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Quantifying energy security: An Analytic Hierarchy Process approach

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Abstract

Energy security, unlike climate change, the other major energy-related challenge the world faces in the twenty-first century, cannot be easily measured. Greenhouse gases can be expressed in terms of their global warming potential, while the carbon intensities of carbon-based fuels associated with various anthropogenic activities are well known. The same cannot be said for energy security, as it exhibits qualitative rather than quantitative characteristics.

Despite this, ranking a jurisdiction's different energy sources would give the public, policy-makers, and politicians a clearer understanding of the jurisdiction's energy mix and the state of its energy security.

This paper presents a methodology which employs the multi-criteria decision analysis tool, Analytic Hierarchy Process (AHP), to produce an energy security index for each source making up a jurisdiction's energy mix. The index, when used in conjunction with the consumption associated with each energy source, can also be displayed graphically, allowing the energy security state to be visualized.

1 Introduction

Over the past year, the world has witnessed a number of energy-related events such as the spiking of crude oil prices, the ongoing Russia-Ukraine natural gas pipeline dispute, and declining production from major world oil fields such as the North Sea and Cantarell (BP 2008). These and other events have all contributed to the increasing importance of energy security (the reliable supply of energy at an affordable price (IEA 2001)) to many jurisdictions and will undoubtedly continue to do so into the future, given the volatility in world energy markets, the growing competition for energy resources, and the need for economic development and poverty reduction (World Bank 2005).

Greenhouse gases, the world's other major energy-related challenge, can be measured quantitatively in terms of their global warming potential and total emissions. The same cannot be said for energy security, as it is a qualitative rather than a quantitative measurement. However, if the different energy sources used by a jurisdiction could be ranked in terms of their energy security, the general public, policy-makers, and politicians would be given a clearer understanding of the jurisdiction's energy mix and the state of its energy security

This paper presents a methodology that employs the decision analysis tool, Analytic Hierarchy Process (AHP), to rank a jurisdiction's energy sources in terms of their relative energy security. The methodology employs three criteria, supply, infrastructure, and affordability, which are applied to the energy sources consumed by the jurisdiction or by energy services within the jurisdiction. The result is a table of the energy sources and their quantitative rankings. The methodology has been extended to include a visualization tool that produces a graphical representation of the ranking and energy consumption of each energy sources.

The paper includes a detailed examination of the methodology and its implementation. Examples of its application to two jurisdictions are presented. Other applications and extensions of the tool are also discussed.

2 Analytic Hierarchy Process

Analytical Hierarchy Process (AHP) is a Multi-Criteria Decision Making (MCDM) technique developed by Saaty in 1980, which decomposes a complex MCDM problem into a system of hierarchies (Triantaphyllou 2000, Forman and Gass 2001). AHP is widely used in the field of energy and environment, including such areas as energy policy analysis, electric power planning, technology choice and project appraisal, energy utility operations and management, energy-related environmental policy analysis, energy-related environmental control and management (Zhou, Ang and Poh 2006). Simplicity, ease of understanding and the fact that AHP decomposes a complex problem into a simple hierarchy, are some of the reasons for AHP's wide application in the field of energy and environmental modeling (Pohekar and Ramachandran 2004, Wedley 1990).

AHP consists of four phases:

1. Decomposition, that is, construction of hierarchical structure,
2. Comparative judgment,
3. Consistency analysis, and
4. Final ranking of the alternatives.

2.1 Phase 1: Decomposition

AHP decomposes a decision problem into a hierarchical structure consisting of three main levels. The highest represents the overall goal of the decision making process. One or more intermediate levels contain the decision criteria and any optional sub-criteria. The lowest one consists of the decision alternatives. The hierarchical structure of the basic AHP model allows dependencies among elements to exist between the levels of the hierarchy only; the direction of impact is toward the top of the hierarchy (Buyukazici and Sucu 2003).

2.2 Phase 2: Comparative judgment

With the decision hierarchy formed, the decision-maker can develop relative weights—or priorities—to rank each criterion and alternative. This begins with a pair-wise comparison of the criteria; to assist in this process, Saaty developed a scale of 1 to 9 to perform pair-wise comparisons, as shown in Table 1.

Table 1. Saaty's pair-wise comparison table (Saaty and Alexander 1989)

Value	Meaning
1	A and B are of equal importance
3	A is moderately or weakly more important than B
5	A is strongly more important than B
7	A is demonstrably or very strongly more important than B
9	A is extremely or absolutely more important than B
2, 4, 6, 8	Intermediate values
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.
Fractions	Only occur when a reciprocal ratio is obtained.

The first step is to perform pair-wise comparisons of the different criterion with respect to the overall goal of the decision-making process and the results of the comparisons are entered into a matrix. An activity is equally important when compared to itself, thus, each element in the diagonal of the matrix has a value of 1. All other elements in the matrix must satisfy the relation $a_{i,j} = \frac{1}{a_{j,i}}$. This matrix is the basic unit of the analysis and is called the "pair-wise comparison matrix" or simply, "judgment matrix".

After the pair-wise comparison is completed, a vector of priorities is computed for the criteria. Saaty suggests a number of ways in which the vector can be obtained (T. Saaty 1980); the method adopted in this research is to multiply the *n* elements in each row and take the n^{th} root (the geometric mean) of the result. The resulting *n*-element vector is then normalized, giving the priority vector.

Next, the alternatives undergo comparisons. If the comparisons are qualitative, the alternatives are subject to pair-wise comparisons with respect to each criterion—as is done for the criteria—creating a judgment matrix for each criterion. A vector of priorities is calculated from the judgment matrix, as described in the previous paragraph. On the other hand, if the comparisons are quantitative, the priority vector is obtained by summing the *n* values of the alternatives and creating a normalized vector of the alternatives.

2.3 Phase 3: Consistency analysis

One of the major advantages of AHP is that it does not demand perfect consistency; it allows inconsistency, while at the same time providing a measure of the inconsistency in each set of comparative judgments. Inconsistencies can occur in the judgment matrix for a variety of reasons, including absence of information, clerical error, and lack of concentration (Forman and Gass 2001).

To measure the inconsistency in the qualitative judgment (quantitative results are not considered inconsistent), Saaty developed a consistency index (CI). For a matrix of order n, $CI = \frac{\lambda_{max} - n}{n-1}$, where λ_{max} is the largest eigenvalue of a reciprocal matrix of order n.

An approximation of the maximum eigenvalue (λ_{max}) can be obtained as follows:

1. Multiply the judgment matrix with the priority vector.
2. Divide the first component of the resulting vector by the first component of the priority vector, the second component by the second component of the priority vector and so on, thereby obtaining a new vector.
3. Take the sum of the components of this vector and divide by the number of components in that vector. The valued obtained approximates the maximum eigenvalue λ_{max}.

The closer λ_{max} is to n (the size of the matrix) the more consistent is the result.

The consistency analysis is completed by determining the consistency ratio (CR), the ratio of the consistency index and the "random index". The random index (RI) values for simulated, random reciprocal matrices of different orders are shown in Table 2.

Table 2. Random Index values for matrices of different orders (Saaty and Alexander 1989)

Matrix order	1	2	3	4	5	6	7	8	9	10
Random Index	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

A consistency ratio of 0.10 (10 percent) is considered acceptable. Hence, avoiding large inconsistencies in the judgment matrices, requires finding the CR for every judgment matrix. If the value of CR is greater than 0.10, a return to the comparative judgment phase and a repeat of the pair-wise comparisons until CR falls into the acceptable range is recommended.

2.4 Phase 4: Final ranking of the alternatives

If the criterion weights are denoted C_j, and weight (or priority) for alternative i with respect to criterion j is $A_{i,j}$, then the final priority of alternative i, P_i, can be calculated from following equation, $P_i = \sum_{j=1}^{n} A_{i,j} \times C_j$, where n is the number of criteria.

The alternative with the highest priority value is considered to be the most suitable solution for the decision problem, while the alternative with the lowest priority value is least appropriate for that decision problem.

3 Quantifying Energy Security with AHP

The state of energy security in a particular service, sector, or jurisdiction is dictated by its energy supplies, the cost of these supplies, and the infrastructure required to produce, distribute, and possibly to store the energy for the consumer. Determining the influence of an energy source on the energy security of a jurisdiction, or an energy service within the jurisdiction, can be more subjective and not as easily quantifiable as identifying the greenhouse gas emissions factor associated with the energy source. In its simplest form, an energy source can be classified as either "secure" or "insecure"; however, this distinction can appear to be arbitrary and without merit or basis. It may also hide the fact that one form of energy may have "shades" of security, with some sources being more secure than others. Any methodology chosen to rank an energy source in terms of a jurisdiction's energy security must be justifiable and should not be jurisdiction-specific.

3.1 Objective

AHP is used to evaluate the different energy alternatives available to a jurisdiction and from this, rank their contribution to the jurisdiction's (or energy service's) energy security. The objective is *to prioritize the energy sources for a given service or task in terms of how secure they are deemed to be*. Applying AHP to the criteria and alternatives will result in a relative ranking of each energy source, in terms of its security, for the jurisdiction's energy portfolio.

3.2 Criteria

The choice of criteria is dictated by the objective, which in this case deals with energy security. Most definitions of energy security can be summarized as the supply of a reliable source of energy at an affordable price. This suggests that energy security depends upon two criteria: supply and price. However, since the supply criterion requires a supply of energy and infrastructure to distribute the energy, it can be further decomposed into supply and infrastructure, giving three criteria: supply, infrastructure, and price.

The judgment matrix for the criteria is created using the pair-wise comparison technique (i.e., qualitative ranking) discussed in section 2.2, with values obtained from Table 1. The criteria are prioritized in accordance with their overall importance to the objective.

3.3 Alternatives

The alternatives are the different energy sources that can be used to meet the objective. They are ranked by applying AHP's qualitative (pair-wise) or quantitative (normalized) rules to the alternatives for each criterion (i.e., supply, infrastructure, and price). The alternatives should be specific to the objective; that is, some sources are not normally used to meet the energy needs of a particular service (for example, low-temperature solar for transportation). The end result is a relative ranking of the energy sources, from the most to the least secure for each criterion.

The following guidelines are recommended when making the pair-wise comparisons of the alternatives for each criterion:

- Supply. The state of the physical or actual supply of energy available for the service or task. This is a qualitative value that takes into account the state of the resource, including competition for the resource, its depletion rate, and any jurisdictional or political issues associated with the resource. Supply can be discussed in terms of the amount available currently or in the future; the timeline chosen must be applied to all criteria. The quantity or consumption of supply is not considered here as it is addressed later.
- Infrastructure. The infrastructure used to either produce the energy or deliver it to the service or task. The results are influenced by such factors as the infrastructure's capacity, age, accessibility, and the distance between the supplier and the consumer, each of which can be expressed quantitatively or qualitatively. As either the distance or the complexity of the infrastructure rises, the security of the system can be decreased.
- Price. The price paid for a unit of energy. Depending upon the objective's service or task, this may be subject to taxation or subsidies.

3.4 Example

The methodology described above will produce an energy security index for each of the sources consumed in a jurisdiction. For example, with it the energy security of Nova Scotia, a small province of about one million people on Canada's Atlantic coast, can be obtained. The province's portfolio of primary energy sources and associated energy suppliers is shown in Table 3.

Table 3. Nova Scotia's energy portfolio (Hughes 2007)

Source	Demand		Supplier
Refined petroleum products and crude oil	178.3 PJ	63.1%	North Sea, Venezuela, Middle East, Newfoundland, U.S.
Coal (imported)	69.1 PJ	24.5%	Colombia, Venezuela, U.S.
Renewables (non-utility)	16.6 PJ	5.9%	Nova Scotia
Coal (domestic)	10.3 PJ	3.7%	Nova Scotia
Primary electricity	2.7 PJ	1.0%	Nova Scotia
Natural gas	5.4 PJ	1.9%	Nova Scotia
Total	282.4 PJ	100.0%	

The objective is to rank Nova Scotia's energy sources in terms of their security. To do so involved the assistance of five regional energy analysts for determining the criteria and priority vectors. The results of the criteria rankings are shown in Table 4, with supply being the most important and infrastructure the least.

Table 4. Ranking of the criteria

Supply	Infrastructure	Price
0.57	0.14	0.29

Next, the priority vectors of the energy sources (from Table 3) were identified in terms of each criterion. Supply and infrastructure required pair-wise comparisons as they are qualitative, while the price vector was obtained quantitatively. The total consumption associated with each energy source was not included in the ranking process. Table 5 shows the results.

Table 5. Ranking of alternatives with respect to each criterion

Source	Supply	Infrastructure	Price
Oil	0.10	0.20	0.11
Domestic coal	0.19	0.14	0.09
Imported coal	0.12	0.12	0.18
Natural gas	0.08	0.09	0.11
Hydroelectricity	0.32	0.25	0.36
Renewables	0.19	0.20	0.16

The final step was to calculate the energy security index for each source. This involved applying the judgment matrix (Table 4) to the ranking of the alternatives (Table 5), producing the indices shown in Table 6.

Table 6. Energy security index for each energy source

Source	Index
Oil	0.12
Domestic coal	0.15
Imported coal	0.14
Natural gas	0.09
Hydroelectricity	0.32
Renewables	0.18

In this example, hydroelectricity is considered the most secure, followed by non-utility renewables and domestic coal. Oil has a low ranking because most oil is imported into Nova Scotia from outside Canada with only an estimated 20 percent from Canadian sources

(Newfoundland and Labrador), while natural gas has limited infrastructure in Nova Scotia and its supply is in decline (NEB 2007).

4 Visualizing Energy Security

The energy security ranking alone does not convey to the reader the importance of or reliance on an energy source—this is because the amount of each energy source consumed is omitted from the methodology. Combining consumption with the ranking, while not part of the AHP process, can produce a better understanding of energy security. Although demonstrable in any number of ways, the approach described here is to create a visualization tool that plots each energy source on a graph, with the consumption or demand on the y-axis and the security ranking on the x-axis. An example of the energy security graph for Nova Scotia, using the results from the previous section, is shown in Figure 1.

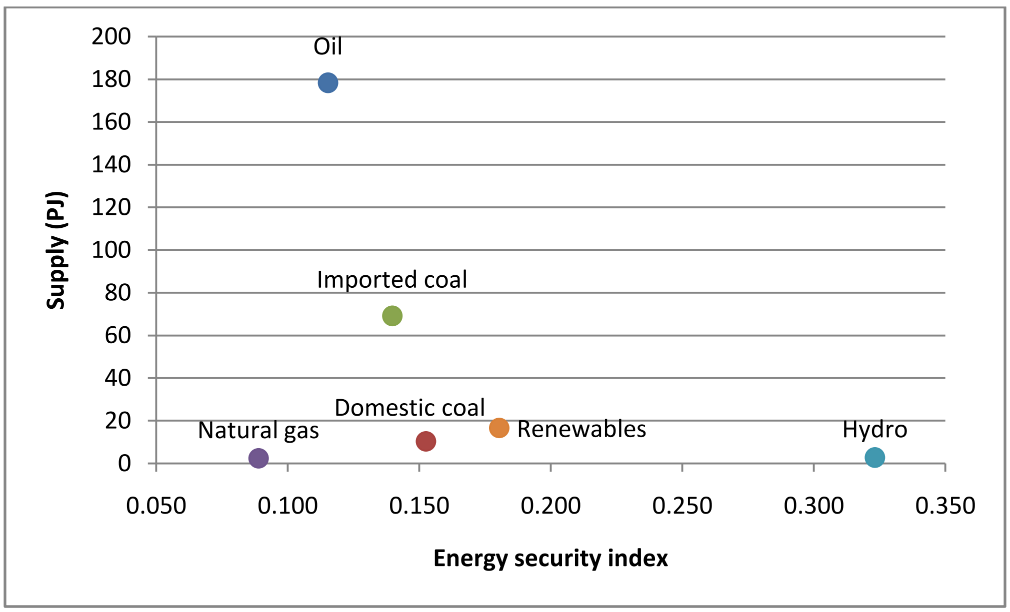

Figure 1. The energy security index for Nova Scotia's energy sources

The graph presents a visualization of the state of Nova Scotia's energy security. It shows that, for example, hydroelectricity is considered to be about 3.5 times more secure than natural gas, although its contribution to Nova Scotia's energy supply is about the same. The graph also highlights the province's overwhelming reliance on oil and imported coal—neither of which is considered to be particularly secure. For the province to improve its energy security, efforts must be made to reduce its dependence on these energy sources.

Other jurisdictions have been examined with the visualization tool. For example, the rankings of Canada's energy sources are shown in Figure 2.

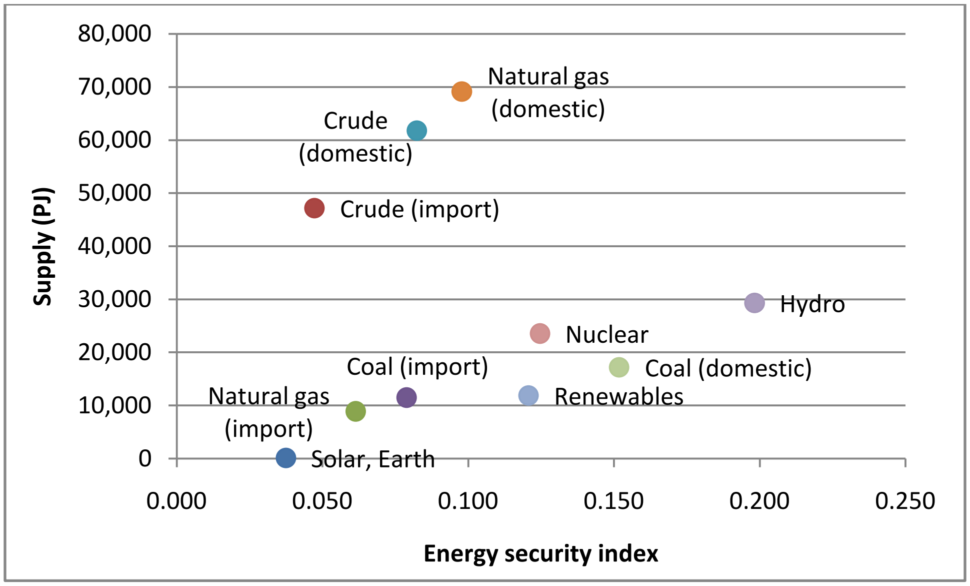

Figure 2. The energy security index for Canada's energy sources

Another benefit of the visualization tool is the ability to show the advantage of examining energy security at a local level. For example, the above graph for Canada masks the fact that most of eastern Canada relies on imports of oil and oil products; however, the graph for the smaller region of Nova Scotia makes this abundantly clear.

5 Implementation

The methodology is implemented as a software tool in Excel and Visual Basic for Applications (VBA) and consists of a series of spreadsheets, each handling one part of the AHP process: creating the criteria, comparing the alternatives, obtaining the final ranking, and producing the graphical visualization of the ranking. Excel and VBA were chosen as they allow the manipulation of matrices. The software is available from the authors.

6 Discussion

We have made the ranking tool available to energy analysts and have used its result to explain regional energy security issues to the general public and a number of politicians. Several analysts found a challenge in adapting to Saaty's pair-wise comparison rules shown in Table 1.

As well, doing the comparisons on paper beforehand, rather than at a computer, allowed for easier adjustment of the input.

The tool is useful in that it illustrates the current state and understanding of energy security. It permits the “what-if” type of questions to be answered; for example, “what if oil prices double?” or “what if more natural gas infrastructure were to be built?” These queries can stimulate debate and, importantly, act as a means to raise awareness of energy security and how it can be improved, as well as the impact associated with doing nothing.

The results from the tool have also been useful in other areas of our research. For example, in the development of energy wedges (Hughes 2009), the security of different energy sources can be judged for their suitability or potential contribution as a wedge.

7 Concluding Remarks

Over the past decade, supply shortages, infrastructure failures, and volatile prices have made energy security an issue in most, if not all, energy importing nations. As the need to improve energy security slowly becomes apparent to the public, policymakers, and politicians, there is a parallel need to improve the way in which it is presented to these groups. This paper has offered a methodology whereby different energy sources used by a jurisdiction can be ranked in terms of supply, infrastructure, and price. The results of the methodology can then be combined with the jurisdiction’s consumption to obtain an energy security graph, permitting the state of energy security in a jurisdiction to be visualized.

The tool used to support the methodology is the Analytic Hierarchy Process (AHP). Using AHP to determine the relative energy security of a jurisdiction’s energy sources makes it possible to compare various energy sources based on quantitative as well as qualitative criteria.

In addition to prioritizing a jurisdiction’s energy sources with the methodology, this paper has also shown how the ranking can be presented graphically to allow a visualization of the jurisdiction’s energy consumption.

The availability of the ranking tool is permitting other areas of research to be pursued; for example:

- Analyzing the impact of distance and infrastructure on regional and local energy security
- Considering alternative energy sources and how they could improve energy security
- Examining energy security from a historical perspective
- Projecting future energy security

We are also creating another version of the tool to allow a jurisdiction to rank its energy security and its greenhouse gas emissions.

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