Department of Minerals and Energy Pretoria

Capacity Building in Energy Efficiency and Renewable Energy

Report No. 2.3.4-30(A)

MONITORING OF ENERGY EFFICIENCY TARGETS:

A Theoretical Review

This Report contains restricted information and is for official use only

February 2005

Department of Minerals and Energy Pretoria

Capacity Building in Energy Efficiency and Renewable Energy

Report No. 2.3.4-30(A)

MONITORING OF ENERGY EFFICIENCY TARGETS:

A Theoretical Review

February 2005

Report no.	2.3.4-30(A) - draft
Issue no.	
Date of issue	February 2005
Prepared	Ian Househam
Checked	
Approved	

Table of Contents

Abbreviations and Acronyms

BEE	Black Economic Empowerment
CaBEERE	Capacity Building in Energy Efficiency and Renewable Energy
CB	Capacity Building
CEF	Central Energy Fund
DANIDA	Danish International Development Assistance
DDG	Deputy Director-General
DEAT	Department of Environmental Affairs and Tourism
DK	Kingdom of Denmark
DKK	Danish Kroner
DME	Department of Minerals and Energy
DTI	Department of Trade and Industry
EE	Energy Efficiency
ESETA	Energy Sector Education Training Authority
FIDIC	International Federation of Consulting Engineers
IDC	Industrial Development Corporation of South Africa
IPM	International Project Manager
NT	National Treasury
NER	National Electricity Regulator
NGO	Non-Governmental Organisation
PDI	Previously Disadvantaged Individual
PM	Project Manager
PQ	Pre-qualification
PSC	Project Steering Committee
PTT	Project Task Team
QA	Quality Assurance
RE	Renewable Energy
RSA	Republic of South Africa
SA	South Africa/South African
SALGA	South African Local Government Association
SANGOCO	South African Non-Governmental Organisations' Committee
SARS	South African Revenue Services
SMME	Small, Medium and Micro Enterprises
SP	Service Provider
ST	Short Term Adviser
TA	Technical Assistance
TOR	Terms of Reference
VAT	Value Added Tax
ZAR	South African Rand

1 Introduction

1.1 Background

Under the Draft Energy Efficiency Strategy of the Republic of South Africa (Department of Minerals and Energy, April 2004) the South African Government set targets for reductions in final energy demand (both overall and sectoral) to be achieved by 2014. Under the auspices of the CaBEERE programme (Capacity Building for Energy Efficiency and Renewable Energy) supported by Danida, IIEC-Africa has been commissioned to design protocols for data gathering and processing that will allow the Department of Minerals and Energy (DME) to monitor progress towards achieving these targets. This paper provides a theoretical background to the methodologies available for data analysis that will form the basis of such protocols.

Although the targets in the Draft Energy Efficiency Strategy are expressed in terms of percentage reductions in final energy demand for each sector, it can be assumed that the expectation is that these reductions will come about as a result of improvements in energy efficiency and not, for example, as a result of economic contraction. We are therefore interested not only in whether South Africa is or isn't meeting the Strategy targets, but also in the underlying reasons for the observed changes. Where possible, it would be useful to be able to point to individual sub-sectors or activities as making a particularly strong contribution to target-meeting (or the failure thereof), thus providing a detailed picture of the effects of policy interventions.

1.2 What do we mean by energy efficiency?

Even at the level of an individual process or activity (for example, the crushing of ore), defining energy efficiency is not as straightforward as it might at first seem. The following three ratios are all perfectly valid definitions of energy efficiency, each having its merits and shortcomings:

1. Theoretical minimum energy requirement for performing task ÷ energy used
2. Current best practice energy requirement for performing task ÷ energy used
3. Useful output obtained ÷ energy used

The first definition, although the most strictly 'correct', is also the least practical and would be virtually impossible to apply on a large scale. The second definition is often applied where a firm wishes to 'benchmark' the energy it consumes for a particular process against the current 'state-of-the-art'. However, this definition is again impractical for tracking energy efficiency at a more macro level. The third definition is the easiest to apply in practice and is thus the most commonly used, although it is furthest removed from the thermodynamically-based 'correct' definition.

The third definition given above is the reciprocal of a quantity that is generally referred to as 'energy intensity' – the energy used per unit of output obtained. However, even this apparently straightforward definition begs the question of how output is to be quantified. Output can be measured either in physical units (tonnes of steel produced, square metres of office space heated etc.) or in monetary terms (value-added produced). Section 2.4 below examines in more detail the use of physical versus monetary units for quantifying output.

For the purposes of this study, the third definition above is the one that will be adopted as our definition of energy efficiency. However, it must be remembered that this quantity is only a proxy or surrogate for 'real' energy efficiency, a quantity which is itself effectively unknowable on a macro level. In fact, for arithmetical simplicity, most of the equations in the following sections use the reciprocal quantity,

energy intensity (i.e. energy per unit of output) rather than energy efficiency. Where necessary, it will always be stated whether it is physical energy intensity or economic energy intensity that is implied.

1.3 Factors affecting energy consumption

It cannot be assumed that a reduction in energy intensity at the macro-level implies that energy efficiency has improved at the process or activity level. Structural changes in the economy can produce changes in macro-level energy intensity independently of any energy efficiency changes taking place.

The following simplified example serves to illustrate the nature of the problem of isolating the effects of energy efficiency improvements from other factors. An industrial sub-sector consists of two industries – Industry A and Industry B. Industry A produces an output measured in tonnes, while Industry B produces an output measured in items. Data on physical output, energy consumption and value-added is available at two points in time (Year 0 and Year t) and is provided in Table 1 below.

Table 1 Data for a hypothetical industrial sector consisting of two industries

		Industry A	**Industry B**	**Sector total**
Output	Year 0	30 tonnes	120 items	-
	Year t	28 tonnes	180 items	-
Energy consumption	Year 0	240 GJ	240 GJ	480 GJ
	Year t	196 GJ	342 GJ	538 GJ
	change	-44 GJ	+102 GJ	+58 GJ
Physical energy intensity	Year 0	8 GJ / t	2 GJ / item	-
	Year t	7 GJ / t	1.9 GJ / item	-
	% change	-12.5%	-5.0%	
Value added per unit of output	Year 0	1000 € / tonne	300 € / item	
	Year t	900 € / tonne	350 € / item	

Between Year 0 and Year t, the total energy consumption of the sector has increased by 58 GJ. However, the physical energy intensity of Industry A has improved by 12.5%, while that of Industry B has improved by 5%. The increase in total energy consumption over the whole sector must therefore have been due to factors other than efficiency changes, namely to increases in overall activity, or to structural shifts towards more energy intensive activities.

To answer the question of how the overall energy efficiency of the industrial sector has changed over the period between Year 0 and Year t, we need to separate out this factor from the other two. There are two ways to approach this problem:

Aggregation. The process of aggregation seeks to devise a meaningful way of combining the 12.5% improvement in physical energy intensity in Industry A with the 5.0% improvement in physical energy intensity in Industry B, to give an overall sectoral improvement in energy efficiency. Clearly the overall figure will be a weighted mean of the two industry figures, but what weighting factors should be used?

Decomposition. The process of decomposition takes the 58 GJ increase in total energy consumption, and seeks to apportion this to a number of different factors, most usually:

- changes in the overall activity of the sector
- changes in the structure of the sector
- changes in the overall energy efficiency of the sector

Each of these three factors represents that change in total energy consumption that would have occurred, had both the other two factors remained constant. The last of these factors should be equal to the result obtained through aggregation. This implies that some partial derivative function needs to be calculated, but what is the nature of this function?

An additional consideration with the aggregation process is the question of whether the individual changes in energy intensity should be taken from *observations* of the industries in questions (an indicators-based approach) or *inferred* from the results of energy-saving activities, projects and programmes (a projects-based approach). This distinction is explored further in the accompanying paper 'Monitoring Energy Efficiency Targets: Review of International Best Practice'. Of course, this distinction does not apply to the decomposition approach, which must by definition be indicators-based.

Considerable literature is available that seeks to answer these questions. The following sections review some of the methodologies that form the 'state of the art' and draw conclusions about the most appropriate approach to take in the South African case.

1.4 Review of methodologies

The methodology chosen for monitoring progress towards achieving energy efficiency targets should satisfy the following criteria:

- *Transparency.* The methodology itself and the results it yields must be comprehensible to the target audience. This does not imply that the methodology has to be computationally simple enough for the target audience to be able to perform it themselves, merely that it must be possible to explain the broad principles in lay-persons language.
- *Appropriateness*. The methodology should yield results that are expressed in the same terms as policy goals.
- *Consistency with international norms*. The ability to compare results between countries may be important, so the methodology should be compatible with those used in other countries.
- *Robustness with time.* It is undesirable to have to make frequent changes to the methodology used, so it should be flexible enough to incorporate future changes (e.g. to the availability of data, to the definitions of sectors and sub-sectors).
- *Comprehensiveness.* The methodology should be 'all-seeing', covering all aspects of energy use in the economy, thereby avoiding the possibility that some important effects might be overlooked.
- *Feasibility.* The data requirements of the chosen methodology should not be impossible to satisfy

1.4.1 Fixed basket approaches

The use of a 'fixed basket' of products is already familiar from its use in deriving indicators of inflation, such as the Consumer Price Index (CPI). Applied to the problem of monitoring changes in energy efficiency, the fixed basket approach in its simplest form would involve calculating the energy required in a given economy to perform a 'fixed basket' of activities. In order to provide a comprehensive picture of the whole economy, the fixed basket would need to contain important activities from all sectors. Some examples might be: the average energy required to produce a tonne of steel; the average energy used to transport 1,000 passengers through 1 km; the average energy used to light 1,000 m^2 of retail space.

A development of this concept would be to express the result of the fixed basket analysis as an index, relative to a particular base year, or as a rolling 'energy inflation' figure relative to the previous year.

While intuitively straightforward, particularly for those already accustomed to dealing with the CPI, this methodology has a major shortcoming. Any such decision about which activities to include in the fixed basket would necessarily have to reflect the current structure of the economy, but in countries such as South Africa, this structure is changing rapidly. Tracking such changes by making frequent adjustments to the composition of the fixed basket makes comparisons over time almost impossible. However, failing to make such adjustments would rapidly render the index meaningless.

A further difficulty with the fixed basket approach is the requirement for large amounts of data. Although the data requirements are probably no greater than for some of the other methodologies described here, these other methodologies are superior in other respects.

A final shortcoming of the fixed basket approaches is that comparison between countries is difficult. Every country would, of necessity, have to develop its own fixed basket of activities appropriate to local circumstances, but no two countries' selections would be the same.

1.4.2 Reference energy intensity approach

This approach provides policymakers with a comparison between how efficiently energy is actually being used and how efficiently it could potentially be used. In this respect, it is more useful than other approaches that simply provide an energy intensity indicator at some level of aggregation, as it allows policymakers to focus on activities and sub-sectors that have the greatest room for improvement.

For each important energy-using activity, a ratio is calculated between the physical energy intensity of the activity as it is currently carried out, and a reference energy intensity representing some notion of best practice. This best practice reference level may correspond to one of a number of figures:

(i) energy intensity currently achieved in the best actual plant in the same country;

(ii) energy intensity currently achieved in the best actual plant internationally;

(iii) energy intensity that would be achieved if the best currently available technologies and methods were all applied in the same plant.

A major difficulty with this methodology is the development of appropriate reference levels with which to compare actual energy intensities. Not only is the effort involved considerable, but there are also conceptual difficulties. Comparison with the current best-in-country is somewhat arbitrary, and does not really provide a useful picture of the room for improvement. Using an internationally-based reference level may be misleading as different countries have different relative factor prices. A technology that represents best practice in a country where, for example, labour is very expensive may not be appropriate in a country where labour is cheaper.

This methodology must, by definition, be applied from the bottom up. There are well-developed techniques for aggregating up the ratios calculated for individual industries, to give sub-sectoral indicators. However, there are some sub-sectors where disaggregation down to the level of individual plants is not possible (either because of the sheer volume of data required or because of issues of data confidentiality). This methodology cannot be used in such situation, and so cannot be considered comprehensive.

A further shortcoming of this methodology is the need for constant updates in the 'best practice' reference levels to reflect continual developments in technologies. Again, this would require considerable effort, and it would also make comparisons over time very difficult.

Finally, it is difficult to see how this methodology could be applied to the residential sector. However, despite these limitations, this methodology could prove very valuable as a supplement to other

techniques, providing as it does a detailed picture of the potential for improvement in certain specific sub-sectors.

1.4.3 Composite indicator approach

This approach focuses on percentage changes, from one time period to the next, in the energy intensity for each activity. These are aggregated using weighting factors that are derived from each activity's share of total energy consumption. A more detailed discussion of these weighting factors is provided in Section 2 below.

The value of this methodology is that energy intensity can be expressed in physical terms or in monetary terms, depending on the availability of data and on the level of disaggregation used[1]. Because it is percentage changes in energy intensity that are being summed, there is no difficulty in aggregating across activities where the outputs are measured in different units.

The methodology provides a picture of the evolution through time of energy intensity, but provides no indication of the room for improvement. In this respect, it differs fundamentally from the reference energy intensity approach described above. However, given that the current Energy Efficiency Strategy in South Africa is expressed in terms of reductions in energy demand relative to a base year, the composite indicator methodology provides a more appropriate set of indicators.

Arithmetically, the composite indicator approach is similar to the process of decomposition, described in the following section, one being the reciprocal of the other. Although the data requirements of both methodologies are high, the amount of information that they provide is considerable. Furthermore, the types of data required by each are likely to remain the same over time, so there should be little need to make major modifications to the methodologies in the future.

1.4.4 Decomposition approaches

As already mentioned, the process of decomposition is the reciprocal of the composite indicator approach described in the previous section. The data requirements of each are identical, and the arithmetic of one can be derived from the arithmetic of the other. The advantages of both of these methodologies have already been mentioned in the previous section. Relative to aggregation, decomposition provides slightly more information than the aggregation of composite indicators, since it also quantifies the effects of structural change.

A further reason for favouring decomposition over aggregation is that, being a top-down process, it is easier to adjust the level of detail of the analysis to suit the amount and quality of the data available. Furthermore, there is an increasing body of literature covering both the theoretical and practical aspects of decomposition methodology. This would appear to be the methodology that best suits the requirements of this project, so it will be discussed in more detail in Section 2 below.

1 See Section 2.4 below for a more complete discussion of physical versus monetary units.

2 Decomposition techniques in detail

The techniques used for decomposing changes in energy consumption into their constituent factors derive from the mathematically identical techniques derived in the late 19th and early 20th Centuries for analysing the underlying causes of differences in total factor productivity. The theory behind this methodology was developed by Laspeyres and Paasche in the 1870s, and refined by Fisher and Divisia in the 1920s[2]. From the 1980s, the methodology began to be applied to the specific problem of analysing the underlying reasons for changes in energy consumption and intensity.

The general approach of decomposition is to take the change in total energy consumption ΔE and to express it as the sum of at least three factors, plus a residual term that results from some decomposition methods[3]. The basic decomposition is:

$$\Delta E = \Delta P + \Delta I + \Delta S + r$$

where: ΔP is the change in energy consumption that is attributable to the overall change in economic activity

ΔI is the change in energy consumption that is attributable to changes in energy intensity

ΔS is the change in energy consumption that is attributable to changes in economic structure

r is a residual term that arises with some decomposition methods

If ΔE is expressed in absolute terms (i.e. in TJ, or some other energy unit) then so are the factors into which it is decomposed. Another possibility is to express ΔE in relative terms (as a percentage), in which case the factors are also expressed as percentages. These two techniques are arithmetically equivalent, but the use of absolute terms is probably slightly easier to interpret, and will be used in this paper.

2.1 Terminology

In the following sections, certain terms are used to convey specific meanings necessary to keep the discussion clear. These terms and the meanings implied are described as follows:

Unit of analysis. The same decomposition techniques can potentially be applied at any level in the economy. The 'unit of analysis' is the item whose total energy consumption is being decomposed, whether it be the whole economy, a particular sector, an individual industry, or even a single activity.

Component. In order to perform the decomposition, a unit of analysis has to be divided into smaller entities. These are referred to as 'components'. In the equations included below, whenever a summation is indicated, this takes place across the components of the unit of analysis.

Factor. A decomposition analysis will always lead to the change in the total energy consumption being attributed to a number of influences. These are referred to as 'factors', and may include changes in population, structural shifts or, most importantly for this discussion, changes in the efficiency of energy use.

2 For a historical and theoretical background, see Balk (2000) and Hoekstra (2000).

3 Some studies have preferred instead to decompose total energy intensity, rather than total energy consumption. In this form, two factors are sufficient – structural changes and changes in the individual component energy intensities.

2.2 Generalised decomposition equations

During the 1990s, a number of papers were published[4] illustrating that all the different decomposition methods previously used could be encompassed by a set of parametric frameworks equations. These equations are discussed in more detail in a review by Nanduri[5] and are represented mathematically below in a slightly modified form. Note that these equations can be applied at any level of decomposition. At the highest level, the unit of analysis is the whole economy, and the components are the major sectors. At lower levels, the unit of analysis may be an individual sector or even a sub-sector, in which case the components would be, respectively, sub-sectors or individual industries.

The parametric framework equations are:

$$\Delta P = \ln\left(\frac{Y_t}{Y_0}\right) \times \sum_j F\left(E_{j,0}, E_{j,t}\right) \quad \text{(Equation 1a)}$$

$$\Delta I = \sum_j \left[F\left(E_{j,0}, E_{j,t}\right) \times \ln\left(\frac{I_{j,t}}{I_{j,0}}\right) \right] \quad \text{(Equation 1b)}$$

$$\Delta S = \sum_j \left[F\left(E_{j,0}, E_{j,t}\right) \times \ln\left(\frac{S_{j,t}}{S_{j,0}}\right) \right] \quad \text{(Equation 1c)}$$

where: subscripts 0, t refer to values at two points in time

Y is the total value added for the unit of analysis

E_j is the energy consumption of the j^{th} component of the unit of analysis

I_j is the energy intensity (energy consumption per unit of value added) of the j^{th} component of the unit of analysis

S_j is the share in total value added of the j^{th} component of the unit of analysis

$F(E_{j,0},E_{j,t})$ is a 'weighting function', the choice of which defines which decomposition method is being used[6]. Table 2 below describes some of the weighting functions commonly used, and the names that have been attached to the respective methods.

Although the Log-Mean Divisia method is arithmetically slightly more complex, this make very little difference when data processing is computerised. Furthermore, this method has the big advantage that it does not lead to a residual term, which is a component of the change in total energy consumption that cannot be attributed to any of the factors under consideration. The residual term has no meaning in reality, and its existence is merely a result of the mathematics of the method chosen[7]. The Log-Mean Divisia method therefore appears to be the most effective decomposition method available, and its use will be assumed henceforth.

---

4 See for example Liu (1992).

5 Nanduri (19980.

6 The weighting function is needed because the process of decomposition results in the need to integrate a function the form of which is not known. The different choices of weighting function correspond to different assumptions about the shape of the function between the two integration limits.

7 Appendix 1 of Lermit (2001) provides a proof that the residual term disappears when the logarithmic mean of $E_{j,0}$ and $E_{j,t}$ is used as the weighting function.

Table 2 Weighting functions and their corresponding decomposition methods

Value of $F(E_{j,0},E_{j,t})$	Name of method
$E_{j,0}$	Laspeyres method
$E_{j,t}$	Paasche method
Arithmetic mean of $E_{j,0}$ & $E_{j,t}$ $\frac{(E_{j,0}+E_{j,t})}{2}$	Marshall-Edgeworth method
Geometric mean of $E_{j,0}$ & $E_{j,t}$ $\sqrt{(E_{j,0}\times E_{j,t})}$	Fisher Ideal method
Logarithmic mean[8] of $E_{j,0}$ & $E_{j,t}$ $(E_{j,t}-E_{j,0}) / \ln(E_{j,t}/E_{j,0})$	Log-Mean Divisia method

2.3 Illustrative application of the Log-Mean Divisia method

Use of the Log-Mean Divisia method can be illustrated by applying it to the data for the hypothetical industrial sub-sector described in Table 1. In this sub-sector, there is an increase in total energy consumption of 58 GJ between Year 0 and Year t. We wish to decompose this change in energy consumption into three factors, attributable to changes in overall economic activity, changes in energy intensity and structural changes.

In order to perform this decomposition, we need to derive some additional figures for each industry: total value added, share of value added and economic energy intensity (in MJ/€). These additional figures are shown in Table 3 below, along with the original data.

Substituting these figure into Equations 1a – 1c gives the following:

$$\Delta P = \ln\left(\frac{88{,}200}{66{,}000}\right)\times 505.26 = 146.50$$

$$\Delta I = 217.26\times\ln\left(\frac{7.78}{8.00}\right) + 288.00\times\ln\left(\frac{5.43}{6.67}\right) = -65.29$$

$$\Delta S = 217.26\times\ln\left(\frac{28.57}{45.45}\right) + 288.00\times\ln\left(\frac{71.43}{54.54}\right) = -23.21$$

8 Note that, when a = b, log-mean(a,b) = a = b.

Table 3 Extended data for a hypothetical industrial sector

		Industry A	Industry B	Sector total
Output	Year 0	30 tonnes	120 items	-
	Year t	28 tonnes	180 items	-
Energy consumption	Year 0	240 GJ	240 GJ	480 GJ
	Year t	196 GJ	342 GJ	538 GJ
	change	-44 GJ	+102 GJ	+58 GJ
	log-mean	217.26	288.00	505.26
Value added per unit of output	Year 0	1000 € / tonne	300 € / item	
	Year t	900 € / tonne	350 € / item	
Total value added	Year 0	€30,000	€36,000	€66,000
	Year t	€25,200	€63,000	€88,200
Share of value added	Year 0	45.45%	54.54%	
	Year t	28.57%	71.43%	
Energy intensity	Year 0	8.00 MJ / €	6.67 MJ / €	
	Year t	7.78 MJ / €	5.43 MJ / €	

Thus, the 58 GJ increase in energy consumption over the sector as a whole can be attributed to three factors, interpreted as follows:

- If the structure of the sector had remained the same, and the energy intensities of the two industries had not changed, the total energy consumption would have risen by 146.5 GJ due to increases in overall activity.
- If the overall activity of the sector, and its structure, had both remained constant, there would have been a decrease in total energy consumption of 65.29 GJ due to improvements in energy intensity.
- If the overall activity and the energy intensities of the two industries had remained constant, structural changes in the sector would have led to a 23.21 GJ decrease in total energy consumption

Note that the 65.29 GJ portion that has been attributed to energy intensity changes may actually include structural changes *within* the two industries (i.e. shifts in the relative levels of production between the plants that comprise the industries). To determine the true effects of structural versus efficiency changes, the analysis would need to take into account these second- and third-order effects. In practice, a real analysis would stop at a level where the cost and effort of collecting the necessary data outweighed the value that the extra precision brings.

2.4 Physical versus monetary measures of activity

As we have seen, energy efficiency is usually defined in terms of the ratio of the energy consumed in performing an activity to the useful output produced from that activity. So, perhaps the first question that has to be addressed when considering changes in energy efficiency is the method that is used to quantify the output from a particular activity. The basic choice is between physical units and monetary units, and each has its own merits and its own difficulties.

The biggest difficulty in using physical units is that the outputs from different sub-sectors are very diverse, and so cannot meaningfully be summed in physical terms. For example, an agricultural sector producing 1,000 tonnes of wheat and 1,000 tonnes of beef in a given year could be said to have produced 2,000 tonnes of agricultural output, but this figure is virtually meaningless on its own. If the respective outputs are expressed in monetary terms, then they can be meaningfully added.

However, using physical units to express energy efficiency has the advantage of coinciding more closely with most people's idea of what energy efficiency really means. To illustrate this, consider the following example that uses monetary units:

A car factory produces 1,000 cars in a given year, with a value-added of €5,000 per car, or €5 million per year total value-added. In doing so, it uses 30 TJ of energy, giving an energy intensity in monetary terms of 6 MJ / €. The following year, it produces the same number of cars and uses the same amount of energy, but the price of cars has risen, such that its total value-added is now €5.5 million. Its energy intensity has therefore fallen to €5.45 MJ / €.

Has the energy efficiency of the plant improved? Most people would instinctively say that it hasn't, as the amount of energy to produce each car has not changed. No technological improvements have taken place in the plant, so it would be wrong to claim that there had been an efficiency improvement. However, it is also worth remembering that energy efficiency is defined in terms of useful output, and the ultimate indication of whether the output from an activity is useful is the value that the market attaches to that output. Since the value of the car factory's outputs has increased, with the same energy consumption, it could be argued that the factory has indeed produced more useful output per unit of energy consumed, so it's energy efficiency has improved by this criterion.

The area where the use of monetary units for quantifying activity is most problematic is in the commodity producing sectors. The price of gold, for example, is very volatile, and depends on a myriad of global factors, most of which have very little bearing on the 'usefulness' of the material itself. Very few people would argue that, all else being equal, a 10% rise in the price of gold should be interpreted as a 10% improvement in the energy efficiency of the gold producing industry.

Table 4 below summarises the main benefits and drawbacks of using physical units versus monetary units for quantifying energy intensity / efficiency[9]. However, it is important to realise that, in performing a decomposition analysis, the choice between physical units and monetary units does not need to be made once and for all for the whole economy. The choice can be tailored to suit the particular 'unit of analysis'. For example, where the unit of analysis is the whole economy, one is more or less forced to quantify activity in monetary terms. The same applies where the unit of analysis is the industrial sector, because the components are very disparate in terms of their products. However, where the unit of analysis is the mining sub-sector, it may be possible to use physical measures for activity (e.g. tonnes of ore extracted) to provide a better picture of the technological changes taking place. Of course, in the case of the residential sector, monetary units cannot be used at all, because this sector does not produce an 'output' that can be valued.

[9] From now on, if the term 'energy intensity' is used without qualification, it should be assumed to mean 'energy consumed per unit of value added'. The term 'energy efficiency' should be assumed to imply the use of physical units for quantifying output.

Table 4 Comparison of the benefits and drawbacks of physical versus monetary units for quantifying levels of activity

Physical units	Monetary units
Chimes more closely with what most people's understanding of energy efficiency really means, and gives a truer picture of technological change	Provides a truer picture of the useful output from an activity, since it considers the value of the output
Particularly in the primary production sectors, allows the effects of volatility in world prices to be separated out	Can lead to misleading results in sub-sectors that are prone to price volatility
In many sectors, outputs from different sub-sectors are not homogeneous, leading to the problem of summing 'apples and oranges'	Provides for easy summation of outputs from widely differing sub-sectors

2.5 Incorporating physical units into the decomposition

The version of the Log-Mean Divisia method introduced in Section 2.2 above makes use of monetary units for intensity. However, as we have seen in the previous section, there may be circumstances under which the use of physical units for energy intensity might be preferable. Lermit and Jollands[10] showed that this can very easily be achieved by further decomposing energy intensity (expressed as energy consumption per unit of value-added) into the product of two terms, as follows:

$$I = \frac{E}{Y} = \frac{E}{Q} \times \frac{Q}{Y}$$

where: I is energy intensity

E is energy consumption

Y is value added

Q is a measure of activity appropriate to the sector or industry in question (e.g. tonnes of ore mined in the mining sector, floor area in the retail sector, tonne-km in the freight transport sector).

The first term in the product is the energy intensity expressed in physical units i.e. the reciprocal of energy efficiency. The second term of the product, referred to as the 'activity intensity' by Lermit and Jollands, is the amount of activity per unit of value added. This quantity, or more commonly its reciprocal, is commonly available for most economic sub-sectors or industries.

The activity intensity can be summed over all the components of the decomposition and subsumed into the expression for the contribution of changes in overall economic activity (Equation 1a above), leading to a modified equation shown as Equation 2a below. Equation 1b above, the contribution of changes in energy intensity, has also been modified into Equation 2b below, which indicates the contribution arising from changes in *physical* energy intensity (i.e. changes in energy efficiency). Equation 1c above, the contribution to the overall change in energy consumption arising from structural changes, remains

[10] Lermit (2001).

unchanged, but is reproduced below as Equation 2c for convenience. The modified parametric framework equations are thus:

$$\Delta P = \left[\ln\left(\frac{Y_t}{Y_0}\right) \times \sum_j F(E_{j,0}, E_{j,t})\right] + \sum_j \left[F(E_{j,0}, E_{j,t}) \times \ln\left(\frac{A_{j,t}}{A_{j,0}}\right)\right] \text{.....(Equation 2a)}$$

$$\Delta H = \sum_j \left[F(E_{j,0}, E_{j,t}) \times \ln\left(\frac{H_{j,t}}{H_{j,0}}\right)\right] \text{.. (Equation 2b)}$$

$$\Delta S = \sum_j \left[F(E_{j,0}, E_{j,t}) \times \ln\left(\frac{S_{j,t}}{S_{j,0}}\right)\right] \text{..(Equation 2c)}$$

where: subscripts 0, t refer to values at two points in time

Y is the total value added for the unit of analysis

E_j is the energy consumption of the j^{th} component of the unit of analysis

A_j is the 'activity intensity' (activity per unit of value added) of the j^{th} component of the unit of analysis

H_j is the energy consumption per unit of physical activity of the j^{th} component of the unit of analysis

S_j is the share in total value added of the j^{th} component of the unit of analysis

$F(E_{j,0},E_{j,t})$ is the logarithmic mean of $E_{j,0}$ and $E_{j,t}$, assuming the log-mean divisia method is being applied

2.5.1 Application of the Log-Mean Divisia method using physical units

To apply Equations 2a – 2c to the data from Table 3, we first need to calculate the 'activity intensities' for both industries. These 'activity intensities' are simply the reciprocals of the 'value added per unit of output' data already given. This data is shown in Table 5 below, along with the original figures.

Substituting these figure into Equations 2a – 2c gives the following:

$$\Delta P = \ln\left(\frac{88{,}200}{66{,}000}\right) \times 505.26 + 217.26 \times \ln\left(\frac{1.11}{1.00}\right) + 288.00 \times \ln\left(\frac{2.86}{3.33}\right) = 125.00$$

$$\Delta H = 217.26 \times \ln\left(\frac{7}{8}\right) + 288.00 \times \ln\left(\frac{1.9}{2.0}\right) = -43.79$$

$$\Delta S = 217.26 \times \ln\left(\frac{28.57}{45.45}\right) + 288.00 \times \ln\left(\frac{71.43}{54.54}\right) = -23.21$$

Thus, the 58 GJ increase in energy consumption over the sector as a whole can be attributed to three factors, interpreted as follows:

- If the structure of the sector had remained the same, and the technical energy efficiencies of the two industries had not changed, the total energy consumption would have risen by 125.0 GJ due to increases in overall activity.
- If the overall activity of the sector, and its structure, had both remained constant, there would have been a decrease in total energy consumption of 43.79 GJ due to improvements in energy efficiency.

- As before, if the overall activity and the energy efficiencies of the two industries had remained constant, structural changes in the sector would have led to a 23.17 GJ decrease in total energy consumption

Table 5 Extended data for a hypothetical industrial sector

		Industry A	**Industry B**	**Sector total**
Output	Year 0	30 tonnes	120 items	-
	Year t	28 tonnes	180 items	-
Energy consumption	Year 0	240 GJ	240 GJ	480 GJ
	Year t	196 GJ	342 GJ	538 GJ
	change	-44 GJ	+102 GJ	+58 GJ
Physical energy intensity	Year 0	8 GJ / t	2 GJ / item	-
	Year t	7 GJ / t	1.9 GJ / item	-
Value added per unit of output	Year 0	1000 € / tonne	300 € / item	
	Year t	900 € / tonne	350 € / item	
Total value added	Year 0	€30,000	€36,000	€66,000
	Year t	€25,200	€63,000	€88,200
Share of value added	Year 0	45.45%	54.54%	
	Year t	28.57%	71.43%	
Activity intensity	Year 0	1.00×10^{-3} tonne/ €	3.33×10^{-3} item/ €	
	Year t	1.11×10^{-3} tonne/ €	2.86×10^{-3} item/ €	

This example illustrates how the use of physical units (energy efficiency) differs from the use of monetary units (energy intensity). Because the average value of the products of the industrial sector increased between Year 0 and Year t, this had a favourable impact on the sector’s ability to produce wealth with the energy it uses. However, the improvement in the sector’s ability to produce physical output from the energy it uses was smaller. Hence, only 43.79 GJ is attributable to improvements in energy efficiency, whereas (from Section 2.2) 65.29 GJ was attributable to improvements in energy intensity.

2.5.2 Mixing physical and monetary units

It can readily be seen from Equations 1a-c and 2a-c that monetary units and physical units can be used side by side in the same decomposition. Because:

$$I = H \times A$$

therefore:

$$\ln\left(\frac{I_{j,t}}{I_{j,0}}\right) = \ln\left(\frac{H_{j,t}}{H_{j,0}}\right) + \ln\left(\frac{A_{j,t}}{A_{j,0}}\right)$$

where: I is energy intensity in monetary units

H is energy intensity in physical units

A is 'activity intensity'

For each component of the decomposition (i.e. for every subscript j) the energy intensity can therefore be expressed in two ways. If no physical output data is available, the energy intensity is expressed in monetary terms and allocated entirely to the ΔI summation. If the appropriate data on physical output is available, energy intensity can be expressed as a sum of a physical energy intensity (which is allocated to the ΔI summation) and an activity term (which is allocated to the ΔP summation).

This 'mixed' decomposition approach is useful in situations where data on physical energy efficiencies is available for some but not all components of the unit of analysis. The following illustration is based on a hypothetical industrial sector, but the method can be applied equally well in other sectors. The industrial sector is divided into components consisting of individual industries, as in the example in Section 2.3. These industries are further divided into two groups – those for which data on physical outputs is available, which are designated by the subscript j, and those for which only data on value added is available, which are subscripted as k. The three factors into which changes in total energy consumption are decomposed are now described by Equations 3a-c below. For brevity, the weighting function previously represented as $F(E_{j,0},E_{j,t})$ is represented instead as W_j (and similarly for subscript k):

$$\Delta P = \left[\ln\left(\frac{Y_t}{Y_0}\right) \times \left(\sum_j W_j + \sum_k W_k\right)\right] + \sum_j \left[W_j \times \ln\left(\frac{A_{j,t}}{A_{j,0}}\right)\right] \text{ ....(Equation 3a)}$$

$$\Delta H = \sum_j \left[W_j \times \ln\left(\frac{H_{j,t}}{H_{j,0}}\right)\right] + \sum_k \left[W_k \times \ln\left(\frac{I_{k,t}}{I_{k,0}}\right)\right] \text{ ....(Equation 3b)}$$

$$\Delta S = \sum_j \left[W_j \times \ln\left(\frac{S_{j,t}}{S_{j,0}}\right)\right] + \sum_k \left[W_k \times \ln\left(\frac{S_{k,t}}{S_{k,0}}\right)\right] \text{ ....(Equation 3c)}$$

Again, Equation 3c remains essentially unchanged, the equivalent term being summed over all components. For each component where data on physical output is available, terms are derived as in Equations 2a&b. For each component where data on physical output is unavailable, a term is derived as in Equation 1b.

The application of these equations is illustrated in the following example. Table 6 below shows data for a hypothetical industrial sector consisting of four industries. Industries A and B are identical to those used in previous examples, while Industries C and D are industries for which data on physical output is unavailable.

The overall energy consumption of the sector has increased by 88 GJ between Year 0 and Year t. Substituting data from Table 6 into Equations 3a-c shows that this change can be attributed as follows:

- If the structure of the sector had remained the same, and the energy intensities / efficiencies of the four industries had not changed, the total energy consumption would have risen by 167.75 GJ due to increases in overall activity.

- If the overall activity of the sector, and its structure, had both remained constant, there would have been a decrease in total energy consumption of 31.76 GJ due to improvements in energy efficiency / intensity.
- If the overall activity and the energy efficiencies / intensities of the four industries had remained constant, structural changes in the sector would have led to a 47.99 GJ decrease in total energy consumption

This mixed decomposition is particularly useful for dealing with ‘unattributed’ portions of a sector which almost inevitably arise in any data set. These are commonly encountered in the industrial and commercial sectors, and consist of all those activities that, for one reason or another, cannot be allocated to any of the standard industrial classifications. By their very nature, these unattributed activities have no available data on physical output, but by using a mixed decomposition, this does not preclude the use of physical units for those components where such data is available.

Table 6 Hypothetical industrial sector consisting of four industries

		Industry A	Industry B	Industry C	Industry D	Sector total
Production	Year 0	30 tonnes	120 items	unknown	unknown	
	Year T	28 tonnes	180 items	unknown	unknown	
Energy consumption (GJ)	Year 0	240	240	200	410	1090
	Year T	196	342	205	435	1178
Value added (€)	Year 0	30000	36000	25000	39000	130000
	Year T	25200	63000	24000	41500	153700
Physical intensity	Year 0	8.00	2.00	unknown	unknown	
	Year T	7.00	1.90	unknown	unknown	
Activity intensity	Year 0	0.001	0.00333	unknown	unknown	
	Year T	0.00111	0.00286	unknown	unknown	
Economic intensity (GJ / €)	Year 0	not needed	not needed	0.008	0.01051	
	Year T	not needed	not needed	0.00854	0.01048	
Share of value added	Year 0	0.231	0.277	0.192	0.300	
	Year T	0.164	0.410	0.156	0.270	
Weighting factor log-mean($E_{m,0}$,$E_{m,t}$)		217.26	288.00	202.49	422.38	1130.128

2.6 The residential sector

The previous sections have focused on the economically productive sectors, where concepts such as value added and energy intensity have some meaning. However, a complete decomposition analysis of

the economy must be able to incorporate the residential sector, where value-added and energy intensity are largely meaningless. The following sections examine some of the possible approaches for achieving this.

2.6.1 The residential sector as a component of the economy-wide analysis

When decomposing economy-wide changes in energy consumption, the influence of the residential sector must be taken into account by treating it as another component in the analysis. Lermit and Jollands examine in some detail the methodology for achieving this. However, while they use population as the key variable in their methodology, it is probably more useful to view the residential sector in terms of its basic economic units, namely households. At the sectoral level, the energy consumption per household then becomes analogous to the energy intensity of the productive sectors, while the number of households is analogous to the level of economic activity.

Since the unit of analysis in this case is the whole economy, and the components are the main sectors, there is no option but to use monetary units as the measure of output in the productive sectors. The equations describing the decomposition of changes in total energy consumption are therefore modifications of Equations 1a-c, as follows:

$$\Delta P = \ln\left(\frac{Y_t}{Y_0}\right) \times \sum_j W_j + \ln\left(\frac{P_t}{P_0}\right) \times W_R \quad \text{.....................(Equation 4a)}$$

$$\Delta I = \sum_j \left[W_j \times \ln\left(\frac{I_{j,t}}{I_{j,0}}\right) \right] + \ln\left(\frac{Q_t}{Q_0}\right) \times W_R \quad \text{...................(Equation 4b)}$$

$$\Delta S = \sum_j \left[W_j \times \ln\left(\frac{S_{j,t}}{S_{j,0}}\right) \right] \quad \text{..(Equation 4c)}$$

where: W_R is the weighting factor for the residential sector, defined as the logarithmic mean of the figures for residential sector energy consumption at Year 0 and Year t

P is the total number of households

Q is the energy consumption per household

all other symbols have the same meaning as previously

The equation for the contribution of structural effects remains unchanged, while the equations for the contributions of changes in activity and changes in energy intensity each gain an additional term corresponding to the residential sector.

2.6.2 The residential sector as an unit of analysis

The most important energy source in households is wood-fuel and other biomass, accounting for over half of all residential sector energy consumption. The type of highly quantified analysis proposed here cannot deal adequately with biomass energy consumption, as quantities such as the thermal efficiency of appliances and the amount of fuels used are not sufficiently precisely known. The analytical methodology described here therefore applies only to the residential sector consumption of ‘commercial’ (non-biomass) energy.

In order to derive a more detailed picture of the factors influencing changes in overall residential sector non-biomass energy consumption, it is necessary to treat the residential sector as the unit of analysis. Of particular interest is the extent to which total sectoral energy consumption is influenced by the technical

energy efficiency of appliances and energy-using activities, as opposed to changes in income and lifestyle. Population growth will also have a strong influence on total residential sector energy consumption, so a decomposition analysis would need to separate out its effect.

In the decomposition analyses of other sectors, structural effects play an important role as a contributory factor to changes in total energy consumption. In the residential sector, there is no exact parallel with these structural effects, so a somewhat different approach has to be taken. Two different methodologies are suggested here. The first uses the numerical breakdown of households having a particular standard of living as an analogy to the structural effect; the second disaggregates according to energy-using activity. These two approaches are examined in more detail in the following sections.

Disaggregation by living-standard measure

In South Africa, a considerable amount of effort has gone into a detailed analysis of living standards of households, resulting in the definition of eight 'Living Standard Measures' (LSMs). These LSMs provide a convenient stratification of households into different living standards, which correlate closely with, but are not defined by, income. Changes in the distribution of households between the different LSMs would result in changes in the energy consumption patterns of the residential sector, and would be analogous to structural changes in the industrial sector.

A useful analysis might therefore be to decompose total residential sector energy consumption into: (i) change due to overall growth in the number of households; (ii) change due to shifts in the relative size of the different LSMs; (iii) change due to overall increase (or decrease) in the energy consumption per household, regardless of LSM. This decomposition would provide a picture of how living standards influence energy consumption, but it would only be meaningful if the definitions of the LSMs remained stable over a prolonged period.

The equations describing this decomposition are:

$$\Delta P = \ln\left(\frac{P_t}{P_0}\right) \times \sum_l W_l \quad \text{..(Equation 5a)}$$

$$\Delta I = \sum_l \left[W_l \times \ln\left(\frac{I_{l,t}}{I_{l,0}}\right) \right] \quad \text{..(Equation 5b)}$$

$$\Delta S = \sum_l \left[W_l \times \ln\left(\frac{S_{l,t}}{S_{l,0}}\right) \right] \quad \text{..(Equation 5c)}$$

where: subscript *l* refers to LSMs

ΔP is the effect of population change

P is the total number of households

ΔI is the effect of overall increases in energy consumption per household

I_l is the energy consumption per household in LSM *l*

ΔS is the effect of living standard changes

S_l is the fraction of total households in LSM *l*

W_l are the log-mean weighting factors as used previously

The following example illustrates the principle of decomposition by LSM. Table 7 below shows data for household energy consumption in a hypothetical residential sector. For simplicity, this sector is stratified into only three LSM categories – in reality there are eight.

Table 7 Energy consumption data for a hypothetical residential sector

		LSM1	LSM2	LSM3	TOTAL
No. of households	Year 0	300	500	600	1400
	Year T	250	560	610	1420
Energy consumption	Year 0	1550	2900	3200	7650
	Year T	1250	3230	3250	7730
Households as share of total	Year 0	21.4%	35.7%	42.9%	
	Year T	17.6%	39.4%	43.0%	
Energy per household	Year 0	5.167	5.800	5.333	
	Year T	5.000	5.768	5.328	
Weighting factor		1394.626358	3062.03686	3224.935399	

The total energy consumption for the sector as a whole increased by 80 units between Year 0 and Year t. Substituting this data into Equations 5a-c yields the following results:

- If the number of households *only* had changed, total energy consumption would have *increased* by 108.96 units
- If the distribution of households between LSMs *only* had changed, total energy consumption would have *increased* by 37.09 units
- If the number of households and the distribution across LSMs had remained constant, total energy consumption would have *decreased* by 66.05 units (due to non-lifestyle related general reductions in energy usage, including improved technical efficiency).

This type of decomposition relies on the assumption that LSM categorisation correlates strongly with a household's *relative* energy consumption. There is good reason for believing that this assumption holds, since part of the definition for LSMs includes ownership of certain categories of household appliance. For example, acquiring an electric stove might be sufficient to move a household into a higher LSM category[11], whereas replacing an existing electric stove with a more efficient model would not. Hence this form of decomposition should be able to distinguish between across-the-board changes in energy intensity (due perhaps to price, or to raised awareness) and changes in energy usage that result from improvements in living standards.

An advantage of this type of analysis is that the data requirements are relatively less onerous. Although the collection of new data through household surveys is necessary for this analysis, as it is for the other methodologies described here, detailed breakdowns of energy use according to application would not be necessary. The type of data required – total energy consumption by LSM – is likely to be relatively

[11] This would not *necessarily* happen, as ownership of an electric stove is only one of a total of 29 criteria that define which LSM a household belongs to.

easily and reliably obtainable from simple household surveys. A major disadvantage of this methodology, however, is the tendency for LSM definitions to be periodically updated. This would render both problematic and suspect any analysis that covers a time period during which the definition of LSMs had changed.

Disaggregation by end-use application

Another approach to analysing residential sector energy consumption is to dissagregate by end-use application. Analyses conducted in other countries have focussed on the share of total household energy consumption accounted for by the different energy-using household activities, treating this analogously to the structural effect that is used as a factor of decomposition in the productive sectors. However, this analogy is weak, and this particular form of analysis does not yield any useful insights into the mechanisms governing changes in household energy consumption. The form of analysis described here is somewhat different, and focuses instead on changes in the ownership level of different energy-using appliances.

In the productive sectors, overall changes in energy consumption have usually been decomposed into three factors: activity-level changes, structural changes and intensity (efficiency) changes. However, these factors are only a matter of choice, and there is no reason why different factors cannot be used. The general process of decomposition involves choosing a set of factors in which total energy consumption can be expressed, such that:

$$E = factor_1 \times factor_2 \times factor_3 \times factor_4 \times \ldots \times factor_n$$

At the same time, the sector in question is disaggregated into a number of different activities with different characteristics. The contribution of each factor to *changes* in total energy consumption over a given time period is given by taking the fractional change in that factor over the time period in question, then calculating the weighted mean of the logarithms of these fractional changes across all the components into which the sector has been disaggregated.

The analysis proposed here disaggregates the residential sector into the main energy-using activities (cooking, water heating, space heating, lighting, refrigeration etc.) and uses the following factorisation of total energy consumed in each activity:

$$E_a = P \times S_a \times I_a \times U_a$$

where: P is the total number of households

S_a is the number of appliances per household for carrying out activity a

I_a is the specific energy consumption of appliances for carrying out activity a (i.e. the energy consumed in carrying out a ‘normal’ cycle of operation)

U_a is the actual duty-cycle of appliances for carrying out activity a (i.e. the number of ‘normal’ cycles of operation carried out per year)

For example, in the case of refrigeration, S would be the national average number of refrigerators per household, I would be the average nameplate power consumption of refrigerators, U would be the average operating hours per year for refrigerators.

Using this method of factorisation, it is possible to derive a set of equations analogous to those used in the productive sectors, presented as Equations 6a-d below, where the summation takes place across all the activities into which the ersidential sector has been disaggregated.

$$\Delta P = \ln\left(\frac{P_t}{P_0}\right) \times \sum_a W_a \quad \text{...(Equation 6a)}$$

$$\Delta I = \sum_a \left[W_a \times \ln\left(\frac{I_{a,t}}{I_{a,0}}\right)\right]$$ ....(Equation 6b)

$$\Delta S = \sum_a \left[W_a \times \ln\left(\frac{S_{a,t}}{S_{a,0}}\right)\right]$$ ....(Equation 6c)

$$\Delta U = \sum_a \left[W_a \times \ln\left(\frac{U_{a,t}}{U_{a,0}}\right)\right]$$ ....(Equation 6d)

where: subscript *a* refers to the activity in question

ΔP is the effect of population change

P is the total number of households

ΔI is the effect of changes in the energy intensity of appliances

I_a is the specific energy consumption of technology *a* expressed in terms of energy consumption per unit of usage (see below)

ΔS is the effect of appliance ownership levels (see below)

S_a is the average number of appliance *a* per household

ΔU is the effect of appliance usage levels

U_a is the average usage level of appliance *a* per household

W_a are the log-mean weighting factors as used previously

Appliance usage levels are likely to be very difficult to gauge, because any data collected would necessarily be based on the subjective judgements of householders, and is therefore unlikely to be reliable. However, if the analysis is constructed correctly, this quantity can be treated as a 'residual' that remains once all the other effects have been accounted for, as illustrated in the example below.

For some activities (e.g. lighting, refrigeration, washing machines), the definitions of specific energy consumption and ownership level are clear. However, in the case of space heating, cooking and water heating, these definitions require some elaboration:

Space heating. The specific energy consumption for heating is not related to the characteristics of the heating appliance itself, but is a function instead of the building in which the heating appliance is used. The figure used should represent the average annual energy consumption required per unit of floor area to heat a dwelling to a 'normal' level. In an actual analysis, this would need to be calculated using data on type of construction and level of insulation, taking a weighted mean across all households. For space heating, the 'appliance ownership level' is actually the fraction of households nationally that use space heating. Changes in space heating demand that result from changes in the average size of dwellings, or from the indoor temperature to which dwellings are heated, would be subsumed into the 'usage level' factor.

Cooking / water heating. The 'appliance ownership level' in this case is actually the fraction of households that perform each of these activities, rather than the number of appliances in use for performing the activities. The ownership level for cooking and water heating is therefore assumed to be 100%, as it can be assumed that all households cook and heat water. The specific energy consumption would be the average energy consumption required to deliver a particular level of energy service in cooking and water heating (energy required to cook a 'standard' meal, energy required to provide a particular volume of hot water). In an actual analysis, these would need to be calculated using

standardised estimates for each cooking / water heating technology employed, taking a weighted mean across all households. Changes in cooking / water heating demand that result from changes in household size, or from changes in the amount of hot water used, would be subsumed into the 'usage level' factor.

The following example is based on a hypothetical residential sector where disaggregation is into six activities: cooking, space heating, water heating, lighting, refrigeration, clothes washing. A seventh category 'Other' is also defined, which accounts for all other energy-using activities. A dummy appliance type 'Other' also has to be defined, which is owned by all households. The specific energy consumption for the dummy appliance 'Other' is calculated by dividing the total energy consumption not accounted for by the appliances analysed by the total number of households.

Hypothetical data on ownership levels and specific energy consumption is provided in Table 8 below. Since usage levels are likely to be very difficult to determine, this data is omitted from the table, and only Equations 6a-c are actually calculated. It is assumed that any unexplained residual factor resulting from the analysis is due to changes in usage levels.

Table 8 Energy consumption data for a hypothetical residential sector

		Base year	Current year
SECTOR TOTAL	Energy consumption	193359	196938
	Number of households	11780	12546
	Weighting factor	195143.03	
Space heating	Energy consumption	19335.9	19693.8
	Appliances per household	0.919	0.922
	Specific energy consumption	987	955
	Weighting factor	19514.303	
Cooking	Energy consumption	29003.85	29540.7
	Appliances per household	1	1
	Specific energy consumption	1222	1165
	Weighting factor	29271.4545	
Water heating	Energy consumption	69609.24	70897.68
	Appliances per household	1	1
	Specific energy consumption	2565	2377
	Weighting factor	70251.4908	
Lighting	Energy consumption	29003.85	29540.7
	Appliances per household	3.82	3.95
	Specific energy consumption	88	79
	Weighting factor	29271.4545	
Refrigeration	Energy consumption	29003.85	29540.7
	Appliances per household	0.799	0.802
	Specific energy consumption	520	510
	Weighting factor	29271.4545	
Clothes washing	Energy consumption	5800.77	5908.14
	Appliances per household	0.501	0.514
	Specific energy consumption	201	208
	Weighting factor	5854.2909	
Other	Energy consumption	11601.54	11816.28
	Appliances per household	1	1
	Specific energy consumption	0.985	0.942

	Weighting factor	11708.5818

The total residential sector energy consumption increased by 3,579 TJ between Year 0 and Year t. Substituting the data from Table 8 into Equations 6a-c provides the following results:

- The increase in the total number of households accounted for an increase of 12,294 TJ
- Increased appliance ownership levels accounted for an increase of 1,303 TJ
- Reductions in energy intensity accounted for a decrease of 11,438 TJ

This leaves an increase in energy consumption of 1,420 TJ unaccounted for. This increase is therefore assumed to be due to increases in the usage levels of appliances, as described by Equation 6d. Note that increases in usage level also include:

- increases in the demand for space heating that result from increases in average dwelling size; increases in the demand for cooking and water heating due to increased household size.
- efficiency effects that are embodied in behaviour rather than in the characteristics of the technology. Examples of behaviour-based efficiency reductions would be: leaving lights switched on unneccesarily; deteriorating performance of refrigerators due to poor maintenance; using a washing machine only part-loaded.

2.7 The commercial / public sector

As a component of a top-level economy-wide decomposition analysis, the most straightforward way to treat the commercial / public sector is in the same way as the industrial sector. This means data on total energy consumption and total value-added are required for both the base year and the year of analysis.

However, although the range of activities that take place in the commercial and public sectors is huge, but by far the most important from the point of view of energy consumption are lighting and HVAC (heating, ventilation and air-conditioning). The energy demand for these activities is likely to be strongly related to the floor area in use, so floor area represents a convenient proxy for the level of activity. Even in the retail sub-sector, where the energy demand for refrigeration is significant, it is still probably the case that floor area is an effective proxy variable. Thus the analysis could (subject to data availability) incorporate a physical measure of activity for the commercial / public sector, as outlined in Section 2.5.2.

The same argument applies in analysing the commercial / public sector as a unit of analysis. The decomposition analysis in this case would be based on a disaggregation into the main sub-sectors (e.g. education, health care, retail, banking / finance, hospitality etc.). A set of equations similar to Equations 3a-c would be used, with total activity, shares of activity and energy intensity being quantified in terms of floor area, where such data is available, and in terms of value-added where it is not. Summation would take place across all of the sub-sectors considered.

2.8 The transportation sector

From the point of view of conducting the type of analysis under discussion here, it is appropriate to examine freight transportation and passenger transportation completely independently of one another. Factors that are of interest are total levels of activity, modal shifts and changes in efficiency. For each of these sub-sectors, there exists a convenient and consistent measure of activity, namely tonne-km for the freight transport sub-sector, and passenger-km for the passenger transport sub-sector. Total activity levels, the shares of each mode of transport and the technical efficiencies of each mode can all be expressed in terms of tonne-km or passenger-km. There is therefore no need to consider value-added,

which, for the productive sectors, provided a useful common yardstick against which widely disparate activities could be compared.

The framework equations for deriving the contributions of each factor to changes in total energy consumption are easily derived, and closely mirror Equations 1a-c. For the transportation sub-sectors, however, these equations are expressed purely in physical units:

$$\Delta P = \ln\left(\frac{A_t}{A_0}\right) \times \sum_m W_m \qquad \text{.......................................(Equation 7a)}$$

$$\Delta H = \sum_m \left[W_m \times \ln\left(\frac{H_{m,t}}{H_{m,0}}\right)\right] \qquad \text{.......................................(Equation 7b)}$$

$$\Delta S = \sum_m \left[W_m \times \ln\left(\frac{S_{m,t}}{S_{m,0}}\right)\right] \qquad \text{.......................................(Equation 7c)}$$

where: ΔP is the change in sub-sectoral energy consumption that is attributable to the overall change in activity

ΔH is the change in sub-sectoral energy consumption that is attributable to changes in energy efficiency

ΔS is the change in sub-sectoral energy consumption that is attributable to modal shifts

subscripts 0, t refer to values at two points in time

A is the total activity level (in tonne-km for freight, in passenger-km for passenger transport)

E_m is the energy consumption of the m^{th} mode of transport

H_m is the energy consumption per tonne-km or per passenger-km of the m^{th} mode of transport

S_m is the share in total activity level of the m^{th} mode of transport

W_m is the log-mean weighting factor for the m^{th} mode of transport

Equations 7a-c can be applied equally well to the freight or passenger transportation sub-sectors, as the following simplified example illustrates. Table 9 below provides data for a hypothetical passenger transportation sub-sector where, for simplicity, it has been assumed that there are five possible modes of transport.

The total energy consumption in the passenger transport sub-sector has increased by 1,000 TJ between Year 0 and Year t. Substituting data from Table 9 into Equations 7a-c yields the following results:

ΔP = 1,605.22 TJ

ΔH = -836.21 TJ

ΔS = 230.99 TJ

Hence it can be seen that, all else being equal, efficiency improvements alone would have yielded a *reduction* in energy consumption of over 836 TJ. But an increase in total activity combined with (to a lesser extent) shifts to less efficient transport modes has more than cancelled out the effects of efficiency gains, resulting in the observed increase of 1,000 TJ in total energy consumption.

Table 9 Energy consumption and activity data for a hypothetical passenger transport sector

		Car	Intercity rail	Urban rail	Intercity bus	Urban bus	Total
Activity level (million passenger-km)	Year 0	2,500	1,200	1,800	2,900	2,150	10,550
	Year t	2,950	1,250	1,950	2,850	2,250	11,250
Total energy consumption (TJ)	Year 0	7,250	2,150	3,950	5,550	5,600	24,500
	Year t	8,250	1,950	3,900	5,750	5,650	25,500
Reciprocal efficiency (MJ / passenger-km)	Year 0	2.90	1.79	2.19	1.91	2.60	
	Year t	2.80	1.56	2.00	2.02	2.51	
Modal share	Year 0	23.70%	11.37%	17.06%	27.49%	20.38%	
	Year t	26.22%	11.11%	17.33%	25.33%	20.00%	
Weighting factor log-mean($E_{m,0}$,$E_{m,t}$)		7739.24	2048.37	3924.95	5649.41	5624.96	24986.93

3 Conclusions

- In terms of the criteria set out in Section 1.4, the log-mean Divisia decomposition methodology appears to be best suited to the requirements of this project.
- This methodology should be applied to the total energy consumption of the whole economy, and then at successively disaggregated levels (sectoral, sub-sectoral etc.) according to the importance of each 'unit of analysis' as an energy user, and as permitted by the availabilty of data.
- The choice between using physical versus monetary units for quantifying levels of activity can be made according to data availability, with preference being given to physical units. However, even when physical units are used, the level of activity quantified in monetary units must still be known.
- Physical and monetary units of activity can be mixed within one decomposition analysis, as outlined in Section 2.5.2.
- Because of the difficulty in clearly separating activities in the residential sector, the decomposition methodology is suited only to analysis of electricity consumption in this sector.
- The commercial / public sectors are not sufficiently significant consumers of energy to merit more detailed analysis at present. However, if such an analysis is required in future, a possible methodology is outlined in Section 2.7.
- The requirements of the log-mean Divisia decomposition methodology determine the data variables that must be collected. The data required for performing a complete analysis is in Table 10 below. However, not all of these indicators will be available immediately, so the methodology may need to be modified to accommodate imperfect data-sets. These issues are discussed in more detail in the accompanying paper 'Monitoring of Energy Efficiency Targets: Selection and Availability of Indicators'.

Table 10 Summary of data requirements

Unit of analysis / component of analysis	**Data required**
Whole economy	Total GDP Total energy consumption
Industry sector	Sector GDP Sector energy consumption
Commercial / public sector	Sector GDP Sector floor area in use Sector energy consumption
Major sub-sectors of the industry sector	Sub-sector value-added Sub-sector energy consumption
Main energy-using industries	Industry value-added Industry physical production Industry energy consumption

Major sub-sectors of the commercial / public sector	Sub-sector floor area in use Sub-sector energy consumption
Residential sector	Total number of households Sector energy consumption Ownership levels of appliances Breakdown of energy consumption by activity Average specific energy consumption of appliances Number of households in each LSM Energy consumption per household in each LSM
Passenger transport sub-sector	Total passenger-km Total energy consumption Passenger-km of each mode Energy consumption of each mode
Freight transport sub-sector	Total tonne-km Total energy consumption Tonne-km of each mode Energy consumption of each mode

4 References

Balk B.M.; 'Divisia price and quantity indices: 75 years after'. Statistics Netherlands (July 2000).

Hoekstra R., van den Bergh J.; 'Comparing and expanding SDA and INA techniques applied to physical flows in the economy'. Free University, Amsterdam (2000).

Lermit J., Jollands N.; 'Monitoring energy efficiency performance in New Zealand: a conceptual and methodological framework'. Energy Efficiency and Conservation Authority (September 2001).

Liu X.Q. *et al*; 'The application of the Divisia index to the decomposition of changes in industrial energy consumption'. Energy Journal **13**(4), pp 161-176 (1992).

Mail & Guardian; 'Survey shows better SA in 2004'. Mail & Guardian, 29 June 2005.

Nanduri M.; 'An assessment of energy intensity indicators and their role as policy-making tools'. Simon Fraser University, November 1998.