On the Choice of Tax Base to Reduce
Greenhouse Gas Emissions in the Context of Electricity
Generation

by

Rob Fraser
Professor of Agricultural Economics
Imperial College London – Wye Campus
and
Adjunct Professor of Agricultural and
Resource Economics, University of Western Australia
Abstract

This paper analyses the role of uncertain demand in determining the government’s choice between an ad valorem and a specific base for its tax to reduce greenhouse gas emissions in the electricity generating sector. Using a model of optimal capacity choice for a price-taking firm facing demand uncertainty it is shown that an ad valorem tax is more effective in reducing emissions than its equivalent specific tax, although this benefit comes at the cost of lower reliability of electricity supply. A numerical analysis provides a robust finding that the ad valorem tax is expected to generate greater tax revenue, thereby providing support for the choice of this tax base in situations where the extra tax revenue can be used to compensate consumers for reduced reliability of supply.
Introduction

In the context of greenhouse gas emissions the environmental economics literature has considered a range of issues relating to the best choice of government policy involvement to reduce such emissions. A central feature of this literature has been the choice between emissions taxes and tradeable permits. For example Fischer, Parry and Pizer (2003) have examined this choice in a theoretical context where technological innovation is endogenous. In contrast, the most important industry sector contributing to these emissions is that of electricity generation, where the focus of the literature has been on the optimal level of carbon tax, probably because the typically small number of producers in this sector undermines the effectiveness of the tradeable permits instrument. For example, in a theoretical context Goulder and Mathai (2000) consider the optimal size of carbon tax, while Burtraw, Krupnich, Palmer, Paul, Toman and Bloyd (2003) use numerical experiments to evaluate the impact of alternative sizes of carbon tax on emissions. Perhaps for reasons of simplification, this literature typically avoids analysing the role of uncertainty in influencing the optimal government intervention. For example: “Our work abstracts from some important issues. One is uncertainty” (Goulder and Mathai, p.30). However, as demonstrated by Weitzman (2002), introducing uncertainty as a feature of the policy context can reverse the optimal choice of policy instrument. In addition, in the area of commodity taxation allowing for uncertainty has been shown to influence the choice between ad valorem and specific tax bases (Fraser, 1985).

To date, by abstracting from uncertainty as a feature of the policy context the literature on the use of carbon taxes to reduce greenhouse gas emissions from electricity generation has trivialised the distinction between ad valorem and specific tax bases as alternative policy instruments. But as recent market behaviour demonstrates, fluctuations in the
demand for energy can be substantial, and it follows that uncertainty of demand is likely to be an important consideration in determining both investment and output in the electricity sector. Therefore, the aim of this paper is to undertake an assessment of the relative performance of ad valorem and specific taxes in reducing greenhouse gas emissions from electricity generation in the situation where the demand for electricity is uncertain.

The structure of the paper is as follows. Section 1 develops a model of optimal investment by a firm in electricity generating capacity in the face of uncertain demands. Being a price-taker, and given this capacity constraint, uncertain demand manifests itself for the firm as uncertainty both of price and of sales, with a positive correlation between these uncertainties. Within this decision-making context consideration is then given to the relative performance of an ad valorem and a specific emission tax base, where these alternative tax bases are linked through the concept of “ad valorem equivalence” (Musgrave, 1959). Relative performance is evaluated by comparison of the impact of the choice of tax base on expected emissions, the reliability of electricity supply and expected tax revenue. In order to deal with ambiguity in the algebraic analysis of this Section, Section 2 of the paper undertakes a numerical analysis of the issue of the choice of tax instrument. This section includes sensitivity analyses of parameter values in order to evaluate the robustness of the findings. The paper ends with a brief conclusion.

1 Weitzman’s analysis shows that allowing for fish stock uncertainty reverses the choice between harvest quotas and landing fees as the socially optimal policy instrument to regulate catch sizes.
Section 1: Model Development

As stated in the Introduction, the price-taking firm’s decision problem is the optimal choice of generating capacity in the face of uncertain demand – which manifests itself as both price and sales uncertainty, with a positive correlation between the two. Given the capacity constraint, sales \(A\) will be the lesser of demand \(x\) and capacity \(k\):

\[
A = \begin{cases} 
  x & \text{if } x < k \\
  k & \text{if } x \geq k 
\end{cases}
\]  

On this basis expected sales \(E(A)\) is given by:

\[
E(A) = \int_0^k xf(x)dx + \int_k^\infty kf(x)dx
\]  

In what follows it is assumed that the firm is risk neutral so that its objective is the maximisation of expected profit \(E(\pi)\). In the absence of an emissions tax this is given by:

\[
E(\pi) = E(pA) - ck
\]  

where:

\(p\) = uncertain price

\(c\) = known cost per unit of capacity.

Given that price and sales are jointly determined by uncertain demand, equation (3) can be rewritten as:

\[
E(\pi) = E(p)E(A) + Cov(p,A) - ck
\]  

where:

\(Cov(p,A)\) = covariance between price and sales

\(E(p)\) = expected price.

\[\text{Note that this price can be specified to be net of any operating costs of satisfying demand.}\]
On this basis, the first order condition for optimal capacity is given by:

$$E(p) \frac{\partial E(A)}{\partial k} + \frac{\partial Cov(p, A)}{\partial k} = c$$  \hspace{1cm} (5)

From equation (2):

$$\frac{\partial E(A)}{\partial k} = (1 - F(k)) > 0$$  \hspace{1cm} (6)

where $F(k) =$ probability of capacity exceeding demand.

Note that $F(k)$ is referred to as the “reliability” of electricity supply (Fraser, 1994). Note also from equation (1) that:

$$\frac{\partial Cov(p, A)}{\partial k} > 0$$  \hspace{1cm} (7)

Next consider the introduction of an emissions tax. Because it has been assumed that the firm uses a single production technology there is a one-to-one relationship between electricity sales and greenhouse gas emissions. As a consequence, expected sales can be used as a substitute measure of expected emissions, and therefore as a measure of the impact of an emissions tax on expected emissions. In what follows the specific emissions tax represents an amount ($t_s$) per unit of sales. While the ad valorem emissions tax is specified as a percentage ($t_v$) of the price per unit of sales. On this basis expected profit in the presence of the specific emissions tax ($E(\pi_s)$) is given by:

$$E(\pi_s) \hspace{0.5cm} = \hspace{0.5cm} E(pA) - t_sE(A) - ck$$ \hspace{1cm} (8)

from which:

$$E(\pi_s) \hspace{0.5cm} = \hspace{0.5cm} E(p)E(A) + Cov(p, A) - t_sE(A) - ck$$  \hspace{1cm} (9)

And the firm’s first order condition for optimal generating capacity is given by:

$$\frac{E(p)\partial E(A)}{\partial k} + \frac{\partial Cov(p, A)}{\partial k} - t_s\frac{\partial E(A)}{\partial k} = c$$  \hspace{1cm} (10)
While in the case of the ad valorem emissions tax expected profit \((E(\pi_v))\) is given by:

\[
E(\pi_v) = E(p(1-t_v)A) - ck
\]  

(11)

from which:

\[
E(\pi_v) = (E(p)E(A) + Cov(p, A))(1-t_v) - ck
\]  

(12)

And the firm’s first order condition for optimal generating capacity is given by:

\[
\left( \frac{E(p)\partial E(A)}{\partial k} + \frac{\partial Cov(p, A)}{\partial k} \right)(1-t_v) = c
\]  

(13)

In order to evaluate their relative performance, the two tax bases are linked together using the concept of ad valorem equivalence.\(^3\) In the context of an uncertain price this concept involves comparing a specific tax to an ad valorem tax which represents an equivalent amount of the expected price:

\[
t_s = t_v E(p)
\]  

(14)

Using this representation, subtracting the first order conditions from each other gives:

\[
\frac{\partial E(\pi_s)}{\partial k} - \frac{\partial E(\pi_s)}{\partial k} = - t_v \frac{\partial Cov(p, A)}{\partial k} < 0
\]  

(15)

It follows from equation (15) that the ad valorem tax will have a larger negative impact on the optimal generating capacity than its equivalent specific tax. Moreover, combining this with equation (6):

\[
\frac{\partial E(A)}{\partial k} > 0
\]  

(6’)

it follows that the ad valorem tax will also have a larger negative impact on expected sales, and therefore expected emissions. As a consequence, if the choice of the tax base is judged by its effectiveness in reducing expected emissions, then it is clear from the above that an ad valorem tax will be more effective than its equivalent specific tax. The explanation for this finding lies in the differential impact of the two taxes on expected emissions.

\(^3\) From Musgrave (1959) “compare a unit tax and an ad valorem tax that imposes the same burden at the initial price” (p303).
profit. In particular, whereas the impact of the specific tax depends only on the expected level of sales \(E(A)\), the impact of the ad valorem tax depends on the expected combined outcomes of uncertain price and sales as expected revenue \(E(pA)\). Given the positive covariance between price and sales, the ad valorem tax takes from the firm a share of the beneficial impact of this positive covariance on expected revenue - which is not the case for the specific tax (compare equations (9) and (12)).

This explanation also suggests that the government’s expected tax revenue from the ad valorem tax will exceed that from its equivalent specific tax. In particular from equation (9) evaluated at the optimal generating capacity for the specific tax expected tax revenue from the specific tax \(ETR_s\) is given by:

\[
ETR_s = t_s E(A_s) \quad (16)
\]

where:

\(E(A_s)\) = expected sales in the presence of the specific tax.

While from equation (12) evaluated at the optimal generating capacity for the ad valorem tax expected tax revenue from the ad valorem tax \(ETR_v\) is given by:

\[
ETR_v = t_v, \quad (17)
\]

where: \(E(A_v)\) = expected sales in the presence of the ad valorem tax.

Substituting equation (14) and subtracting equation (16) from equation (17) gives:

\[
ETR_v - ETR_s = t_v E(p)(E(A_v) - E(A_s)) + t_v \text{Cov}(p, A_v) \quad (18)
\]

\footnote{Note that if the firm was risk averse then the ad valorem tax would have the additional beneficial effect of sharing the uncertainty of profit with the government.}
It follows that since:

\[ E(A_s) < E(A_v) \]  \hspace{1cm} (19)

the first term on the right-hand-side of equation (18) is negative, while the second term is positive. Therefore, while it is analytically unambiguous that the ad valorem tax is more effective than its equivalent specific tax in reducing expected emissions, it is unclear whether it also provides greater expected tax revenue.

In addition, note that since:

\[ \frac{\partial F(k)}{\partial k} > 0 \]  \hspace{1cm} (20)

it may be concluded the ad valorem tax also results in a larger probability of demand exceeding capacity than its equivalent specific tax. Consequently, the greater expected social benefit of reduced greenhouse gas emissions from the ad valorem tax comes at greater expected cost to consumers in terms of the reduced reliability of electricity supply.

In summary, it has been shown in this section that the ad valorem emissions tax is more effective in reducing expected emissions than its equivalent specific tax. However, with the ad valorem tax there is also an associated greater expected cost of reduced reliability of supply, and between the two tax bases there is an analytical ambiguity in terms of the relative level of expected tax revenue. Therefore, in the next section a numerical analysis is undertaken with a view both to clarifying this analytical ambiguity and to evaluating the trade-off between expected social benefits and consumer reliability costs of the choice of emissions tax base.
Section 2: Numerical Analysis

In order to undertake a numerical analysis of the model developed in the previous section it is necessary to specify both the probability distributions characterising price and sales uncertainty and a set of base case parameters values.

With the firm’s price and sales uncertainties jointly determined by fluctuations in market demand, it is assumed in what follows that the underlying distribution of these two variables is a joint normal distribution. On this basis the covariance between price and sales is given by:

$$\text{Cov}(p, A) = \rho \sigma_p \sigma_A$$

(21)

where:

- $\rho$ = correlation coefficient
- $\sigma_p$ = standard deviation of price
- $\sigma_A$ = standard deviation of sales

Since the distribution of sales is a Winsorising of a normal demand distribution and the firm’s capacity constraint, its variance ($\text{Var}(A)$) is given by:

$$\text{Var}(A) = \int_{0}^{k} (x - E(A))^2 f(x)dx + \int_{k}^{\infty} (k - E(A))^2 f(x)dx$$

(22)

where:

- $E(A)$ is given by equation (2).

Using this formulation it is shown in the Appendix that:

$$\frac{\partial \text{Cov}(p, A)}{\partial k} = \frac{\text{Cov}(p, A)}{\text{Var}(A)} \left( k - E(A) \right) \left( 1 - F(k) \right)$$

(23)

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5 See Mood, Graybill and Boes (1974), p165
6 See Johnson and Leone (1964), p128
Finally, equations (2) and (22) can be re-written as:

\[
E(A) = F(k) \left( \bar{x} - \sigma_x Z(k) / F(k) \right) + (1 - F(k))k
\]

(24)

\[
Var(A) = F(k) \sigma^2_x \left[ 1 + \frac{(\bar{x} - k) Z(k)}{\sigma_x F(k)} - \left( \frac{-Z(k)}{F(k)} \right)^2 \right]
\]

\[
+ F(k) (1 - F(k)) \left( \bar{x} - \sigma_x Z(k) / F(k) - k \right)^2
\]

(25)

when:

\[\sigma^2_x = \text{variance of } x\]

\[\sigma_x = \text{standard deviation of } x\]

\[\bar{x} = \text{mean of } x\]

\[Z(k) = \text{ordinate of the standard normal distribution at } k\]

The base case set of parameter values is as follows:

\[
E(p) = 100
\]

\[
Var(p) = 625 \ (\sigma_p = 25)
\]

\[
\bar{x} = 100
\]

\[
Var(x) = 625 \ (\sigma_x = 25)
\]

\[
\rho = 0.75
\]

\[
t_s = 10; \quad t_v = 10\%
\]

\[
c = 20 \text{ or } 70
\]

Note from the above that:

\[
t_v E(p) = t_s
\]

as is required for ad valorem equivalence, and that two levels of capacity cost are used in the base case to represent low and high cost production technologies.

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\(^7\) See Johnson and Leone (1964), p129
On this basis Table 1 contains details of the base case set of numerical results. These numerical results confirm the algebraic findings of Section 1 that the ad valorem tax is more effective than its equivalent specific tax in reducing emissions, but that this greater effectiveness comes at the cost of reduced reliability of supply for consumers. In addition, these results clarify the algebraic ambiguity of Section 1 regarding which tax base features the larger expected tax revenue. In particular, Table 1 shows that expected tax revenue is greater for the ad valorem tax, and that this finding is robust with respect to the cost of the production technology. In relation to the magnitude of the various impacts, the emission-reducing effectiveness of the ad valorem tax is greater for the high cost technology (+0.5% compared with +0.1%), but so is the extra cost of reduced reliability of supply (+2.5% compared with +0.5%). By contrast, the enhanced revenue-raising feature of the ad valorem tax is more apparent for the low cost technology (+4.0% compared with +1.8%). Overall, the results in Table 1 suggest that the case for choosing one tax base over the other is ambiguous, although on balance the ad valorem tax may be preferred as an emission-reducing instrument if its greater expected tax revenues could be used to compensate consumers for its lower reliability of supply.

Consider next the robustness of these findings with respect to the level of demand uncertainty. In this context Table 2 contains details of the impact on the numerical results for the high cost technology of an increase in the standard deviation of both price and demand (i.e. $\sigma_s$ and $\sigma_p$ increase from 25 to 40). In the absence of an emissions tax Table 2 shows that such an increase lowers both optimal generating capacity and expected emissions, but increases the reliability of supply. Moreover, with the introduction of each of the two taxes their performance improves in that the magnitude of the percentage reduction in expected emissions is greater for both taxes, (e.g. up from 4.6% to 7.2% in the case of the ad valorem tax) but the reduction in reliability is smaller
(e.g. down from 22.4% to 20.4% in the case of the ad valorem tax). However, for both taxes expected tax revenue is smaller reflecting the associated decrease in expected emissions. Nevertheless, in comparing the two taxes ambiguity in their relative performance remains, with the ad valorem tax outperforming its equivalent specific tax in terms of emission reduction (by 12%) and expected tax revenue (by 5.8%), but resulting in a greater reduction in reliability of supply (by 3.8).

In this context consider also the results in Table 3 which reports details of the impact for the low cost technology of an equivalent increase in the standard deviation of both price and demand. In the absence of an emissions tax Table 3 shows that such an increase is beneficial in itself, resulting in both a decrease in expected emissions (because of the associated higher probability of low demand outcomes) and increased reliability (because the reluctance of the firm to lose high demand/high profit opportunities results in an increase in optimal capacity). Moreover, with the introduction of each of the two taxes their performance once again improves in that the magnitude of the percentage reduction in expected emissions is greater for both taxes (e.g. up from 0.3% to 0.5% in the case of the ad valorem tax), but the reduction in reliability is smaller (e.g. down from 2.4% to 2.1% in the case of the ad valorem tax). However, unlike the case of the high cost technology, in this case the impact of increased uncertainty on expected tax revenue differs between the two tax bases. In particular, for the specific tax there is once again a decrease in expected tax revenue associated with the decrease in expected emissions. But for the ad valorem tax the associated increase in the magnitude of the positive covariance between price and sales dominates the decrease in expected emissions in determining expected tax revenue so that overall it increases (by 5.4%). Consequently, this sensitivity analysis has revealed an additional advantage to the choice of the ad valorem tax base over the specific tax base in the context of a relatively low cost technology and increased
uncertainty of demand. It follows that the case for choosing an ad valorem tax base because of its greater effectiveness in reducing expected emissions is strengthened in a situation where its greater expected tax revenue can be used to compensate consumers for lower reliability of supply.
Conclusion

The aim of this paper has been to contribute to the literature on the use of taxation to reduce greenhouse gas emissions. The particular context of the research has been the electricity generating sector, and the focus of the analysis has been on the role of uncertain demand in determining the government’s choice between an ad valorem and a specific base for its emissions tax.

Section 1 of the paper developed a model of a price-taking firm choosing optimal generating capacity while facing uncertain demand – which therefore manifests itself as uncertainty of both price and sales. The alternative tax bases were introduced into this framework and their impacts compared using the concept of ad valorem equivalence – whereby the specific tax is set equal to the amount of the expected price captured by the ad valorem tax. On this basis it was shown that the ad valorem tax is more effective in reducing emissions than its equivalent specific tax, but that this benefit is achieved at the cost of a lower reliability of electricity supply.

In order to clarify an algebraic ambiguity regarding the relative performance of the two tax bases in generating expected tax revenue, a numerical analysis of this model was undertaken in Section 2 of the paper. This numerical analysis included a sensitivity analysis with respect to both the cost of the production technology and the level of demand uncertainty. Overall, the results provided a robust finding that the ad valorem tax generates a higher expected tax revenue than its equivalent specific tax. Therefore, it was concluded that in situations where consumers could be compensated for lower reliability of supply with these higher tax revenues, then the ad valorem tax should be preferred because of its greater effectiveness in reducing emissions. Moreover, although the performance of both tax bases was shown to improve with increases in the level of
demand uncertainty, in the particular case of the low cost technology the ad valorem tax was shown also to capture an increase in expected tax revenue despite an associated reduction in expected emissions. As a consequence further strength was added to the argument for using an ad valorem tax in situations of uncertain demand.

However, as pointed out in the Introduction, most of the literature on the role of taxation in reducing greenhouse gas emissions has focussed on the use of specific taxes for this purpose (e.g. $/tonne of carbon), and has excluded any consideration of uncertainty. This is in any case surprising given the well-known advantages of ad valorem taxes in an inflationary economic context. But added to this case for ad valorem taxes must be the conclusion of this paper that in the context of fluctuating demand for electricity an ad valorem tax will be more effective in reducing emissions than its equivalent specific tax.
Appendix

Using equation (22):

\[
Var(A) = \int_{0}^{k} (x - E(A))^2 f(x) dx + \int_{k}^{\infty} (k - E(A))^2 f(x) dx \quad (A1)
\]

it follows that:

\[
\frac{\partial Var(A)}{\partial k} = \int_{0}^{k} 2(x - E(A)) \left( - \frac{\partial E(A)}{\partial k} \right) f(x) dx
\]

\[
+ \int_{k}^{\infty} 2(k - E(A)) \left( - \frac{\partial E(A)}{\partial k} + 1 \right) f(x) dx
\]

\[
= \int_{0}^{\infty} 2(A - E(A)) \left( - \frac{\partial E(A)}{\partial k} \right) f(x) dx
\]

\[
+ \int_{k}^{\infty} 2(k - E(A)) f(x) dx
\]

\[
= 2(k-E(A))(1 - F(k)) \quad (A2)
\]

In addition:

\[
\frac{\partial Cov(p, A)}{\partial k} = \rho \sigma_p \frac{\partial \sigma_A}{\partial k} \quad (A3)
\]

and

\[
\frac{\partial \sigma_A}{\partial k} = \frac{\partial (Var(A))^{\frac{1}{2}}}{\partial k}
\]

\[
= \frac{1}{2} (Var(A))^{-\frac{1}{2}} \frac{\partial (Var(A))}{\partial k} \quad (A4)
\]

Substituting (A2) and (A4) into (A3) and rearranging gives:

\[
\frac{\partial Cov(p, A)}{\partial k} = \frac{\text{Cov}(p, A)}{Var(A)} \left( k - E(A) \right) \left( 1 - F(k) \right) \quad (A5)
\]

which is used in the main text as equation (23).
References


Table 1

Emissions Tax Base Case Results for Low and High Cost Production Technologies

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<th>No Tax</th>
<th>Ad Valorem</th>
<th>Specific</th>
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<td>k</td>
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<td>124.6</td>
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<td>F(k)</td>
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<td>0.818</td>
<td>0.822</td>
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<tr>
<td>E(A)</td>
<td>97.93</td>
<td>97.61</td>
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<td>ETR</td>
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<table>
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<td>k</td>
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<td>91.18</td>
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<td>F(k)</td>
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<tr>
<td>ETR</td>
<td>-</td>
<td>830.7</td>
<td>816.1</td>
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Table 2

Sensitivity of the Results to the Level of Demand Uncertainty –
High Cost Production Technology \( (c = 70) \)

<table>
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<th>( \sigma_x = \sigma_p = 25 )</th>
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<td>( F(k) )</td>
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<td>( E(A) )</td>
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<td>( ETR )</td>
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</table>
**Table 3**

**Sensitivity of the Results to the Level of Demand Uncertainty - Low Cost Production Technology \((c=20)\)**

\(\sigma_s = \sigma_p = 25\) \hspace{1cm} No Tax \hspace{1cm} Ad Valorem \hspace{1cm} Specific

\[
\begin{align*}
\text{k} & \quad 124.6 \hspace{1cm} 122.7 \hspace{1cm} 123.1 \\
F(k) & \quad 0.838 \hspace{1cm} 0.818 \hspace{1cm} 0.822 \\
E(A) & \quad 97.93 \hspace{1cm} 97.61 \hspace{1cm} 97.68 \\
ETR & \quad - \hspace{1cm} 1015.9 \hspace{1cm} 976.8 \\
\end{align*}
\]

\(\sigma_s = \sigma_p = 40\)

\[
\begin{align*}
\text{k} & \quad 142.4 \hspace{1cm} 139.4 \hspace{1cm} 140.28 \\
F(k) & \quad 0.856 \hspace{1cm} 0.838 \hspace{1cm} 0.843 \\
E(A) & \quad 97.15 \hspace{1cm} 96.70 \hspace{1cm} 96.83 \\
ETR & \quad - \hspace{1cm} 1070.9 \hspace{1cm} 968.3 \\
\end{align*}
\]