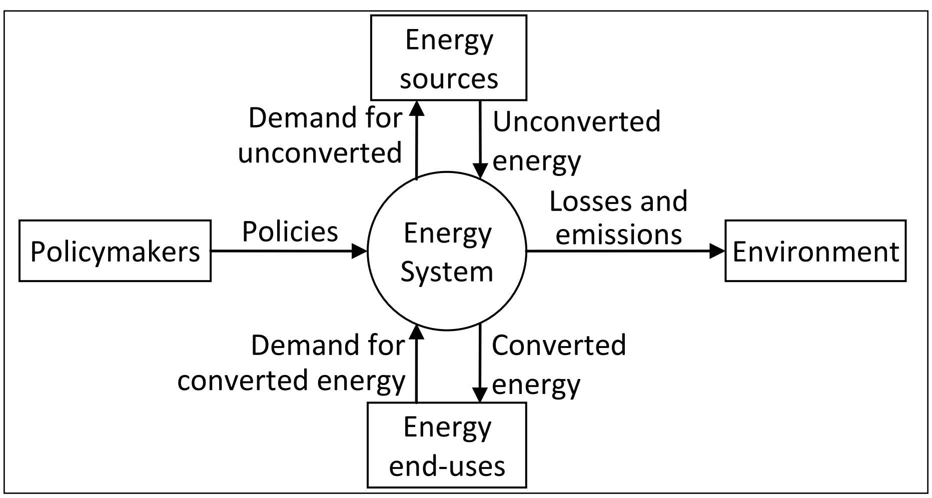

Figure 1: A generic energy system, its terminators, and flows

While the environmental model shows the relationship between a system and the entities with which it interacts, the behavioural model examines the system's internal structure. In the case of an energy system, the behavioural model consists of one or more energy chains or pathways (van de Vate, 1997), each responsible for the conversion of an unconverted energy flow from the different energy sources and the eventual distribution of the converted energy to other conversion processes intended to meet the energy demands of the end-uses. Each process is associated with losses or emissions, or both, which flow to the environment. The various flows within the system (between processes and between terminators and processes), like those between the system and its terminators, reflect the state of each process and, if measurable, mean that changes to a flow are eventually reflected in the corresponding flow from the system to one of its terminators.

As previously mentioned, a number of different techniques have been proposed for analysis of energy security in energy systems, most with different definitions of energy security and indicators. Although there is no agreement on a universal definition of energy security (Kruyt, van Vuuren, de Vries, & Groenenberg, 2009), the one developed by the IEA is representative of many of them, “the uninterrupted physical availability at a price which is affordable, while respecting environment concerns” (2010). This definition can be parsed into three energy security indicators: availability (“the uninterrupted physical availability”), affordability (“a price which is affordable”), and acceptability (“respecting environment concerns”). As with the IEA’s definition of energy security being representative of many other definitions, the three indicators (or variations on them) are found in most energy security indicator sets.

The definition and its indicators are directly applicable to the energy system shown in Figure 1: the availability and affordability indicators refer to the unconverted and converted energy flows, while acceptability refers to the losses and emissions flow. Given the temporal nature of energy security (Chester, 2010), comparing current and past measurements of the flows will indicate whether the energy security of the energy system is improving or deteriorating. By analyzing the results of the comparisons, policies can be developed to address both short-term and, potentially long-term (or temporal), energy-security issues.

Since the energy chains that constitute the energy system ultimately support the same flows as the system, a uniform approach to energy security analysis can be developed: a process’s flows can be measured and if necessary, can result in policy being developed to address the changes found.

3 Energy processes, flows, and chains

An energy system is composed of one or more energy chains responsible for meeting the energy demands of energy services or end-uses. Each chain can be represented as a series of processes connected by flows. A flow is a logical connection between entities (i.e., processes, energy sources, or end-uses), describing the components—such as demand, cost, energy, or emissions—passing between them; it gives no indication about how the component is actually moved. Processes are entities responsible for converting one form of energy to another or transporting energy from an energy source or process to another process or an energy service.

Figure 2 is a representation of a generic energy process (*Process*) and its flows. The process receives demands for energy (the flow $Demand_{IN}$) and responds with an energy flow ($Energy_{OUT}$). It also receives flows of energy ($Energy_{IN}$) in response to its demand flows ($Demand_{OUT}$). The actions taken by the process on the input energy flow to create the output energy flow results in losses or emissions that are released to the environment ($Environment_{OUT}$). The generic energy process shown in Figure 2 can either convert or transport energy.

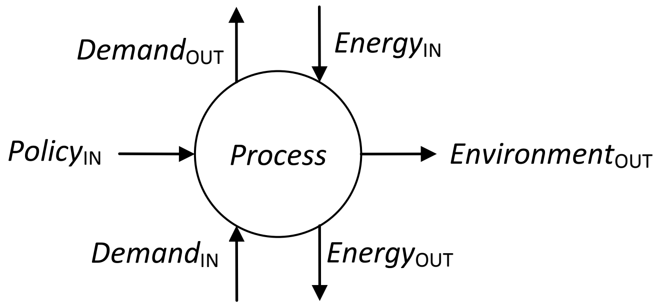

Figure 2: A generic energy process and its flows

The *Policy*$_{IN}$ flow is intended to change the behaviour of the process to improve its contribution to the overall energy security of the system; these changes can affect either of the energy flows, the environment flow, or potentially the demand flows. The *Policy*$_{IN}$ flow can be based on the result of analysing the process's energy and environment flows.

Since processes are chained together, an *Energy*$_{OUT}$ flow from a process becomes an *Energy*$_{IN}$ flow for a downstream process or an energy end-use terminator in the chain. Similarly, a *Demand*$_{OUT}$ flow from a process becomes a *Demand*$_{IN}$ flow for the upstream process or terminator producing the *Energy*$_{IN}$ flow. The initial *Energy*$_{IN}$ flow to an energy chain is an unconverted energy flow from an energy source terminator.

If necessary, a process can be discussed in terms of its constituent sub-processes, which function collectively, responding to the *Demand*$_{IN}$ flow by transforming the *Energy*$_{IN}$ flow into the *Energy*$_{OUT}$ flow. The *Demand*$_{OUT}$ flow is greater than the *Demand*$_{IN}$ flow as it takes into account any losses and emissions from the sub-processes that appear in the *Environment*$_{OUT}$ flow. The actions by the sub-processes are subject to the process's *Policy*$_{IN}$ flow.

3.1 Conversion processes

A conversion process is the technology and its associated infrastructure that transforms one energy flow (*Energy*$_{IN}$) into another (*Energy*$_{OUT}$) in order to meet a demand for energy (*Demand*$_{IN}$) from other processes or energy services. With the exception of processes that convert variable sources of energy such as hydroelectricity, wind, or solar, the process can, in turn, issue its own demand for energy (*Demand*$_{OUT}$) to other processes or energy sources. The environment flow (*Environment*$_{OUT}$) represents the emissions and losses associated with the conversion process such as SO_2 or CO_2, radioisotopes, and heat.

Examples of conversion processes include oil refineries that accept crude oil flows (in response to crude-oil demand flows) and convert it into a series of refined petroleum product flows; losses in the form of heat and emissions such as greenhouse gases and sulphur compounds are two environment flows often associated with a refinery. A process can be discussed in terms other processes, such as an electricity supplier with a fleet of generating facilities that produce a flow of electricity to meet demand; in this case, the electricity supplier would have a series of *Energy*$_{IN}$ flows to meet the different fuel requirements of these processes, while its *Environment*$_{OUT}$ flow would include the losses and emissions from them.

3.2 Transportation processes

When transporting energy, a process moves or carries an energy flow ($Energy_{IN}$) from one or more energy sources or processes through the technology and infrastructure it supports to meet the demand ($Demand_{IN}$) of another process or energy service. Since some form of energy is required for its movement, the transportation process is associated with losses or emissions to the environment (the environment flow, $Environment_{OUT}$); the amount of energy supplied to the process ($Energy_{IN}$) is always greater than the energy supplied to the recipient ($Energy_{OUT}$).

A transportation process uses energy to move the energy it is carrying. The energy to move electricity comes from the electricity itself overcoming the impedance of the transmission and distribution network; the emissions are in the form of heat. With natural gas, small amounts of natural gas are often used to fuel turbine compressors or reciprocating engines built into the pipeline network (NaturalGas.org, 2010); emissions from natural gas networks include fugitive emissions (natural gas escaping from the pipeline) and combustion products from the compressors or engines (Environment Canada, 2010).

In some transportation processes a completely different source of energy is required; for example, a wood-pellet delivery process would require fuel for its vehicles, meaning that the process would have two energy demands and supplies: wood pellets and vehicle fuel. The emissions from this process would be the combustion products of the vehicle fuel as opposed to the wood pellets.

3.3 Energy storage

Structured analysis can also represent the storage of a flow. It is depicted as a pair of horizontal lines with the name of the entity or type of entity that is held in storage; there are at least two flows, one from a process and the other to a process. In structured analysis, stores are assumed to be perfect (i.e., they do not have losses) and inert (i.e., processes are responsible for controlling the flows to and from a store). In an energy system, a store could hold an energy flow such as coal (coal bunker), oil products (tank farms), or electricity (batteries); energy stores can be associated with losses. Other flows, such as emissions or demand, can also be stored.

3.4 Energy chains

An energy chain consists of interconnected conversion and transportation processes. The generic energy chain shown in Figure 3 consists of three processes, the first of which takes a flow of primary energy (1°) and converts it into a secondary energy (2°) flow. In this case, the next process in the chain is responsible for transporting and possibly storing the secondary energy for subsequent use in processes that converts it into a tertiary energy (3°) flow to meet the needs of an energy service. In addition to the energy flows, each process is typically subject to some form of policy or regulation and these will also be associated with losses and emissions.

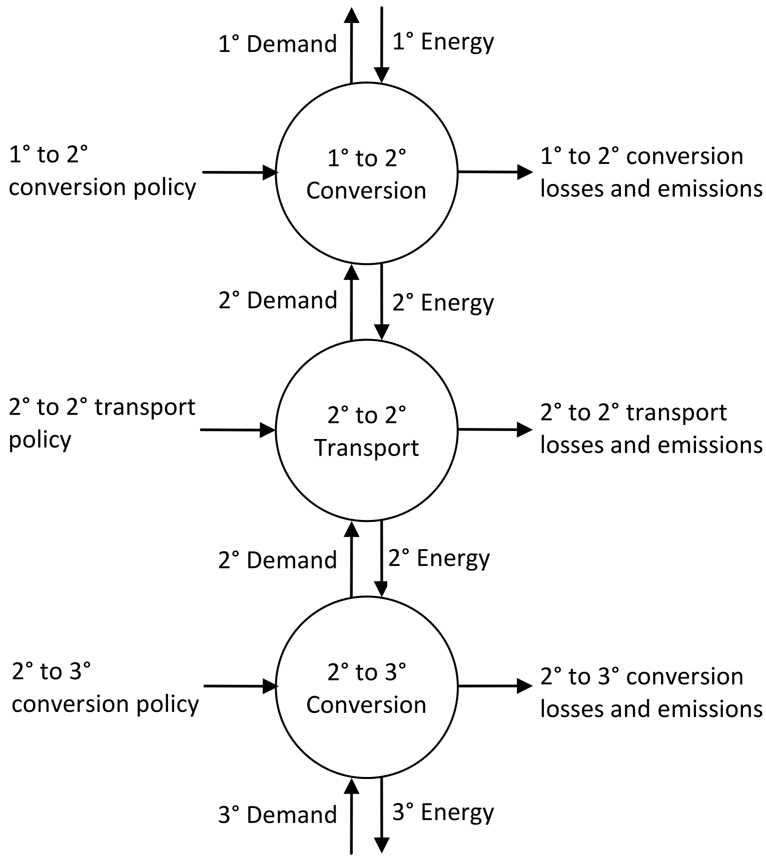

Figure 3: A generic energy chain

Coal, converted to electricity in a thermal generating station, then transported over an electrical grid to a building, and finally converted to light in a fluorescent tube is an example of an energy chain. Each process in the chain has some form of emissions or losses, or both; in this example, the thermal generating station has air emissions such as carbon dioxide as well as thermal losses, while the electrical grid experiences resistance and reactive power losses, and the light-fixture consuming the electricity will have inherent inefficiencies that result in losses in the form of heat. The policies applied to the processes will vary between jurisdictions and may depend upon international standards.

$Energy_{OUT}$ flows can fan-out from a process. In the case of an oil refinery, there may be a number of refined products, including asphalt, heavy fuel oil, diesel, and motor gasoline, while the electricity from an electrical grid could fan-out to a number of tertiary processes such as transportation (kinetic energy), heating, and lighting. Similarly, a cogeneration facility could produce electricity and heating water for district heating (which could, in turn, be used for space heating and domestic hot water). On the other hand, a number of $Energy_{IN}$ flows can fan-in to a process; the district heating plant in Uppsala, Sweden uses municipal waste, woodchips, peat, and bunker oil (Karlsson, 2009).

Although the energy flows are shown in terms of increasing entropy from top-to-bottom, in some cases an energy flow may move in a horizontal or upwards direction if a process requires an additional energy input to allow it to operate. A refinery with petroleum coke or heavy oil as an *Energy*$_{OUT}$ flow used as an *Energy*$_{IN}$ flow for electrical generation (1° to 2° conversion) would logically flow "down" from the refinery to the oil transport process and then flow "up" to the conversion process.

4 Indicators and metrics

An energy system's converted energy flows and losses and emissions flows are the products of the energy flows and environment flows, respectively, of the processes in its energy chains. As shown earlier, the state of energy security can be described by three indicators derived from the IEA's definition of energy security: availability and affordability (of its converted energy flows) and acceptability (of its losses and emissions flows). Since the system flows are ultimately the products of the process flows, these indicators are also applicable to the *Energy*$_{IN}$, *Energy*$_{OUT}$, and *Environment*$_{OUT}$ flows of each process.

The condition of a process's flows will be driven by changes to either the unconverted energy flows into the system or the process itself, or some combination of both. While any changes taking place within a process are typically not visible directly, its *Energy*$_{IN}$, *Energy*$_{OUT}$, and *Environment*$_{OUT}$ flows are. If these flows are measured regularly with indicator-specific metrics, variations in their availability, affordability, and acceptability can be detected and used as indications of existing and potential changes to the overall energy security of the system.

4.1 Metrics and their application

Although the energy and environment flows of each process in the system are subject to the same indicators, the metrics associated with the flows can be different, dictated by their position in the energy chain and the context in which they are used. Despite these differences, three broad categories of metric can be described: current, derived, and temporal.

The current metric is a measure of a flow over a given period of short duration which produces its current value. Derived metrics use ratios of current values and other data (such as a jurisdiction's population), to produce derived values. Current values and derived values can be compared with known standards or objectives to establish whether or not certain targets have been achieved and from this, the impact on the system's energy security. Alternatively, they can be compared with other processes to ascertain the relative efficiency or effectiveness of the process.

Temporal metrics produce trends from datasets of historical current and derived metric values showing the changes to an indicator over time. Temporal values can be used to indicate whether the system's energy security is unchanged, improving, or deteriorating.

The metrics of all three indicators can also be used to develop future energy security scenarios.

Although each of the indicators is applied to the energy and environment flows of a single process, it is the processes and terminators upstream from the process which dictate the availability, affordability, and acceptability of its *Energy*$_{IN}$ flows; a change to an upstream flow will affect all downstream processes that rely (directly or indirectly) on it. Similarly, all processes and terminators downstream from a process relying on a process's *Energy*$_{OUT}$ flow will be affected by the process and the cumulative effects of all the flows in the chain.

4.2 The indicator set

The framework has three indicators: availability, affordability, and acceptability.

4.2.1 Availability

The availability indicator refers to the availability of an energy flow ($Energy_{IN}$ or $Energy_{OUT}$) between processes or processes and terminators. An $Energy_{OUT}$ flow from a process is a response to a demand flow and depends upon the state of the process and its $Energy_{IN}$ flows. If the process fails to operate as expected or the $Energy_{IN}$ flow does not meet the process's $Demand_{OUT}$ flow, the value of $Energy_{OUT}$ will be less than anticipated or possibly required. A decline in the availability of an energy flow can be detrimental to the system's energy security.

The current values of the availability of an energy flow are expressed in terms of available energy for a certain time period, such as barrels per day, tonnes per hour, and MWh per year. Availability metrics for derived values are obtained from ratios of current values with energy security indicators or other data values; examples include price per kilowatt-hour and greenhouse gas emissions per tonne of fuel, while other derived values include electricity consumption per capita, litres per 100 km, and gigajoules per household.

Temporal values associated with the availability indicator are long-term or historical current or derived values; the resulting trends can indicate whether the availability of the energy flow is increasing or decreasing.

If a process has multiple $Energy_{IN}$ flows, their individual contributions can be used to determine the overall diversity of the combined flows using the Shannon-Weaver diversity index (Sterling, 2010); this can be treated as the current diversity of the combined flows. The application of the diversity index to a process's $Energy_{IN}$ flows for different years can show whether the temporal values of the combined flows are becoming more (or less) diverse; an increase in availability diversity can be interpreted as an improvement in energy security.

4.2.2 Affordability

The current value of the affordability of an $Energy_{IN}$ flow is simply the cost of the flow as determined by the costs associated with the upstream conversion or transportation process, the cost of its $Energy_{IN}$ flow, and any costs associated with its $Environment_{OUT}$ flow. Examining long-term datasets of current values will produce temporal values, showing whether the price of the energy flow is increasing or decreasing.

While it is possible to use the flow's temporal cost trends as an indication of the system's energy security, the IEA's definition of energy security requires that an energy flow will be available at a "price which is affordable". For this, it is necessary to obtain a derived value which combines the cost of the energy flow with other indicator values to obtain the flow's affordability:

- If the cost-per-unit of different potential energy-flows can be determined for a particular process, the flows can be ranked to obtain their relative affordability; the less expensive an energy flow, the more affordable it is considered to be. In this interpretation of affordability, the indicator refers to the price paid for a unit of energy.

- The impact of an energy flow cost to a customer varies, often depending upon the customer's income—the lower the income, the larger the percentage required to cover the cost of the energy (Boardman, 2009). This interpretation of affordability refers to the ability-to-pay for a unit of energy.

By considering the temporal trends of the two interpretations of affordability, increasing costs (decreasing affordability) imply a deterioration in security, while decreasing prices (increasing affordability) imply an improvement in security.

Although some national statistical services and public interest groups maintain affordability indices for items such as food, clothing, shelter, and heating, it can be difficult to apply this uniformly across a population (Hughes & Ron, 2009). Ranking the costs of the different energy flows that meet a particular energy end-use is perhaps the simplest interpretation of affordability; although this is not "affordability" in the true sense of the word, the lowest cost-per-unit energy could be assumed to be the most affordable and hence the most secure.

The interpretation of affordability can also depend upon what the jurisdiction represents. If it (and the data used) pertains to a regional, national, or supranational entity, the affordability indicator can be interpreted as the cost-per-unit of energy. On the other hand, if statistics allows a jurisdiction to be defined at the household-level, the ability-to-pay can be used as the affordability indicator.

Regardless of how the affordability indicator is interpreted, if higher per-unit energy costs are regarded as being less secure than those with lower per-unit costs, a rise in the cost of energy will cause security to deteriorate, while a decline in the cost will cause security to improve.

4.2.3 Acceptability

Acceptability, the third indicator based on the IEA's definition of energy security, refers to the need for energy that respects environmental concerns (the reference to the environment has been shortened to "acceptability" to be in keeping with the terminology adopted in other energy security indicator sets). This definition of acceptability is naturally applied to the $Environment_{OUT}$ flow of a process, leading to current metrics that focus on environmental impacts caused by the process such as annual greenhouse gas or SO_x emissions. Derived metrics can include emissions per kilometer or deaths from particulate emissions, while temporal metrics can show whether the acceptability of a flow (i.e., its emissions) is improving or deteriorating.

Since politics is often associated with energy systems, acceptability indicator metrics need not be restricted to environment flows: they can refer to political and social metrics, often based upon opinion rather than evidence. In these cases, acceptability can refer to an energy flow, a process, or both. Examples include limiting the flow of energy from a particular terminator or process or encouraging a flow from another; reasons for the acceptability of a flow can include the stability of the supplier, the perceived or anticipated environmental impacts of the process, and the relationship of the producing and consuming jurisdictions.

5 Energy policy

Regardless of the indicator and metric, the indicator values are the result of processes attempting to meet *Demand*$_{IN}$ with supplies of *Energy*$_{IN}$. The success of a process maintaining or improving the energy security of a jurisdiction ultimately requires an individual or organizations (such as institutional, corporate, or governmental) to develop and implement energy policy. These are the *Policy*$_{IN}$ flows shown in Figure 1 and Figure 2. Policies are not considered to be measurable; however, the outcomes of policies are measureable indirectly and are reflected in one or more of a process's output flows (*Demand*$_{OUT}$, *Environment*$_{OUT}$, and *Energy*$_{OUT}$) and possibly *Energy*$_{IN}$. For a policy to have improved the system's energy security, at least one of the indicators associated with a flow's characteristic must have improved as well.

In (Hughes, 2009), it was shown that energy policies could be discussed in terms of their reduction, replacement, and restriction potential; while such policies can affect the *Energy*$_{OUT}$ and *Environment*$_{OUT}$ flows, it is the process and the *Energy*$_{IN}$ flow that ultimately undergo the change. The relationship between the policies, the process, and *Energy*$_{IN}$ is shown in Table 1; for example, if a policy results in a new process and a new *Energy*$_{IN}$, it is a restriction, whereas a new process using an existing *Energy*$_{IN}$ is a replacement. A detailed description of each type of policy and how it can influence the characteristics of different flows now follows.

Table 1: The relationship between policies, the process, and the type of *Energy*$_{IN}$

		Process	
		Unchanged	**New**
Type of *Energy*$_{IN}$	**Unchanged**	Reduction	Replacement
	New	Replacement	Restriction

5.1 Reduction

Reduction policies, typically conservation or energy efficiency measures, target a process to reduce its *Energy*$_{IN}$ flow or its *Environment*$_{OUT}$ flow, or both. Neither the process nor the type of energy associated with *Energy*$_{IN}$ is changed. These actions can be driven by a need to improve energy security because of the declining affordability or declining availability of *Energy*$_{IN}$, the declining acceptability of *Environment*$_{OUT}$, and the declining affordability of *Energy*$_{OUT}$. The success of these policies is reflected in the metrics applied to *Energy*$_{IN}$, *Environment*$_{OUT}$, and *Energy*$_{OUT}$.

A decline in the *Demand*$_{IN}$ flow, often in response to the affordability of the process's *Energy*$_{OUT}$ flow becoming an issue to the downstream entities (i.e., processes or terminators) that use it, can have the same effect as a reduction policy. This can result in formal reduction policies in response to the decline. By reducing consumption of *Energy*$_{OUT}$, affordability can improve in that the consuming entity uses less energy and hence pays less; however, the benefits associated with such actions can be short-lived if the process is forced to increase the cost of the *Energy*$_{OUT}$ flow to cover expenses caused by the reduction.

Some jurisdictions create explicit reduction policies to discourage or modify the use of a particular process or an *Energy*$_{IN}$ flow. Such policies often impose taxes on the *Energy*$_{OUT}$ flow to increase its cost thereby decreasing its affordability and discouraging its consumption.

Carbon-taxes on the consumption of a specific type of fuel to improve the acceptability of the $Environment_{OUT}$ flow is an example of such a policy.

5.2 Replacement

Replacement policies target the process or the $Energy_{IN}$ flows by replacing one of them with something more secure. In a replacement, if the process is changed, its $Energy_{IN}$ flows remain unchanged; whereas if the process remains unchanged, the $Energy_{IN}$ flow is changed. Regardless of the change, the $Energy_{OUT}$ flow to other processes or terminators that use it remains unchanged, although one or more of its energy security indicators should improve.

Examples of such policies include replacing an existing low-efficiency conversion process with a high-efficiency one (such as a subcritical coal-generating facility with a supercritical or ultra-supercritical facility), replacing an aging distribution process which is prone to losses with a new, more efficient process (such as the construction of a electrical grid upgrade or connecting to a natural gas distribution network rather than using deliveries of CNG), and replacing an $Energy_{IN}$ flow from a politically unstable jurisdiction with one that comes from a stable supply. Successful outcomes should be apparent by improvements in one or more of the metrics measuring the $Energy_{OUT}$ flow.

A policy that subsidizes an existing $Energy_{OUT}$ flow can also be treated as a replacement in that by improving its affordability, it can be considered a lower-cost replacement of the original flow. Similarly, policies that increase an $Energy_{IN}$ flow to an existing process are considered to be replacements as the availability of the flow improves.

5.3 Restriction

The third policy, restriction, changes both the process and the $Energy_{IN}$ flow to improve the energy security of the $Energy_{OUT}$ flow or the $Environment_{OUT}$ flow, or both. The type of energy associated with the $Energy_{OUT}$ flow remains unchanged. Restriction policies can be driven by the cost of ageing infrastructure, the advent of new, more efficient technologies that rely on different energy sources, or politically-motivated decisions.

There are numerous examples of restriction policies throughout history, often reflecting the evolution of a society; some informal, while others are driven by government or corporate policy. Evolving modes of transportation are one such example, where the process converts $Energy_{IN}$ into kinetic energy to move people or goods from one location to another, as shown in Table 2.

Table 2: Transportation modes, conversion processes, and $Energy_{IN}$

Mode	Conversion process	$Energy_{IN}$
Horse and cart	Metabolic actions (horse)	Carbohydrates, fats, proteins (for horse)
Bicycle	Metabolic actions (human)	Carbohydrates, fats, proteins (for human)
Conventional vehicle	Internal combustion engine	Refined liquid fuels
Electric vehicle	Electric motor	Electricity

In these cases, the energy produced by the process is passed through some form of mechanical transmission that results in motion; the choice of mode restricts the user to the specific process and the form of $Energy_{IN}$. Changes in the availability, affordability, and acceptability of the $Energy_{IN}$ flow can drive the restriction policy: while the supply and cost of horse-feed in the early 20th century may have been competitive with that of automotive liquid fuels, the emissions associated with horses on city streets were considered unacceptable. The shift to electric vehicles is based on similar arguments, as the acceptability of the emissions associated with conventional vehicles deteriorates; however, the long-term availability and affordability of petroleum when compared to electricity is another factor.

At the national and international level, the decision taken by many western governments in the 1960s and 1970s to restrict electrical generation to technologies and energy sources other than petroleum resulted in the growth in nuclear for electrical generation; $Energy_{OUT}$ remained electricity. In this case, the availability and affordability of petroleum, especially after the "first oil shock", helped make the choice of nuclear acceptable. Subsequent accidents and declining affordability of nuclear electricity is, for the moment at least, clouding its future in a number of jurisdictions.

At the household level, the arrival of electricity and electric-refrigeration meant an end to the ice-box (a refrigeration system using blocks of ice keeping the refrigerated items cool). To the consumer, items were still kept cool; however, the energy conversion technology and the energy source had changed. In addition to the availability of electricity when compared to the delivery of ice-blocks, electric refrigerators had the advantage of being easier to maintain since it was not necessary for the homeowner to deal with the emissions associated with melting ice (water), making electricity that much more acceptable.

5.4 Unintended consequences

Ideally, any policy decision taken to improve energy security should do so; however, in some cases, the policy can have unintended consequences, three of which are considered here.

The rebound effect (Sorrell, 2007) occurs when a policy applied to a process improves the affordability of its $Energy_{OUT}$ flow (such as reduction policies that decrease the flow's energy intensity), thereby reducing the cost of the flow to the downstream entities (i.e., processes or terminators) that consume it. If the improved affordability causes these entities to increase their demand for the flow, the additional demand may impact the availability of the flow (direct rebound). Should any savings made be parlayed into new or additional demand for a different $Energy_{OUT}$ flow, this new demand could prove detrimental to the security of the second flow (indirect rebound).

Policies that cause a decline in the $Demand_{OUT}$ of a process can affect the processes or terminators responsible for the $Energy_{IN}$ flow as they might find it difficult or impossible to supply the energy because of reduced revenues. Take-or-pay contracts are one way to protect the suppliers of the $Energy_{IN}$ flow; however, such contracts will not improve the affordability of the energy flow unless the contract is renegotiated.

Improving a system's $Environment_{OUT}$ flow by increasing the use of variable sources of electricity such as wind can have other repercussions since ensuring the availability of on-demand electricity requires backup sources of electricity. If the backup source is carbon intensive, the anticipated improvements in the environmental acceptability might not be realized; similarly, any expected improvements in affordability could be offset by the costs associated with the backup source.

6 Example: Space heating with wind-electricity

Space heating is essential to jurisdictions with lengthy heating seasons. The Canadian province of Prince Edward Island is one such example, where space heating is responsible for over two-thirds of residential energy demand and limited domestic energy supplies (both traditional renewables and non-renewables) and the historically high cost of electricity have made fuel oil the energy source of choice for space heating in about 75% of households.

Over the past decade, changing conditions in world energy markets have made the use of fuel oil for space heating less secure in jurisdictions such as Prince Edward Island for households, energy suppliers, and the provincial government:

Availability: Because of its size and population, Prince Edward Island has no refinery; refined petroleum products are brought to the island by boat and truck, which can mean the disruption of supplies during periods of severe winter weather.

Affordability: Between 2005 and 2011, the cost of light fuel oil has increased by slightly over 39% and is having a detrimental effect on all household budgets, especially low-income (NRCan, 2011).

Acceptability: The greenhouse gas emissions associated with the combustion of fossil-fuels is of concern, given the importance of agriculture to the provincial economy and the anticipated impacts of sea-level rise.

(Although Prince Edward Island, like most of eastern Canada, relies overwhelmingly on imported crude oil, accessibility to crude oil supplies has gained little political, media, or public attention (Hughes, 2010c).)

The Prince Edward Island government's response has been the introduction of residential energy-retrofit programs (reduction) and limited fuel subsidies (replacement). Only one jurisdiction, the City of Summerside, appears to be making any attempt to encourage households to restrict their space heating demands to energy sources other than fuel oil.

Summerside is unique in the province as it has a municipally-owned electricity supplier, Summerside Electric, and a municipally-owned 12MW wind farm located within the city limits on an abandoned landfill site. Summerside Electric purchases electricity from three sources, listed in Table 3. The two wind-farms are variable sources of electricity (Prince Edward Island has an exceptional wind resource (PEI, 2008)), while the contract with NB Power is a stable source of electricity that can be changed by Summerside Electric (i.e., increased or decreased, depending upon the variability of the wind supply) without penalty.

Table 3: Electricity sources for Summerside Electric (Gaudet, 2010)

Supplier	Type of supply	Range
NB Power	Stable	0 MW to winter-peak (about 23 MW)

West Cape wind-farm	Variable	0 MW to 9 MW
Summerside wind-farm	Variable	0 MW to 12 MW

Summerside Electric has a declining block rate structure for its residential customers; in each two-month billing period the first 2,000 kWh is charged \$0.1205/kWh, while any excess demand is charged at \$0.0920/kWh. There is also a connection charge of \$24.57 each billing period (Summerside, 2006).

While the cost of electricity in Summerside may appear to be high by Canadian standards, the rising cost of fuel oil is beginning to make electricity a more affordable source of energy for space heating, especially in residential structures with high energy-intensities (due to heating preferences or vintage or size of building) and furnace efficiencies less than 78%. Figure 4 illustrates this point using the cost of fuel oil and electricity for single-detached households with differing energy intensities; the average energy-intensity falls into the range of 55 GJ to 65 GJ per household. Furnace efficiencies are given as normal (60%), medium (78%), and high (85%); almost all fuel oil furnaces in Prince Edward Island are classified as having medium efficiency (OEE, 2010).

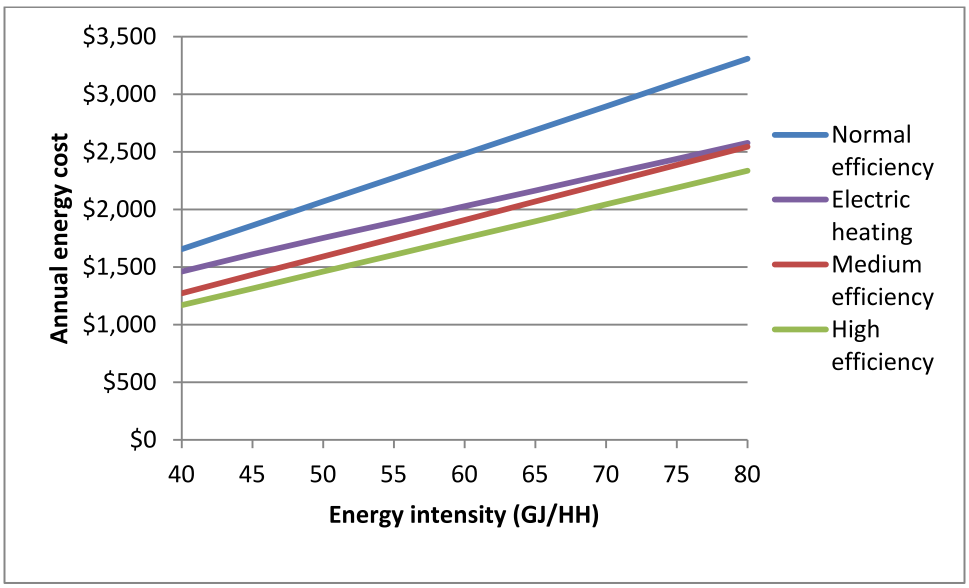

Figure 4: Space heating costs for Summerside (Winter 2010-2011; taxes included)

While restricting space heating usage to electricity may make an individual household more secure, the same cannot be said of the electricity supplier. Although Summerside Electric has a declining block rate structure for its residential customers, NB Power has a price differential for on-peak and off-peak electricity which means that customers who consume more electricity during the on-peak hours can make Summerside Electric less secure as the price it pays for electricity can increase. Not only would a significant move to on-demand baseboard (resistive) electric heating by consumers affect the affordability of electricity, it could also affect the availability of electricity if the increased demand during the on-peak led to brownouts or blackouts (Gaudet, 2010).

Both the City of Summerside and Summerside Electric have recognized that the electricity energy-chain will become less secure if significant numbers of electricity customers restrict their space heating requirements to on-demand, baseboard electric-heating. An electric-heating pilot program supported by a $450,000 (Canadian) low-interest loan from the Canadian Federation of Municipalities' Green Municipal Fund is in operation to make wind-electricity available for use with electric thermal storage heaters (Gaudet, 2010). The ETS units are charged to their maximum from both stable and variable supplies of electricity during the off-peak hours (23h to 7h) and on weekends and holidays, while during the on-peak (7h to 23h), the variable supply is used to meet heating and recharging first, with any excess supplementing on-demand electricity services (Hughes, 2010c). In order to ensure that the storage heaters are only charged with wind during the on-peak, recharging is controlled by Summerside Electric and monitored using a smart grid; off-peak electricity is charged at a lower rate than on-peak. The energy chains for both the on-demand electricity services and the heating service are shown in Figure 5; the availability, affordability, and acceptability of wind-electricity for heating from both wind-farms is intended to make the heating energy-chain more secure (Gaudet, 2010).

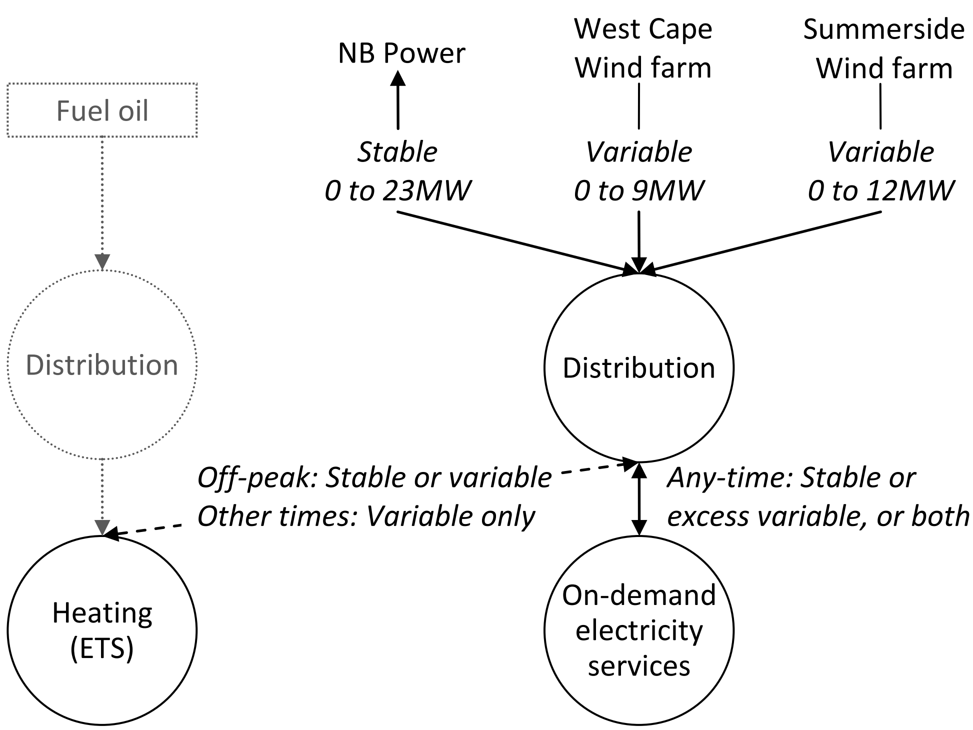

Figure 5: Proposed uses of electricity energy-chain for Summerside Electric

We have developed four charging control methods for Summerside, each of which ensures that the ETS is fully charged at the end of the charging period (i.e., 7h on any non-holiday weekday) using a combination of stable and variable electricity. All methods have been simulated using actual wind-farm production data from the 2010-2011 heating season; the results also include DHW demand, which is met from stable or excess variable electricity at anytime throughout the day. The results described here are for the control method that attempts to maximize the use of wind each hour for recharging and heating, with the minimum amount of stable electricity from NB Power consumed for heating.

Energy source	Indicator (and metric)		
	Availability (ETS Heating)	**Affordability (Annual cost)**	**Acceptability (kg CO_2e)**
Light fuel oil only	0%	$2,507	6,606
Electric heating (no wind, stable only plus oil backup)	36%	$1,994	11,887
Wind-heating (stable and variable plus oil backup)	94%	$1,605	893

Table 4 shows the results of the simulation for a single household (the average of 100 households with annual consumption of 48 GJ for space heating and 18 GJ for domestic hot water (OEE, 2010); the results would change as the number of households increases or decreases (Hughes, 2010)). Three different heating sources are considered: light fuel oil alone; a combination of the minimum hourly volume of stable electricity to recharge the ETS (off-peak only with no wind) and oil as backup; and a combination of the maximum hourly volume of wind-electricity with stable backup for simultaneous ETS charging and hourly heating (during the off-peak) and variable supply with oil (during the on-peak). The results are categorized by indicator and metric: availability (the percentage of ETS for heating), affordability (the annual household heating costs for any electricity and oil consumed), and acceptability (the total CO_2e emissions).

Energy source	Indicator (and metric)		
	Availability (ETS Heating)	**Affordability (Annual cost)**	**Acceptability (kg CO_2e)**
Light fuel oil only	0%	$2,507	6,606
Electric heating (no wind, stable only plus oil backup)	36%	$1,994	11,887
Wind-heating (stable and variable plus oil backup)	94%	$1,605	893

Table 4: Energy security indicator values for various heating sources for a single household

The focus of the Green Municipal Fund is greenhouse gas reduction (that is, acceptability) as opposed to availability or affordability; however, as the table shows, those households restricting a percentage of their heating to ETS will improve their energy security when compared households using light fuel oil: in terms of availability (94% from ETS), affordability (an annual savings of $901), and acceptability (a decline in emissions by about 5,700 kg CO_2e). Acceptability can also be discussed in terms of the fact that households using wind-heating have a secure source of energy for heating rather than one that is insecure; for example, an energy source that is not subject to weekly price variations.

In addition to the above, Summerside Electric's revenue per household is slightly higher in the wind-heating case ($90.24) than in the electric-heating case ($72.24).

7 Discussion

7.1 Energy security indicators

The parsing of the IEA's definition of energy security results in the framework's three indicators: availability, affordability, and acceptability. While there is no universally agreed upon definition of energy security, many indicator sets echo the three IEA-derived indicators or can be considered variations on them:

- The World Energy Council has three sustainability objectives (the three 'A's) (WEC, 2007): *Accessibility* to modern, affordable energy for all; *Availability* in terms of continuity of supply and quality and reliability of service; and *Acceptability* in terms of social and environmental goals.
- The Asia-Pacific Energy Research Center is somewhat similar, but has four indicators (the four 'A's) (APERC, 2007): *Availability* refers to the availability of oil (and other fossil fuels) and nuclear energy; *Accessibility* considers the barriers to accessing energy resources; *Affordability* of energy (limited to fuel prices, price projections, and infrastructure costs); and *Acceptability* surrounding environmental issues dealing with coal (carbon sequestration), nuclear, and unconventional fuels (biofuel and oil sands).
- Hughes and Shupe reworked APERC's four 'A's to be more in line with the IEA definition, dividing availability into changes in current (or short-term) conditions (*Availability*) and changes to long-term conditions (*Accessibility*) (2011), while Kruyt, van Vuuren, de Vries, and Groenenberg (2009) extended the work by Jansen, van Arkel, and Boots (2004) on the social stability of an energy supplier to *Acceptability*. Domestic security and political stability risk data can also be applied to an energy flow (Hughes, 2010).
- Sovacool and Mukherjee (2011) have divided APERC's four 'A's into five dimensions: *Availability*, *Affordability*, *Technology Development*, *Sustainability*, and *Regulation*, while in Sovacool and Brown (2010) energy security has four indicators: *Availability*, *Affordability*, *Energy and Economic Efficiency*, and *Environmental Stewardship*.

Most of the indicators (or dimensions) and objectives are captured in the IEA's definition of energy security and, as a result, the three indicators described in the paper. One exception is the IEA's apparent omission of accessibility, which can be considered as part of availability in that for an energy flow to be accessible, it must be available; if access to an energy flow is problematic, this is reflected in its availability. Although the World Energy Council seemingly omits affordability as an objective, it is mentioned in the definition of accessibility.

Technology development, sustainability, and regulation are not explicitly described as indicators and cannot be easily extracted from the IEA's definition. With respect to technology (i.e., a process or processes in an energy chain as opposed to the energy flows that supply the processes) and technology development—if advanced technologies cannot produce energy flows which are secure when compared to less-advanced technologies, then the jurisdiction would be more secure using the less-advanced technologies. Technology and its associated infrastructure constitute the chain itself, not the supply of energy to the chain from an external terminator; technological advances do not necessarily translate into an improvement in security.

The sustainability of an energy system, an energy chain, or a process can be ascertained from how secure the entity has been in the past and, possibly through the use of forecasting with scenarios, how secure it is expected to be in the future. In this interpretation of sustainability, the application of the three 'A's to the entity's flows indicates whether security is unchanged, improving, or deteriorating.

Scenarios can be developed in conjunction with the framework to examine the robustness of the energy system in the face of evolutionary or revolutionary changes. For example, the effect of removing one or more processes to emulate the effects a major energy disruption caused by an extreme event such as a terrorist attack can show the impact on energy security on different processes, chains, and services.

The regulations (or policies) applied to a process or series of processes may indicate the jurisdiction's intent to improve its energy security; however, unless the regulations are enforced, there is no guarantee that they will be acted upon. Worse, the regulations may prove detrimental to energy security. As discussed in the section on energy policy (above), it is the outcomes of the changes to the flows targeted by the regulations that indicate the effectiveness of the regulations, not the regulations themselves.

7.2 The energy security model

The energy security model was developed from the observation that the IEA's definition of energy security could be applied to a variety of different jurisdictions, from households to regional administrations to national and supranational governments. The common thread found in all examples considered—energy inputs, energy processing, and energy outputs—mean that systems analysis techniques can be employed to represent and define energy systems and their constituent elements or processes. Moreover, since processes are effectively systems in their own right, they can be expressed using the same flows as a system, meaning that the IEA's definition of energy security (and hence the framework) is also applicable to processes.

The framework has evolved from earlier work using AHP and expert-based opinions for the analysis of a jurisdiction's energy security (Hughes & Sheth, 2009), in which it was found that opinions varied widely and the opinion of a single expert could change quite rapidly. Consequently, the framework described in this paper was originally devised with the intention of using quantitative data only to avoid some of the experiences of relying on the opinions of experts; although quantitative metrics exist for each of the three indicators, the quantitative-only requirement was relaxed for evidence-based qualitative data.

Because of the nature of the energy chains, a changing condition or policy applied to a process anywhere in an energy chain can have far-reaching effects throughout the entire system. The most obvious of these is a decline in the availability of an $Energy_{IN}$ flow from a terminator to the system and the resulting impacts on availability to downstream processes throughout the energy chains associated with the original flow: diversifying the number of $Energy_{IN}$ terminators is often seen as the best approach to overcoming potential single points-of-failure. On the other hand, a policy decision taken closer to an end-use can also have far-reaching effects throughout the entire system, both upstream from the process and to other end-uses: changing a conversion process and *Energy*$_{IN}$ to meet the same *Energy*$_{OUT}$ requirements (i.e., a restriction) can put additional demand on the availability of the processes and flows associated the *Energy*$_{IN}$ flow, potentially affecting its availability and affordability for other end-uses.

Although the method is described in terms of a jurisdiction's energy system, if sufficient data exists, parts of an energy chain can be examined and measured, allowing the energy security of, for example, a specific end-use or energy service to be analysed.

Flows or processes can be changed, removed, or added. Modifications to an actual system can be represented by the framework; conversely, potential modifications shown using the model can be made to the system if deemed necessary.

7.3 Limitations

Although the framework has been applied to specific energy services in a limited number of jurisdictions, it is assumed that the framework is applicable to any energy system that can be expressed in terms of energy chains and processes. Moreover, since the model is based upon the IEA's definition of energy security, it is assumed that the energy security framework can be applied, in turn, to each process. Finally, it is assumed that the structure of the framework is such that the energy security of a process can be represented and measured by applying metrics associated with the indicator set to the process's two energy flows (*Energy*$_{IN}$ and *Energy*$_{OUT}$) and its environment flow (*Environment*$_{OUT}$). While these assumptions seem reasonable, it is possible that there are energy systems whose energy security cannot be represented using the framework.

The indicators and their definitions are applicable to the flows associated with any process thereby making analysis more uniform and systematic, avoiding the need to develop ad hoc indicators for specific processes or situations. Metrics for each indicator can be tailored to meet the idiosyncrasies of different flows.

A process is associated with six flows: two energy, two demand, one environment, and one policy. Other flows are not considered as these six flows appear to be sufficient for representing and measuring a jurisdiction's energy security. One possible addition to this list is an input flow from the environment; all environmental impacts are represented by the *Environment*$_{OUT}$ flows. The IEA's definition of energy security is applicable to the system analytic process model upon which the framework is built. If the IEA's definition were to change, the framework could evolve with it as long as the definition was still applicable to the process model.

Like most frameworks and indicator sets, the framework described in the paper and its use of the three 'A's offers a snapshot of energy security at a given moment in time—it is not dynamic. The dynamic changes in energy security can be appreciated through the use of temporal indicators to show how the system has reacted in the past or the development of scenarios to model how it would react to future events.

8 Summary

While a number of energy security indicator sets have been developed and applied to specific jurisdictions or types of energy, few can be described as generic, applicable to any energy system. The framework described in this paper attempts to address this issue by combining a commonly accepted definition of energy security with systems analysis techniques to create a set of energy security indicators and an energy systems model applicable to those energy systems which can be represented in terms of energy suppliers, energy services, the environment, and the system.

The International Energy Agency's definition of energy security, "the uninterrupted physical availability at a price which is affordable, while respecting environment concerns" is the foundation of the framework. The definition is parsed to create three energy security indicators: availability ("the uninterrupted physical availability"), affordability ("a price which is affordable"), and acceptability ("respecting environment concerns").

The model defines an energy system as an entity that takes flows of unconverted energy from energy suppliers and transforms them into converted energy flows in response to demands from energy services. The transformation of the energy flows has inherent inefficiencies, the system produces losses and emissions which are released to the environment and represented as a flow. The system is comprised of one or more energy chains, each consisting of processes responsible for either converting or transporting the different energy flows. Each process, like its encompassing system, takes unconverted energy flows, produces flows of converted energy, and has flows to the environment in order to meet a demand.

The analysis of the system involves applying the three indicators and their metrics to the energy and environment flows. If a flow experiences a short- or long-term change, it can have a positive or negative effect on the jurisdiction's energy security, depending upon the nature of the change. Energy flows can be associated with availability, affordability, and acceptability, while the environment flows are typically linked with acceptability. Depending upon the data, metrics can measure current, derived, and temporal changes to a flow.

The limited number of indicators is seen as sufficient for energy security analysis as they were obtained from a commonly accepted definition of energy security applicable to most, if not all, energy systems and can be applied directly to a process's energy and environment flows. The framework expands the acceptability indicator to include social and political issues as these can also contribute to the acceptability of a process and its associated flows.

As well as the energy and environment flows and the demand flows, a system and its processes are also subject to policy requirements from an individual or organization. The framework treats policies as if they are flows; however, unlike the other flows, they are not considered to be measureable although their outcomes, in the form of changes to the other flows, can be measured in terms of their impact on the indicators and hence any changes to the system's energy security.

Summerside Electric's decision to use wind-electricity for household space and domestic hot water heating was presented as an application of the framework. The resulting analysis showed that households restricting part of their heating to wind improved their energy security as compared to existing use of light fuel oil.

In addition to its application to wind-heating in Summerside, the framework is an integral part of a graduate course in energy systems analysis and is being used as a vehicle to introduce energy issues in general and energy security in particular to the public and politicians in the region. We are now examining the relationships between resilience and robustness and how it can be applied to the energy security framework to assist in the analysis of a jurisdiction's energy security.

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