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# Creating energy security indexes with decision matrices and quantitative criteria

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## Abstract

Energy security is becoming an important policy issue in a growing number of jurisdictions because of volatile energy markets and the production challenges faced by many producers. As a result, policymakers and politicians are looking for tools or methods that allow them to determine the security of the various energy supplies used in their jurisdiction. Ideally, a tool that can create an energy security index should have the objective of producing results that are justifiable, understandable, and reproducible.

This paper describes one such method, which, in keeping with other approaches, employs a decision matrix to produce the energy security index. To meet the objectives, the method relies on quantitative criteria and metrics. Rather than relying on a single set of weights to create the index, the method allows a range of indexes to be produced, thereby offering further insight into the state of a jurisdiction's energy security.

**Keywords:** Energy security, APERC

## 1 Introduction

Volatile energy markets and supply challenges are making energy security an important issue worldwide (Constantini, 2007; Grubb, et al., 2006). The possibility of ranking a jurisdiction's energy security is of interest politicians and policymakers alike as it can highlight those supplies, sectors, and services vulnerable to shortages or price fluctuations. An energy security index can assist in the development of new energy policy or climate policy, or both by comparing the choices or alternatives available to the jurisdiction.

The process of creating an energy security index typically requires criteria and metrics to judge and rank the different alternatives under consideration and methods which define how the criteria and metrics are applied; examples of existing approaches include (Brown, et al., 2007; Clingendale, 2004; WEC, 2007; Hughes, et al., 2009b)). If the index is to gain acceptance amongst its potential users, the criteria, metrics, and methods should be justifiable, understandable, and reproducible.

In (Hughes, et al., 2009b), an energy security index generator is developed based on the Analytic Hierarchy Process (AHP) using three criterion: supply, infrastructure, and price, while the alternatives were ranked by individuals and groups using AHP's pair-wise comparisons. Although AHP is a widely used ranking method, its pair-wise technique proved to be a challenge for many people since the results it produced were qualitative, appeared to be arbitrary, and were not easily reproducible.

This paper shows how energy security indexes can overcome the shortcomings such as the ones described above. First, rather than using AHP's qualitative, pair-wise comparison technique, quantitative ranking is achieved using actual data and a decision matrix; by using publically-accessible, quantitative data, the results are reproducible. Second, the criteria is based upon the Asia-Pacific Energy Research Center's (APERC) four 'A's (Availability, Accessibility, Affordability, and Acceptability) (APERC, 2007). Although the four 'A's were developed to discuss energy security in terms of fossil energy supplies and nuclear energy, by redefining them and associating them with a clearly defined set of metrics, a justifiable energy security index can be created.

The example presented in the paper demonstrates that the approach is broad enough to represent the energy needs of the basic modern energy services: transportation, heating and cooling, and applications requiring access to a continuous supply of electricity (Mathiesen, 2009).

## 2 Background

The challenges associated with qualitative ranking using Analytic Hierarchy Process (AHP) are illustrated and APERC's existing definitions of the four 'A's are discussed.

### 2.1 Qualitative ranking with Analytic Hierarchy Process

AHP is a multi-criteria decision analysis tool. Broadly speaking, it allows alternatives to be ranked qualitatively by either comparing each alternative independently against some common standard or performing a pair-wise comparison, comparing each alternative against all other alternatives in turn. In both cases, it is assumed that the comparisons are performed by one or more people (the respondents) who are well-versed in the jurisdiction's energy situation; when multiple respondents are involved, it is recommended that the final choice be reached by consensus.

For example, consider the question, "How secure is this energy source's supplier?" When comparing alternatives independently, the respondents are often given a range of choices such as "completely insecure" through "completely secure" to be applied to each energy supplier. The textual choices can be mapped into numeric values and assigned to the corresponding alternative. This is the ranking of the alternatives.

If a pair-wise comparison is performed, the question becomes "How secure is the supplier of energy source 'X' when compared to the supplier of energy source 'Y'?" The answers can be entered into an N-by-N judgement matrix, with each row and column corresponding to one of the alternatives. In AHP, each pair-wise comparison is assigned a value between 1 and 9 (see Table 1). Once the judgement matrix is completed, the ranking of each alternative is determined by applying a function to the values in each alternative's row; in (Saaty, 1980) a number of different ranking functions are described. The resulting rankings are subject to a "consistency analysis" to determine whether the pair-wise comparisons are consistent; if inconsistent, they can be rejected and the comparison repeated. The ranking is done by the respondents.

**Table 1: Saaty's pair-wise comparison table (Saaty, et al., 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 alternative *i* has one of the above numbers assigned to it when compared with alternative *j*, then *j* has the reciprocal value when compared with *i*. |
| Fractions | Only occur with a reciprocal ratio arising from the scale. |

Although both of these techniques work, they are potentially error-prone, can produce inconsistent results, and the results are often not reproducible. When performing pair-wise comparisons using the values in Table 1, some respondents find difficult to interpret and apply them. Part of the problem stems from the use of groups of people who must reach a consensus on the choices put before them. A second problem arises from the fact that the results are qualitative, subject to the whims and moods of the respondents at the time the questions are asked.

## 2.2 APERC's four 'A's

The four 'A's developed by the Asia-Pacific Energy Research Council (APERC) are based loosely on the World Energy Council's 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. APERC added a fourth, *Affordability* (APERC, 2007).

APERC's four 'A's can be summarized as follows:

**Availability**. APERC's view of availability focuses on oil (and other fossil fuels) and nuclear energy (APERC, 2007 p. 7):

> *Thus, this growing dependence on oil, coupled with current high oil prices, declining oil discoveries, and the low level of spare oil-production capacity worldwide, have generated concern about the future adequacy of oil supply. How much oil do we have in the world? Is that enough to meet the ever increasing global demand and if not, what will be the substitute? These questions have become increasingly important since oil is the dominant source of world energy today and will continue to be so for the foreseeable future.*

Availability is meant to indicate the amount of supply of a given primary energy resource in terms of known reserves. In (Kruyt, et al., 2009), the definition is refined to mean "elements relating to geological existence".

APERC's definition of availability is too narrow for a general purpose energy security index as it assumes underground resources only; that is, fossil fuels and radioactive materials. Instead, availability should include all primary energy sources including renewables such as hydroelectricity, biomass, solar, and wind.

**Accessibility**. APERC's description of accessibility refers barriers to accessing energy resources (APERC, 2007 p. 17):

*Besides the availability of energy resources, the ability to access these resources is one of the major challenges to securing energy supply to meet future demand growth. Barriers to energy supply accessibility* [include] *economic factors, political factors, and technology.*

Accessibility refers to the ease in which a proven energy reserve can be relied upon to supply the market, which (Kruyt, et al., 2009) define as "geopolitical elements". Including economic factors in the accessibility definition can be confusing, as there is also a definition for affordability.

**Affordability**. APERC's definition is limited to fuel prices (and price projections) and infrastructure costs.

This view of affordability can be expanded to take the cost of energy services into consideration, and can include the cost of energy to the consumer at a time specified by the analysis.

**Acceptability**. APERC considers acceptability to refer to environmental issues dealing with coal (carbon sequestration), nuclear, and unconventional fuels (biofuel and oil sands). The description of acceptability is (APERC, 2007 p. 27):

*Energy demand in the APEC region is projected to increase nearly three-fold, as the region experiences robust economic growth. This energy demand trend is expected to increase energy-related environmental impacts. Faced with this impending problem, policy makers around the world are trying to curb pollution from the energy industry by imposing stricter environmental regulations. Strict environmental regulations combined with enhanced environmental awareness for issues related to the energy sector will create fossil fuel use constraints and affect future energy resources mix.*

APERC's focus is on changes in the energy market regarding GHG emissions and tax mechanisms for "dirty" fuels that will impact the relative security of a given resource. Kruyt defines it as pertaining to "environmental or social elements" (Kruyt, et al., 2009).

Although APERC's view on acceptability is important, it could be broader than the economic impact of environmental regulations; for example, it could also include social and political issues such as the food-fuel debate and the displacement of indigenous peoples because of energy extraction. Measuring this can be a challenge.

## 3 Developing a general-purpose energy security index

Although AHP and the four 'A's have been used together to produce energy security indexes (Hughes, et al., 2009b), they need further refinement if they are to create results that are justifiable, understandable, and reproducible. This section shows how such results can be achieved with a variation on AHP and quantitative data using the four 'A's.

### 3.1 The decision matrix and ranking vector

A decision matrix is a tool that allows alternatives to be ranked. Decision analysis tools such as AHP use decision matrices to determine the final ranking of a group of alternatives. In fact, if the ranking includes quantitative values, AHP operates as a decision matrix.

A decision matrix is a two-dimensional matrix consisting of alternatives (in this example, the energy "choices" available to a jurisdiction) and criteria (the metrics and weightings). The decision matrix consists of 'c' columns (one per criterion) and 'a' rows (one per alternative). Figure 1 shows the decision matrix and the metrics vector with 'c' elements (one metric, m, per criterion).

| | | |
|---|---|---|
| $m_1$ | … | $m_c$ |

| | $C_1$ | … | $C_c$ |
|---|---|---|---|
| $A_1$ | $r_{1,1}$ | | $r_{c,1}$ |
| … | | | |
| $A_a$ | $r_{1,a}$ | | $r_{c,a}$ |

**Figure 1: A decision matrix (including the metrics vector)**

Each element of the matrix contains the ranking, $r_{i,j}$, of alternative *i* with respect to criterion *j* and is obtained by applying the criterion's metric to the alternatives in its column (Figure 2).

```
for i = 1 to c              ' C1 through Cc
        for j = 1 to a      ' A1 through Aa
                ranking (i, j) = C(i)'s metric applied to A(j)
        end
end
```

**Figure 2: Determining the rank of each alternative with respect to each criterion**

Each row contains the rankings of its alternative with respect to the criteria. The final ranking of each alternative is obtained by applying the weighting associated with each criterion to the ranking of each alternative with a row and summing them to create a ranking vector. The weighting vector, w, contains 'c' elements, one for each criterion, while the ranking vector, v, contains 'a' elements, one for the final rank of each alternative, as shown in Figure 3.

| | | |
|---|---|---|
| $w_1$ | … | $w_c$ |

| | $C_1$ | … | $C_c$ | | |
|---|---|---|---|---|---|
| $A_1$ | $r_{1,1}$ | | $r_{c,1}$ | $v_1$ | $v_1 = w_1 \times r_{1,1} + \ldots + w_c \times r_{c,1}$ |
| … | | | | … | … |
| $A_a$ | $r_{1,a}$ | | $r_{c,a}$ | $v_a$ | $v_a = w_1 \times r_{1,a} + \ldots + w_c \times r_{c,a}$ |

**Figure 3: Determining the ranking vector**

The resulting ranking vector contains the index of each alternative; the larger the value, the higher the index. If the alternatives are various energy sources or services, the ranking vector can be interpreted as the energy security index, indicating the level of security associated with each alternative. The final ranking is determined by the different metrics employed and the weighting chosen for each criterion.

Before the ranking vector can be created it is necessary to identify the alternatives, criteria, metrics, and weightings.

## 3.2 Alternatives

The alternatives can be any group of related energy supplies, services, or infrastructure that is necessary for the functioning of the jurisdiction. The choice of alternatives should not be influenced or restricted by the criteria; however, the alternatives may influence the choice and interpretation of the criteria, as the example in this paper will show.

## 3.3 Criteria and metrics

Each criterion is associated with a metric. The criterion defines or explains what part or component of the alternative is of interest, while the metric is a means of measuring or representing the criterion numerically.

Metrics can be qualitative or quantitative. Qualitative metrics should be produced by a group of people well-versed in the subject; however, as discussed above, the results may be consistent but might not be reproducible by other groups of people equally well versed in the subject. On the other hand, quantitative data obtained from publically accessible sources are reproducible and their application can be justified.

This section discusses how the four 'A's can be extended beyond acting as energy security criteria for fossil and nuclear energy supply and applied to any energy source, including renewables, energy services, and energy infrastructure. In all cases, the criteria are associated with quantitative metrics. The higher the value, the more secure the energy product.

### 3.3.1 Availability

Availability (AVA) refers to the state of supply or production of the energy alternative. There are a number of metrics that can be considered for availability, two of which are considered here: the reserve-to-production (R/P) ratio and historical production.

The R/P ratio is an indication of future, rather than past, production. Reserve numbers are notoriously inaccurate as they can be reported inaccurately by the owners of the resource, be it a publically traded oil company (Mortished, 2004) or a national oil company (Simmons, 2005). The R/P ratio cannot reasonably represent some renewables, as the concept of "reserve" is not applicable to renewables such as wind and tidal.

Historical production data are often available as time-series from national data suppliers such as the Energy Information Administration (EIA), the International Energy Agency (IEA), and BP Statistical Review of World Energy. The production data can show long-term trends with respect to the availability of the energy product and are not restricted to energy alternatives that have reserves.

The availability metric for the current state of production can be obtained from a linear regression of the supplier's annual production numbers from some point in the past to the present. A negative value indicates a decline in production, whereas a positive one signifies an increase in production; the regression gives the trend in current (or recent) supply. There are many possible sources of production data, at a coarse level, BP's annual statistics could be used; alternatively, national energy production data could be used. The end point is known, the starting point must be determined.

One possible starting point is the last observed inflection point (that is, the most recent peak or trough). As an example, consider annual crude oil production from three different producers, the Russian Federation, Norway, and Brazil, shown in Table 2. The inflection points are underlined; in the case of the Russian Federation and Norway, the inflection point is at a peak (in 2007 and 2001, respectively), whereas Brazil's inflection point is a trough (in 2004).

**Table 2: Annual production (million tonnes oil) (BP, 2009)**

| Producer | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| Russian Federation | 323.3 | 348.1 | 379.6 | 421.4 | 458.8 | 470.0 | 480.5 | <u>491.3</u> | 488.5 |
| Norway | 160.2 | <u>162.0</u> | 157.3 | 153.0 | 149.9 | 138.2 | 128.7 | 118.8 | 114.2 |
| Brazil | 63.2 | 66.3 | 74.4 | 77.0 | <u>76.5</u> | 84.6 | 89.2 | 90.4 | 93.9 |

Table 3 shows the result from the linear regression from the inflection point year to 2008 for each of the producers listed in Table 2. This is the value of the availability criterion for each alternative.

**Table 3: Production trends from Table 2**

| Producer | Year | Trend |
|---|---|---|
| Russian Federation | 2007 | -2.82 |
| Norway | 2001 | -7.28 |
| Brazil | 2004 | 4.08 |

The inflection-point metric is limited in that it can be influenced by a recent, short-term production phenomenon. In the above example, Russian production in the previous decade witnessed continuous and significant growth, meaning that the inflection point in 2007 could have been an anomaly caused by any number of events in 2008. This limitation can be overcome by selecting a common starting year for all producers and obtaining the linear regression from that date. For example, Table 4 shows the production trends obtained from a linear regression from 2000 to 2008 for the three producers.

**Table 4: Long-term crude oil production trends**

| Producer | Trend |
|---|---|
| Russian Federation | 22.35 |
| Norway | -6.43 |
| Brazil | 3.88 |

The trend is the value of the availability criterion from the linear regression metric. A more positive (negative) trend means the supplier's product is more (less) available. The volume produced (or imported) each year is not considered at this point. In fact, all that matters is the state of energy source in terms of its increasing or decreasing availability. The higher the value of the availability metric, the more secure the energy source. In this case, the Russian Federation would be considered the most secure, with Norway the least secure in terms of its availability.

The oil production examples are relatively clear-cut, with production increases or decreases appearing reasonably linear. This need not be the case in all oil producing regions or other forms of energy supply; consider the graph of electrical generation in Nova Scotia between 2000 and 2008, shown in Figure 4. Between 2000 and 2004, generation increased steadily; however, in late 2005 and into 2006, the shutdown of a major paper mill due to industrial action and a warm winter resulting in a significant drop in electrical demand. The following year (2007), demand increased again, only to drop off in 2008, in part because of rising electricity costs. This example also shows the difficulty of selecting a single inflection point as there are three inflection points in four years.

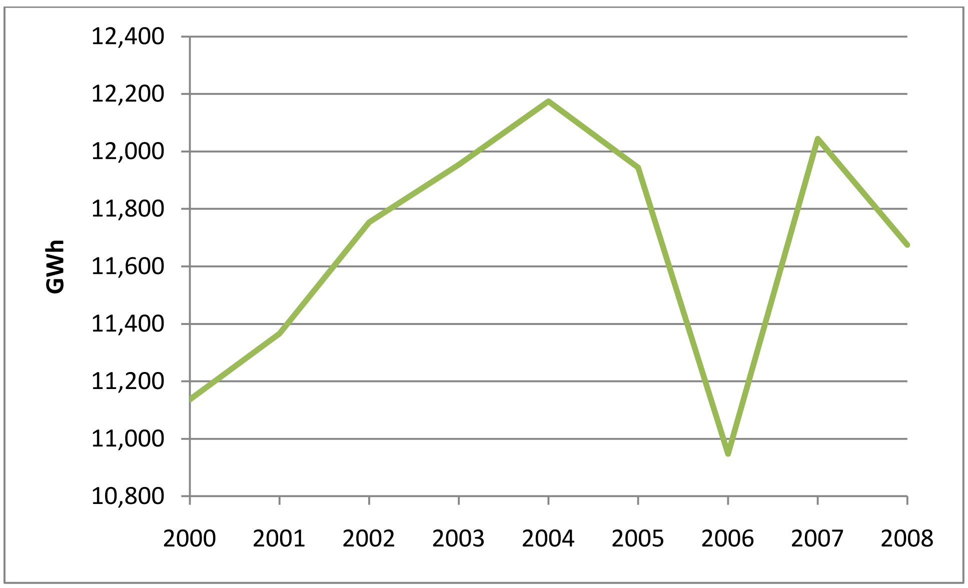


**Figure 4: Electrical supply in Nova Scotia between 2000 and 2008**

To overcome the appearance of arbitrariness, the choice of starting point for the availability metric must be justifiable. When the production curve is effectively linear, as with the oil production data, the starting point can almost be anywhere along the line; however, if the production curve nonlinear, the choice of starting point may be harder to justify. An alternative means of determining the availability is to calculate the least squares for all data points up to the penultimate year and then determine their average. For example, the linear regression obtained from Nova Scotia's electrical supply for each year from 2000 to 2007 is shown in Table 5, since there is considerable variance between the individual regressions, there is no clear "best" choice. Although there are undoubtedly other methods that could be used, the average of the linear regressions is a reasonable compromise. In this example, the value of the availability criterion is -18.3.

**Table 5: Linear regressions for Nova Scotia's electrical demand between 2000 and 2007**

| Year | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| **Demand** | 11,137 | 11,366 | 11,753 | 11,954 | 12,174 | 11,944 | 10,947 | 12,044 | 11,674 |
| **Regression** | 42.7 | 4.3 | -45.8 | -79.6 | -90.0 | 28.7 | 363.5 | -370.0 | |

The average of the linear regressions can be applied to the oil production data, the results of which are shown in Table 6. By including the average, minor variations in the data are captured; for example, the Russian value declines because of a marked change in output starting in 2004, Norway's value declines slightly because of a greater decline between 2003 and 2005, while Brazil's shows a slight decline because growth between 2005 and 2007 dropped marginally.

**Table 6: The effect of metric changes in the availability criterion**

| Producer | Linear regression | 2000-07 average | Normalized average |
|---|---|---|---|
| Russian Federation | 22.35 | 11.11 | 0.63 |
| Norway | -6.43 | -7.38 | 0.00 |
| Brazil | 3.88 | 3.48 | 0.37 |

The availability of the alternatives is obtained from the average linear regression associated with each alternative. Normalizing these values allows the weighting to be applied to all other criterion values. The rightmost column in Table 6 (Normalized average) shows the normalized average of the different oil producer alternatives; if the average linear regression list contains negative values, the absolute value of the lowest negative value is added to each element in the list, effectively shifting them and ensuring no negative values.

### 3.3.2 Accessibility

Accessibility (ACS) refers to the degree or level of access that a consumer has for a particular energy alternative. The underlying premise is that accessibility refers to a means of accessing the available energy, which suggests that it can be associated with a wide variety of possible metrics. For example, if accessibility is discussed in terms of long-term changes in access, it shows the changes of growth or demand for the energy alternative. On the other hand, if the present level of demand is considered, it can show the demand for the product relative to other energy alternatives. The importance of both the change or trend in accessibility and the current accessibility suggests that two metrics should be used: one as a time-series and the other as the current demand. The metric for accessibility over time (ACS.t) and the metric for the current demand (ACS.c) can be obtained from the same time-series dataset.

As an example of the two accessibility metrics, consider the use of energy in the Swedish transportation sector between 1998 and 2007; the different energy sources and their demand (in TWh) is shown in Table 7.

**Table 7: Energy use in Swedish transportation sector (TWh) (Energimyndighet, 2008)**

| Energy source | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|
| Petrol | 47.0 | 47.2 | 46.5 | 48.4 | 48.9 | 48.6 | 47.1 | 46.5 | 45.2 | 45.8 |
| Diesel/gas oil | 26.5 | 27.0 | 26.1 | 26.6 | 30.3 | 31.6 | 34.6 | 36.4 | 37.7 | 41.8 |
| Electricity | 2.8 | 3.0 | 3.2 | 2.9 | 2.9 | 2.8 | 3.0 | 2.8 | 2.9 | 3.0 |
| Bunkers oils | 17.8 | 17.4 | 16.9 | 16.2 | 14.3 | 19.2 | 22.5 | 23.0 | 24.7 | 25.7 |
| Medium/heavy fuel oils | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.8 | 0.8 | 0.8 | 0.6 | 0.5 |
| Aviation fuels etc. | 9.6 | 9.7 | 10.8 | 10.2 | 9.3 | 9.0 | 10.0 | 10.3 | 10.6 | 11.1 |
| Natural gas, incl. LPG | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 |
| Ethanol | 0.0 | 0.1 | 0.2 | 0.2 | 0.5 | 0.9 | 1.5 | 1.7 | 1.9 | 2.1 |

Both temporal (ACS.t) and current (ACS.c) accessibility can be determined from this data. Temporal changes show the changes in demand of each energy source over time and can be obtained from the normalized, average linear regression (as is done with availability). The current demand is simply the normalized value of the final year of data, showing how transportation energy demand is met from the different energy sources. Table 8 shows the temporal and current accessibility rankings for Sweden's transportation energy sources for 1998 through 2007 and 2007, respectively.

**Table 8: Temporal and current accessibility ranking of Swedish transportation alternatives**

| Energy source | ACS.t | ACS.c |
|---|---|---|
| Petrol | 0.000 | 0.352 |
| Diesel and gasoil | 0.401 | 0.321 |
| Electricity | 0.054 | 0.023 |
| Bunkers oils | 0.259 | 0.197 |
| Medium/heavy fuel oils | 0.047 | 0.004 |
| Aviation fuels etc | 0.094 | 0.085 |
| Natural gas, incl. LPG | 0.055 | 0.002 |
| Ethanol | 0.091 | 0.016 |

In terms of temporal accessibility, diesel and gasoil have the highest ranking (0.401), followed by bunker oils (0.259), the lowest rankings are natural gas (0.055), electricity (0.054), and petrol (0.000). These values show that diesel and gasoil exhibited the greatest growth in demand between 1998 and 2007. However, current accessibility tells a somewhat different story, with petrol exhibiting the greatest demand in 2007.

### 3.3.3 Affordability

Affordability (AFF) refers to the ability to pay for a unit of energy for a particular energy service and how important the cost of energy is to the users of the service.

Although many statistical services and public interest groups maintain affordability indexes for things such as food, clothing, shelter, and heating, many are not collected over the long-term and, in some cases, appear arbitrary. Accordingly, it can be difficult in some jurisdictions to find an indicator based upon the ability to pay that can be applied uniformly across a population.

A simple ranking of the different energy sources based upon a normalization of each energy cost is another view of affordability.[1] 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.

Two ways of determining affordability are considered:

- A multi-year indicator determined from a linear regression (obtained the same way the availability and accessibility were calculated). This would indicate the change in affordability over time of each energy source.
- A single value reflecting the current cost of the different energy sources. The changing cost of an energy source does little to reflect its affordability (a low cost energy source may be increasing while an expensive one may be decreasing).

High energy costs impact those on low-income disproportionately (for example, see (Hughes, 2009d; Hughes, et al., 2009a)), suggesting that a high value of affordability (that is, cost), cannot be considered secure. Furthermore, this runs counter to the interpretation of the availability and accessibility indicators, where higher values mean more secure energy sources. Accordingly, it is necessary to reverse the ordering in affordability; that is, interpret higher cost-per-unit energy values as less secure.

Taking the reciprocal of the value and using it as the affordability indicator, means that the resulting higher values (i.e., those that are less costly per unit energy) indicate more secure energy sources. Table 9 shows the changes in residential space heating costs for 70 GJ over three heating seasons in Nova Scotia for a variety of fuel sources and heating plant efficiencies.

**Table 9: Residential space heating costs for 70 GJ (Hughes, et al., 2009a)**

| Energy source | 2006-07 | 2007-08 | 2008-09 | Temporal | Current |
|---|---|---|---|---|---|
| Biomass 60% | $955 | $1,114 | $1,592 | 0.060 | 0.220 |
| Natural gas 90% | $1,256 | $1,335 | $1,775 | 0.074 | 0.198 |
| Fuel Oil 85% | $1,857 | $2,251 | $1,962 | 0.370 | 0.179 |
| Natural gas 62% | $1,750 | $1,862 | $2,500 | 0.051 | 0.140 |
| Electricity 100% | $2,359 | $2,359 | $2,570 | 0.183 | 0.137 |
| Fuel Oil 60% | $2,631 | $3,189 | $2,779 | 0.261 | 0.126 |

In terms of temporal affordability (the normalized linear regression over the three heating seasons), fuel oil used in an 85% efficient furnace has the highest rank since the price of fuel oil dropped in 2008-09 after peaking in the 2007-08 heating season. Natural gas, biomass, and electricity have the lowest rankings (0.074, 0.060, and 0.051, respectively) because their prices increased over the three heating seasons.

[1] Note that "cost" is being used rather than "price". It is assumed that "price" refers to the price of a unit of energy, whereas the "cost" is what the consumer must pay for the energy units required by the service. Different energy conversion systems may purchase energy at the same price, but because of their differences in efficiencies, the cost to the consumer may differ.

Current affordability (the normalized reciprocal of the final year of affordability data) sees biomass ranked highest in terms of affordability and fuel oil in a 60% efficient furnace ranked the lowest.

Depending upon the energy service, the affordability criterion can include both operating and capital costs. Affordability need not have anything to do with environmental charges or taxes associated with the energy alternative.

#### 3.3.4 Acceptability

Acceptability (ACP) refers to a jurisdiction's acceptance of an energy alternative; there are a number of ways it can be defined, ranging from the environmental to the political. A common method of reflecting society's acceptance of an energy alternative is through taxation or emissions charges—higher taxes or charges are levied on those energy sources that are deemed by society to be less desirable than others. On the other hand, some energy exporting countries are considered unacceptable trading partners and their imports are shunned.

When acceptability is defined in terms an environmental or social cost, a metric for acceptability could be the sum of the charges (per unit energy) associated with each energy alternative. In this case, an increasing value implies a less secure energy alternative; however, since higher values are to indicate more secure energy alternatives, another metric is needed. Taking the reciprocal of the acceptability value may not be possible if the sum of the alternative's charges happens to be zero. Another possible metric is to reorder the acceptability values (obtained from summing the charges) by subtracting each value from the maximum acceptability value in the list. This results in the reversal of values in the list of alternatives, although the values relative to each other remain the same. The resulting values can be used as the acceptability ranking for the alternatives.

A jurisdiction's acceptance of an energy alternative can change rapidly. In a time of energy shortages, alternatives once considered unacceptable can quickly become acceptable.

### 3.4 Weights

The weight associated with each criterion, like the metrics, should be justifiable and reproducible. In AHP, the weights are determined by the respondents who are expected to have an understanding of how each criterion relates to, or impacts, the jurisdiction. The pair-wise comparison technique (described in section 2.1) is also used to compare the weights. These can then be applied to the criterion values associated with each alternative, producing the ranking vector from which the energy security indexes are obtained. Since there are typically fewer criteria than alternatives, the pair-wise comparison is not as onerous, making the results less error-prone.

The limitation of this approach is not so much that it is qualitative, but that it produces a single ranking vector based upon the current views of the respondents. These views, like those obtained when determining the alternatives' rankings, should reflect the nature of the jurisdiction. However, in some cases they may not be a true reflection of the relationship between the jurisdiction and the criteria. Furthermore, two (or more) groups of respondents may produce different weightings for the same criteria. On the other hand, if a range of weightings could be produced, a variety of questions could be asked about the different ranking vectors; for example:

- What is the resulting ranking of the alternatives from a given combination of criteria?
- How does one criterion influence the alternative ranking differently from another?
- How sensitive is an alternative's energy security index to changes in the weights?
- If certain alternatives are considered more favourable than others, what combination (or combinations) of criteria should encouraged?

# 4 Example

Eastern Canada, like most regions in the world, relies on imported oil products to meet a portion of its energy demand (Hughes, 2010). The suppliers and the volume of imports are shown in Figure 5. With rising demand for oil products elsewhere in the world and some producers struggling to maintain production, it is important to determine how secure each of the suppliers is.

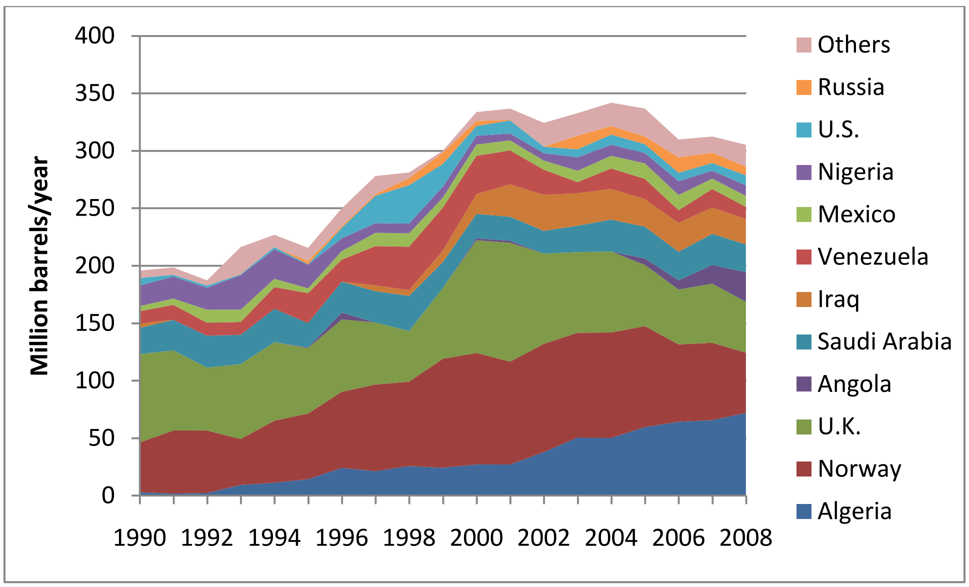


**Figure 5: Changes in eastern Canadian crude oil supplies (1990-2008) (Statistics Canada, 2009e)**

## 4.1 The ranking metrics

The ranking of the different energy suppliers (the alternatives) is based on the five criteria discussed in the previous section:

- The values for availability were obtained from the 2009 edition of the BP Statistical Review of World Energy (BP, 2009) for each of the supplying countries. The ten years between 1999 and 2008 were used to determine the average linear regression for each supplier; the worst rankings were Norway, Mexico, and the U.K.—all of whom have seen marked declines in production during this period. The country with the highest ranking for availability is Russia, followed by Angola and Saudi Arabia. Since some linear regression values were negative, the rankings were shifted to ensure that all values became zero or positive.

- Both temporal and current accessibility are obtained from the Statistics Canada data for crude oil imports into eastern Canada (Statistics Canada, 2009e). The normalized reciprocal of the average linear regression between 1999 and 2008 was calculated as the temporal accessibility of each supplier. Algeria and Angola showed the greatest growth in access during this period while Norway exhibited the least.

  Current accessibility is the most recent annual supply from each alternative. In this example, the greatest level of accessibility was Algeria, followed by Norway and the U.K. The supplied with the lowest accessibility was Russia. The ranking was obtained by normalizing the accessibility values.

- The most uniform rankings were for affordability, which was taken as the reciprocal of the price of a barrel of crude oil—higher prices are considered less secure. The values were obtained from EIA data (EIA, 2009); and differences in price were attributable to the price of a barrel of each supplier's respective type of crude oil.

- Environmental and political acceptability were not chosen as the acceptability metric as what limited environmental charges Canada imposes on carbon emissions would be uniform across all oil products and Canada makes no distinction between suppliers based upon politics. Instead, the risk associated with each supplier, as determined by the Economist Intelligence Unit (EIU), was employed as the acceptability metric (EIUCM, 2008); since lower values indicate less risk, the reciprocal of each value was obtained and the resulting list normalized. In terms of country risk, Norway is the most acceptable while Iraq, Venezuela, and Nigeria are the least acceptable.

The decision matrix is shown in Table 10.

**Table 10: Decision matrix for eastern Canadian oil imports**

| Country | Availability | Accessibility | | Affordability | Acceptability |
|---|---|---|---|---|---|
| | | Temporal | Current | | |
| Algeria | 0.1026 | 0.1635 | 0.2510 | 0.0903 | 0.0596 |
| Norway | 0.0000 | 0.0000 | 0.1834 | 0.0897 | 0.2566 |
| U.K. | 0.0086 | 0.0319 | 0.1544 | 0.0906 | 0.1390 |
| Angola | 0.1994 | 0.1632 | 0.0905 | 0.0910 | 0.0618 |
| Saudi Arabia | 0.1863 | 0.0945 | 0.0840 | 0.0933 | 0.0710 |
| Iraq | 0.1538 | 0.0894 | 0.0771 | 0.0909 | 0.0417 |
| Venezuela | 0.0329 | 0.0715 | 0.0371 | 0.0904 | 0.0445 |
| Mexico | 0.0008 | 0.0935 | 0.0333 | 0.0905 | 0.0814 |
| Nigeria | 0.0480 | 0.0983 | 0.0323 | 0.0892 | 0.0498 |
| U.S. | 0.0138 | 0.0978 | 0.0305 | 0.0930 | 0.1390 |
| Russia | 0.2540 | 0.0964 | 0.0263 | 0.0912 | 0.0556 |

The values from the decision matrix can also be represented graphically, as in Figure 6, which shows the importance of the criteria within each alternative and the contribution of the alternatives to each criterion.

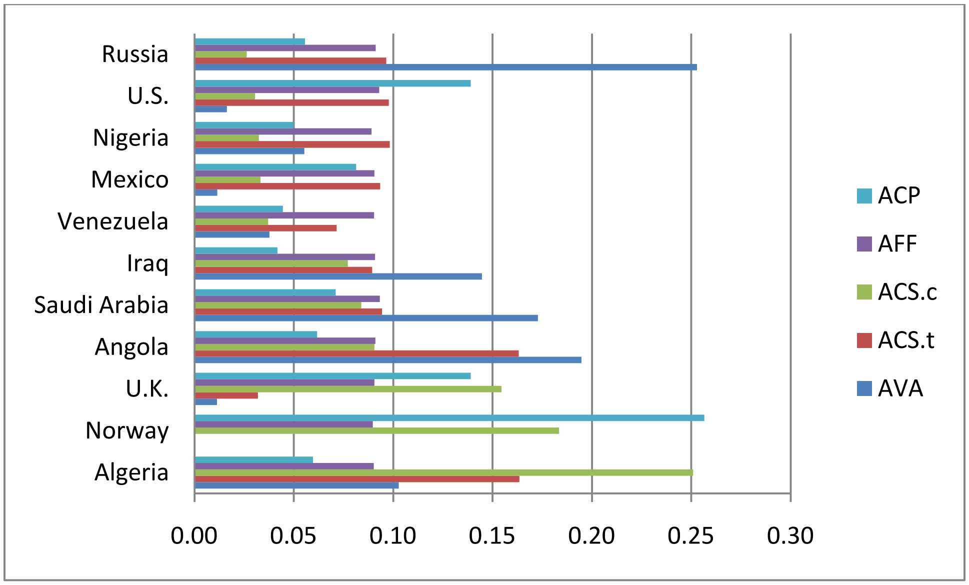


**Figure 6: Graphical representation of decision matrix (Table 10)**

Since each value in the decision matrix was obtained from quantitative data, it is reproducible.

## 4.2 Ranking vectors

A ranking vector is produced by applying criterion-specific weights to the criterion rankings of each alternative, as described in section 3.1. The simplest ranking vectors are the rankings associated with each criterion, equivalent to a weighting of 1.0 for the criterion and 0.0 to the others. Table 11 shows the highest and lowest ranking for each criterion.

**Table 11: Highest and lowest rankings for each criterion (from Table 10)**

| Criterion | Highest rank | Lowest rank |
|---|---|---|
| Availability | Russia | Norway |
| Accessibility (Temporal) | Algeria | Norway |
| Accessibility (Current) | Algeria | Russia |
| Affordability | Saudi Arabia | Nigeria |
| Acceptability | Norway | Iraq |

Although applying a weight of 1.0 to a criterion and ignoring the others is somewhat unusual, it does allow a cursory examination of the data. In this example, Table 11 exhibits some interesting combinations. For example, Russia has the highest availability but the lowest current accessibility, while Norway has the lowest availability and its temporal accessibility is the lowest. Finally, not only is Algeria experiencing the highest temporal accessibility (i.e., demand growth), it is also the most significant supplier at present (it has the highest current accessibility).

Non-zero weightings are normally applied to more than one criterion to represent the state of energy security in the jurisdiction. For example, in AHP, the weightings could reflect the respondents' view of energy in the jurisdiction. Table 12 shows the indexes for the case in which the weights are uniform (that is, equal in value). Here, Algeria is considered the most secure with Venezuela the least secure.

**Table 12: Index values from uniform weighting**

| Country | Index |
|---|---|
| Algeria | 0.133 |
| Norway | 0.106 |
| U.K. | 0.085 |
| Angola | 0.120 |
| Saudi Arabia | 0.103 |
| Iraq | 0.089 |
| Venezuela | 0.056 |
| Mexico | 0.062 |
| Nigeria | 0.065 |
| U.S. | 0.075 |
| Russia | 0.104 |

Since decision analysis techniques such as AHP recommend that the respondents reach a consensus on a single set of weights for the criteria, many weight-combinations are ignored, despite the possibility that some may lead to other conclusions or policy choices. To avoid ignoring other weight-combinations, a program has been written to enumerate the possible weight values for all criteria; weights range in value from 0.0 to 1.0 in steps of 0.05. Once the table of the different weight-combinations has been created, the values can be extracted, compared, and analyzed, as the following examples illustrate.

Figure 7 shows the range of energy security indexes if the value of acceptability varies between 0.85 and 1.0 (the other criteria can have values between 0.0 and 0.15). Norway has the best range of indexes in this case, with values between 0.218 and 0.256, while Iraq has the worst, with values between 0.042 and 0.058 (Venezuela is marginally better at the low end with a value of 0.043).

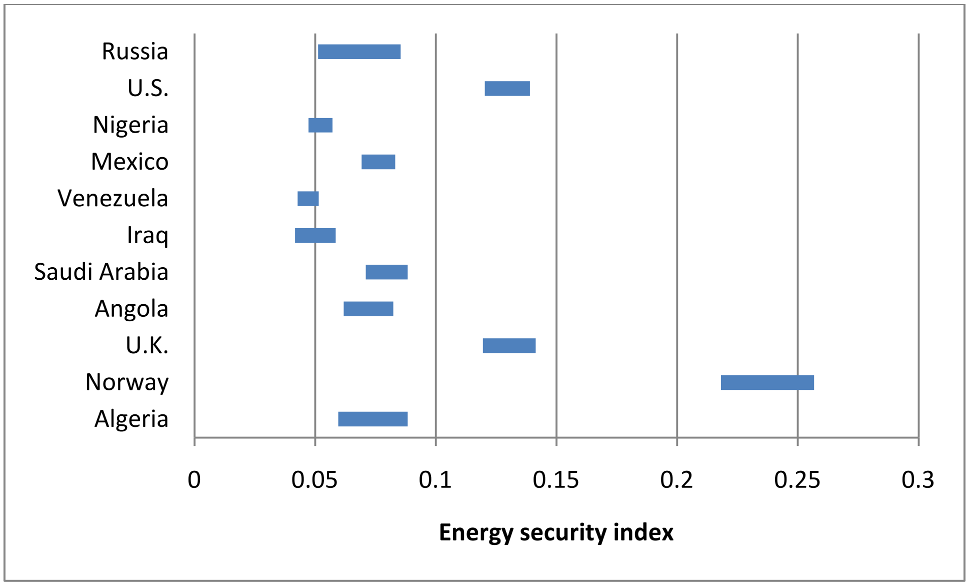


**Figure 7: Indexes with acceptability: 0.85 to 1.0**

A supplier's long-term production trend (availability) and the consumer's long-term reliance on the supplier (temporal accessibility) can give a better indication as to the range of indexes of the different alternatives. An example of this is shown in Figure 8, with availability set at 0.30 and temporal accessibility varying between 0.35 and 0.65 (temporal accessibility is considered the most important criterion in this case). The emphasis on temporal accessibility improves the indexes of Algeria, Angola, and Russia, whereas Norway, which is declining in both availability and temporal accessibility, receives a much lower index range.

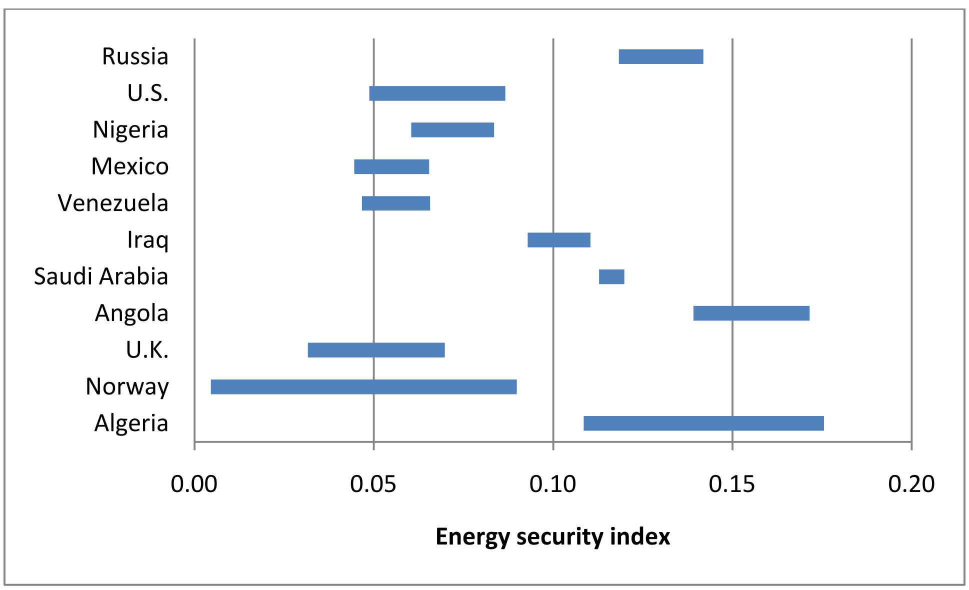


**Figure 8: Indexes with availability: 0.30 and temporal accessibility: 0.35 to 0.65**

The greater the difference between an alternative's high and low index (indicated by the line length), the more sensitive the alternative in terms of the criteria. In Figure 8, Algeria's lowest security index value occurs when acceptability is given a weight of 0.35, whereas this is when

Norway receives it highest index. Conversely, when temporal accessibility has its highest possible weight, Algeria receives its highest index and Norway its lowest.

## 5 Discussion

This paper has introduced a method of producing an energy security index for the different energy sources, infrastructure, and services used by a jurisdiction. Like other multi-criteria decision analysis tools, the method uses a decision matrix in the creation of the index. The method has five criteria and metrics, based upon APERC's four 'A's: availability (historical production from a supplier), temporal accessibility (historical supply from a supplier), current accessibility (present supply from a supplier), affordability (cost of the energy), and acceptability (environmental, social, or political acceptance of an energy source).

The ranking of the different energy alternatives under consideration can be done qualitatively or quantitatively. Although both approaches work, ranking metrics based on quantitative data are typically easier to reproduce and can be more justifiable than methods using qualitative results obtained from a group of respondents. The paper developed metrics that could be used with quantitative data to rank the alternatives.

The five criteria must be assigned weights for use in calculating the ranking vector. Rather than creating one set of weights, the paper showed how enumerating a range of weights allowed a number of possible rankings to be considered.

Perhaps not surprisingly, when creating a decision matrix with different energy sources (for example, coal, oil, and natural gas) or with data from different sources, a common energy unit must be adopted; for example, terawatt-hours (TWh), petajoules (PJ), or million-tonnes oil equivalent (Mtoe).

When determining the rankings for availability and temporal-accessibility, the average of the linear regressions from a starting year through all years to a target year is used. In many cases, the coefficient of determination ($R^2$) indicates that the regression does not fit the data well, implying that fewer years should be used in determining the average. Depending upon the data, reducing the number of years may not result in a good fit until there are so few years remaining that the influence of the earlier years is completely lost.

The example showed that the choice of criteria is up to the person or organization producing the energy security index. If the results are to compare one jurisdiction with another or simply to indicate how the jurisdiction's energy security has changed, the criteria chosen should be consistent between the jurisdictions or over time. However, the metrics should, as has been discussed, be quantitative rather than qualitative.

## 6 Concluding remarks

Energy security is becoming an important policy issue in a growing number of jurisdictions because of volatile energy markets and the production challenges faced by many producers. As a result, policymakers and politicians are looking for methods in which they can rank and then assign an energy security index to the various energy supplies used in their jurisdiction.

Many ranking techniques use a decision matrix to apply a set of criteria and their metrics and weights to rank a number of alternatives. The metrics are used to rank the alternatives within each criterion and then a ranking vector is produced by summing the products of the weights and the ranks. Each element in the ranking vector is the energy security index of the corresponding alternative.

The metrics for ranking the alternatives can be qualitative or quantitative. Qualitative metrics most often require the use of a group of respondents who are knowledgeable of the jurisdiction's energy requirements. The respondents are expected to reach a consensus on the ranking of each alternative and in determining the weights of the criteria. Although this method works, the results produced are subject to the whims and moods of the group, and the results need not be the same if a second group of respondents are asked to rank the alternatives.

The problems associated with qualitative metrics can be addressed with metrics that are applied to quantitative data. If the data is publically accessible, the results are reproducible and can be compared with results using the same data sources for other jurisdictions. The choice of metrics should be justifiable and understandable to those relying on the results.

The method for determining energy security indexes presented in this paper uses five criteria (based upon APERC's four 'A's): availability (historical production from a supplier), temporal accessibility (historical supply from a supplier), current accessibility (present supply from a supplier), affordability (cost of the energy), and acceptability (environmental, social, or political acceptance of an energy source). The metrics associated with the criteria use quantitative data. Rather than using a single set of weights, the paper showed that a range of weights allows further insight into the state of energy security in a jurisdiction.

At present, we are applying the method to examine the impact of changes in the energy security index on different energy services. We are also developing software to animate the effects of changing the criteria-weighting.

Finally, it is important to note that an energy security indexing method, such as the one described in this paper, is only one of a number of tools needed to improve a jurisdiction's energy security. The energy security index should be used to influence energy policy decisions, including energy and infrastructure choices for all energy services. It should also be revisited on a regular basis to determine whether the new state of energy security in the jurisdiction.

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