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# Energy security, energy modelling and uncertainty ☆

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ABSTRACT

The paper develops a framework to analyze energy security in an expected utility framework, where there is a risk of disruption of imported energy. The analysis shows the importance of an energy tax as a tool in maximizing expected utility, and how the level of that tax varies according to the key parameters of the system: risk aversion, probability of disruption, demand elasticity and cost of disruption.



## 1. Introduction

The concern with energy security has been rising in importance since the 1970s for many countries, industrialised and industrialising, energy importers and energy producers. Among importers of energy in Europe the picture is one of increasing dependence on imported energy to 2030 (Costantini et al., 2006), with some estimates also showing concentration of supplies as increasing. On the energy producers' side security fears also surface of a large and sudden reduction in demand for their products. This aspect is not as appreciated as much as it should among the major energy users.

A huge amount has been written on many aspects of energy security. *Ad hoc* measures have been constructed by a number of authors (IEA, 2001; Kendell, 2001; von Hirschhausen and Neumann, 2003). These measures of supply security can be grouped into two categories: dependence, and vulnerability, represented both in physical and economic terms. Physical measures describe the relative level of imports of energy or the prospects for shortages of energy and disruptions of flows. Economic measures describe the cost of imports or the prospects for price shocks.

One strand, which has been less *ad hoc* has emphasised the role diversity as a basis for measuring energy security. This has lead to measures such as the Herfindahl and Shannon Indices, developed further by Stirling (1996) and more recently by Jansen et al. (2009) as long-term security of supply indicators.

A different approach to the diversity concept is that of portfolio-based energy planning. Here, portfolio theory, as used traditionally in financial planning, is employed for the purpose of selecting an optimal mix of energy sources. For an example of this, see Awerbuch (2004).

Notwithstanding all these efforts it is fair to say that the subject lacks a strong theoretical basis. What are the welfare implications of increasing insecurity? How much does it matter at the individual level? Can we design policies that reduce such insecurity and that can be evaluated against indicators that are based on measures of social well-being?

This paper is an attempt to develop a model that helps us understand energy security questions in a traditional economic framework. The uncertainty associated with energy supply is explicitly modelled and linked to the consumer and producer surplus associated with the use of energy. Policies are set to maximise this expected surplus. The results are examined in a simple simulation of the model with plausible numerical parameters.

Of course no theoretical model can capture all aspects of the complex reality of the energy security problem, but we would argue that simple models such as this add to our understanding of the issues involved and contribute significantly to the debate. We also believe that the model can be developed further to make it more realistic.

The paper is structured as follows. Section 2 provides a statement of the problem. Section 3 provides a formal statement of the problem, Section 4 reports numerical results and Section 5 gives some conclusions.

## 2. The statement of the problem

The following model has been designed to capture the following elements of the energy security problem:

(A) The cheapest source of energy is imported energy, when it is supplied under 'normal' conditions. However, if the imported

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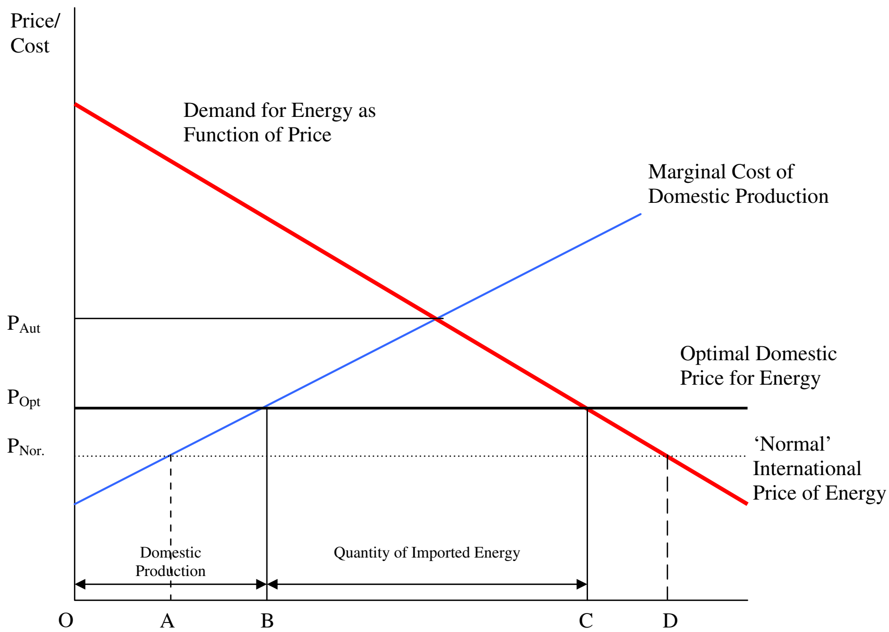


**Fig. 1.** Optimal response to insecure imported energy. *Notes*: $P_{\text{Aut}}$ = price with no imports (i.e. under autarky), $P_{\text{Opt}}$ = price that maximises expected consumer surplus and $P_{\text{Nor}}$ = Price that would prevail in the absence of any disruptions to supply.

energy supply fails, for one reason or another, the result is a shortage in the domestic markets and prices are substantially higher.

(B) Domestic production can and does meet a part of the national energy demand. The higher the supply price of energy, the more will be met from domestic sources.[1]

(C) The risks of energy supply disruptions or failures are well understood and can be characterized in probability terms, based on the historic experience.

Few would argue with elements A and B. There could be some dispute as to whether risks of disruption can indeed be captured in probabilistic terms. We have some historic data on the frequencies of disruptions of oil supplies, for example, and of certain types of natural disasters that disrupt energy flows, but we are less able to derive frequencies for nuclear accidents and failures of supply from that source. To assume that probabilities of disruption can be defined is therefore a simplification but one that serves to provide some insight into the appropriate controls for responding to the security problem. It is also a simplification in that the probabilities are not stationary, but change as the geopolitical situation changes. Eventually we may wish to look at endogenous or Bayesian probabilities, but before we can do that we need to investigate the case of exogenously given probabilities.

The social problem is also tremendously simplified to deal make the analysis tractable. Society's well-being is a function of the utility it derives from the consumption of energy, and that utility function is a well-behaved von Neumann–Morgernstern utility function that exhibits risk aversion. The main argument of the utility function is the consumer and domestic producer surplus that a given level of energy provides. Recall that consumer surplus is the difference between the total willingness of consumers to pay for a given amount of a commodity and the amount that they actually pay. Producer surplus is the difference between the revenues received by the suppliers and their full costs of supply.

Society's choice can be described in terms of setting the total consumption of energy to maximise the expected utility of consumer plus producer surplus.[2] Of course, in a market economy the government does not directly determine levels of imports and domestic output. But, by setting the domestic price of energy, it can influence both these variables. This price will typically be higher than the 'normal' international price of imported energy, the 'premium' being added to encourage domestic production and reduce dependence on imports.

The problem is shown in Fig. 1. At the normal international price of energy domestic production would be OA. This price does not, however, maximize the expected consumer surplus because there are times when the price is much higher for external reasons. In order to maximise consumer surplus, a tax has to be placed on imported energy. This tax increases the returns to domestic production, raising it to OB, representing an increase in domestic production of AB. At the same time it reduces the returns to the importing party, and imports fall from AD to BC, a reduction of AB+CD.[3]

There are many aspects of energy security that this analysis captures but not all. A recent UNECE publication (UNECE, 2007) identifies the following sources of energy security:

(a) The narrowing margin between oil supply and demand, which has driven up prices.

[1] This is a medium to long term perspective, as potential for switching to domestic sources in the short term is limited.

[2] Of course by taking a consumer and producer surplus approach in one market we are ignoring effects across markets. This limitation should be recognized. We would argue that in the context of understanding the energy market better much can be gained from such an approach, although further work in a general equilibrium context also needs to be pursued.

[3] A referee has noted that a regulation that reduced overall demand would have a similar effect, of reducing energy consumption and increasing energy security through lower imports. It would also induce measures for energy efficiency. The tax proposed here seeks to do much the same thing.

(b) The volatility of oil prices arising from international tensions, terrorism and potential for supply disruptions.
(c) The concentration of known reserves and resources in a limited number of the world's sub-regions.
(d) The restricted access to oil and gas companies for developing hydrocarbon reserves in some countries.
(e) The rising cost of developing incremental sources of energy supplies.
(f) The lengthening supply routes.
(g) The lack of adequate investment along the energy supply chain.

We do not agree with (a)—energy security is not really an issue of high prices but of volatile prices. The model focuses therefore on (b). It should be possible to look at the impacts of (e) and (f) using this model—i.e. the increase in costs of energy supply over time but this has not been done in the present paper.

In terms of policies the same publication identifies the following measures as addressing the problem of energy security:

(i) Promoting investment in the energy sector though the provision of legal frameworks, regulatory environments, tax incentives together with fair and transparent processes to foster the public–private partnerships needed to promote and protect investments in existing and new oil and gas supplies.
(ii) Removing barriers to promote and protect investment in existing and new oil and gas supplies.
(iii) Removing barriers to trade and investment for both private and public energy companies.
(iv) Encouraging both energy producers and consumers to secure long term contract that reflect a committed demand for hydrocarbons.
(v) Seeking convergence of norms, standards and practices as well as new forms of cooperation to facilitate the financing of resource developments.

The model looks at how policies under (i) specifically tax policies can help increase security. Policies under (ii)–(v) can be seen as reducing the risks of disruptions and can thereby also be modelled in this framework.

## 3. A formal representation of the problem

The problem can be represented mathematically as follows:
The objective is to maximize with respect to $x_0$ and $x_1$:

$$\underset{x_0,x_1}{Max}\left[\left(\pi\cdot U\left(\int_0^{x_0+x_1}P(x')\,dx'-C(x_0)-c_{1a}x_1\right)\right)+\left((1-\pi)U\left(\int_0^{x_0+x_1}P(x')\,dx'-C(x_0)-c_{1b}x_1\right)\right)\right] \quad (1)$$

where, $U(\cdot)$ is the von Neumann Morgernstern concave utility function; $P(x)$ is the inverse demand function for energy ($P'(x)<0$); $C(x_0)$ is the total cost function for domestic energy ($C'(x_0)>0$, $C(0)<c_{1a}$); $c_{1a}$ is the normal cost per unit of imported energy; $c_{1b}$ is the cost per unit of imported energy with disruption; $x_0$ is the quantity of domestic energy produced and consumed; $x_1$ is the quantity of imported energy produced nd consumed; $1-\pi$ is the probability of a disruption in supply of imported energy; $x$ is the total energy consumed $=x_0+x_1$.

If the problem has an interior solution it is characterized with levels of $x_{0^*}$, $x_{1^*}$ and $x_*$ by:

$$P(x_*)=\frac{dC(x_{0^*})}{dx_0} \quad (2)$$

$$\pi U_1'\{P(x_*)-c_{1a}\}+(1-\pi)U_1'\{P(x_*)-c_{1b}\}=0 \quad (3)$$

Eq. (2) states that at the optimum the marginal cost of domestic production equals the consumer price. This has the important implication that *at the optimum there are no specific subsidies or taxes on domestic production*.

Eq. (3) states that the expected marginal utility from an additional unit of imports is equal to zero.

It can also be shown that the solution characterized above has the property that the optimal price $P(x_*)$ will have the following properties:

$$\pi\cdot c_{1a}+(1-\pi)\cdot c_{1b}\leqslant P(x_*) \quad (4)$$

That is, the optimal domestic price is not less than the expected price of imports. The difference between the domestic price and the expected price of imports reflects the risk premium—the greater this risk or the greater the risk aversion, the greater will be this premium. The proof of this statement is given in Appendix A.

### 3.1. Numerical analysis using specific functional forms

In order to gain some further insight into the problem we take specific functional forms and look at how the solution behaves for plausible parameter values. The forms of the equations are:

(a) The utility function is the familiar iso-elastic form:

$$U(\cdot)=\frac{(1-\beta)}{\beta}(\cdot)^{\beta} \quad (5)$$

where $\beta<1$ and is the coefficient of relative risk aversion.

(b) The inverse demand function is linear in prices

$$P(x)=a+bx \quad a>0,\ b<0 \quad (6)$$

(c) The total cost function is a simple quadratic form

$$C(x_0)=c_0x_0^2 \quad (7)$$

Note that a problem only exists if the price at which domestic production would satisfy the entire demand is greater than the 'normal' price in international markets. In terms of Fig. 1 $P_{Aut}>P_{Nor}$. For the specific functional forms chosen this implies:

$$a+\frac{a\cdot b}{(2c_0-b)}>c_{1a} \quad (8)$$

### 3.2. Numerical ranges for the parameters

The following ranges have been taken for the key parameters in making the calculations reported below.

$\beta$ The range taken is 0.3–0.7, which is the typical range in the risk literature for the coefficient of relative risk aversion (Mehra and Prescott, 1995).

$1-\pi$ The probability of a disruption in supply in any year is set at between 0.1 and 0.3. This guess is based on the frequency of disruptions observed in the last 50 years, when there have been 17 disruptions to oil deliveries, but only 4 of these were major (Hunt and Markandya, 2004)

$a$, $b$ The values of the demand equation parameters have been chosen to that the demand elasticity ranges from −0.4 to −0.7.

$c_0$ The coefficient on the cost equation is set so that at the world price of $c_{1a}$, domestic production meets 25% of domestic demand. Note that the form of the cost

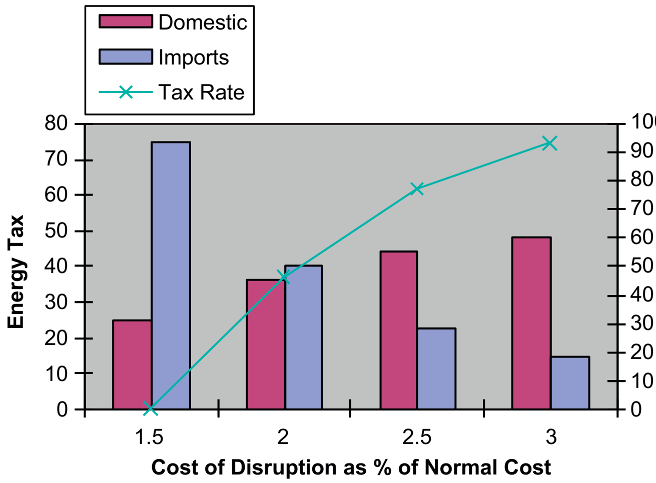


**Fig. 2.** Variation by cost of disruption.

function in (7) fixes the supply elasticity from domestic production is equal to one. Both these values are not regarded as untypical for European countries.

$c_{1b}/c_{1a}$ The costs of foreign supply with a disruption relative to the costs without disruption are set to range from 1.5 to 3.0. Experience from oil disruptions indicates that the price can increase by over 100% during the period of the disruption and there are other costs to consider (e.g. costs in terms of direct loss of welfare).

## 4. Numerical results

The numerical results of the model are given below. In each case the sensitivity of the optimal solution to the parameters of the model are measured in terms of changes in the output of domestic energy, the level of imported energy, total consumption and the optimal tax rate as a percentage of the price of energy.

### 4.1. Sensitivity to costs of disruption[4]

Fig. 2 shows how the solution varies with the costs of disruption. At a cost of 1.5 times the normal price there is no restraint on total energy consumption and so the tax on energy is zero. As costs rise to 2 times the normal price of energy, however, total consumption falls by 24%, implying substantial demand restraint. Energy dependence also decline substantially with increasing costs of disruption. As the cost rises from 1.5 to 3.0 for example, the amount of imported energy declines by 80% and domestic production trebles. The taxes on energy go from zero with a cost of 1.5, to 70% with a cost of 3. *Hence the solution is very sensitive to this parameter.*

### 4.2. Sensitivity to probability of disruption

Fig. 3 shows the sensitivity of the solution to the probability of disruption. With a probability of 0.1 (10%), demand is restrained by 22% (i.e. it is 22% less than it would be with no probability of disruption. When the probability increases to 0.3 (30%), however, the restraint increases only marginally—to 26%. Imports fall with the increased probability by 16% as we go from 0.1 to 0.3, and domestic production increases by 10%. The tax on energy ranges from 42% (0.1) to 53% (0.3). *Hence, although the probability is important in determining the scope of the reduction in imports, the impact is not as much as one might expect.*

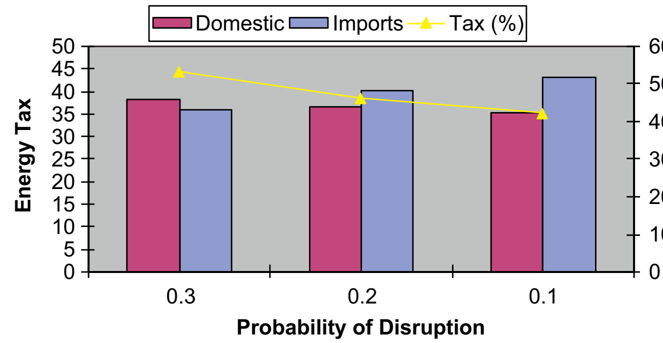


**Fig. 3.** Energy variations by probability disruption.

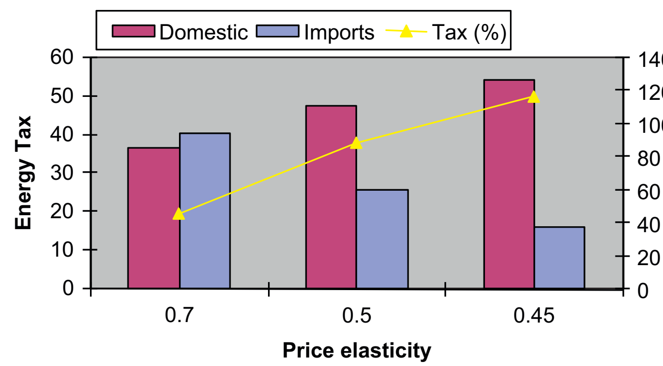


**Fig. 4.** Variations with elasticity of demand.

### 4.3. Sensitivity to the price elasticity of demand

Fig. 4 shows the sensitivity to the price elasticity of demand. Lowering the elasticity from 0.7 to 0.5 has major implications for energy policy. When the energy tax increases from 50% to 117%, imports fall by 60% and domestic production increases by 50%. Hence the model is very sensitive to this parameter. The more inelastic demand is, the greater the incentives to go for reduced energy dependence and to develop domestic resources.[5]

### 4.4. Sensitivity to risk aversion parameter

The results of varying the risk aversion parameter are shown in Fig. 4. There is little impact within the range of this parameter: lowering the coefficient of relative risk aversion from 0.7 to 0.5 causes energy taxes to fall by about 6%, imports to rise by about 12% and domestic output to fall by 10%.

[4] In each simulation the 'default values of the parameters that are not changing are: costs of disruption (2.0), probability of disruption (0.20, elasticity of demand (0.5) and risk aversion (0.5).

[5] is worth noting that the model does not work for elasticities lower than 0.45, as the expected utility is not defined—i.e. a solution to Eqs. (2) and (3) cannot be found. Further work on lower elasticity demand functions is being undertaken.

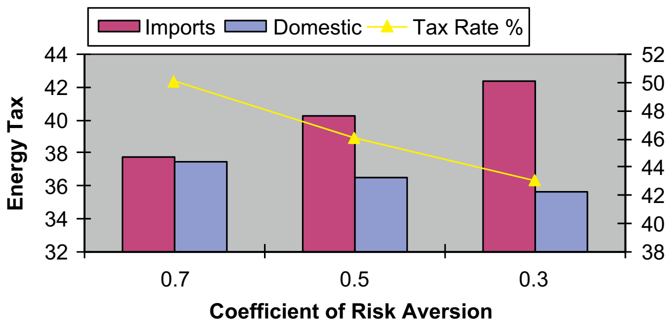


**Fig. 5.** Variations by risk aversion.

## 5. Conclusions

This analysis has shown how important a tool is the energy tax in addressing energy security, and how the level of that tax varies according to the key parameters of the system: risk aversion, probability of disruption, demand elasticity and cost of disruption (Fig. 5).

The key findings from the paper are:

(a) It is never optimal to tax or subsidize only the domestic production of energy. All taxes should be applied to all energy sources. In this context the WTO rules in terms of forbidding public support to specific domestic industries and altering market competition make sense. Nevertheless, there are a number of instances where subsidies are effectively provided to domestic energy producers. Cases in point include, for example biofuel programs in the EU and US.

(b) The optimal tax rate is:
  (i) Very sensitive to the costs arising from a disruption of supply and to the elasticity of demand for energy.
  (ii) Somewhat less sensitive to the probability of disruption and the degree of risk aversion.

The model is of course, only a partial representation of reality. But it is an important one and captures the significant role that internal energy pricing can play in reducing the impacts of uncertainty of foreign supply. To make the model more 'realistic' we need to:

- Model risk and costs more realistically as joint probability distribution for the two.
- Take account of measures that reduce costs of disruption but have a cost themselves (e.g. holding of stocks). Stock levels are not calculated in this way at present.
- Develop links between measures of dependence and vulnerability and parameters such as risk of disruption.
- Assess more carefully exactly how much ES is an externality—how much of the risk has been internalized.

We intend to continue this work under future projects on energy security.

## Appendix A

The proof of statement (4) is as follows:
Eq. (3) in full is

$$\pi U'(f(c_{1a}))(P(x)-c_{1a})+(1-\pi)U'(f(c_{1b}))(P(x)-c_{1b})=0$$

where

$$f(c)=\int_0^{x_0+x_1} P(x')\,dx'-C(x_0)-cx_1.$$

This gives

$$\{\pi U'(f(c_{1a}))+(1-\pi)U'(f(c_{1b}))\}P(x)$$
$$=c_{1a}\pi U'(f(c_{1a}))+c_{1b}(1-\pi)U'(f(c_{1b})).$$

Write

$$EPI=\pi c_{1a}+(1-\pi)c_{1b}$$

and note that this can also be written as

$$EPI=c_{1a}+(1-\pi)(c_{1b}-c_{1a}).$$

Then

$$\{\pi U'(f(c_{1a}))+(1-\pi)U'(f(c_{1b}))\}(P(x)-EPI)$$
$$=c_{1a}\pi U'(f(c_{1a}))+c_{1b}(1-\pi)U'(f(c_{1b}))$$
$$-EPI\{\pi U'(f(c_{1a}))+(1-\pi)U'(f(c_{1b}))\}.$$

This reduces to

$$\{\pi U'(f(c_{1a}))+(1-\pi)U'(f(c_{1b}))\}(P(x)-EPI)$$
$$=(c_{1b}-c_{1a})(1-\pi)\pi\{U'(f(c_{1b}))-U'(f(c_{1a}))\}.$$

Since $c_{1b}>c_{1a}$, it follows that $P(x)>EPI$.

## References

Awerbuch, S., 2004. Portfolio-based electricity generation planning: implications for renewables and energy security. Report submitted to Renewable Energy & Energy Efficiency Partnership (REEEP), FCO London and UNEP Paris.
Costantini, V., Gracceva, F., Markandya, A., Vicini, G., 2006. Security of energy supply: comparing scenarios from a European perspective. Energy Policy 35, 210–226.
Hunt, A.S.P., Markandya, A., 2004. Final Report on Work Package 3: The Externalities of Energy Insecurity: ExternE-Pol Research Project for European Commission. Available at: 〈http://www.externe.info/expolwp3.pdf〉.
IEA, 2001. Toward a Sustainable Energy Future, OECD/IEA, Paris.
Jansen, J., Scheepers, M., Seebregts, A., 2009. "Energy Security": What is it and (How) Can it be Measured? Energy Policy, this volume.
Kendell, J.M., 2001. Measures of Oil Import Dependence, EIA-DOE.
Mehra, R., Prescott, E.C., 1995. The equity premium—a puzzle. Journal of Monetary Economics 15, 145–161.
Stirling, A.C., 1996. On the economics and analysis of diversity, Paper No. 28, Science Policy Research Unit (SPRU) University of Sussex.
UNECE, 2007. Emerging global energy security issues. The Energy Series No. 36. UN, Geneva.
von Hirschhausen, C., Neumann, A., 2003. Security of 'Gas' Supply: Conceptual Issues, Contractual Arrangements, and the Current EU Situation. In: Paper at INDES Workshop on Insuring against Disruptions of Energy Supply, 6–7 May 2003, Amsterdam.