Greenhouse Gas Emissions and the Productivity Growth of Electricity Generators

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Staff
Research Paper

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Contents

Acknowledgments **VI**

Abbreviations **VII**

Glossary **VIII**

Key messages **X**

Overview **XI**

CHAPTERS

1 Introduction **1**

2 The greenhouse effect and electricity generation **3**

2.1 Greenhouse gas emissions from electricity generation 4

3 Productivity measurement and the environment **9**

3.1 Index number studies 9

3.2 Production frontier studies 10

4 Methodology and data **19**

4.1 Methodology 19

4.2 Data 22

4.3 Descriptive analysis of emissions 26

5 Quantitative Results **31**

5.1 Decomposition of emission intensity growth 35

5.2 Abatement elasticities 38

5.3 Abatement costs 39

6 Concluding comments **41**

APPENDIXES

A Production frontier analysis 45

B Decomposition of emission intensity growth 55

C Carbon dioxide emissions 59

References 63

FIGURES

2.1 Greenhouse gas emissions from electricity generation, 1989–99 4

2.2 Emission intensities of fossil fuels 5

2.3 Electricity generated by fuel source, 1999-00 6

2.4 Greenhouse gas emissions from electricity generation by fuel, 1998-99 6

4.1 Employment in the Australian electricity supply industry 25

4.2 CO_2 emissions and net electricity generated, 1996-97 26

4.3 Cumulative distribution by emission intensity, 1996–00 27

4.4 CO_2 emissions and fuel consumption per Gwh of net electricity generated, 1996-97 28

5.1 Comparison of pooled and Malmquist results 34

TABLES

4.1 Variables used in the quantitative analysis 22

4.2 Growth of CO_2 emissions from electricity generation, 1996–00 26

5.1 Estimates of the productivity and emission intensity growth of electricity generators, 1996–00 32

5.2 Decomposition of emission intensity growth, 1996–00 36

5.3 Estimates of partial abatement elasticities, 1996–00 38

5.4 Estimates of the marginal producer cost of abating CO_2 emissions, 1997–00 40

A.1 Average sales revenue 49

A.2 Malmquist estimates of the productivity and emission intensity growth of electricity generators, 1996–00 53

C.1 Australian CO_2 emission factors 59

C.2 Procedure for calculating US CO_2 emissions 60
C.3 Conversion procedure for energy content 61

BOXES

3.1 Alternative distance measurement techniques 12
3.2 Disposability of undesirable outputs 13
3.3 Deriving prices for non-marketed undesirable outputs 15
3.4 The Malmquist index of productivity growth 17
4.1 Why firms are benchmarked against a CRS production frontier 21

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Abbreviations

AGO	Australian Greenhouse Office
BIE	Bureau of Industry Economics
Btu	British thermal unit
CO_2	Carbon dioxide
CRS	Constant returns to scale
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEA	Data envelopment analysis
ESAA	Electricity Supply Association of Australia
GWh	Gigawatt hour
IC	Industry Commission
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
PC	Productivity Commission
SFA	Stochastic frontier analysis
SO_2	Sulphur dioxide
TFP	Total factor productivity
TJ	Terajoule
US	United States
VRS	Variable returns to scale

Glossary

Emission factor	Emissions per unit of fuel consumed.
Emission intensity	Emissions per unit of electricity supplied.
Marginal producer cost of abatement	The cost to producers of reducing their environmental impact by an additional unit.
Marginal social cost of environmental damage	The cost to society of increasing an environmental impact by an additional unit.
Net electricity generated	Electricity production net of internal usage by power plants, such as for fuel pulverisation. This is the electricity sent out to the grid.
Partial productivity	A measure of productivity that quantifies how much of an output is produced per unit of a single input (eg: output per employee).
Productivity	The rate at which inputs are transformed into outputs.
Public electricity supply	Electricity supplied to the public grid.
Thermal efficiency	Net electricity generated per unit of fuel.
Total factor productivity	A measure of productivity that quantifies the outputs produced from a combination of two or more inputs.

OVERVIEW

Key messages

- The environmental impacts of economic activity are often ignored when estimating productivity growth. The main reason for this is that productivity growth is normally estimated using techniques that can only take account of inputs and outputs that have an observable price.
- This paper develops a methodology that can incorporate unpriced environmental impacts and applies it to one of the more important environmental issues facing Australia — greenhouse gas emissions from electricity generation.
- It is shown that ignoring greenhouse gas emissions causes the productivity growth of electricity generators to be under-estimated in some years and over-estimated in other years.
- Productivity growth tends to be under-estimated when 'emission intensity' (emissions per unit of electricity supplied) falls and over-estimated when emission intensity rises.
  - This is because emissions are undesirable and so if they fall (grow) per unit of output then this will tend to increase (decrease) estimated productivity.
- Changes in emission intensity (and hence the impact of emissions on estimated productivity growth) appear to have been largely driven by movements in thermal efficiency (electricity supplied per unit of fuel).
- There are regional differences in the cost of abating emissions (in terms of foregone output of electricity) once a generator has fully exploited emission abatement opportunities that do not require the use of additional inputs and/or a reduction in output.

Overview

Ideally, estimates of productivity growth should take account of all inputs and outputs associated with a production process, including changes to the environment. In practice, productivity growth is normally estimated using techniques that can only take account of inputs and outputs that are priced. Since most environmental impacts are not traded in markets, they rarely have observable prices and so tend to be ignored when estimating productivity growth.

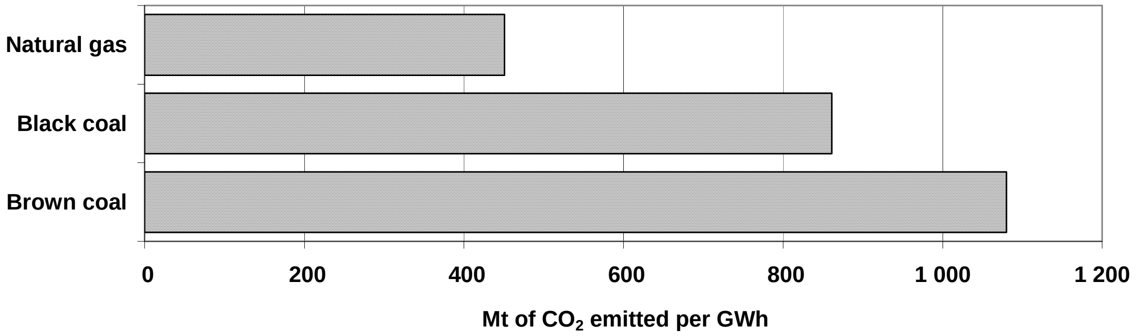
This paper develops and applies a measure of productivity growth that can incorporate unpriced environmental impacts. The methodology builds on the established technique of data envelopment analysis and is applied to one of the more significant environmental issues facing Australia — greenhouse gas emissions from electricity generation.

In 1998-99, electricity generation accounted for 38 per cent of Australia's net greenhouse gas emissions from sources other than land clearing. When measured in terms of global warming potential, carbon dioxide (CO_2) accounts for almost 100 per cent of the greenhouse gases emitted by Australian electricity generators. As a result, CO_2 is used as a proxy for greenhouse gas emissions in this paper's analysis.

In 1999, around 80 per cent of Australia's electricity was generated from coal, compared to just 29 per cent in OECD Europe and 52 per cent in the United States. This is significant because coal tends to have a relatively high emission intensity (CO_2 emissions per unit of electricity supplied). This is particularly the case for brown coal (figure 1).

Most of the electricity generated in New South Wales and Queensland comes from black coal, whereas brown coal is the dominant fuel in Victoria (figure 2). South Australia and Western Australia rely on sizeable quantities of coal and natural gas. In contrast to the other states, Tasmania has a very low dependence on fossil fuels, sourcing almost all of its power from hydro-electric plants.

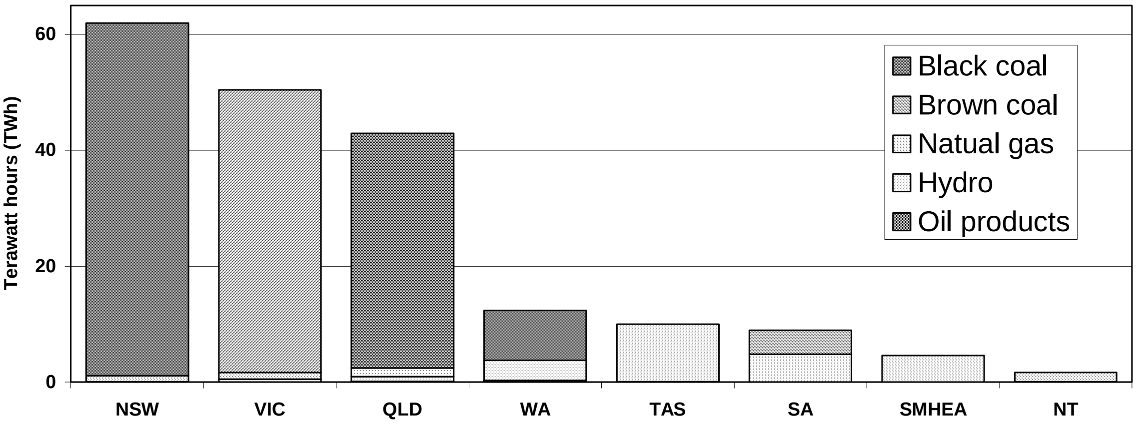
Figure 1 **Emission intensities of fossil fuels[a]**



[a] Emission intensity is defined as CO_2 emissions per unit of net electricity generated (excludes electricity consumed by power plants). The emission intensities shown in the figure are Australian best performance for the late 1990s and were determined from an analysis of survey returns.

Source: Sinclair Knight Merz (2000).

Figure 2 **Electricity generated by fuel source, 1999-00[a]**



[a] Electricity generated includes that consumed by power plants. These data are for generators that supply the public grid. SMHEA refers to the Snowy Mountains Hydro-Electric Authority, which is a cooperative venture between New South Wales, Victoria and the Commonwealth.

Source: ESAA (2001).

In this paper, productivity growth is measured by how far an electricity generator moves towards an estimated best practice frontier from one year to the next. The best practice frontier specifies the maximum possible electricity and minimum possible CO_2 emissions that a generator can produce from its inputs. It is estimated using the observed performance of Australian and US generators in the late 1990s.

Mathematical programming models are used to determine each generator's distance in a given year from the best practice frontier. These models measure distances from the frontier by finding a generator's largest possible simultaneous increase in net electricity generated and reduction in emissions. This movement *towards* the frontier involves taking advantage of emission abatement opportunities that do not require additional inputs or a reduction in net electricity generated. If a generator is already on the frontier then only costly emission abatement opportunities remain, which involve movements *around* the frontier.

The analysis is conducted using data on Australian generators that supply the public grid. These generators account for the majority of electricity produced in Australia. The period of analysis was restricted to 1996-97 to 1999-00 because earlier data on people employed in electricity generation were not available. This is due to the vertically integrated utilities (combining generation, transmission and distribution) that used to dominate the Australian electricity supply industry. Western Australia and Tasmania still had a vertically integrated reporting structure until 1998-99 and 1997-98 respectively, and so had to be excluded from our analysis. Thus, this paper analyses data for New South Wales, Victoria, Queensland, South Australia and the Northern Territory. They accounted for 86 per cent of total Australian public electricity production in 1999-00.

For comparison purposes, we estimated productivity growth both excluding and including CO_2 emissions. The resulting exclusive and inclusive estimates are given in the first and second columns of numbers in table 1. The third column shows the percentage point change in productivity growth due to including CO_2 emissions (column two minus column one). For example, productivity growth for New South Wales from 1996-97 to 1997-98 is estimated to be 0.80 percentage points lower when its CO_2 emissions are included.

Overall, our results show that ignoring greenhouse gas emissions causes the productivity growth of electricity generators to be under-estimated in some years and over-estimated in other years. Productivity growth tends to be under-estimated when emission intensity falls and over-estimated when emission intensity grows. This is evident from the relationship between the third and fourth columns of numbers in table 1. The intuitive explanation for this relationship is that emissions are undesirable and so if they fall per unit of output then this will tend to increase estimated productivity. And if emissions rise per unit of output, estimated productivity will tend to decrease.

Changes in emission intensity (and hence the impact of CO_2 emissions on estimated productivity growth) during the late 1990s appear to have been largely driven by movements in thermal efficiency (electricity supplied per unit of fuel). Fuel substitution and changes in the carbon content of particular fuels were also important sources of emission intensity growth in a few cases.

Table 1 Estimates of the productivity and emission intensity growth of electricity generators, 1996–00

	Productivity Growth			
	Excluding CO_2 emissions	*Including CO_2 emissions*	*Impact of CO_2 emissions on productivity growth*[a]	*Change in emission intensity*[b]
	%	%	%	%
New South Wales[c]				
1996-97 to 1997-98	–0.79	–1.58	–0.80	1.61
1997-98 to 1998-99	1.36	1.55	0.19	–1.53
1998-99 to 1999-00	–0.76	–0.77	–0.02	0.78
Victoria[c]				
1996-97 to 1997-98	4.16	4.52	0.35	–4.00
1997-98 to 1998-99	–3.15	–3.56	–0.41	3.83
1998-99 to 1999-00	0.18	0.90	0.72	–0.83
Queensland[c]				
1996-97 to 1997-98	–4.87	–5.01	–0.14	4.92
1997-98 to 1998-99	1.66	3.39	1.72	–3.32
1998-99 to 1999-00	2.04	2.57	0.54	–2.51
South Australia[d]				
1996-97 to 1997-98	0.08	0.42	0.34	–0.20
1997-98 to 1998-99	–2.01	–1.42	0.60	–1.15
1998-99 to 1999-00	5.62	8.96	3.34	–4.71
Northern Territory[e]				
1996-97 to 1997-98	0.14	0.26	0.12	1.16
1997-98 to 1998-99	–2.37	–2.81	–0.45	2.33
1998-99 to 1999-00	2.43	2.77	0.35	–6.97

[a] Percentage point change in productivity growth due to taking account of CO_2 emissions (column two minus column one). [b] Emission intensity is defined as CO_2 emissions per unit of net electricity generated. [c] Productivity growth estimated using the sample of New South Wales, Victoria, and Queensland, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from coal. [d] Productivity growth estimated using the sample of all Australian states and the Northern Territory, plus US steam power plants which sourced more than 90 per cent of their fuel (measured in TJ) from coal and/or gas. [e] Productivity growth estimated using the sample of South Australia and the Northern Territory, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from gas.

Source: PC estimates.

We extended our methodology to also estimate partial abatement elasticities. These show the proportionate reduction in output (net electricity generated) required to abate CO_2 emissions by 1 per cent, holding inputs constant. Thus, they reflect the cost (in terms of foregone output) of reducing emissions once a generator has fully exploited emission abatement opportunities that do not require the use of additional inputs and/or a reduction in output. The estimated elasticities range from 0.44 to 1.11 (an elasticity of 0.44 indicates that a 1 per cent reduction in CO_2 emissions requires a 0.44 per cent reduction in net electricity generated). It therefore appears that there are regional differences in the cost of abating emissions once a generator has fully exploited emission abatement opportunities that do not require the use of additional inputs and/or a reduction in output.

In conclusion, the methodology used in this paper has the major advantage that it can readily incorporate unpriced environmental impacts into productivity growth estimates. A disadvantage is that the methodology is data intensive and technically challenging. Nevertheless, it can provide useful insights into how estimated productivity growth can be affected by the environmental impacts of economic activity. The quantitative results show that when a firm’s environmental impacts are large, they can have a significant effect on its estimated productivity growth.

1 Introduction

Productivity growth can be a major source of improvements in living standards through its positive impact on real incomes. However, the link between *estimates* of productivity growth and increases in living standards may be less strong. One possible reason for this is that estimates of productivity growth often ignore the environmental impacts of economic activity.

Ideally, estimates of productivity growth should take account of all inputs and outputs associated with a production process, including changes to the environment. In practice, productivity growth is normally estimated using techniques that can only take account of inputs and outputs that are priced. Since most environmental impacts are not traded in markets, they rarely have observable prices and so tend to be ignored when estimating productivity growth.

This paper develops and applies a measure of productivity growth that can incorporate unpriced environmental impacts. The methodology builds on the established technique of data envelopment analysis (DEA). While its application to Australia is relatively novel, similar approaches have been used in overseas studies that incorporate unpriced environmental effects (see, for example, Arocena and Price 1999; Chung, Färe and Grosskopf 1997; Hailu and Veeman 2000; Korhonen and Luptacik 2000; Lovell and Luu 2000; Yaisawarng and Klein 1994). Further details about our methodology are provided in later sections of this paper.

We apply our methodology to one of the more important environmental issues facing Australia — greenhouse gas emissions from electricity generation. In 1998-99, electricity generation accounted for 38 per cent of Australia's net greenhouse gas emissions from sources other than land clearing (AGO 2001b). If environmental impacts do have a notable effect on estimated productivity growth, then this is most likely to be evident in such cases where the environmental impacts are thought to be large.

The next section of this paper provides background information on Australia's greenhouse gas emissions from electricity generation. We then review past research on productivity measurement and the environment to provide a context for our methodology. This is followed by details about the methodology and data used in our quantitative analysis. Results are then presented, followed by concluding comments.

2 The greenhouse effect and electricity generation

The greenhouse effect is a natural occurrence that results from a blanket of atmospheric gases that surrounds the Earth. These gases (carbon dioxide (CO_2), methane, nitrous oxide, halocarbons, and others) act to trap heat in the atmosphere and so keep the Earth's temperature at a level necessary to support life.

In recent years, there has been much debate about how this natural phenomenon has been affected by human activities that increase greenhouse gas concentrations in the atmosphere. It is difficult to provide a precise answer, given the uncertainties associated with atmospheric science. Indeed, some argue that human activity has had a negligible impact (see, for example, Foster 2000). However, the majority of scientific opinion appears to support the view that human activity has created an enhanced greenhouse effect that is causing global climate change.

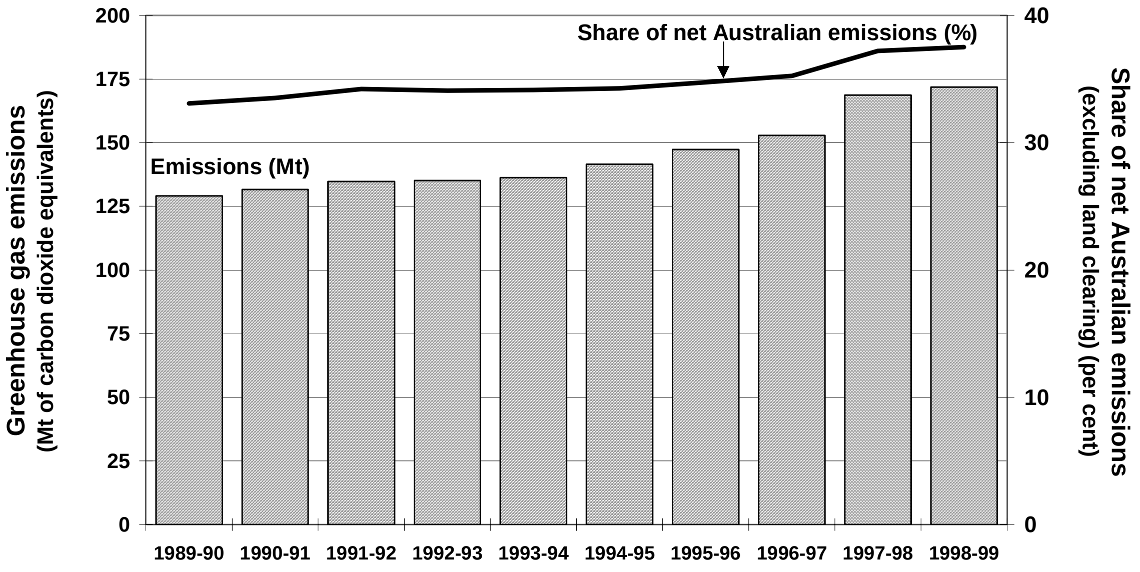
Most notably, the Intergovernmental Panel on Climate Change (IPCC 2001) expects an average global surface temperature increase of 1.4°C to 5.8°C over the period 1990 to 2100. For Australia, the CSIRO (2001a, 2001b) projects that, compared to 1990, there will be an average warming of 0.4°C to 2°C over most of the country by 2030 and 1°C to 6°C by 2070. Temperature increases are expected to vary between seasons and across regions. Marked changes in rainfall, also with seasonal and regional variations, are likewise projected by the CSIRO.

The Australian Government has deemed such scientific assessments to be of sufficient concern to justify large expenditures on programs to encourage emission abatement. Most notably, the Commonwealth Government plans to spend almost $1 billion on greenhouse initiatives and has established the world's first government agency dedicated solely to greenhouse issues — the Australian Greenhouse Office (AGO). In addition, State Governments have adopted policies which will limit future growth in greenhouse gas emissions (Beardow and Schaap 2000). Australia is also an active participant in negotiations for an international agreement to curb global greenhouse gas emissions.

2.1 Greenhouse gas emissions from electricity generation

Electricity generation accounts for a relatively large (and growing) proportion of Australia’s greenhouse gas emissions (figure 2.1). The latest estimates indicate that, in 1998-99, electricity generation accounted for 38 per cent of net Australian greenhouse gas emissions from sources other than land clearing (land clearing is not included due to a high level of uncertainty about its emissions). When measured in terms of global warming potential, CO_2 accounts for almost 100 per cent of the greenhouse gases emitted by Australian electricity generators (AGO 2001b).

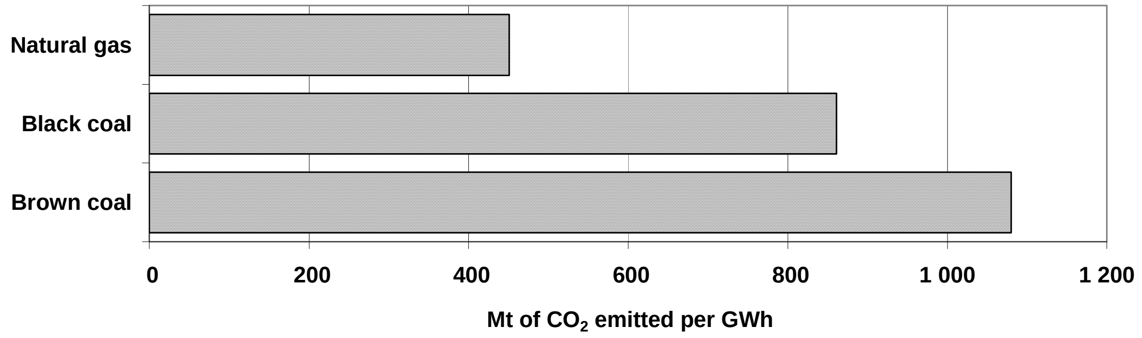
Figure 2.1 **Greenhouse gas emissions from electricity generation, 1989–99**



Source: AGO (2001b).

An important determinant of greenhouse gas emissions from electricity generation is the type of fuel used. Electricity generated from non-fossil fuel sources, such as hydro-electric (hydro) and solar, has a very low emission intensity (emissions per unit of electricity supplied). Among fossil fuels, brown coal tends to have a higher emission intensity than black coal and natural gas (figure 2.2).

Figure 2.2 **Emission intensities of fossil fuels**[a]



[a] Emission intensity is defined as CO_2 emissions per unit of net electricity generated (excludes electricity consumed by power plants). The emission intensities shown in the figure are Australian best performance for the late 1990s and were determined from an analysis of survey returns.

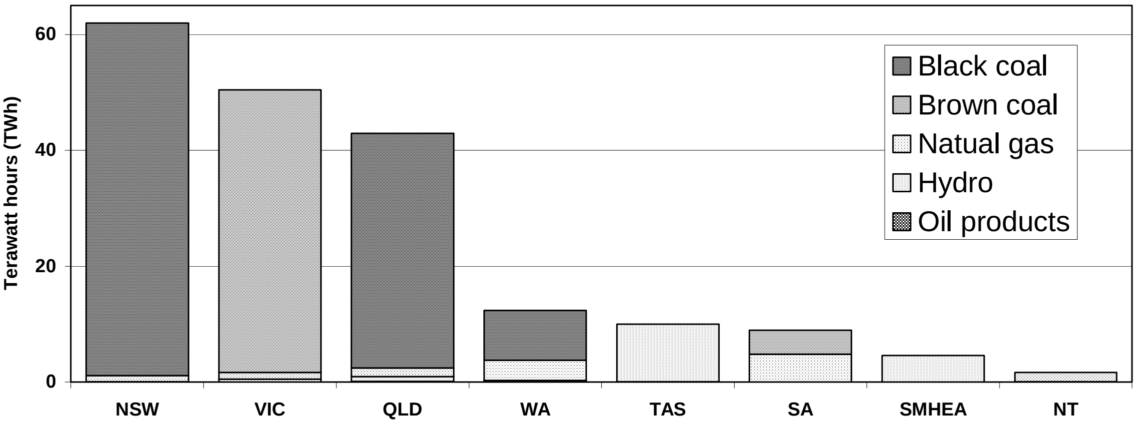
Source: Sinclair Knight Merz (2000).

In 1999, around 80 per cent of Australia's electricity was generated from coal, compared to just 29 per cent in OECD Europe and 52 per cent in the United States (IEA 2000). Black coal accounted for around two-thirds of Australia's coal based electricity production, with the remainder sourced from brown coal (ESAA 2001).

The widespread use of coal in Australia reflects the fact that coal fired power plants have tended to have the lowest variable cost (Allen Consulting and McLennan Magasanik Associates 1999). This cost advantage is largely due to the abundance of coal reserves in close proximity to electricity consumers. In comparison, gas and hydro plants have typically had the advantage of faster start-up and quicker load following capability. Thus, coal is generally used to meet the large component of demand that is relatively stable over time (base load) whereas gas and hydro tend to be more attractive in satisfying short term peaks in demand (peak load).

While coal is the dominant fuel in Australia at a national level, it is important to note the significant regional differences. Most of the electricity generated in New South Wales and Queensland comes from black coal, whereas brown coal is the dominant fuel in Victoria (figure 2.3). South Australia and Western Australia rely on sizeable quantities of both coal and natural gas. In contrast to the other states, Tasmania has a very low dependence on fossil fuels, sourcing almost all of its power from hydro.

Figure 2.3 **Electricity generated by fuel source, 1999-00**[a]

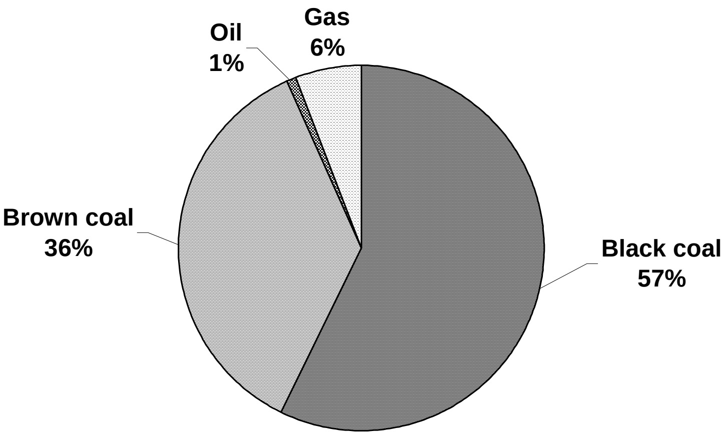


[a] Electricity generated includes that consumed by power plants. These data are for generators that supply the public grid. SMHEA refers to the Snowy Mountains Hydro-Electric Authority, which is a cooperative venture between New South Wales, Victoria and the Commonwealth.

Source: ESAA (2001).

At a national level, coal accounts for more than 90 per cent of Australia's greenhouse gas emissions from electricity generation (figure 2.4). Most of this is attributable to black coal, reflecting the fact that it is more widely used than brown coal. Nevertheless, brown coal accounts for a disproportionate share of coal based emissions, due to its very high emission intensity. Less than 10 per cent of emissions are attributable to other fuels.

Figure 2.4 **Greenhouse gas emissions from electricity generation by fuel, 1998-99**[a]



[a] The different greenhouse gases are measured in terms of their global warming potential.

Source: AGO (2001a).

The above discussion suggests that changes in fuel mix could have a notable effect on an environmentally sensitive measure of productivity growth for electricity generators. Another important factor could be changes in thermal efficiency (electricity supplied per unit of fuel) since there is a close relationship between emissions and fuel consumption. Prior to investigating this further, the following section reviews past research on productivity, with emphasis on the Australian electricity industry and the incorporation of environmental impacts.

3 Productivity measurement and the environment

In essence, productivity is the rate at which inputs are transformed into outputs. There are two broad approaches to measuring productivity:

- *partial productivity*, which quantifies how much of an output is produced per unit of a single input (eg: output per employee); and
- *total factor productivity* (TFP), which measures the quantity of outputs produced from a combination of two or more inputs.

Partial productivity measures have the advantage that they are easy to calculate and understand. However, they can be misleading because of the focus on a single input. TFP measures can overcome this problem because they recognise that a variety of inputs are used in combination. For this reason, our review of past research focuses on TFP studies. These studies were divided into two groups, based on whether they used an index number or production frontier approach. The features of these alternative approaches are discussed below, with emphasis on applications to electricity generation and environmental impacts.

3.1 Index number studies

Index number studies estimate productivity as the ratio of an index of total outputs to an index of total inputs. Firms often have multiple outputs and/or inputs and so it is usually necessary to aggregate them to get a single output or input index. This aggregation is achieved by constructing indices that are weighted sums of individual outputs or inputs. The weights used to construct a total output index are output revenue shares (based on output prices) and for a total input index are input cost shares (based on input prices).

Most index number studies of the Australian electricity supply industry have followed this weighting procedure by calculating Törnqvist indices (see for example Bell 1993; BIE 1994; Lawrence, Swan and Zeitsch 1990; London Economics 1993; Pierce, Price and Rose 1995; Price and Weyman-Jones 1993; Productivity Commission 1996; Swan Consultants 1991; Zeitsch and Lawrence 1996). These studies were largely conducted from the late 1980s to mid 1990s, reflecting the then debate about major electricity reforms. Their results indicate that there was negligible productivity growth in the Australian electricity supply industry from the mid 1970s to mid 1980s, and the level of productivity was significantly below world best practice. In contrast, a marked increase in Australian productivity was found from the mid 1980s to early 1990s. The studies also found notable productivity differences between states. Queensland appeared to be close to world's best practice in the early 1990s, while Victoria was the least productive among Australian states.

We are not aware of any index number studies of the Australian electricity supply industry that have taken account of the environmental impacts of production. This has, however, been attempted for various industries including electricity in other countries (see, for example, Oskam 1991; Pittman 1983; Repetto et al. 1996). But a weakness of these index number studies is the reliance on price data to aggregate inputs and outputs. Prices are rarely available for environmental impacts because they are seldom traded in markets. To overcome this, most studies have used 'shadow' prices for environmental impacts, which are based on estimates of either the:

- *marginal producer cost of abatement* (cost to producers of reducing their environmental impact by an additional unit); or the
- *marginal social cost of environmental damage* (cost to society of increasing an environmental impact by an additional unit).

Leaving aside the issue of how accurate these estimates are, there is a question about which is the more appropriate measure. Marginal abatement and damage costs will only be equal if environmental impacts are at a level which maximises community welfare. If environmental impacts exceed this level, marginal abatement costs will be less than marginal damage costs. Most index number studies have used marginal abatement costs to incorporate environmental impacts. This may be because marginal abatement costs are easier to estimate than marginal damage costs.

3.2 Production frontier studies

Production frontier studies benchmark firms against an estimated best practice production frontier. This estimated frontier specifies the maximum possible output that can be produced from different combinations of inputs, based on the observed input-output mixes of sampled firms. Benchmarking each firm against such a frontier generates a relative measure of its productivity compared to what is theoretically possible by following best practice. This relative measure is termed an ‘efficiency score’ and ranges from zero (no output produced) to one (on the frontier). When a firm has an efficiency score of one it is ‘technically efficient’, which means that it produces the maximum possible output from its inputs.

There are various approaches to measuring efficiency scores, but they are all based on a distance from the estimated production frontier (box 3.1). Hence, the production function technique is sometimes referred to as a distance function approach.

One of the main advantages of the production frontier approach is that, unlike index number studies, it does not require price data. It does, however, need a sizeable sample of firms to ensure that the estimated production frontier closely approximates what can be achieved if firms adopt best practice. Most production frontier studies of the Australian electricity supply industry have included data on foreign producers to ensure a sufficient sample against which to benchmark local firms.

The production frontier against which firms are benchmarked can be estimated using data envelopment analysis (DEA) or stochastic frontier analysis (SFA). DEA involves the use of (non-parametric) mathematical programming techniques whereas SFA is based on (parametric) econometric techniques (for details see Charnes et al. 1994; Coelli, Rao and Battese 1998; Fried, Lovell and Schmidt 1993; Steering Committee for the Review of Commonwealth/State Service Provision 1997).

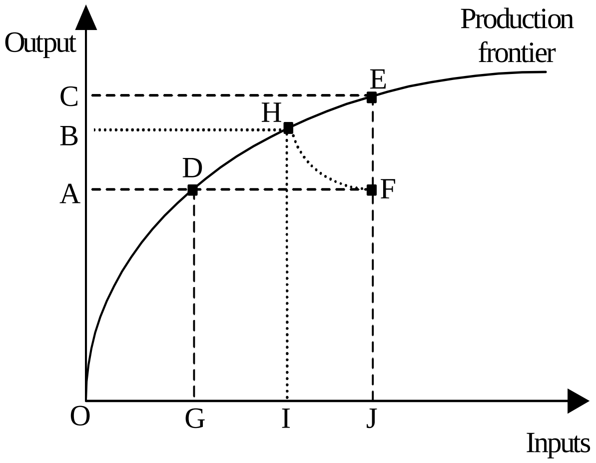
An advantage of DEA is that the production function does not need to be specified. However, the estimated frontier can be very sensitive to measurement error and it is not possible to test hypotheses using standard statistical tests. These problems can be addressed using SFA. But SFA has the disadvantage that an arbitrary assumption has to be made about the distribution of residuals from econometric estimation (part of which is used to determine productivity) (Coelli, Rao and Battese 1998).

DEA has been by far the most popular approach for estimating production frontiers in Australian electricity studies (see, for example, Bell 1993; BIE 1994; ESAA 1994; Productivity Commission 1996; Zeitsch and Lawrence 1996). The results of these studies indicate that, between the mid 1970s and early 1990s, the productivity of electricity generators varied markedly between Australian states. Their findings also suggest that the most productive Australian producer in the early 1990s was Queensland, and that it was close to international best practice.

Some studies extended the ‘basic’ DEA approach to examine productivity in more detail. For example, ESAA (1994) used econometric techniques to adjust their DEA efficiency scores to reflect differences in operating environments, such as power plant age. The Productivity Commission (1996) decomposed efficiency scores to investigate whether generators were operating at an efficient scale, and if there was excessive or wasteful use of particular inputs (termed congestion).

Box 3.1 **Alternative distance measurement techniques**

A firm's distance from the production frontier (and hence its efficiency score) can be measured by varying its inputs, outputs, or both. The accompanying diagram illustrates this for a firm whose input-output combination is represented by the point F.



Point F is technically inefficient since it is not on the production frontier. The output-based distance from point F to the frontier is equal to the distance AC, because it is possible to increase outputs by this amount while still using inputs equal to OJ. The output-based efficiency score is:

$$\frac{\text{Productivity at point F}}{\text{Productivity at point E}} = \frac{OA/OJ}{OC/OJ} = \frac{OA}{OC}$$

The input-based distance from point F to the production frontier is equal to distance GJ, since the firm could reduce inputs by this amount without changing output. The input-based efficiency score is:

$$\frac{\text{Productivity at point F}}{\text{Productivity at point A}} = \frac{OA/OJ}{OA/OG} = \frac{OG}{OJ}$$

A firm's distance from the frontier can also be measured by allowing an equi-proportionate increase in outputs and decrease in inputs. This is termed a hyperbolic distance because it involves forming a hyperbola from point F to the frontier at point H. The hyperbolic efficiency score is:

$$\frac{\text{Productivity at point F}}{\text{Productivity at point H}} = \frac{OA/OJ}{OB/OI}$$

The output, input and hyperbolic efficiency scores will only be equal if firms are using a constant returns to scale technology. In this case, the production frontier would be a straight line projecting out from the origin (point O).

We are not aware of any production frontier studies of the Australian electricity supply industry that have incorporated the environmental impacts of production. There are, however, a number of overseas studies of various industries including electricity that have done so (such as Boyd and McClelland 1999; Färe, Grosskopf and Pasurka 1989; Färe, Grosskopf, Lovell and Pasurka 1989; Korhonen and Luptacik 2000; Yaisawarng and Klein 1994). This research has largely built on an approach pioneered by Färe, Grosskopf, Lovell and Pasurka (1989).

Färe, Grosskopf, Lovell and Pasurka (1989) incorporated environmental impacts into their analysis as undesirable outputs by modifying the conventional DEA technique in two ways. First, distances from the production frontier were measured by expanding desirable output and contracting environmental impacts by an equi-proportionate amount. Thus, desirable and undesirable outputs were treated asymmetrically. Second, they assumed that there was a cost associated with reducing undesirable outputs. In particular, pollutants were treated as being weakly disposable (see box 3.2 for technical details).

Box 3.2 **Disposability of undesirable outputs**

It is usually assumed that outputs are freely disposable. This means that a firm can reduce one or more of its outputs without changing the quantity of its inputs or the production of other outputs. Free disposal can be stated formally as:

$$y' \leq y \in P(x) \Rightarrow y' \in P(x)$$

where y is a vector of outputs, x is a vector of inputs, and P(x) is the output set (the set of all output vectors producible using input vector x).

The assumption of free disposability is not necessarily valid when firms produce undesirable byproducts, such as CO_2 emissions from electricity generation. This is because reduction of an undesirable output (emissions) often requires a decrease in desirable outputs (electricity generated) and/or the use of additional inputs (such as pollution controls). In other words, disposal of an undesirable output is rarely costless.

This can be handled by assuming that undesirable outputs are weakly disposable. This means that an undesirable output can only be reduced for a given level of inputs by reducing other outputs. Thus, abatement of an undesirable output uses resources and so has an associated opportunity cost in terms of foregone production of desirable outputs. The free disposability assumption is retained for desirable outputs, so that:

$$(y_D, y_U) \in P(x) \Rightarrow (y'_D, y_U) \in P(x) \quad \forall \quad y'_D \leq y_D$$

where y_D is the vector of desirable outputs and y_U is undesirable outputs.

Source: Färe, Grosskopf, Lovell and Pasurka (1989).

Färe, Grosskopf, Lovell and Pasurka (1989) applied their methodology to a sample of US paper mills which used four inputs to produce paper and four pollutants. They found that firms' efficiency scores were sensitive to whether or not pollutants were included in the analysis. This indicates that a firm's impact on the environment can have a notable effect on its estimated productivity.

Färe et al. (1993) extended the methodology of Färe, Grosskopf, Lovell and Pasurka (1989) to derive shadow prices for non-marketed outputs, such as pollution. The procedure used to derive shadow prices is detailed in box 3.3.

The shadow prices derived for environmental impacts can be interpreted as the marginal producer cost of abatement. They reflect the trade-off between desirable and undesirable outputs and will vary between firms if environmental impacts are not at their optimal level (since this implies that marginal abatement costs have not been equalised across firms).

These estimated abatement costs should be considered as providing an upper bound on the actual marginal cost of abatement. This is because they are derived by assuming that the relevant firm is already on the frontier, its inputs are fixed, and the only way it can abate an environmental impact is to reduce output.

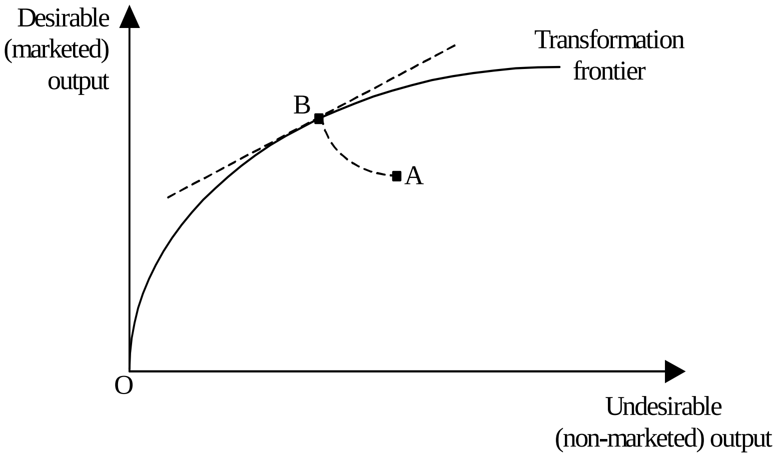
Coggins and Swinton (1996) applied this technique to a sample of US power plants to estimate the marginal abatement cost for sulphur dioxide (SO_2) emissions. Similar studies have been undertaken for other industries (see, for example, Hailu and Veeman 2000; Reig-Martínez, Picazo-Tadeo and Hernández-Sancho 2001).

Lovell and Luu (2000) showed that a modified version of the procedure to derive shadow prices can be used to generate partial abatement elasticities (see box 3.3). These elasticities show the proportionate reduction in desirable output required to abate an environmental impact by 1 per cent, holding all other variables constant.

Like the shadow prices mentioned above, these abatement elasticities should be considered as providing an upper bound on the actual adjustment associated with abating an environmental impact. This is because they are derived on the basis that the relevant firm is already on the frontier and the only way it can abate an environmental impact is to reduce output.

Box 3.3 **Deriving prices for non-marketed undesirable outputs**

The shadow prices of undesirable outputs not traded in markets (such as pollution) can be derived using the production frontier approach. This is illustrated in the diagram for a firm at point A. This firm can be projected onto the transformation frontier at point B by an equi-proportionate increase in desirable output and decrease in undesirable output. The transformation frontier shown in the diagram indicates the maximum desirable output that can be produced for a given level of undesirable output, holding firm A's inputs constant.



Point B supports a tangent plane, which in the two dimensional space shown in the diagram is the straight line through point B. The slope of this line is termed the shadow price ratio because it is equal to the ratio $\left(SP_U/SP_D\right)$, where SP_U is the shadow price of the undesirable output and SP_D is the shadow price of the desirable output. The shadow price ratio can be interpreted as the trade-off between the desirable and undesirable outputs. That is, it shows the additional amount of undesirable output that would be produced if there was a small increase in desirable output.

Calculating the shadow price ratio is straightforward when using the production frontier approach, since it is based on the estimated production frontier. It is then possible to derive an estimated price for the undesirable output ($\tilde{P}_U$), by first assuming that the shadow price of the desirable output equals its observed price (P_D) and then applying the formula $\tilde{P}_U = P_D\left(SP_U/SP_D\right)$.

The shadow price ratio can also be used to get the **partial abatement elasticity** for the undesirable output. This measures the proportionate reduction in a desirable output required to abate an undesirable output by a given amount, holding all other variables constant. It is calculated as $\left(Q_U/Q_D\right)\left(SP_U/SP_D\right)$, where Q_U and Q_D are the quantities of undesirable and desirable outputs respectively. Note this does not require the assumption that the shadow price of the desirable output equals its observed price.

Sources: Färe et al. (1993) and Lovell and Luu (2000).

Productivity growth

When data are available for more than one period, the production frontier approach can be extended to the analysis of productivity growth. This may be done using either a pooled data approach or a Malmquist index approach.

Pooled approach

The pooled approach benchmarks each firm in each period against the same production frontier. This frontier is estimated by combining cross-section and time-series data. Thus, the production frontier used to benchmark firms represents the best practice over the entire sample period. The strength of this approach is that it maximises the sample used to estimate the frontier and so may lead to more robust results. However, it does not allow researchers to separate technological progress from improvements in the technical efficiency of individual firms. In addition, it may be inappropriate to use the pooled approach to analyse long periods or industries with rapid technological progress, since the shape of the production frontier could change significantly over time.

The pooled approach has been used in a number of studies (such as Berg et al. 1993; Productivity Commission 1999; Scarsi 1999). Scarsi (1999) uses this technique to examine local electricity distributors in Italy. This study was over the short time span of 1994 to 1996 and used an output-oriented DEA model.

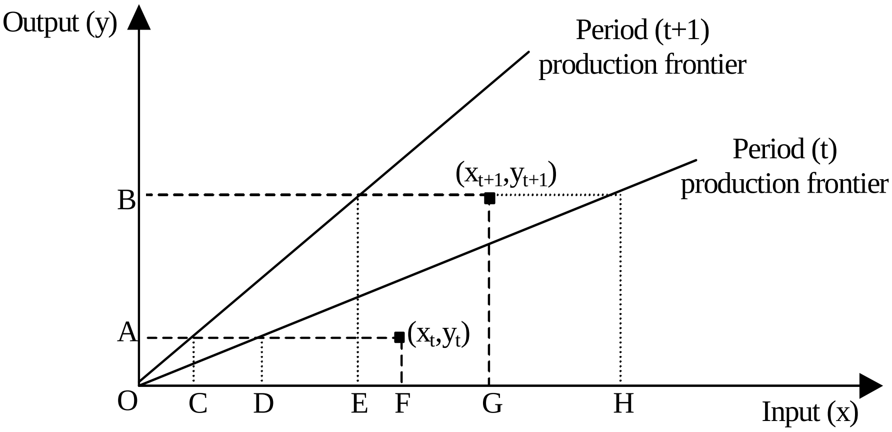
Malmquist approach

An alternative approach to estimating productivity growth is to use efficiency scores to calculate what are known as Malmquist indices (box 3.4). The main advantage of this approach is that it enables productivity growth to be decomposed into that due to technological progress (shifts in the frontier between periods) and changes in technical efficiency (movement towards a given period's frontier). However, it has the disadvantage that firms are benchmarked against a frontier that is estimated using a single period's data. Thus, a large number of observations are required in each period to ensure robust results.

The Malmquist approach was first applied by Färe et al. (1994) and has since been used in a number of published studies. Few of these studies have looked at the Australian electricity supply industry. Two exceptions are the analyses of electricity generators by Coelli (1998) and distributors by London Economics (1993).

Box 3.4 **The Malmquist index of productivity growth**

The Malmquist approach uses efficiency scores to produce a measure of productivity growth. This is done by benchmarking firms against a single period's production frontier and assuming constant returns to scale (Grifell-Tatjé and Lovell (1995) showed that the Malmquist index does not correctly measure productivity changes when variable returns to scale are permitted). The diagram below illustrates how the Malmquist index is applied when using input-based efficiency scores.



The firm's input-output combination in period t is $(x_t,\ y_t)$, which is inefficient when benchmarked against the period t production frontier (assuming constant returns to scale). In the next period (t+1), the firm's efficiency score is greater than one when benchmarked against period t technology since $(x_{t+1},\ y_{t+1})$ is beyond the period t production frontier. The input-based Malmquist index, benchmarked against the period t production frontier, is the following ratio of efficiency scores:

$$\frac{OH/OG}{OD/OF}$$

This is greater than one because the firm's efficiency score at $(x_{t+1},\ y_{t+1})$ is greater than one and so the firm has experienced productivity growth.

The input-based Malmquist index, benchmarked against period t+1 technology, is:

$$\frac{OE/OG}{OC/OF}$$

This is also greater than one because, benchmarked against period t+1 technology, the firm is very inefficient at $(x_t,\ y_t)$ and less inefficient at $(x_{t+1},\ y_{t+1})$.

Similar Malmquist indices could be calculated using output-based or hyperbolic efficiency scores. The choice of which period to use as a benchmark is arbitrary and can lead to different results when there are multiple inputs and/or outputs. Therefore, it is common to report the geometric average of Malmquist indices benchmarked on period t and t+1 technologies. Caves, Christensen and Diewert (1982) proved that this geometric average of Malmquist indices closely approximates a Törnqvist productivity index.

Source: Färe et al. (1994).

Coelli (1998) analysed data for 1981–91 on 13 coal-fired power plants which accounted for around 50 per cent of Australia's electricity production. An interesting feature of this study was that Malmquist results were calculated using both the DEA and SFA approaches to estimating production frontiers. These were also compared to Törnqvist indices. Markedly different results were generated from the three approaches. Coelli noted that the Törnqvist index is based on the assumption of optimising behaviour (cost minimisation/revenue maximisation), which may not have been appropriate for publicly owned utilities. He also found evidence of excessive or wasteful use of labour (termed congestion), which he did not allow for in his DEA model.

Several overseas studies have calculated Malmquist indices that incorporate environmental impacts (see, for example, Arocena and Price 1999; Chung, Färe and Grosskopf 1997; Hailu and Veeman 2000; Lovell and Luu 2000; Yaisawarng and Klein 1994). Research by Yaisawarng and Klein (1994) is probably among the more relevant to our research. They took account of SO_2 emissions when calculating Malmquist indices for US coal-fired power plants. Emissions were treated as being a weakly disposable output and Malmquist indices were calculated using a modified version of input-based DEA in which capital inputs were held fixed.

4 Methodology and data

Our review of past research revealed that environmental impacts can be incorporated into productivity measures using variants of either the index number or production frontier approaches. We decided not to use an index number approach because it would require:

- behavioural assumptions (cost minimisation/revenue maximisation) which are probably inappropriate for some electricity generators (Coelli 1998); and
- an arbitrary decision about whether to price greenhouse gas emissions using (debatable) estimates of either marginal abatement or damage costs.

In contrast, the production frontier approach does not require price data or impose behavioural assumptions about producers. We therefore decided to use elements of the environmentally sensitive production frontier approaches developed by Fare, Grosskopf, Lovell and Pasurka (1989) and Yaisawarng and Klein (1994).

A detailed mathematical exposition of our approach is given in appendix A. In this section, we describe our methodology in general terms, with reference to the intuitive expositions of particular techniques given in section 3. This is followed by details about the data we used in our analysis.

4.1 Methodology

As noted above, our quantitative analysis is based on the production frontier approach to productivity measurement. A key feature of our methodology is that it recognises that emission abatement is costly but not necessarily a waste of resources. We do this by assuming that:

- emissions are weakly disposable (box 3.2), so that they are jointly related to fuel use and output; and
- emissions are an undesirable output, so that less is preferred to more.

We used the pooled approach to measuring productivity growth. This involves the benchmarking of each firm in each period against the same production frontier. This frontier is estimated by combining cross-section and time-series data. Thus, the production frontier used to benchmark firms represents the best practice over the entire sample period. A firm's distance from the frontier was measured by finding the maximum possible equi-proportionate expansion of desirable output (electricity supplied) and contraction of emissions, for a given combination of inputs. Thus, our methodology searches for opportunities to reduce emission intensity through decreases in emissions per unit of fuel and higher thermal efficiency (increases in output per unit of fuel).

This approach means that there are two distinct ways in which emission abatement can occur. First, through movement *toward*s the frontier, which involves taking advantage of emission abatement opportunities that do not require additional inputs and/or a reduction in net electricity generated. Second, once these options are exhausted (with respect to the observed sample) then only emission abatement opportunities that require additional inputs and/or reduced output remain. These are represented by movements *around* the frontier. It should be noted that the frontier is based on the observed outcomes for sampled firms. Thus, the frontier only takes account of emission abatement opportunities that have been exploited by the sampled firms.

Like almost all production frontier studies of the Australian electricity supply industry, we used the mathematical programming techniques of DEA to measure distances from production frontiers. This avoids the problem with the alternative technique of SFA, which depends on an arbitrary assumption about the distribution of residuals from econometric estimation. However, DEA results can be sensitive to measurement error. Thus, we carefully scrutinised our data for implausible outliers (see section 4.2 for details). Our quantitative results were produced using version 2.5 of the General Algebraic Modelling System (GAMS) and version 5 of the MINOS programming model solver.

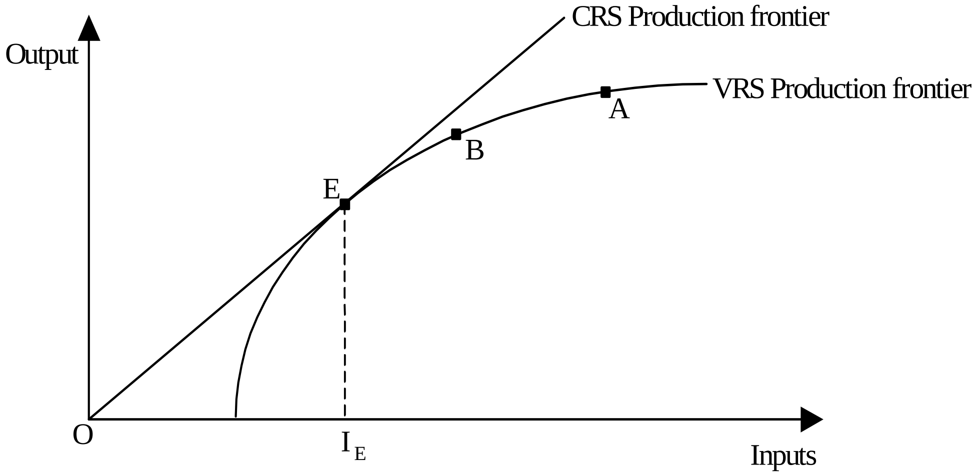
Because our sample may include generators with different operating environments, we decided not to focus on inter-firm comparisons of efficiency scores for a given point in time (box 3.1). Rather, our focus was on inter-temporal comparisons of individual generators. That is, we examined how the incorporation of greenhouse gas emissions changed productivity growth rates for each generator. This was done by calculating efficiency scores for individual generators with and without taking account of their emissions in each period. Efficiency scores were calculated by benchmarking each generator in each year against the same production frontier formed from a pooled (cross-section and time-series) sample.

Finally, we used the techniques of Fare et al. (1993) and Lovell and Luu (2000) to derive partial abatement elasticities and shadow prices for emissions (box 3.3). Note that our shadow prices are the marginal producer cost of abating greenhouse gas emissions rather than the marginal social cost of emissions. Elasticities and shadow prices were calculated for individual generators in each period.

Productivity growth was calculated using a constant returns to scale (CRS) production frontier. Use of a variable returns to scale (VRS) frontier would have led to misleading results because improvements in scale efficiency would have been ignored (see box 4.1). In contrast, partial abatement elasticities and the shadow prices for emissions were calculated using a VRS frontier. This is because elasticities and shadow prices depend on the slope of the 'true' frontier and it is likely that electricity generation is subject to variable returns to scale.

Box 4.1 **Why firms are benchmarked against a CRS production frontier**

Using a pooled approach, a constant returns to scale (CRS) frontier should be used to calculate productivity growth. This is the case even when the actual technology of an industry is more closely approximated by variable returns to scale (VRS). This is illustrated in the diagram.



The CRS frontier is a ray from the origin (point O). The VRS frontier touches the CRS frontier at the scale efficient point E. For input quantities less than I_E there are increasing returns to scale. Inputs greater than I_E involve decreasing returns to scale.

A firm that moved from point A to point B between periods would continue to produce the maximum possible output for a given quantity of inputs but its scale efficiency would improve (it moves closer to point E). Based on the VRS frontier, the firm's estimated productivity growth would be zero since it remained on the VRS frontier. Using the CRS frontier, the firm would record an increase in productivity because it had moved closer to that frontier. This reflects the fact that scale efficiency had improved.

Thus, using a CRS production frontier captures the effects of changes in both technical and scale efficiency. Grifell-Tatjé and Lovell (1995) reached a similar conclusion for the Malmquist index approach to measuring productivity growth.

4.2 Data

We specified our DEA programming problem so that generators had:

- one desirable output (electricity supplied);
- one undesirable output (emissions); and
- three inputs (capital, labour, and fuel).

The variables used for inputs and desirable output closely matched those used by the ESAA (1994) in its DEA study of electricity generators. Indeed, all our Australian data except emissions were obtained from the ESAA (2001). These data are for generators that supply the public grid. These generators account for the majority of electricity produced in Australia. Because published data on people employed in electricity generation are only available since the late 1990s, our analysis was restricted to the period 1996-97 to 1999-00. Earlier data on generation employees have not been published because vertically integrated utilities (combining generation, transmission and distribution) used to dominate the Australian electricity supply industry.

Table 4.1 **Variables used in the quantitative analysis**

Category	*Variable*	*Units*
Desirable output	Net electricity generated[a]	Gigawatt hours (GWh)
Undesirable output	CO_2 emissions	Tonnes (t)
Inputs	Generation plant installed (nameplate capacity)	Megawatts (MW)
	Employees	Full-time equivalents[b] (Australia) Number of employees[c] (US)
	Fuel consumption	Terajoules (TJ)

[a] Electricity production net of internal usage by power plants, such as for fuel pulverisation. [b] Xing, F., ESAA, Sydney, pers. comm., 27 June 2001. Data are for 30 June in each year. [c] Average number of employees in each year.

Western Australia and Tasmania still had a vertically integrated reporting structure until 1998-99 and 1997-98 respectively, and so had to be excluded from our analysis. Thus, our study covers New South Wales, Victoria, Queensland, South Australia and the Northern Territory. This accounted for 86 per cent of total Australian public electricity production in 1999-00 (ESAA 2001).

As noted in section 3.2, Australian DEA studies often include data on foreign producers to ensure a sufficiently large sample against which to benchmark local firms (see for example ESAA 1994). We followed the same approach by including data on US producers. Plant-level information submitted for the US Federal Energy

Regulatory Commission’s Form 1 was obtained from the Utility Data Institute’s Steam Electric Plant Operation and Maintenance Database. This contained information on 706 steam power generating units. We excluded 228 of these units from our analysis because incomplete data were reported for at least one of the years we analysed. An additional 13 units were excluded because of implausible capital or fuel data. Thus, we used data on 465 US steam power generating units. Like ESAA (1994), we aggregated these units into ‘simulated’ utilities. A simulated utility comprises all the thermal power stations run by a particular operator. As a result, our sample comprised a panel of 4 years by 5 Australian and 156 US observations, giving a pooled sample of 644 observations.

In an effort to compare like with like, this paper also uses a sub-sample of US utilities reliant on coal (in which coal accounted for more than 97 per cent of total fuel consumption). This comprised 269 US generating units, which were aggregated into 119 simulated utilities. The sub-sample of plants reliant on gas (in which gas accounted for more than 97 per cent of total fuel consumption) had 83 US generating units, aggregated into 37 simulated utilities.

Emissions

Burning coal, oil and gas releases various greenhouse gases, including CO_2, methane, various oxides of nitrogen, and carbon monoxide. To compare the global warming potential of these gases, they can be converted to CO_2-equivalents. In 1998-99, CO_2 accounted for 99.6 per cent of the total CO_2-equivalent emissions from electricity generation in Australia (AGO 2001a). Thus, we decided to use CO_2 emissions as the undesirable output in our analysis.

The CO_2 emissions of a given generator were estimated by multiplying its consumption of each fuel by the relevant emission factor (using data from AGO 1999a, 2000, 2001a; and EIA 1994, 2000). These emission factors quantify the average mass of CO_2 released per joule of fuel burnt. They can differ between location and over time. Further details are given in appendix C.

This approach gives an estimate of CO_2 emissions in the absence of pollution control equipment specifically designed to abate the greenhouse effect. This is probably not a major problem, since neither Australia or the United States had greenhouse policies in the late 1990s that imposed binding restrictions on CO_2 emissions. Thus, generators did not have a significant financial incentive to undertake major investments to curtail their CO_2 emissions. The United States did have a tradeable permit scheme to control sulphur dioxide (SO_2) emissions, but this is a relatively minor greenhouse gas from electricity generation.

Capital Input

Like ESAA (1994), we used the installed nameplate capacity of power plants as a measure of capital input (this approach was also followed by Arocena and Price 1999; Bell 1993; and Zeitsch and Lawrence 1996). This corresponds with the concepts of production frontier analysis, which focus on physical inputs.

Our measure of capital does not take account of differences in pollution control equipment between plants, such as scrubbers for the removal of gas contaminants. This is probably not a major problem, since pollution control equipment is typically used to reduce SO_2 emissions rather than CO_2 (Center, R., Loy Yang Power, Traralgon, pers. comm., 26 October 2001). As noted above, neither Australia or the United States had greenhouse policies in the late 1990s that imposed binding restrictions on CO_2 emissions from electricity generation. It should also be noted that data on post-treatment (end-of-pipe) CO_2 emissions were not available. In such circumstances, it would have been inconsistent to use a capital measure that took account of any differences in pollution control equipment when it was not possible to obtain emissions data that reflected the impact of such equipment.

Nevertheless, it has to be acknowledged that our capital measure does not capture differences in plant design that enable some plants to operate at a higher level of thermal efficiency (electricity supplied per unit of fuel) than others. This can in turn have implications for emission intensity since there is a close relationship between emissions and fuel consumption per unit of electricity supplied. We could, in theory, have used a measure of the value of capital services provided by a generator’s capital. However, such a value approach would lead to major problems in constructing consistent data. In particular, there are undoubtedly diverse accounting treatments across our international sample. Also, we would need to decide how to convert values into common units. Options include the observed exchange rate ($A per $US) or an estimate of purchasing power parity. A decision would also have to be made about whether to use an annual average, or a value from either the end or start of a period. It was felt that the biases introduced into the data by using a value approach would not outweigh any advantage that it may have over the physical measure of nameplate capacity.

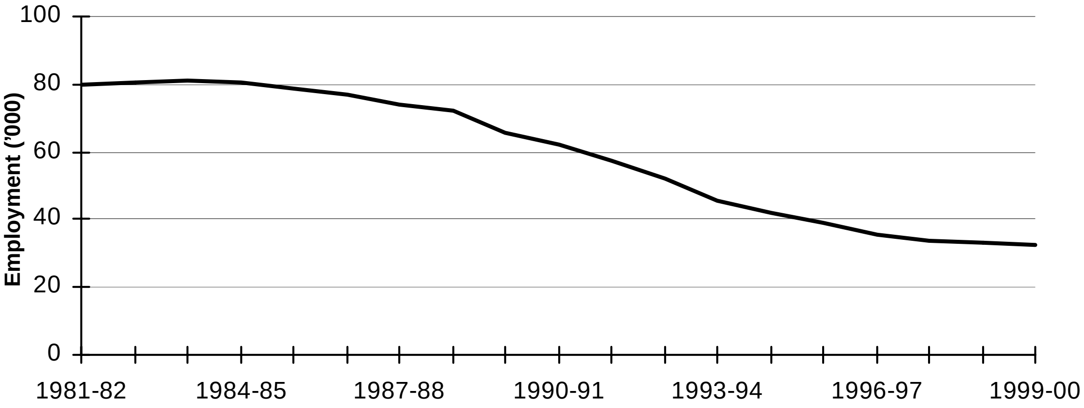
Labour Input

Ideally, the measure of labour input should reflect the total number of hours worked and labour quality. However, the only Australian data available for this study were the number of full-time equivalent employees. The US data reported the average number of employees at the plant in the reporting year. There may be some downward bias in the Australian labour data since only labour inputs for 'major electricity companies' are reported by the ESAA.

A further potential source of downward bias in the labour data (for both countries) is the use of outsourced contract labour. However, this would not have a significant impact on our results unless the ratio of employees to contractors varies markedly over time (since a constant ratio implies that total labour input changes at the same rate as employees).

It is widely recognised that the restructuring of the Australian electricity industry involved a significant fall in employees from the late 1980s to mid 1990s (figure 4.1). Part of this reduction may have involved a substitution towards contract labour rather than a decline in total labour input. However, since 1996-97 employment has stabilised, possibly indicating that the share of labour input contracted out has also stabilised. If this is the case, then contracting out of labour will have little impact on our productivity growth estimates.

Figure 4.1 **Employment in the Australian electricity supply industry**[a]



[a] Includes employment in generation, transmission and system operation as well as distribution and retailing, for major electric companies.

Source: ESAA (2001).

Fuel consumption

Fuel usage was measured in terms of energy content (TJ) rather than volume (tonnes, m^3 etc). This enabled us to construct a single measure of fuel consumption for the many utilities that used more than one type of fuel. It also has the advantage that it recognises that the energy content of a particular fuel may not be homogeneous across utilities and over time. However, it does not directly pick up other quality variations, such as moisture and ash content, that impact on the efficiency of energy conversion.

4.3 Descriptive analysis of emissions

We estimate that there were large increases in CO_2 emissions from electricity generators during 1996–00, particularly in Victoria, Queensland, and South Australia (table 4.2). However, this was generally matched by growth in net electricity generated. Thus, emission intensity (emissions per unit of net electricity generated) did not necessarily grow as rapidly as total emissions.

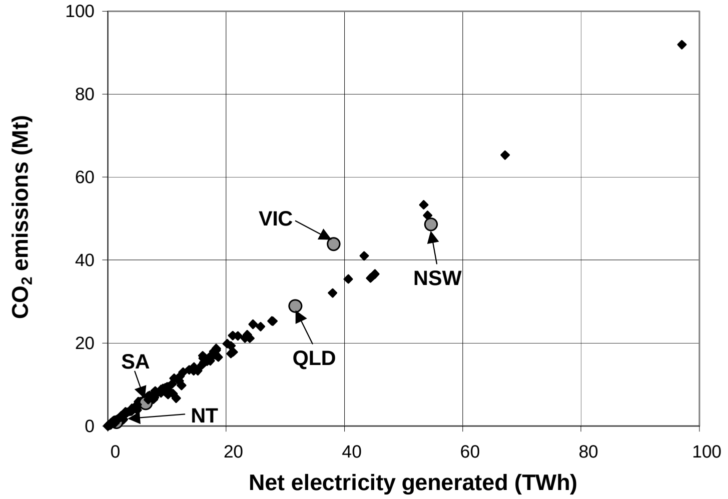
Table 4.2 **Growth of CO_2 emissions from electricity generation, 1996–00**

	1996-97 to 1997-98	*1997-98 to 1998-99*	*1998-99 to 1999-00*
	%	%	%
New South Wales	2.3	1.9	4.1
Victoria	10.4	6.1	1.6
Queensland	19.8	0.1	3.8
South Australia	4.8	13.6	3.3
Northern Territory	3.8	4.6	–5.2

Source: PC estimates.

At a given point in time, there is a strong correlation between emissions and net electricity generated (figure 4.2). Emission intensity grows as a ray from the origin rotates in an anti-clockwise direction in figure 4.2. Thus, Victoria has among the highest emission intensity in the sample (and higher than all other Australian observations), reflecting its reliance on brown coal. In contrast, the Northern Territory has a low emission intensity due to its reliance on gas-fired plant.

Figure 4.2 **CO_2 emissions and net electricity generated, 1996-97**[a]

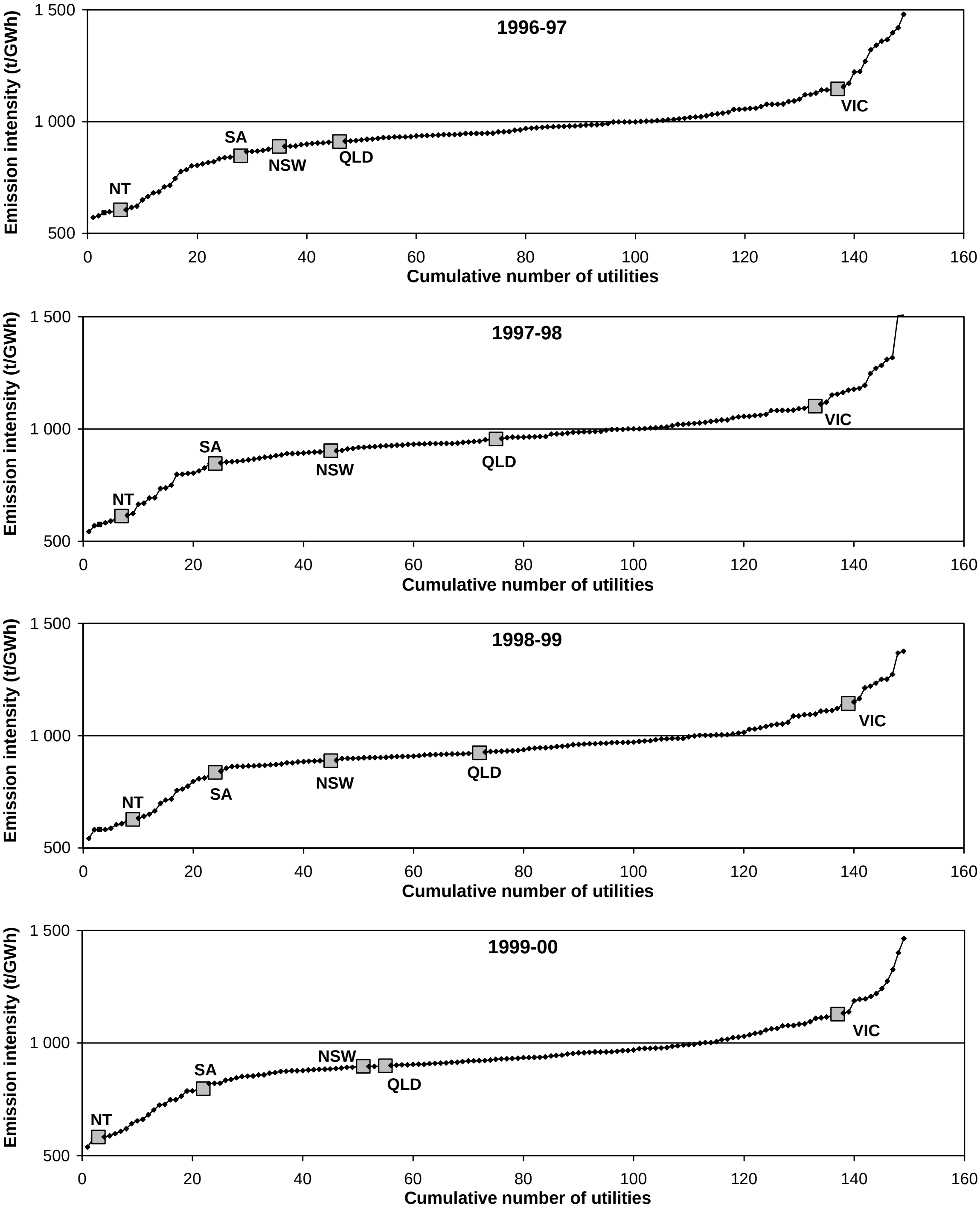


[a] Unlabelled data points are the US simulated utilities.

Source: PC estimates.

Figure 4.3 ranks the emission intensities of all the utilities from lowest to highest in each year. This shows how the emission intensities of the Australian observations move over time and relative to each other and the US sample.

Figure 4.3 **Cumulative distribution by emission intensity, 1996–00**[a]



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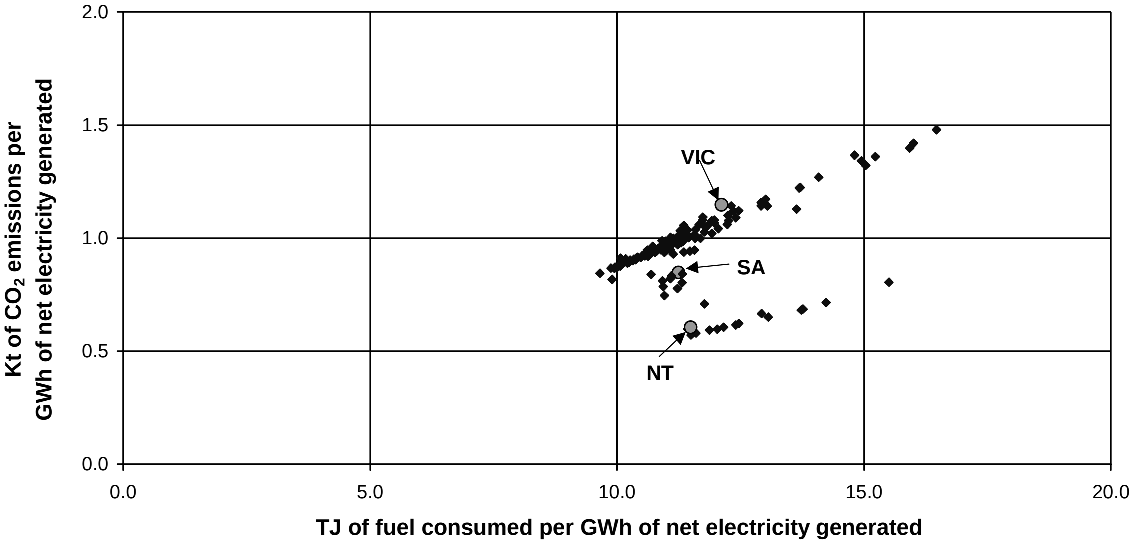
[a] Unlabelled data points are the US simulated utilities.

Source: PC estimates.

The ranking of the Australian observations relative to each other does not change over the four years. However, their position relative to the US utilities does change somewhat. Nevertheless, Victoria remains around the top 10 per cent of the distribution in terms of its emission intensity, due to its reliance on brown coal. The Northern Territory remains at the other extreme. South Australia, New South Wales and Queensland tend to be in the lower half of the distribution.

Figure 4.4 compares emissions and fuel consumption per GWh of net electricity generated in 1996-97. The slope of a ray from the origin to a particular utility reflects its average CO_2 emission factor (emissions per unit of fuel consumed). Thus, generators reliant on coal, such as Victoria, are grouped along a cluster with the highest emission factor. The Northern Territory is in a lower cluster of utilities which rely heavily on gas. South Australia lies between the two extremes, reflecting its use of both brown coal and gas.

Figure 4.4 **CO_2 emissions and fuel consumption per Gwh of net electricity generated, 1996-97[a]**



[a] Unlabelled data points are the US simulated utilities.

Source: PC estimates.

Figure 4.4 raises a potential concern with using the full sample in our programming model. Since our model allows the ratio of emissions to inputs to vary (see appendix A), it could in theory benchmark high emission coal specialists like Victoria against low emission gas specialists like the Northern Territory. This is not a significant problem for the purposes of calculating productivity *growth*, since the frontier merely serves as a fixed frame of reference against which to measure how far a particular generator’s productivity moves between periods. As noted previously, we do not conduct inter-firm comparisons of productivity *levels*.

Nevertheless, differences in plant types (such as coal versus gas-fired plants) may have implications for calculating partial abatement elasticities and shadow prices, since they are based on the shape of the frontier. For this reason, including all generators in the same sample would be inappropriate. It may nevertheless provide an insight into longer term possibilities for utilities to replace plants as they are retired with less emission intensive production methods. However, it should be noted that our model does not take account of the varying capabilities of different types of plant in meeting base and peak load demand. In particular, coal and gas-fired plant are to some extent complements rather than substitutes. Thus, we opted to use different samples, depending on which observation was being benchmarked.

- New South Wales, Victoria and Queensland were included in a sample of US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from coal.
- South Australia was included in a sample of all Australian states (excluding Western Australia and Tasmania) and the Northern Territory, plus US steam power plants which sourced more than 90 per cent of their fuel from coal and/or gas.
- The Northern Territory was included in a sample of South Australia and US steam power plants which sourced more than 97 per cent of their fuel from gas.

This approach is analogous to the method developed by Banker and Morey (1986) to deal with exogenously fixed factors.

Ideally, we would have included Victoria in a sample of generators that specialised in using the type of brown coal used in that state. This would be desirable for the purposes of calculating partial abatement elasticities and shadow prices because Victorian brown coal has an unusually high moisture content (Sinclair Knight Merz 2000). This makes it difficult for Victorian plants to achieve the lower level of emission intensity typically recorded by plants using black coal and relatively low moisture brown coal. However, it was not possible to get a sufficiently large sample of generators using the same type of brown coal as that in Victoria. Therefore, our estimates of partial abatement elasticities for Victoria should be interpreted with caution (Victorian shadow prices were not calculated due to a lack of data on average sales revenue — see chapter 5). This limitation does not apply to our productivity growth estimates for Victoria. As noted above, the frontier merely serves as a fixed frame of reference against which to measure how far a particular generator's productivity moves between periods.

5 Quantitative results

For comparison purposes, we estimated productivity growth both excluding and including CO_2 emissions. The resulting exclusive and inclusive estimates are given in the first and second column of numbers in table 5.1. The third column shows the percentage point change in productivity growth due to including CO_2 emissions (column two minus column one). For example, productivity growth for New South Wales from 1996-97 to 1997-98 is estimated to be 0.80 percentage points lower when its CO_2 emissions are included.

The last column of table 5.1 shows the growth of emission intensity. It can be seen that an increase (decrease) in emission intensity has a negative (positive) impact on estimated productivity growth in all but one case. Thus, productivity growth tends to be under-estimated when emission intensity falls and over-estimated when emission intensity grows. The intuitive explanation for this is that emissions are undesirable and so if they increase (decrease) per unit of output then this will lower (raise) estimated productivity.

The one exception to this general pattern is the Northern Territory for the period 1996-97 to 1997-98. In this case, an increase in emission intensity is associated with a small positive increase in estimated productivity growth when CO_2 emissions are included. This is obviously counter-intuitive, but may expose a potential limitation of this technique of productivity measurement or sensitivity to the relatively small size of the Northern Territory’s generating capacity.

The estimates in table 5.1 suggest that productivity growth is volatile, rarely moving in the same direction from one year to the next. This pattern seems to be largely driven by movements in thermal efficiency (the correlation coefficient between changes in thermal efficiency and productivity is over 95 per cent). Thermal efficiency may be volatile because it oscillates around an essentially fixed engineering relationship between fuel and output for a given capital plant. Any variation around this thermal efficiency may be largely due to one-off factors, such as temporary shutdowns for maintenance and changes in the demand profile from year to year linked to unusual weather patterns.

Table 5.1 Estimates of the productivity and emission intensity growth of electricity generators, 1996–00

	Productivity Growth			
	Excluding CO_2 emissions	*Including CO_2 emissions*	*Impact of CO_2 emissions on productivity growth*[a]	*Change in emission intensity*[b]
	%	%	%	%
New South Wales[c]				
1996-97 to 1997-98	–0.79	–1.58	–0.80	1.61
1997-98 to 1998-99	1.36	1.55	0.19	–1.53
1998-99 to 1999-00	–0.76	–0.77	–0.02	0.78
Victoria[c]				
1996-97 to 1997-98	4.16	4.52	0.35	–4.00
1997-98 to 1998-99	–3.15	–3.56	–0.41	3.83
1998-99 to 1999-00	0.18	0.90	0.72	–0.83
Queensland[c]				
1996-97 to 1997-98	–4.87	–5.01	–0.14	4.92
1997-98 to 1998-99	1.66	3.39	1.72	–3.32
1998-99 to 1999-00	2.04	2.57	0.54	–2.51
South Australia[d]				
1996-97 to 1997-98	0.08	0.42	0.34	–0.20
1997-98 to 1998-99	–2.01	–1.42	0.60	–1.15
1998-99 to 1999-00	5.62	8.96	3.34	–4.71
Northern Territory[e]				
1996-97 to 1997-98	0.14	0.26	0.12	1.16
1997-98 to 1998-99	–2.37	–2.81	–0.45	2.33
1998-99 to 1999-00	2.43	2.77	0.35	–6.97

[a] Percentage point change in productivity growth due to taking account of CO_2 emissions (column two minus column one). [b] Emission intensity is defined as CO_2 emissions per unit of net electricity generated. [c] Productivity growth estimated using the sample of New South Wales, Victoria, and Queensland, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from coal. [d] Productivity growth estimated using the sample of all Australian states and the Northern Territory, plus US steam power plants which sourced more than 90 per cent of their fuel (measured in TJ) from coal and/or gas. [e] Productivity growth estimated using the sample of South Australia and the Northern Territory, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from gas.

Source: PC estimates.

The difference between the exclusive and inclusive estimates of productivity growth varies markedly over time. In addition, the proportionate change from the exclusive to inclusive estimate (ratio of column three to column one) varies over a wide range. In many cases, the change is substantial. For example, the inclusive productivity growth estimate for New South Wales from 1996-97 to 1997-98 is double the change measured by the corresponding exclusive estimate. Nevertheless, there is a strong inverse relationship between emission intensity growth and the impact of

CO_2 emissions on estimated productivity growth (correlation coefficient of –62 per cent). This issue is examined further in section 5.1.

Comparison with Malmquist estimates

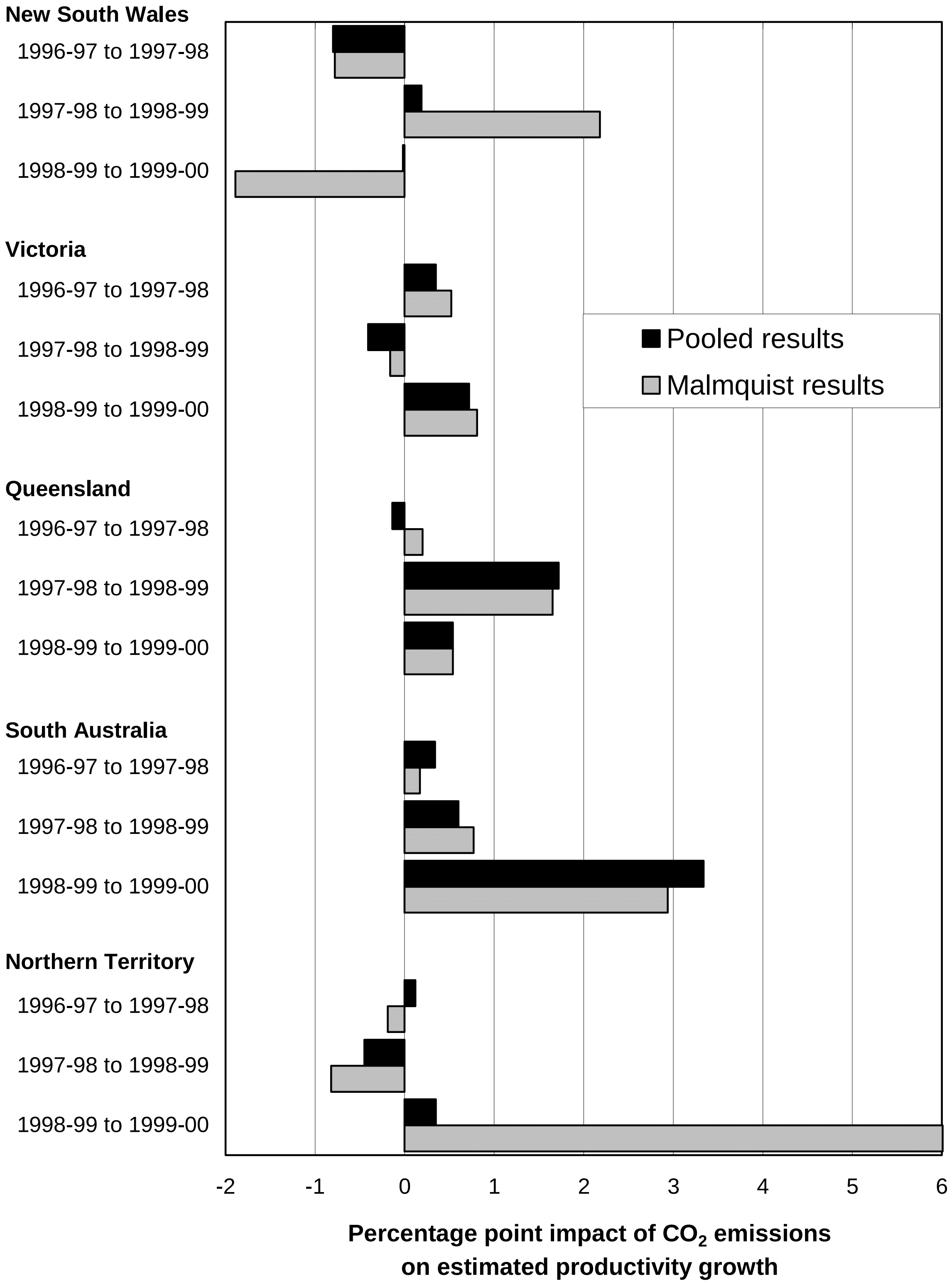
We also estimated productivity growth using the Malmquist approach (see appendix A for details about the models used and resulting estimates). Recall that this involves benchmarking firms against a single period's production frontier (see box 3.4).

The percentage point impact on estimated productivity growth of incorporating CO_2 emissions using the Malmquist approach was often similar to that using the pooled approach (figure 5.1).

However, the Malmquist results had greater variance, possibly because they are not as robust as the pooled estimates. The percentage point changes in productivity growth due to including CO_2 emissions under the Malmquist approach had a variance of 3.54. The equivalent pooled estimates in table 5.1 had a variance of 1.00. This is probably due to the Malmquist production frontiers being more sensitive to individual data variation, since each frontier only uses the observations for a single period.

In contrast, the full sample (each generator in each of the four years) was used to estimate the pooled results in table 5.1. Thus, the pooled results are based on a frontier estimated with four times as many observations as that used for the Malmquist results. Therefore, the results derived from a production frontier based on the pooled data are considered more robust, and are presented as the primary results in this paper.

Figure 5.1 **Comparison of pooled and Malmquist results**



Source: PC estimates.

5.1 Decomposition of emission intensity growth

To understand the underlying causes of emission intensity growth, we developed a technique to decompose it into the following three effects (see appendix B for details):

1. *carbon content effect* (changes in the carbon content of individual fuels, holding fuel mix and thermal efficiency constant);
2. *fuel mix effect* (substitution between fuels with different carbon contents, holding each fuel’s carbon content and thermal efficiency constant); and
3. *thermal efficiency effect* (changes in net electricity generated per unit of a particular fuel, holding fuel mix and the carbon content of each fuel constant).

Applying this technique to the data, we found that the causes of emission intensity growth varied markedly from year to year and by state (table 5.2). Overall, changes in emission intensity (the last column of table 5.2) were volatile for most Australian states, rarely moving at a similar rate or in the same direction over time. One exception was South Australia, which consistently reduced its emission intensity during 1996–00 (at an accelerating rate). On average, there was also a downward trend in the emission intensity of the US utilities.

Changes in emission intensity for New South Wales and Victoria were largely driven by movements in their thermal efficiencies (the third column), reflecting the limited fuel substitution that occurred during 1996–00. In contrast, Queensland experienced sizeable declines in emission intensity from 1997-98 to 1999-00 due to changes in fuel mix as well as thermal efficiency. This reflects the four percentage point increase in the share of Queensland’s net electricity generated from gas-fired plant during that period.

South Australia expanded the share of its gas-fired plant by almost five percentage points from 1997-98 to 1998-99 and so its fuel mix effect placed downward pressure on its emission intensity over that period. Nevertheless, changes in South Australia’s average carbon content and thermal efficiency placed upward pressure on its emission intensity from 1997-98 to 1998-99, possibly due to greater use of oil. The Northern Territory slightly increased its share of gas at the expense of oil over the period of our analysis. This probably explains its fuel mix effect from 1997-98 onwards.

Table 5.2 Decomposition of emission intensity growth, 1996–00[a]

	Sources of emission intensity growth[b]			
	Carbon content effect[c]	*Fuel mix effect*	*Thermal efficiency effect*[d]	*Change in emission intensity*
	%	%	%	%
New South Wales				
1996-97 to 1997-98	0.82	–0.01	0.80	1.61
1997-98 to 1998-99	0.41	0.01	–1.95	–1.53
1998-99 to 1999-00	0.00	0.02	0.76	0.78
Victoria				
1996-97 to 1997-98	–1.06	0.13	–3.08	–4.00
1997-98 to 1998-99	–0.03	–0.04	3.90	3.83
1998-99 to 1999-00	0.00	–0.85	0.02	–0.83
Queensland				
1996-97 to 1997-98	0.00	0.03	4.89	4.92
1997-98 to 1998-99	–0.23	–2.15	–0.94	–3.32
1998-99 to 1999-00	0.00	–0.58	–1.93	–2.51
South Australia				
1996-97 to 1997-98	0.00	–0.12	–0.08	–0.20
1997-98 to 1998-99	0.01	–3.10	1.94	–1.15
1998-99 to 1999-00	0.00	0.63	–5.34	–4.71
Northern Territory				
1996-97 to 1997-98	–0.03	0.00	1.19	1.16
1997-98 to 1998-99	0.05	–0.05	2.32	2.33
1998-99 to 1999-00	0.00	–2.55	–4.42	–6.97
United States[e]				
1996 to 1997	0.03	–0.11	–0.73	–0.81
1997 to 1998	–1.67	–0.47	0.25	–1.90
1998 to 1999	0.00	–0.11	–0.66	–0.78
United States (coal)[f]				
1996 to 1997	0.02	0.01	–0.52	–0.49
1997 to 1998	–1.83	–0.01	0.00	–1.83
1998 to 1999	0.01	–0.01	–0.65	–0.65

[a] Emission intensity is defined as CO_2 emissions per unit of net electricity generated. [b] Components of emission intensity growth were estimated using the formula derived in appendix B and by taking the geometric means using adjacent time periods as the base and apportioning each effect so that the sum of effects equalled the total growth in emission intensity. [c] 1999-00 CO_2 emission factors are based on those for the previous year due to the lack of data and so no carbon content effect was estimated for 1998-99 to 1999-00. [d] A positive (negative) number for the thermal efficiency effect indicates that emission intensity increased (decreased) because thermal efficiency declined (increased). [e] Steam power plants. US data is reported by calendar year. [f] Steam power plants which sourced more than 97 per cent of their fuel (in TJ) from coal.

Source: PC estimates.

Based on our decomposition of emission intensity growth (table 5.2), it appears that movements in thermal efficiency explain most of the difference between the exclusive and inclusive estimates of productivity growth (table 5.1). Nevertheless, some significant fuel mix effects are observed. For example, fuel mix changes in South Australia during 1996–99 seem to have been the main factor influencing emission intensity changes. Most states and the Northern Territory experienced limited changes in the carbon content of particular fuels during 1996–00. However, shifts in carbon content seem to have been important (in conjunction with thermal efficiency changes) for New South Wales during 1996–99 and Victoria during 1996–98.

It is also generally true that when the exclusive estimate of productivity growth is positive (negative), productivity growth including CO_2 emissions is always higher (lower). This reflects the fact that changes in estimated productivity growth (excluding emissions) are largely driven by movements in thermal efficiency, and this is highly correlated with CO_2 emissions (since, per unit of output, the more fuel used, the more emissions result).

Therefore, including emissions in our calculations tends to reinforce the effects already evident in the exclusive (without emissions) estimates of productivity growth. This is why excluding emissions tends to cause productivity growth to be under-estimated when emission intensity falls and over-estimated when emission intensity grows.

The one exception (South Australia, 1997-98 to 1998-99) is attributable to a shift towards (less emission intensive) gas-fired power plants in South Australia in the late 1990s. In this case, a large fuel mix effect moved emission intensity in the opposite direction to the prevailing thermal efficiency effect. In the exclusive measure of productivity growth, the thermal efficiency effect dominates because emissions are excluded. In the estimate of productivity growth that is inclusive of emissions, the fuel mix effect dominates to give an overall decrease in the South Australia’s emission intensity.

To explore the relationships further, we regressed the difference between the exclusive and inclusive estimates of productivity growth on the components of emission intensity growth. The resulting estimated equation was:

$$\begin{array}{ccccccccc} \begin{array}{c}\text{Impact of CO}_2\text{ emissions}\\ \text{on estimated productivity}\\ \text{growth of utility } u\end{array} & = & \begin{array}{c}0.47\\(0.03)\end{array} & - & \begin{array}{c}1.51\boldsymbol{cc}_u\\(0.01)\end{array} & - & \begin{array}{c}0.17\boldsymbol{fm}_u\\(0.31)\end{array} & - & \begin{array}{c}0.16\boldsymbol{te}_u\\(0.02)\end{array} \end{array}$$

where cc_u is the carbon content effect (as discussed in the decomposition of emission intensity growth), fm_u is the fuel mix effect, and te_u is the thermal efficiency effect. The numbers reported in brackets below the estimated coefficients are p-values, which show the probability that a coefficient is not statistically significant. This linear regression explained 69 per cent of the total variation in the observed difference between exclusive and inclusive estimates of productivity growth ($R^2 = 0.69$).

The regression results imply that the carbon content and thermal efficiency effects are both significant explanators of the impact of CO_2 emissions on estimated productivity growth. Note, however, that te_u tended to be much greater that cc_u and so changes in thermal efficiency have the greatest impact on estimated productivity growth.

5.2 Abatement elasticities

Our estimates of partial abatement elasticities are given in table 5.3. These show the proportionate reduction in output (net electricity generated) required to abate an environmental impact by 1 per cent, holding all other variables constant. Recall that abatement elasticities are based on the slope of the production frontier. Thus, they reflect the cost (in terms of foregone output of electricity) of reducing emissions once a generator has fully exploited emission abatement opportunities that do not require the use of additional inputs and/or a reduction in output.

Table 5.3 **Estimates of partial abatement elasticities, 1996–00[a]**

	1996-97	*1997-98*	*1998-99*	*1999-00*
New South Wales[b]	1.06	1.08	1.06	1.07
Victoria[b]	1.11	0.71	0.66	0.65
Queensland[b]	0.56	1.10	1.10	1.07
South Australia[c]	0.47	0.47	0.46	0.44
Northern Territory[d]	0.83	0.84	0.86	0.80

[a] Partial abatement elasticities show the percentage reduction in output (net electricity generated) required to reduce CO_2 emissions by 1 per cent, holding all other variables constant. [b] Estimated using the sample of New South Wales, Victoria, and Queensland, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from coal. [c] Estimated using the sample of all Australian states and the Northern Territory, plus US steam power plants which sourced more than 90 per cent of their fuel (measured in TJ) from coal and/or gas. [d] Estimated using the sample of South Australia and the Northern Territory, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from gas.

Source: PC estimates.

All the estimated elasticities have the expected positive sign, indicating that there is a cost associated with abating CO_2 emissions. For a given state, the values of the estimated elasticities were broadly similar over time. The notable exceptions are the 1996-97 observations for Victoria and Queensland. The elasticities for New South Wales are all greater than one, implying that abating CO_2 during 1996–00 would have required a greater than proportionate reduction in output (once it had exploited all emission abatement opportunities that did not require the use of additional inputs and/or a reduction in output). The South Australian elasticities are all below one, suggesting that emission abatement was less costly (in terms of foregone output) in that state. The Victorian elasticities are below one from 1997-98 onwards. However, as noted in chapter 4, the Victorian elasticities should be interpreted with caution because they were estimated using a sample of mainly black coal producers.

These elasticities raise the question of how far generators could reduce their emissions through actions that do not require the use of additional inputs and/or a reduction in output before the abatement opportunities represented by the elasticities become the only option. This can be determined from a generator's distance from the frontier.

Our results suggest that the black coal specialists (New South Wales and Queensland) could, on average, have reduced their emissions by around 4 per cent without using additional inputs and/or reducing output. Greater opportunities to abate emissions without using additional inputs and/or reducing output were estimated for Victoria (11 per cent reduction in emissions), South Australia (7 per cent), and the Northern Territory (9 per cent). However, the estimates for Victoria, South Australia and the Northern Territory should be treated with caution. As noted previously, Victoria uses a type of brown coal that has an unusually high moisture content. This makes it difficult for Victorian plants to achieve the lower level of emission intensity typically recorded by plants using black coal and relatively low moisture brown coal. The result for South Australia may be affected by it being benchmarked against a sample that includes generators specialising in (less emission intensive) gas-fired plants. Recall that South Australia uses a sizeable quantity of brown coal (see chapter 2). The result for the Northern Territory should be treated with caution because its circumstances are unusual. In particular, it has a relatively small population dispersed over a large area.

5.3 Abatement costs

We also estimated shadow prices for emissions. Recall that these can be interpreted as the marginal producer cost of abatement (the dollar cost to generators of abating emissions by an additional tonne) once opportunities to reduce emissions without using additional inputs and/or reducing output have been exhausted. As discussed in chapter 3, they are estimated by assuming that the observed output price equals its shadow price. We used the average sales revenue of generators (based on data reported in ESAA 2001) as a proxy for the price of electricity (see table A.1 in appendix A for details). This information was only available for New South Wales, Queensland and South Australia from 1997-98 onwards (but no 1999-00 data were available for South Australia).

The estimated shadow prices range from $26 to $41 per tonne of CO_2. These figures should be considered as upper bounds on the abatement cost since they are derived from partial adjustment and are only binding after opportunities to abate emissions without using additional inputs and/or reducing output are exhausted (through movement towards the production frontier).

Table 5.4 **Estimates of the marginal producer cost of abating CO_2 emissions, 1997–00**[a]

	1997-98	*1998-99*	*1999-00*
	$/t	$/t	$/t
New South Wales[b]	36	37	40
Queensland[b]	38	41	39
South Australia[c]	27	26	na

[a] Estimated by assuming that the shadow price of net electricity generated equals average sales revenue. [b] Estimated using the sample of New South Wales, Victoria, and Queensland, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from coal. [c] Estimated using the sample of all Australian states and the Northern Territory, plus US steam power plants which sourced more than 90 per cent of their fuel (measured in TJ) from coal and/or gas. **na** Not available.

Source: PC estimates.

In a discussion paper on tradeable greenhouse gas emission permits, the AGO (1999b, p. 14) argued that ‘it is feasible to assume that permits in the first commitment period (of the Kyoto Protocol) could be valued at between $10 and $50 per tonne of carbon dioxide’. Our shadow price estimates are within this range. Our estimates also suggest that marginal abatement costs for electricity generators are at the mid to high end of the range mentioned by the AGO.

6 Concluding comments

Our quantitative results show that when a firm's environmental impacts are large, they can have a significant effect on its estimated productivity growth. In particular, we found that ignoring greenhouse gas emissions causes the productivity growth of electricity generators to be under-estimated in some years and over-estimated in other years. Productivity growth tends to be under-estimated when emission intensity (emissions per unit of electricity supplied) falls and over-estimated when emission intensity grows.

Changes in emission intensity (and hence the impact of CO_2 emissions on estimated productivity growth) during the late 1990s appear to have been largely driven by movements in thermal efficiency (electricity supplied per unit of fuel). Fuel substitution and changes in the carbon content of particular fuels were also important sources of emission intensity growth in a few cases.

Our estimates of partial abatement elasticities and shadow prices indicate that there are regional differences in the cost of abating CO_2 emissions (in terms of foregone output of electricity) once a generator has fully exploited emission abatement opportunities that do not require the use of additional inputs and/or a reduction in output.

In conclusion, we have shown that the methodology used in this paper has the major advantage that it can readily incorporate unpriced environmental impacts into productivity growth estimates. A disadvantage is that the methodology is data intensive and technically challenging. Nevertheless, it can provide useful insights into how estimated productivity growth can be affected by the environmental impacts of economic activity. There may be scope to extend our analysis to incorporate other environmental by-products of electricity generation. This would require, for example, the measurement and consideration of other gas emissions such as sulphur dioxide which can result in acidified rain, and the thermal effects that the release of water used in the electricity generation process may have.

APPENDIXES

A Production frontier analysis

A.1 Pooled model

We assume that there are u = 1,…,U utilities; t = 1,…,T time periods; and i = 1,…,I inputs. Let $X_{u,t}^{i}$ be input i used by utility u in period t; $EM_{u,t}$ greenhouse gas emissions from utility u in period t; and $Y_{u,t}$ output.

Productivity growth was calculated using distance functions that benchmark a given utility in adjacent periods (t and t+1) against a production frontier estimated from the pooled sample of all observed utilities in all periods:

$$PG_{u,t+1} = \left[\frac{D_u^{CRS}\left(X_{u,t+1}, EM_{u,t+1}, Y_{u,t+1}\right)}{D_u^{CRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)} \right]^2 - 1 \tag{A.1}$$

where $PG_{u,t+1}$ is productivity growth of utility u in period t+1, $D_u^{CRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)$ is the constant returns to scale (CRS) distance function for utility u in period t; and $D_u^{CRS}\left(X_{u,t+1}, EM_{u,t+1}, Y_{u,t+1}\right)$ is the CRS distance function for utility u in period t+1. The reason for using a CRS production frontier is discussed in box 4.1.

Inclusive model

In the model that is inclusive of emissions, the CRS distance function, $D_u^{CRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) = 1/\theta_{u,t}^{CRS}$, was calculated for utility u as the solution to the non-linear programming problem:

$$
\begin{aligned}
&\max_{\theta,w} \theta_{u,t}^{\mathrm{CRS}} \qquad \text{subject to:}\\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau} Y_{j,\tau}\right) - \theta_{u,t}^{\mathrm{CRS}} Y_{u,t} \geq 0\\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau} EM_{j,\tau}\right) - \frac{EM_{u,t}}{\theta_{u,t}^{\mathrm{CRS}}} = 0 \qquad\qquad (A.2)\\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau} X_{j,\tau}^{i}\right) - X_{u,t}^{i} \leq 0 \qquad \mathrm{i} = 1,\ldots,\mathrm{I}\\
&w_{j,\tau} \geq 0 \quad \forall \quad \mathrm{j} = 1,\ldots,\mathrm{U} \quad \tau = 1,\ldots,T
\end{aligned}
$$

where $1/\theta_{u,t}^{CRS}$ is the efficiency score for utility u in period t benchmarked on the pooled sample under CRS technology; and $w_{j,\tau}$ is the weight applied to utility j in period τ to form the hypothetical producer against which utility u is benchmarked.

Problem (A.2) states that $\theta_{u,t}^{CRS}$ should be maximised subject to four constraints. The factors that can be varied to do this are the weights $w_{j,\tau}$ and the measure $\theta_{u,t}^{CRS}$ itself. The weights are used to form a hypothetical utility lying on the production frontier against which utility u is benchmarked.

The constraints state that the weighted average of other utilities (the hypothetical utility) must:

- produce at least as much as utility u's output scaled up by the factor $\theta_{u,t}^{CRS}$ (first constraint);
- have the same emissions as utility u scaled down by $1/\theta_{u,t}^{CRS}$ (second constraint); and
- not use any more inputs than utility u (third constraint).

The final constraint is concerned with the weights used to form the hypothetical utility. It states that the individual weights must not be negative.

The second constraint is an equality because we assume that emissions are weakly disposable. If emissions were a freely disposable (and desirable) output then '≥' would be substituted for '=' in the second constraint (and emissions would be scaled up by the factor $\theta_{u,t}^{CRS}$) .

Problem (A.2) can be interpreted as a variant of an output-based DEA model in which one of the outputs (emissions) is treated as being undesirable. In particular, $EM_{u,t}$ is scaled by the inverse of $\theta_{u,t}^{CRS}$, the variable used to vary the desirable output

$Y_{u,t}$. Most studies of electricity generators also treat emissions as an undesirable output (see, for example, Arocena and Price 1999; Fare et al. 1989; Korhonen and Luptacik 2000; Yaisawarng and Klein 1994).

Alternatively, we could have treated emissions as the consumption of clean air and hence an input. This would be similar to the approach used by Lovell and Luu (2000), who treated the environmental impact in their study, water pollution from pesticide use, as an input. We did consider incorporating emissions as an input but a limitation of this approach is that it would maintain a fixed relationship between emissions and other inputs (since both $EM_{u,t}$ and $X^i_{u,t}$ would be scaled by the same factor, $1/\theta^{CRS}_{u,t}$). We felt that it was desirable to give generators the option to vary the relationship between their emissions and inputs in order to abate their emissions. Given this, it was considered more appropriate to treat emissions as an undesirable output.

Exclusive model

The same procedure was undertaken for the model that is exclusive of emissions, with the exception that the emission constraints were not used. This means that the programming problems have the general form of a traditional output-based DEA model:

$$\begin{aligned}
&\max_{\theta,w} \theta^{\mathrm{CRS}}_{u,t} \qquad \text{subject to:} \\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau} Y_{j,\tau}\right) - \theta^{\mathrm{CRS}}_{u,t} Y_{u,t} \geq 0 \\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau} X^i_{j,\tau}\right) - X^i_{u,t} \leq 0 \qquad \text{i = 1,...,I} \\
&w_{j,\tau} \geq 0 \quad \forall \quad \text{j = 1,...,U} \quad \tau = 1,\ldots,T
\end{aligned} \tag{A.3}$$

In this exclusive model, the CRS distance function is $D^{CRS}_u\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) = \dfrac{1}{\sqrt{\theta^{CRS}_{u,t}}}$.

Partial abatement elasticities

Partial abatement elasticities measure the proportionate reduction in output required to abate emissions by a given amount, holding all other variables constant. The abatement elasticity for utility u in period t ($\varepsilon_{u,t}$) depends on the slope of the production surface. In particular, it is derived from partial derivatives of the distance function (Lovell and Luu 2000). Thus, it is desirable to ensure that the estimated production surface is representative of the ‘true’ surface. In the case of electricity generation, this means allowing for variable returns to scale (VRS).

The VRS distance benchmarked on period t technology, $D_u^{VRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) = 1/\theta_{u,t}^{VRS}$, was calculated for utility u as the solution to the non-linear programming problem:

$$\begin{aligned}
&\max_{\theta,w} \theta_{u,t}^{\mathrm{VRS}} \qquad \text{subject to:} \\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau}Y_{j,\tau}\right) - \theta_{u,t}^{\mathrm{VRS}}Y_{u,t} \geq 0 \\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau}EM_{j,\tau}\right) - \frac{EM_{u,t}}{\theta_{u,t}^{\mathrm{VRS}}} = 0 \\
&\left(\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau}X_{j,\tau}^{i}\right) - X_{u,t}^{i} \leq 0 \qquad \text{i = 1,...,I} \\
&\sum_{\tau=1}^{T}\sum_{j=1}^{U} w_{j,\tau} = 1 \\
&w_{j,\tau} \geq 0 \quad \forall \quad \text{j = 1,...,U} \quad \tau = 1,...,T
\end{aligned} \tag{A.4}$$

This is identical to problem (A.2) except for the additional constraint that the weights sum to one. This has the effect of pulling in the frontier to form a tighter envelope around the data.

The (U x T) solutions to (A.4) were used in the following formula to calculate abatement elasticities for each utility (1,…,U) in each period (1,…,T):

$$\varepsilon_{u,t} = \frac{\partial Y_{u,t}}{\partial EM_{u,t}}\frac{EM_{u,t}}{Y_{u,t}} = -\frac{\partial D_u^{VRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)\big/\partial EM_{u,t}}{\partial D_u^{VRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)\big/\partial Y_{u,t}}\frac{EM_{u,t}}{Y_{u,t}} \tag{A.5}$$

The partial derivatives in the above formula were an output of the MINOS programming model solver (version 2.5) that we used in conjunction with the General Algebraic Modelling System (version 5).

Shadow prices of emissions

The shadow price of emissions ($SP_{u,t}^{EM}$) for a given utility in a given year was derived by assuming that the observed price of output ($P_{u,t}^{Y}$) equals its shadow price ($SP_{u,t}^{Y}$). Then it was possible to calculate $SP_{u,t}^{EM}$ using the formula:

$$SP_{u,t}^{EM} = -P_{u,t}^{Y} \frac{\partial D_u^{VRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) \big/ \partial EM_{u,t}}{\partial D_u^{VRS}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) \big/ \partial Y_{u,t}} \tag{A.6}$$

$SP_{u,t}^{EM}$ can be interpreted as the marginal abatement cost. Note that there is a shadow price of emissions for each utility in each year (that is, U x T shadow prices). These shadow prices will vary between utilities in a given year if the sum of emissions across all utilities is not at its optimal level (since this implies that marginal abatement costs have not been equalised across utilities).

We used the average sales revenue of generators (based on data reported in ESAA 2001) as a proxy for the price of electricity. This information was only available for New South Wales, Queensland and South Australia from 1997-98 onwards (but no 1999-00 data were available for South Australia). The data for average sales revenue are shown in table A.1.

Table A.1 **Average sales revenue**

	1997-1998	*1998-1998*	*1998-2000*
	$/GWh	$/GWh	$/GWh
New South Wales	33 734	33 727	34 765
Queensland	35 037	36 233	33 630
South Australia	57 551	50 716	na

na Not available.

Source: PC estimates.

A.2 Malmquist model

Malmquist indices were calculated using distance functions that benchmark a given firm in adjacent periods (t and t+1) against a constant returns to scale (CRS) production frontier for one of those periods (t or t+1) (see box 3.4 for an intuitive explanation). The choice of which period to use as a benchmark is arbitrary and can lead to different results. Therefore, we calculated the geometric average of Malmquist indices benchmarked on period t and t+1 technologies, using the following formula:

$$M_u = \frac{D_u^{CRS,t}\left(X_{u,t+1}, EM_{u,t+1}, Y_{u,t+1}\right)}{D_u^{CRS,t}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)} \frac{D_u^{CRS,t+1}\left(X_{u,t+1}, EM_{u,t+1}, Y_{u,t+1}\right)}{D_u^{CRS,t+1}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)} \qquad \text{(A.7)}$$

where $D_u^{CRS,t}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)$ is the within-period CRS distance for utility u; $D_u^{CRS,t}\left(X_{u,t+1}, EM_{u,t+1}, Y_{u,t+1}\right)$ is the mixed-period CRS distance benchmarked on period t technology; and $D_u^{CRS,t+1}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right)$ is the mixed-period CRS distance benchmarked on period t+1 technology. When these distances are calculated without taking account of emissions, it is necessary to take the square root of the expression in equation (A.7). This is because our programming models then use the output-based approach to productivity measurement.

Within-period model

In the model that is inclusive of emissions, the within-period CRS distance function, $D_u^{CRS,t}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) = 1/\theta_{u,t}^{CRS,t}$, is calculated for utility u as the solution to the non-linear programming problem:

$$\begin{aligned}
&\max_{\theta,w} \theta_{u,t}^{CRS,t} \qquad \text{subject to:} \\
&\left(\sum_{j=1}^{U} w_{j,t} Y_{j,t}\right) - \theta_{u,t}^{CRS,t} Y_{u,t} \geq 0 \\
&\left(\sum_{j=1}^{U} w_{j,t} EM_{j,t}\right) - \frac{EM_{u,t}}{\theta_{u,t}^{CRS,t}} = 0 \\
&\left(\sum_{j=1}^{U} w_{j,t} X_{j,t}^{i}\right) - X_{u,t}^{i} \leq 0 \qquad \text{i = 1,...,I} \\
&w_{j,t} \geq 0 \quad \forall \quad \text{j = 1,...,U}
\end{aligned} \qquad \text{(A.8)}$$

where $\theta_{u,t}^{CRS,t}$ is the efficiency score for utility u in period t benchmarked on period t CRS technology; and w_{jt} is the weight applied to utility j to form the hypothetical producer against which utility u is benchmarked.

Mixed-period models

In the model that is inclusive of emissions, the mixed-period distance benchmarked on period t technology, $D_u^{CRS,t}\left(X_{u,t+1}, EM_{u,t+1}, Y_{u,t+1}\right) = 1/\theta_{u,t+1}^{CRS,t}$, is calculated for utility u as the solution to the non-linear programming problem:

$$\max_{\theta,w} \theta_{u,t+1}^{CRS,t} \quad \text{subject to:}$$

$$\begin{aligned}
&\left(\sum_{j=1}^{U} w_{j,t} Y_{j,t}\right) - \theta_{u,t+1}^{CRS,t} Y_{u,t+1} \geq 0 \\
&\left(\sum_{j=1}^{U} w_{jt} EM_{jt}\right) - \frac{EM_{u,t+1}}{\theta_{u,t+1}^{CRS,t}} = 0 \\
&\left(\sum_{j=1}^{U} w_{j,t} X_{j,t}^{i}\right) - X_{u,t+1}^{i} \leq 0 \qquad i = 1,...,I \\
&w_{j,t} \geq 0 \quad \forall \quad j = 1,...,U
\end{aligned} \tag{A.9}$$

In the model that is inclusive of emissions, the mixed-period distance benchmarked on period t+1 technology, $D_{u}^{CRS,t+1}\left(X_{u,t}, EM_{u,t}, Y_{u,t}\right) = 1/\theta_{u,t}^{CRS,t+1}$, is calculated for utility u as the solution to the non-linear programming problem:

$$\max_{\theta,w} \theta_{u,t}^{CRS,t+1} \quad \text{subject to:}$$

$$\begin{aligned}
&\left(\sum_{j=1}^{U} w_{j,t+1} Y_{j,t+1}\right) - \theta_{u,t}^{CRS,t+1} Y_{u,t} \geq 0 \\
&\left(\sum_{j=1}^{U} w_{j,t+1} EM_{j,t+1}\right) - \frac{EM_{u,t}}{\theta_{u,t}^{CRS,t+1}} = 0 \\
&\left(\sum_{j=1}^{U} w_{j,t+1} X_{j,t+1}^{i}\right) - X_{u,t}^{i} \leq 0 \qquad i = 1,...,I \\
&w_{j,t+1} \geq 0 \quad \forall \quad j = 1,...,U
\end{aligned} \tag{A.10}$$

The within-period model (A.8) has to be solved for each utility in each period (U x T times). The mixed-period models (A.9 and A.10) have to be solved U x (T-1) times each. Thus, constructing Malmquist indices requires the solution of (3 x U x T) – (2 x U) non-linear programming problems. There are U x (T-1) resulting Malmquist indices.

Exclusive models

The same procedure is undertaken for the model that is exclusive of emissions, with the exception that the emission constraints are not used. This means that the programming problems have the general form of a traditional output-based DEA model. The within-period model was of the form:

$$
\begin{aligned}
&\max_{\theta,w} \theta_{u,t}^{CRS,t} \quad \text{subject to:}\\
&\left(\sum_{j=1}^{U} w_{j,t} Y_{j,t}\right) - \theta_{u,t}^{CRS,t} Y_{u,t} \geq 0\\
&\left(\sum_{j=1}^{U} w_{j,t} X_{j,t}^{i}\right) - X_{u,t}^{i} \leq 0 \qquad \text{i = 1,...,I}\\
&w_{j,t} \geq 0 \quad \forall \quad \text{j = 1,...,U}
\end{aligned}
\tag{A.11}
$$

Mixed-period models were also used. These were similar to problems (A.9) and (A.10) but without the emissions constraints.

Malmquist results

The estimates in table A.2 were obtained from the application of this Malmquist technique to the data set of Australian and US electricity generation observations. This table is analogous to table 5.1, which presents results from the pooled model.

As in the pooled case, the difference between the exclusive and inclusive estimates of productivity growth varies markedly over time. In many cases, the change is substantial. For example, the inclusive productivity growth estimate for New South Wales from 1997-98 to 1998-99 is more than two and a half times the corresponding exclusive estimate. There is also an inverse relationship between emission intensity growth and the impact of CO_2 emissions on estimated productivity growth (correlation coefficient of –76 per cent).

Table A.2 Malmquist estimates of the productivity and emission intensity growth of electricity generators, 1996–00

	Productivity Growth		Impact of CO_2 emissions on productivity growth[a]	Change in emission intensity[b]
	Excluding CO_2 emissions	Including CO_2 emissions		
	%	%	%	%
New South Wales[c]				
1996-97 to 1997-98	–0.79	–1.56	–0.78	1.61
1997-98 to 1998-99	1.36	3.54	2.18	–1.53
1998-99 to 1999-00	–0.76	–2.65	–1.89	0.78
Victoria[c]				
1996-97 to 1997-98	4.43	4.96	0.52	–4.00
1997-98 to 1998-99	–3.36	–3.51	–0.16	3.83
1998-99 to 1999-00	0.09	0.90	0.81	–0.83
Queensland[c]				
1996-97 to 1997-98	–4.70	–4.50	0.20	4.92
1997-98 to 1998-99	1.67	3.32	1.65	–3.32
1998-99 to 1999-00	2.04	2.57	0.54	–2.51
South Australia[d]				
1996-97 to 1997-98	0.08	0.26	0.17	–0.20
1997-98 to 1998-99	–2.01	–1.24	0.77	–1.15
1998-99 to 1999-00	5.62	8.56	2.94	–4.71
Northern Territory[e]				
1996-97 to 1997-98	0.19	–0.01	–0.19	1.16
1997-98 to 1998-99	–2.36	–3.17	–0.82	2.33
1998-99 to 1999-00	6.30	12.32	6.01	–6.97

[a] Percentage point change in productivity growth due to taking account of CO_2 emissions (column two minus column one). [b] Emission intensity is defined as CO_2 emissions per unit of net electricity generated. [c] Productivity growth estimated using the sample of New South Wales, Victoria, and Queensland, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from coal. [d] Productivity growth estimated using the sample of all Australian states and the Northern Territory, plus US steam power plants which sourced more than 90 per cent of their fuel (measured in TJ) from coal and/or gas. [e] Productivity growth estimated using the sample of South Australia and the Northern Territory, plus US steam power plants which sourced more than 97 per cent of their fuel (measured in TJ) from gas.

Source: PC estimates.

B Decomposition of emission intensity growth

In a given time period, the greenhouse gas emissions of utility u using f = 1,…,3 fuels (coal, oil and gas) will be:

$$EM_u = \sum_{f=1}^{3} EM_{uf} = \sum_{f=1}^{3} CC_{uf} F_{uf} \tag{B.1}$$

where EM_{uf} is the greenhouse gases emitted by utility u from fuel f; CC_{uf} is the carbon content of fuel f used by utility u (CO_2 emissions per unit of fuel); and F_{uf} is the quantity of fuel f used by utility u (expressed in terms of energy content, such as TJ).

Utility u's emission intensity (EI_u) is the amount of CO_2 it emits per unit of net electricity generated (EL_u):

$$EI_u = \frac{EM_u}{EL_u} = \frac{\sum_f CC_{uf} F_{uf}}{EL_u} \tag{B.2}$$

Taking differential logs of (B.2) gives the following growth equation for emission intensity:

$$ei_u = \sum_f \left[S_{uf}^{EM} \left(cc_{uf} + f_{uf} \right) \right] - el_u \tag{B.3}$$

where lower case letters indicate growth rates. S_{uf}^{EM} is the share of utility u's emissions attributable to fuel f:

$$S_{uf}^{EM} = \frac{EM_{uf}}{\sum_f EM_{uf}} \tag{B.4}$$

Utility u's growth in net electricity generated (el_u) is the weighted sum of the growth in electricity production from each fuel (el_{uf} for f = 1,…,3), where the weights used are the share of electricity generated from each fuel:

$$S_{uf}^{EL} = \frac{EL_{uf}}{\sum_f EL_{uf}} \tag{B.5}$$

(B.5) can be substituted into (B.3) to give:

$$ei_u = \sum_f \left[S_{uf}^{EM} \left(cc_{uf} + f_{uf} \right) \right] - \sum_f \left[S_{uf}^{EL} el_{uf} \right] \tag{B.6}$$

The net electricity generated from fuel f is equal to the quantity of fuel used multiplied by the thermal efficiency of converting that fuel into electricity:

$$EL_{uf} = F_{uf} TE_{uf} \tag{B.7}$$

where TE_{uf} is the thermal efficiency achieved by utility u in converting fuel f into electricity. Hence, growth in net electricity generated from fuel j is:

$$el_{uf} = f_{uf} + te_{uf} \tag{B.8}$$

Substituting (B.8) into (B.6) gives:

$$ei_u = \sum_f \left[S_{uf}^{EM} \left(cc_{uf} + f_{uf} \right) \right] - \sum_f \left[S_{uf}^{EL} \left(f_{uf} + te_{uf} \right) \right] \tag{B.9}$$

which can be rearranged as:

$$ei_u = \sum_f S_{uf}^{EM} cc_{uf} + \sum_f \left(S_{uf}^{EM} - S_{uf}^{EL} \right) f_{uf} - \sum_f S_{uf}^{EL} te_{uf} \tag{B.10}$$

This shows that changes in emission intensity are the result of the following three effects:

1. *carbon content effect* (changes in the carbon content of individual fuels, holding fuel mix and thermal efficiency constant);
2. *fuel mix effect* (substitution between fuels with different carbon contents, holding each fuel’s carbon content and thermal efficiency constant); and
3. *thermal efficiency effect* (changes in net electricity generated per unit of a particular fuel, holding fuel mix and the carbon content of each fuel constant).

The fuel mix effect is captured by the term $\sum_j \left(S_{ij}^{EM} - S_{ij}^{EL} \right) f_{ij}$ in equation (B.10). Note that $\left(S_{uf}^{EM} - S_{uf}^{EL} \right) < 0$ if fuel f accounts for a smaller share of utility u’s emissions than its contribution to utility u’s net electricity generated. Greater use of such a fuel would have a dampening effect on the growth of utility u’s emission intensity and so the weight $\left(S_{uf}^{EM} - S_{uf}^{EL}\right)$ on f_{uf} is negative in equation (B.10). Conversely, $\left(S_{uf}^{EM} - S_{uf}^{EL}\right) > 0$ for more emission intensive fuels because their growth would place upward pressure on utility u’s emission intensity.

C Carbon dioxide emissions

C.1 Australia

The AGO (1999a, 2000, 2001a) reports emission factors for most power stations. These quantify the average mass of CO_2 released per PJ of fuel burnt. The plant-level emission factors were used to construct state-level emission factors, by weighting them by each plant's share of its state's installed capacity. Since oil emission factors were only available for New South Wales and Queensland, these were aggregated to provide an estimate for the other states. The resulting estimates are given in table C.1.

Table C.1 **Australian CO_2 emission factors**

Region	*Fuel*	*1996-97*	*1997-98*	*1998-99*
		Gg/PJ	Gg/PJ	Gg/PJ
New South Wales	Black Coal	87.9	88.6	88.9
New South Wales	Oil	69.7	69.3	70.0
Victoria	Brown Coal	95.1	94.0	94.0
Victoria	Gas	50.9	50.9	51.0
Queensland	Black Coal	90.5	90.5	90.1
Queensland	Oil	69.5	69.5	69.7
South Australia	Brown Coal	96.4	96.4	96.4
South Australia	Gas	51.4	51.4	50.8
Northern Territory	Gas	51.7	51.7	51.7
Australia[a]	Oil	69.7	69.4	69.9

[a] Excluding New South Wales and Queensland.

Source: PC estimates based on data published by AGO (1999a, 2000, 2001a).

The CO_2 emissions of each state were calculated by multiplying the relevant emission factor for each fuel by the amount of fuel consumed (in terms of energy content).

C.2 United States

US CO_2 emissions were derived from estimated emission factors that depended on the state in which a power plant was located (in the case of coal and oil) or on the energetic content of the fuel (in the case of gas). Table C.2 summarises the calculation procedure.

Table C.2 **Procedure for calculating US CO_2 emissions (in tonnes)**

Fuel		*Energy*		*Mass of CO_2 per Btu*				*Quantity conversion*
Coal	=	Btu	x	pounds of carbon dioxide per Btu[a]			x	tonnes per pound[b] (0.0004536)
Oil	=	Btu	x	tonnes of carbon per Btu[c]	x	mass of CO_2 compared to carbon[d] (44/12)		
Gas	=	Btu	x	tonnes of carbon per Btu[a]	x	mass of CO_2 compared to carbon[d] (44/12)		

[a] Energy Information Administration (Chou, P., EIA, Washington, pers. comm., 2 May 2001). [b] United States National Institute of Standards and Technology: Office of Weights and Measures. [c] PC estimates. [d] Zumdahl (1993).

CO_2 emission factors for US coal are published in EIA (1999a) in terms of pounds of CO_2 per million Btu. We adjusted these to reflect the fact that incomplete combustion results in some coal not being oxidised during combustion. This was done using the technique of Marland and Pippin (1990). Australian emission factors published by the AGO (1999a, 2000, 2001a) are for combustion and so did not require such an adjustment.

A similar approach to that used by Hong and Slatick (1994) can be used to establish emission factors for oil used in electricity generation (Lindstrom, P., EIA, Washington, pers. comm., 2 May 2001). Specifically, we calculated oil carbon emission coefficients for each state and year by weighting the emission coefficients for distillate and residual fuel (published in EIA 2000) by sales to utilities of these fuels in each state (published in EIA 1997, 1998, 1999b). The resulting carbon emission factors were then adjusted to reflect incomplete combustion resulting in some oil not being oxidised during combustion, as per the technique of Marland and Pippin (1990). The mass of carbon was then converted to CO_2 using the procedure shown in table C.2.

Liss et al. (1992) estimated carbon emission factors for gas in a range of energy contents from 975 Btu per cubic foot to 1100 and greater. These were for full combustion and so we adjusted them to reflect incomplete combustion, resulting in some gas not being oxidised during combustion, as per the technique of Marland and Pippin (1990).

Data in the Utility Data Institute’s database were reported in units of the US Customary System. Table C.3 sets out the conversion procedure used to convert energy content to joules.

Table C.3 **Conversion procedure for energy content (in joules)**

Fuel		*Quantity*		*Quantity conversion*[a]		*Energy content*		*Energy conversion*[b]
Coal	=	short tons	x	pounds per short ton (2000)	x	Btu per pound	x	joules per Btu (1055.06)
Oil	=	barrels	x	US gallons per barrel (42)	x	Btu per US gallon	x	joules per Btu (1055.06)
Gas	=	cubic feet			x	Btu per cubic foot	x	joules per Btu (1055.06)

[a] Utility Data Institute. [b] United States National Institute of Standards and Technology: Office of Weights and Measures.

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