ENERGY EFFICIENCY OPPORTUNITIES

ENERGY–MASS BALANCE: MINING
VERSION 1.0

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ENERGY EFFICIENCY OPPORTUNITIES

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CONTENTS

1 INTRODUCTION .......................................................... 5
1.1 EEO requirements for EMBs ............................................. 5
1.2 What is an EMB? ......................................................... 6
1.3 What are the benefits of an EMB? ................................... 7
1.4 Where does an EMB fit in the assessment process? .............. 7
1.5 Is there a prescribed method for a mine site EMB? .............. 8

2 WHAT DOES AN EMB LOOK LIKE FOR A MINE SITE? .......... 9
2.1 Levels of analysis ....................................................... 9
2.2 What are the steps involved in developing an EMB for a mine site? 11
  2.2.1 Personnel and skill requirements ................................ 11
  2.2.2 The EMB project plan ............................................. 12
2.3 Mass flows and effects in mining .................................... 13
2.4 Mapping the energy and mass flows ................................ 13
2.5 Defining the boundary of the EMB .................................. 15
2.6 Specific systems used in mining operations ......................... 16

3 COMMINUTION: CRUSHING AND GRINDING ...................... 17
3.1 Examining the baseline performance of the comminution circuit 17
3.2 Modelling energy use relative to throughput ..................... 17
  3.2.1 Estimating energy use per tonne: Bond’s formula ............ 18
3.3 Potential efficiency opportunities in comminution .............. 19

4 MATERIALS HANDLING: RESOURCE EXTRACTION, EXCAVATION AND HAULAGE SYSTEMS ......................... 21
4.1 Examining the baseline performance of excavation and haulage systems 21
4.2 Modelling energy and mass flows .................................. 21
  4.2.1 Resource extraction ................................................ 21
  4.2.2 Example of resource extraction principles .................... 21
  4.2.3 Excavation and mucking equipment ............................ 22
  4.2.4 Haulage trucks ..................................................... 22
4.3 Simplified energy use model for a mining haulage truck ............ 23
4.4 Potential energy saving measures .................................. 26
  4.4.1 Reducing vehicle weight ......................................... 26
  4.4.2 Payload management ............................................. 26
  4.4.3 Operational improvements: maintenance, tyres and driver training . 28
  4.4.4 Vehicle selection and haul road design ....................... 28
  4.4.5 Aerodynamic resistance considerations ...................... 28

5 COMPRESSED AIR SYSTEMS ...................................... 29
5.1 Types of air compressors ............................................. 29
5.2 Measuring compressor efficiency .................................... 29
  5.2.1 Volumetric flow rate—Equation 2 ............................... 31
  5.2.2 Isothermal power—Equation 3: example ....................... 31
  5.2.3 Compressor efficiency—Equation 4: example ................. 32
  5.2.4 Equation 2—variables in energy savings ...................... 32
  5.2.5 Energy efficiency opportunities—variable speed drives .... 33
  5.2.6 Variable speed drives energy savings example—start-up ...... 34
  5.2.7 Compressor maintenance ........................................ 34
5.3 Measurement techniques for compressed air systems .................................................. 35
  5.3.1 Measuring and fixing air leaks .............................................................................. 35
  5.3.2 Multiple compressor systems ............................................................................. 35

6 VENTILATION SYSTEMS ......................................................................................... 37
  6.1 Measuring baseline energy use ................................................................................ 37
  6.2 Modelling ventilation system energy use ................................................................. 37
    6.2.1 Flow resistance .................................................................................................. 37
  6.3 Potential energy savings measures .......................................................................... 40
    6.3.1 Lower cost opportunities ................................................................................ 40
    6.3.2 Matching supply to demand ............................................................................ 40
    6.3.3 Other equipment replacement or retrofit options .............................................. 41

7 PUTTING THE EMB TOGETHER ............................................................................... 42

8 CONCLUSION ........................................................................................................... 45

9 APPENDICES ........................................................................................................... 46
  9.1 Integrating data using the trapezoidal rule ............................................................... 46

FIGURES
  Figure 1: Three levels of analysis for a mining EMB .................................................. 10
  Figure 2: Influences on the EMB for a mine site ......................................................... 10
  Figure 3: Basic steps to develop a mining EMB ............................................................. 11
  Figure 4: Example of a high-level energy and mass flow map for a mine site, prior to processing. .............................................................. 14
  Figure 5: Gradeability/speed/rimpull curve (CAT 789C Mining Truck) ...................... 25
  Figure 6: Sensitivity analysis: Effect of velocity constraints on fuel intensity ............ 27
  Figure 7: Equipment arrangement for free air delivery test .......................................... 30
  Figure 8: Graphed relationship between isothermal power requirements and inlet air temperature .............................................................. 33
  Figure 9: Relationship between isothermal power requirements and air receiver pressure .............................................................. 33
  Figure 10: Comparison of VSD and fixed speed drive start-up power ......................... 34
  Figure 11: Overview of the relationship between compressor size and demand profile . 36
  Figure 12: Fan performance curves ............................................................................. 39
  Figure 13: Energy and mass flows for a dewatering operation ..................................... 43
  Figure 14: Energy and mass flows for a dewatering operation ..................................... 44
  Figure 15: Comparison of start-up power for a VSD and a non-VSD system ................ 46
  Figure 16: Application of the trapezoidal rule .............................................................. 47

TABLES
  Table 1: Simplified project plan for stage 1 of a mine site EMB ..................................... 13
  Table 2: Boundary considerations for a hypothetical coal mine site ............................ 16
  Table 3: Estimating the energy used by a haul truck for an average loading/unloading cycle .............................................................. 23
  Table 4: Fuel use variation with loading ..................................................................... 26
1 INTRODUCTION

Mining consumed 450 PJ of energy in 2007–08 or 11% of national energy end use. Energy consumption and intensity in mining is rising at around 6% annually due to deeper and lower grade ores, and greater liquefied natural gas production.\(^1\) Mining operations use energy in a variety of ways, including comminution, excavation, materials transfer and haulage, ventilation and dewatering.

This guidance document will outline the key considerations and potential approaches for the development of an energy–mass balance (EMB) for a mining operation to meet the requirements of the Energy Efficiency Opportunities (EEO) program, as detailed in the EEO legislation.\(^2\) This document focuses on open pit and long wall mining operations for the extraction of mineral and fossil fuel resources rather than oil and gas extraction.\(^3\)

1.1 EEO REQUIREMENTS FOR EMBS

Key requirements 3.2(d), 3.3(b) and 3.3(c) of the EEO Assessment Framework, which is at Schedule 7 of the Energy Efficiency Opportunities Regulations 2006 (and also outlined in the Industry Guidelines), require that:

- the data collection process include ‘The energy and material flows through the site/fleet (e.g. through using an EMB or similar technique)’
- the energy analysis process include ‘Application of a range of methods of data analysis (e.g. EMB, review of graphs and charts) to explore relationships between energy use and variables that may influence it, using data collected at appropriate time intervals’
- a comparison of performance to theoretical and actual energy use benchmarks be undertaken, at the relevant level (process, technology, site, or indicator). Where appropriate, other detailed numerical analysis or the application of indicators and other comparative techniques are used to fully understand energy consumption, including its variability.

Box 1 provides further detail of the requirements for EMBs in the regulations.

 BOX 1. EMBS IN THE ENERGY EFFICIENCY OPPORTUNITIES REGULATIONS 2006

Regulation 1.3 defines an EMB as a method of accounting for:

a) the materials and energy entering and leaving a site or fleet and its processes, systems or equipment; and

b) the energy and material flows, energy conversions and energy use within the site or fleet and its processes, systems or equipment.

Note 1 To enable an appropriate coverage, an EMB should define, to an accuracy of ±5%, at least 80% of a site’s energy use and all processes not already included in the 80% that use at least 0.1 PJ of energy per year.\(^4\)

Note 2 An EMB should provide a thorough understanding of:

(a) the material flows and energy use through a site, its processes and systems, and items of equipment including items such as pipes and ducts; and

(b) the specific services and products the energy use delivers; and

(c) the energy conversion processes within a system, and identification of conversions that are essential and efficient; and

(d) the identification of energy waste and energy efficiency opportunities.

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\(^2\) The EEO program was established under the *Energy Efficiency Opportunities Act 2006*, and detailed requirements are outlined in the Energy Efficiency Opportunities Regulations 2006. The EEO Industry Guidelines explain in plain English what participating corporations need to do to meet the requirements of the program.

\(^3\) Any inquiries about EMBs for oil and gas extraction can be directed to EEOtechnical@ret.gov.au.

\(^4\) 0.1 PJ, or $0.1 \times 10^{15}$ joules, is equivalent to approximately 2.6 million litres of diesel fuel.
There is scope for error margins larger than ±5% for some flows or items of equipment in a mine site, consistent with being able to prepare a business case with sufficient rigour to meet the overall assessment data accuracy requirement. These larger error margins will typically apply for those energy and mass flows that cannot be accurately measured and therefore may require engineering calculations or estimates. For example, the electricity and gas consumption at a site should be known to within ± 5% from billing data. By contrast, the heat released from furnaces, grinding mills and boilers, for example, might have higher error margins. Accuracy requirements should not be seen as a disincentive to detailed investigation of processes in the EMB.

More broadly, Key Requirement 3 sets out requirements for data collection and analysis, which provide guidance for developing an EMB. Energy consumption and cost data is required for each energy source. Data should be entered at the frequency that bills and other records are received (typically monthly) for a total of 24 months. The accuracy of data must be within ±5%. A less accurate level may only be used if this was approved in the Assessment and Reporting Schedule.

For verification purposes an EMB will be good evidence of having addressed key requirements 3.2(d) and 3.3. Assumptions, calculations, equations used and decision processes should all be documented and kept for at least seven years.

This document provides guidance on the level of detail and considerations required in an EMB (or similar technique) to satisfy these requirements and indicates the standard that industry should attain. The document complements the Energy Efficiency Opportunities Assessment Handbook, which outlines the complete EEO assessment process on pages 10–12. This EMB guidance also complements the Energy Savings Measurement Guide, which provides guidance on how to estimate, measure, evaluate and track energy and financial savings from opportunities. Energy Efficiency Opportunities program technical staff can also assist with specific enquiries related to EMBs and other technical aspects of EEO assessments. Any enquiries can be directed to EEOtechnical@ret.gov.au.

1.2 WHAT IS AN EMB?

In principle, an EMB is an approach used to understand the efficiency of energy conversion and how other inputs are used to deliver goods and services. Box 2 explains the technical underpinnings of the EMB. Preparation of an EMB involves a number of steps that are discussed in Section 2.3.

**BOX 2. TECHNICAL BASIS OF AN EMB**

An energy balance is a mathematical statement of the conservation of energy, and a systematic accounting for energy flows and transformations in a system. The theoretical basis for the energy balance is the first law of thermodynamics, which states that ‘energy cannot be created or destroyed, only modified in form’. Contrary to mass balances, a system can only have one energy balance that describes it, since different types of energy are considered, mathematically, to be interchangeable. Specifically, the change in energy for a system equals the heat transferred into the system minus the work done by the system plus the net energy input associated with mass flows. Mass flows carry enthalpy\(^5\), kinetic and potential energies.

An EMB is a model of how a process or system works, from an energy perspective. It helps to understand the energy flows, mass flows, and other factors influencing energy use, to determine the efficiencies of processes and equipment, and to evaluate the effects of external factors. For mine sites these may include the depth of deposits, the geology of sites, climatic factors and regulations. For example, a mine located in a remote area may have more blasting options than mines built closer to residential areas.

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5 Enthalpy is a measure of the ‘heat content’ of a material, and is tabulated in engineering texts and handbooks. It equals the sum of the internal energy and the product of the pressure and volume of the material.
1.3 WHAT ARE THE BENEFITS OF AN EMB?

Thorough EMBs reveal significant energy and cost savings by identifying:

- how much energy is being used, wasted or lost—and where this occurs
- whether the systems and equipment are operating according to design and work schedules
- energy use variability and its underlying causes
- if useable waste heat is being produced—or processes could be alternatively powered
- the efficiency of energy-using processes within the business.

EMBs also provide a structure for examining interactions between the different components of a business operation. For example, an EMB can be used to examine whether energy use adjusts to the demand for services. An EMB can also help to identify interactions between people, technologies and energy use, rather than looking independently at the technical performance of individual items of equipment. Accounting for these interactions and human factors helps to ensure that identified opportunities can be effectively and reliably implemented.

An EMB requires a company to look at their business or site as a whole system. This can provide the data required to question assumptions about existing patterns of energy use and production. In the process, an EMB can help to identify novel or innovative ways of producing products or services with substantially lower energy and resource inputs. The EMB can potentially incorporate other resource constraints such as water usage, use of non-renewable resources, waste, logistics and occupant behaviour.

As with other business improvements, the benefits from an EMB are dependent on the level of detail in the analysis involved. Experience with the EEO program to date suggests that detailed EMBs that analyse the way in which energy is used by specific processes, sub-processes and items of equipment deliver favourable benefit–cost ratios. By comparison, companies that merely develop high-level energy use breakdowns, for example pie charts of energy end uses by technology, derive much less benefit from the process.

1.4 WHERE DOES AN EMB FIT IN THE ASSESSMENT PROCESS?

As noted in Section 1.1, an EMB is a major component of the data collection and analysis component of an EEO assessment. An EMB systematically collects and analyses data on energy use, and investigates where losses occur. It is therefore a useful input to background papers, workshops, meetings, specialist studies and other activities used to identify and investigate opportunities. Developing a first iteration of the EMB for opportunities identification workshops focuses the opportunity identification process on those areas with the greatest energy-saving potential. This enables workshop participants to develop more rigorous ideas and opportunity savings estimates.

Once companies have identified an initial list of opportunities, the preliminary EMB should be improved to build up a detailed and accurate understanding of the energy and material flows through the fleet or site. The first iteration of the EMB should provide the highest accuracy obtainable with the available data and analysis tools, plus a clear plan to improve accuracy over time so as to better understand energy use and identify further opportunities. A detailed EMB will determine the energy use of specific processes, ancillary equipment, and the variables that influence energy use at all three levels.

In addition, a detailed EMB will be very useful for evaluating the opportunities already identified to an accuracy of 30% or better (as specified by key requirements 4.3 and 4.4 of the Assessment Framework). Thorough EMBs can be used to estimate energy savings and other whole-of-business costs and benefits for an opportunity. Following opportunity implementation, EMBs can also be used to measure the actual savings realised from implementing projects, and to examine interactions between different projects.

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6 Providing a more detailed EMB for workshops will produce more realistic and feasible ideas and opportunities.
1.5 IS THERE A PRESCRIBED METHOD FOR A MINE SITE EMB?

Under the EEO program, companies are required to analyse energy and mass flows sufficiently to satisfy the EEO requirements for an EMB or equivalent. Subject to this constraint, the EMB or an equivalent technique can be adapted to company circumstances to meet program requirements efficiently.

In addition to physical factors, the EMB approach may be determined initially based on data/measurement availability as well as company organisation. The optimal approach for any company will depend on initial data availability, measurement systems and the personnel available for the EMB process. For verification purposes companies should be able to justify the chosen approach to collecting and analysing energy and material flows and should make sufficient resources available to satisfy program requirements.

Mine sites often use more than 0.5 PJ of energy annually, so a representative assessment approach may not be applicable to entire mine sites. Nonetheless, there may be scope for a representative assessment approach to be applied to specific energy-using processes that may be operating at different mine sites. For example, materials haulage, dewatering or ventilation systems can potentially be analysed using the same modelling approach at various sites. The EEO Representative Assessment Guide provides guidance on assessing energy usage and opportunities in multiple, similar operations, including modelling techniques relevant to mine sites. Section 2 of this document presents a general approach to developing an EMB for a mining operation.
2 WHAT DOES AN EMB LOOK LIKE FOR A MINE SITE?

Energy use in mining operations is influenced by a number of organisational, site specific and external factors, many of which also affect productivity. The EMB process aims to identify and analyse the impacts of these factors on energy use and how these factors interact. This document presents the key considerations involved in developing an EMB for mining operations.

As a first step, it is advisable to map out the mining operation so as to identify the key factors that will impact on energy use. This mapping is a brainstorming process that helps to identify how operational factors, external influences and site characteristics interact and contribute to energy use. Mapping these influences will help to establish which data need to be collected and may indicate which energy-using systems at the site have the strongest interactions. Figure 1 presents a high-level schematic of factors affecting energy use in an EMB for a mine site.

Having mapped out the various factors that influence energy use, the next step is to determine how best to organise the analysis and which parts of the mining operation should be given priority. The proposed approach is to examine mining operations for the corporation as a whole, breaking down the portfolio into three broad levels for analysis, as discussed in Section 2.1.

2.1 LEVELS OF ANALYSIS

An effective EMB for mining operations has three broad levels of analysis, each of which interacts to form a complete system. These three levels are described below and illustrated in Figure 1.

Level 1—At the top level, there is the breakdown of the site into subsystems based on plant and/or functional categories, such as blasting, excavation, haulage and comminution. This high level breakdown helps to identify priorities for further analysis, clarifies which subsystems at the site should be included in the EMB, and indicates appropriate subsystem boundaries. At Level 1 only the aggregate annualised data, such as annual fuel use for the site haulage fleet, might be considered.

Level 2—At the next level of the EMB there is the analysis of the key data and characteristics of each secondary subsystem, such as energy use per tonne of ore or overburden hauled, and patterns of energy use for haulage from high level fleet data. Such analysis may reveal the key factors affecting energy use within each Level 2 subsystem as well as highlight which systems to prioritise when allocating resources for more detailed investigation or additional metering. In some cases level 2 analysis might reveal clear energy saving opportunities for immediate implementation, such as turning off equipment during downtimes.

Level 3—Finally, the next level of the EMB models the energy use and mass flows for specific plant and equipment in detail. One example is modelling the effects of changes in loading, vehicle mass, vehicle speed and road conditions on haulage truck energy use. Other examples might include detailed analysis of comminution energy use based on loading and material properties, or investigation of dewatering system energy use and its variation with piping system configurations.

Energy use models enable estimation of the benefits of implementing energy efficiency opportunities for specific plant. This includes investigating the physical mechanisms by which the broad energy use factors identified in the level 2 analysis affect the energy use of individual items of equipment. For example, a model of haulage truck energy use might investigate the contribution of rolling resistance to haulage truck energy use, and options to reduce this resistance.
The guidance provided in this document concentrates on the EMB process at level 3, presenting techniques that can be used to break down energy consumption on an end-use and time of use basis for a mine site. Each of section 3–6 addresses an energy using system found in mining operations and suggests techniques that could contribute to an EMB of that subsystem.

As a first step, it is advisable to map out the mining operation to identify the key factors that will impact on energy use. This mapping is a brainstorming process that helps to identify how operational factors, external influences and site characteristics interact and contribute to energy use. Mapping these influences will help to establish which data need to be collected and may indicate which energy using systems at the site have the strongest interactions. Figure 2 presents a high-level schematic of factors affecting energy use in an EMB for a mine site.
Having mapped out the various factors that influence energy use, the next step is to determine how best to organise the analysis and which parts of the mining operation should be given priority.

An EMB can use a variety of modelling approaches, such as engineering calculations, regression analysis or direct measurement. These and other methods are described in the *Energy Savings Measurement Guide*.

### 2.2 WHAT ARE THE STEPS INVOLVED IN DEVELOPING AN EMB FOR A MINE SITE?

Figure 3 illustrates the basic steps involved in developing an EMB for a mine site. An EMB is an iterative process, and typically needs to be refined as the analysis progresses so as to obtain the required accuracy.

**Figure 3: Basic steps to develop a mining EMB**

<table>
<thead>
<tr>
<th>Steps</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEP 1 Develop an EMB project plan</td>
<td>• Select the EMB team based on the required skills and knowledge</td>
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<td></td>
<td>• Identify and schedule the key steps and tasks that will be undertaken during the EMB</td>
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<tr>
<td>STEP 2 Collect data for the EMB</td>
<td>• Prepare an energy and mass flow mapping</td>
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<td>• Define the EMB boundaries, based on business needs, to meet the regulations</td>
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<td></td>
<td>• Identify and capture the required data sets</td>
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<tr>
<td>STEP 3 Construct version 1 of the EMB</td>
<td>• Balance electricity and gas end use data</td>
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<td>• Collate energy and mass inflows and outflows</td>
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<td>STEP 4 Analyse version 1 of the EMB and identify potential energy efficiency opportunities</td>
<td>• Analyse results of the first iteration of the EMB process</td>
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<td>• Identify areas of energy wastage</td>
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<td>• Propose and analyse potential efficiency opportunities</td>
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<td>STEP 5 Identify considerations for version 2 of the EMB and subsequent versions</td>
<td>• Improve data acquisition and collation, refine analysis to improve accuracy</td>
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<td></td>
<td>• Collate energy and mass inflows and outflows</td>
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<td>• Refine analysis of identified opportunities</td>
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#### 2.2.1 Personnel and skill requirements

As outlined in step 1 of Figure 3, in order to develop an EMB, input from a range of people from the site and possibly external to the site will be needed to provide information and expertise. In addition to the need for organisational skills to ensure that the EMB process is planned and resourced appropriately, there is a need for staff with appropriate knowledge of the energy using systems and business activities conducted at the site.
Mine sites have a range of energy-using systems, which calls for a multidisciplinary EMB approach. The kinds of knowledge and skills you will need for the EMB team are:

- an understanding and appreciation of mine planning and design (i.e. the energy, materials and resources required to reach a defined ore body from the natural surface and the energy, materials and resources required to mine the ore body and haul it to the designated run-of-mine storage area)
- an understanding and appreciation of mine dewatering systems and requirements (i.e. the energy, materials and resources required to maintain a given mine water level in the pit or workings)
- for underground works, an understanding of mine ventilation systems and requirements, including cooling where required and purging of noxious/toxic gases and dust after blasting (i.e. the energy and airflows throughout the underground mine works)
- an understanding and appreciation of mine power supply and distribution systems and requirements including, as applicable, fuel sources for power generation plant, potential losses, power quality etc.
- an understanding and appreciation of mine compressed air supply and distribution systems and requirements including, as applicable, fuel sources for air compressor plant, potential losses, air quality etc.
- analytical skills, including the ability to use computer-based spreadsheets to record and analyse data at a level where suitable graphical charts can be produced that summarise overall flows into and out of the mining operation and the ability to provide a breakdown of energy and mass flows by logical function or activity within the mining operation in line with established mining key performance measures and other additional measures where required (e.g. mine dewatering, compressed air, mine ventilation, haulage etc.)
- the ability (such as that held by business improvement managers and/or energy managers) to evaluate potential savings from opportunities.

While mining engineers are trained across most of these areas, input from geologists or geotechnical engineers may be required, together with input from mechanical engineers for analysis of flows and vehicle energy use, electrical engineers for power systems optimisation and materials or chemical engineers for analysis of crushing and grinding processes. Environmental scientists or environmental engineers may also need to be involved in opportunity investigation to ensure environmental compliance. For example, changes to ventilation systems could adversely affect air quality if poorly implemented.

### 2.2.2 The EMB project plan

An EMB requires effective project management so as to ensure that the process is completed within business and EEO program timelines. The project schedule should identify the main steps and milestones involved in developing the EMB, bearing in mind the quantity and quality of data available. EMBs are an iterative process, which can incorporate data from additional measurement systems as they are implemented. An example of a simplified project plan for an EMB is shown in Table 1. Further iterations of this plan may be required for subsequent stages of the EMB, in order to improve data accuracy.
Table 1: Simplified project plan for stage 1 of a mine site EMB

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<td>Schedule tasks</td>
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<td>Prepare energy system mapping</td>
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<td>Identify systems to analyse</td>
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<td>Identify required data</td>
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<td>Conduct initial EMB analysis based on estimates and available data</td>
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<td>Construct version 1 of the EMB</td>
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<td>Analyse results to identify data and measurement gaps</td>
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<td>Refine analysis and install any additional metering</td>
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<td>Capture required energy and mass flow data</td>
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<td>Construct revised EMB</td>
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<td>Rectify any remaining data gaps and refine analysis</td>
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<td>Analyse results of implemented opportunities</td>
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<td>Collate revised results for public and government reporting</td>
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</table>

2.3 MASS FLOWS AND EFFECTS IN MINING

Energy requirements in mining are dictated by the requirement to excavate, break down, transfer and sort materials. Some of the mass flows in a mine site are continuous; others are batch processed. Accounting for mass ‘flows’ through a mine site is necessary to gain an effective understanding of overall mining energy use. The mass flows will depend on the type of mining operations that are conducted at the site. For example, overburden is a major mass flow in open pit operations but less significant in long wall mining. Of course, both operations may exist at the same site. Other significant mass flows include ores, which progress through various crushing stages, water, chemicals (flocculents, for example) and lubricants. Sections 3–6 discuss the types of data and analysis that may be required to develop EMBs for specific subsystems as part of a site EMB.

2.4 MAPPING THE ENERGY AND MASS FLOWS

The aim of the EMB is to improve understanding of the overall energy system and to provide insights into potential energy efficiency opportunities. The first step in an EMB is to investigate the various factors that influence site energy use and to map out these influences. Brainstorming the factors that influence mine site energy use and their interactions helps to determine the appropriate way to break down the EMB and prioritise the analysis.

7 Lubricants affect friction and wear losses, which can be significant for major items of equipment. These losses are described and summarised in JA Hawk & RD Wilson, ‘Tribology of earthmoving, mining, and minerals processing’ in Modern tribology handbook, volume one: principles of tribology, CRC Press, Boca Raton, 2001, ch. 35.
Energy and mass flow losses

Energy flow
- Waste Heat 95,609 GJ

Mass flow
- Combustion Exhaust Gases 11,983 T
- Process water (lost via evaporation) 438,000 kL (438,000 T)

Transfer
- Ore 622,853 T

Recovery
- Surface ore 499,988 T
- Underground ore 122,865 T

MINING OPERATIONS

Extraction
- Long wall or open pit

Mined Material 2,474,076 T

External Influences on Energy Use
- Weather
- Regulations and Standards
- Market Demand
- Mine design and characteristics
- Equipment Selection
- Employee attitudes and training
To map the system, start by considering:

- resource characteristics (the nature of the resource and surrounding geology, ore quality and grade)
- type of operation (open pit, long wall or underground)
- crushing and grinding requirements
- overall system configurations (such as the methods of excavation, haulage routes and ventilation equipment used at the site)
- climate and local water resources
- regulatory and environmental constraints
- factors that define quality of output (these might be described in key performance indicators (KPIs) used by the organisation)
- the factors which influence overall energy efficiency.\(^8\)

An initial energy use and mass flow mapping is illustrated in Figure 4. This figure is indicative of the outcomes of the Level 2 analysis, though some data (such as the mass flows of combustion exhaust gas) has been developed through more detailed analysis at Level 3.

Mapping site energy use can assist in identifying interactions between energy-using systems and processes at the site. Materials flows in a mine site should ideally be scheduled so that equipment use is maximised, minimising downtime and operating capital equipment as close as possible to their optimum point. For example, in an open pit mine blasting operations should loosen enough material to keep excavation equipment in continuous operation, haulage trucks should be fully loaded, and waiting times should be avoided. In turn, crushing and grinding rates should take into account the rate at which the feed can be supplied and the storage constraints of the run-of-mine pad.

### 2.5 DEFINING THE BOUNDARY OF THE EMB

Defining the boundary of the overall system and its subsystems is an important part of the EMB development process. As a minimum the EEO program requires the boundary of an EMB to cover 80% of a site’s energy use and all processes, not already included in the 80%, that use 0.1 PJ of energy or more per annum (see Section 1.1). Business benefits from the EMB will be maximised if the boundary includes all significant energy and material inputs and outputs and their interactions.

To set the boundary for the EMB, the first step is to determine how much energy is used at the site. In this process, site energy use should be broken down into key areas, processes (such as blasting, excavation, haulage, comminution) and energy sources, such as diesel, natural gas and electricity. Interactions and influences between areas and processes should then be examined to identify any processes that do not interact with or influence other processes. These processes may be left out of an EMB if coverage rules can be met.

For example, in Table 2 the requirement to assess 80% of coal mine site energy use is met by assessing each system in the table up to Materials handling electrical equipment. If none of the other systems use more than 0.1 PJ annually, the decision on which systems to include in the EMB might be based on the degree of interaction with the other systems being assessed. For example, it would be advisable to assess crushing (and possibly blasting) in conjunction with grinding operations, because each of these processes affects grinding energy use.

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8 For a comprehensive overview of mining operations, see the Society for Mining, Metallurgy and Exploration Inc., Mining engineering handbook, various editions (henceforth referred to as ‘SME Mining Handbook’).
Table 2: Boundary considerations for a hypothetical coal mine site

<table>
<thead>
<tr>
<th>Process</th>
<th>Percentage of energy use</th>
<th>Cumulative percentage</th>
<th>Inclusion in EMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grinding</td>
<td>40.15</td>
<td>40.15</td>
<td>Required</td>
</tr>
<tr>
<td>Ventilation</td>
<td>20.05</td>
<td>60.20</td>
<td>Required</td>
</tr>
<tr>
<td>Materials handling diesel equipment</td>
<td>11.69</td>
<td>71.89</td>
<td>Required</td>
</tr>
<tr>
<td>Materials handling electrical equipment</td>
<td>9.34</td>
<td>81.22</td>
<td>Required</td>
</tr>
<tr>
<td>Drilling</td>
<td>5.71</td>
<td>86.93</td>
<td>Required</td>
</tr>
<tr>
<td>Digging</td>
<td>5.44</td>
<td>92.37</td>
<td>Required</td>
</tr>
<tr>
<td>Crushing</td>
<td>3.01</td>
<td>95.38</td>
<td>Recommended</td>
</tr>
<tr>
<td>Separations</td>
<td>1.81</td>
<td>97.20</td>
<td>Recommended</td>
</tr>
<tr>
<td>Ancillary operations</td>
<td>1.42</td>
<td>98.62</td>
<td></td>
</tr>
<tr>
<td>Blasting</td>
<td>1.38</td>
<td>100.00</td>
<td>Recommended</td>
</tr>
</tbody>
</table>


Similarly, minor processes that are relatively difficult to assess may be a lower priority for the EMB than processes that are easily modelled. For example, office or residential buildings at a mine would be largely independent of other site operations and likely to use less than 0.1 PJ annually. Assessing building energy use might also require a different skills set, so these buildings could potentially be left out of the site EMB.

Once the overall EMB boundary has been set it may be practical to break the site down into the key energy using processes and develop separate EMBs for these areas (as in Section 4) so that detailed analysis can occur in parallel. This introduces a need for ongoing project management and systems engineering. Individual EMBs can then be integrated to give an overall site EMB, which allows interactions between key processes to be taken into account. This approach can be especially useful if different team members have responsibility for particular processes, such as haulage and comminution.

As the EMB develops and knowledge of energy and mass flows improves, the boundaries set for key energy using processes at the site may need to be adjusted and refined.

2.6 SPECIFIC SYSTEMS USED IN MINING OPERATIONS

Sections 3 to 6 provide guidance on the key considerations for the assessment of energy and mass flows associated with four key energy-consuming systems and elements within a mining operation. Each section provides a general overview of the system, examines factors that affect energy use, and illustrates the types of analysis that might be needed to develop an EMB for each system.

Example analyses are provided for these key systems, which are:

- comminution: crushing and grinding (Section 3)
- resource extraction, excavation and haulage systems (Section 4)
- compressed air systems (Section 5)
- ventilation systems (Section 6).

Sections 3 to 7 apply the steps following the planning stage and the overall mapping of energy and mass flows, namely steps 2 to 5 from Figure 3. Sections 3 to 6 also discuss energy efficiency opportunities associated with each of these systems, and present different modelling approaches. While the material may be familiar to some mine staff and to experienced engineers, these summaries of specific systems provide information that is not otherwise freely available and that may be of value to other mine staff.

In undertaking an assessment of the energy and mass flows associated with a mining operation, it is important to note that the EMB process is not conducted for the sole purpose of obtaining and collating data. The EMB is also used to help identify, investigate and quantify energy efficiency opportunities, providing associated efficiency benefits. Accordingly, potential opportunities for each system are briefly discussed.
3 COMMINUTION: CRUSHING AND GRINDING

Comminution—crushing and grinding processes used to reduce the size of ore bodies down to fine granules or powders—contributes around 30% of the energy use involved in mining operations, depending on the material properties of the ores being comminuted. Most of this energy use is consumed at the grinding stage.

Comminution energy use is dependent on the material being comminuted, the type of crushing or grinding equipment used, the material properties of the work surfaces, lubrication, and whether the comminution is performed in a wet or dry process. Establishing the energy baseline for comminution (Section 3.1) is not especially difficult, though modelling energy use and estimating savings from opportunities can be challenging, as discussed in sections 3.2 and 3.3.

3.1 EXAMINING THE BASELINE PERFORMANCE OF THE COMMINUTION CIRCUIT

Determining the baseline energy use for the comminution circuit is relatively straightforward if accurate energy sub-metering is in place. Each separate item of comminution equipment should be separately metered to ensure accuracy of data and enable optimisation of the whole circuit.

In the absence of metering, engineering calculations or computerised simulations can be used as an interim measure. Simple engineering calculations can provide a first-pass estimate which will indicate which energy and mass flows require more detailed examination and should be prioritised for metering.

For the EMB, throughput of product should also be recorded together with energy use. Ideally, product throughput would be measured frequently and compared with energy use over the same period. Measurements could potentially be made downstream, using load cells on trucks and other loading or materials transfer equipment. Over longer periods, throughput can be estimated based on the number of trucks or containers and average measured or calculated loads.

To provide a detailed understanding of the energy use of comminution equipment, the materials being processed should also be recorded. As discussed in Section 3.2, the properties of the feed product will directly influence energy use. Ideally, key performance indicators for comminution should account for the energy intensity of each material so as to provide a realistic measure as throughput as material properties change.*

3.2 MODELLING ENERGY USE RELATIVE TO THROUGHPUT

Comminution processes have very low energy efficiency, and the energy required increases as the particle sizes produced become smaller and as the feed rate into the equipment is reduced. In practice it is difficult to isolate the energy that is actually expended in comminution because energy is dissipated in various ways: as heat losses, through vibration, plastic deformation of materials, motion in directions normal to the crushing action, and lubrication and wear.

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* In practice, material properties can vary significantly for a given site by location and over time, so keeping track of these variations in KPIs may present practical difficulties.
3.2.1 Estimating energy use per tonne: Bond’s formula

The energy required for comminution can be estimated using the Bond equation, which takes into account material properties and the dimensions of the feed and the comminuted product. Specifically, the Bond ‘Third Theory’, Equation 1, estimates the energy required for comminution, W, as:

\[
W_b = 10W_i \left( \frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}} \right)
\]

Equation 1. Bond’s formula

Where:

• \(W_b\) is the work input measured in kilowatt hours per tonne
• \(W_i\) is the Bond work index in kilowatt hours per tonne (kWh/t), a parameter that is derived experimentally\(^\text{12}\) for different materials and tabulated in mining engineering handbooks
• \(F\) is the ‘passing size’ for 80% of the feed in microns
• \(P\) is the ‘passing size’ for 80% of the product in microns.\(^\text{13}\)

In this context, ‘passing size’ is the size of a screen that the particles would pass through. An 80% passing size indicates that 80% of a sample, by weight, exists as particles lower than the specified size.\(^\text{14}\)

Equation 1 can be used to provide a first-pass estimate of comminution energy requirements for crushing and grinding operations. Although the Bond work index has been tabulated for many common materials, it is advisable to determine the work index experimentally at each site, preferably in several locations.\(^\text{15}\)

Using the Bond formula makes it possible to model the effects of process requirement variations and how they affect system energy use. As an example, the effects of reducing feedstock particle size, by increased blasting or changed excavation regimes, can be balanced against the energy saved in the comminution process. Even though the work index will vary within a site, the bond formula is useful for modelling the sensitivity of energy use to various parameter values.

Since the energy requirement estimated by the Bond formula is based on the material properties, its value must also be adjusted to account for the equipment used and for specific circumstances. At a minimum, adjustments should be made for the type of mill, the dimensions/diameter of mills and for ‘fines’ finer than 70 microns.\(^\text{16}\) Other adjustments can also be made. Motor power requirements for crushing may be estimated as:

• 2 \(W_b\) for jaw crushers
• 1.6 \(W_b\) for primary gyratory crushers/hammer crushers
• 1.3 \(W_b\) for cylindrical crushers.\(^\text{17}\)

Comminution processes can also be modelled using computer simulations. Such simulations are a specialist area and are the topic of continuing research. Some research bodies and consultancies specialise in these areas.\(^\text{18}\)

\(^{12}\) Note that the Bond work index is often expressed in kilowatts per short tonne (2000 lb), which equates to kW/0.907t.

\(^{13}\) Tanaka & Kanda (see note 11).


\(^{16}\) The SME Mining Handbook (see note 9) provides a number of adjustments to the Bond formula for different types of equipment. ‘Fines’ are particles that are significantly smaller than the minimum dimension required.

\(^{17}\) Università di Bologna, Frantumazione, [Lecture notes, in Italian], available from http://serwebdicma.ing.unibo.it/labingmin/Didatticastudenti/ing.materieprime/Frantumazione%20%20dispense.pdf.

\(^{18}\) See, for example, Centre for Sustainable Resource Processing (CSRP), Delivering sustainable solutions to the minerals and metals industries, 2nd annual conference, CSRP, Kensington, 2008.
3.3 POTENTIAL EFFICIENCY OPPORTUNITIES IN COMMINUTION

Rocks are heterogeneous, and tend to have fractures and micro-cracks which can lead to large variations in mechanical properties. To break down rocks, comminution equipment applies a combination of compression, bending, cutting and impact. Energy is required to bring about elastic deformation, followed by plastic deformation and breakage once the ultimate strength of a material is exceeded. Energy required to break down materials tends to increase as particles become smaller. This is partly due to the fact that smaller particles will have a smaller number of micro-fractures.\footnote{Università di Bologna, Comminuzione (see note 12).}

Within comminution equipment it is not always clear how much stress is being applied to the feed. However, there are basic principles that can be used to identify opportunities. One important principle is that the presence of additional fines can significantly increase energy consumption. Being harder to break down than larger particles, fines tend to be displaced rather than breaking, dissipating energy. Another important principle is that larger particles can reduce the efficiency of finer grinding processes. Using classifiers to maintain a more consistently sized feed for the grinding process will typically provide efficiency gains.\footnote{Screening is discussed in detail in Chapter 25 of the SME Mining Handbook (see note 9).}

Reduction ratios for each successive crushing and grinding process can be adjusted so as to obtain feed size distributions that minimise energy use, bearing in mind overall cost and productivity.\footnote{Università di Bologna, Frantumazione (see note 18).} Crushing and grinding should be jointly optimised, as the size at which the change from crushing to grinding is made will affect costs and energy use.

Examining energy requirements during the design and procurement phases of mining projects is recommended. Optimising the type of comminution equipment used and the operating parameters can provide significant energy savings, which vary depending on the materials being comminuted. Using Equation 1 above, it is possible to model the relationship between energy use and particle size. Screens and filtering devices can reduce energy consumption of comminution machinery by making feed size more consistent.\footnote{Chapter 25 of the SME Mining Handbook (note 9) discusses classifying and screening in some detail.}

Another outcome of Equation 1 is the relationship between energy use, the material being comminuted and the comminution equipment used. Equipment charged with grinding media (balls or rods) is a case in point. The charge of metal balls used in SAG mills should be chosen in the right size for the desired task and feed material. Hardness is an important consideration, with a ball charge of harder material lasting longer.\footnote{Università di Bologna, Macinazione, [Lecture notes, in Italian], available from http://serwebdicma.ing.unibo.it/labingmin/Didatticastudenti/ing.materieprime/Macinazione\%20\%20dispense.pdf.}

For ball mills, it is advisable to avoid feed over 8–10 mm in diameter, as larger particles will significantly raise energy requirements. It can be useful to use a rod mill in an open circuit, then a ball mill in a closed circuit, with a classifier. Rod mills act on the largest particles, due to their geometry, and consequently limit production of fines.\footnote{Università di Bologna, Macinazione (see note 26), and the SME handbook (see note 9), which discusses open and closed circuit as well as screening methods.} Cylindrical mills are also relatively efficient, partly because they operate almost purely in compression, and produce particles of a consistent size.\footnote{SME Mining Handbook, ch. 25 (see note 9).}

When the ball charge wears well, the spheres become polygons of 8–12 sides with slight concavities on the faces. If breakage occurs and the balls become discs, semicircles or irregular shapes, the ball charge may be of poor quality. Grinding performance and efficiency will be affected.\footnote{Università di Bologna, Macinazione (see note 26).} Applied stresses will vary depending on the area over which the forces are applied, so a flat disc applies dramatically lower stresses to feed particles than the original sphere. Liner material choice can also be important for grinding optimisation, since it affects the stress applied to the feed and the extent of wear losses.

\footnote{19 Università di Bologna, Comminuzione (see note 12).}
\footnote{20 Screening is discussed in detail in Chapter 25 of the SME Mining Handbook (see note 9).}
\footnote{21 Università di Bologna, Frantumazione (see note 18).}
\footnote{22 Chapter 25 of the SME Mining Handbook (note 9) discusses classifying and screening in some detail.}
\footnote{23 Università di Bologna, Macinazione, [Lecture notes, in Italian], available from http://serwebdicma.ing.unibo.it/labingmin/Didatticastudenti/ing.materieprime/Macinazione\%20\%20dispense.pdf.}
\footnote{24 Università di Bologna, Macinazione (see note 26), and the SME handbook (see note 9), which discusses open and closed circuit as well as screening methods.}
\footnote{25 SME Mining Handbook, ch. 25 (see note 9).}
\footnote{26 Università di Bologna, Macinazione (see note 26).}
Other important comminution parameters or attributes affecting energy use include:

- dimensions of the feed material, and the extent of micro-fractures introduced by previous rounds of crushing, grinding or blasting
- reduction ratio, \( n = \frac{F_{80}}{P_{80}} \), noting that reducing ‘fines’ will reduce the energy required
- loading, as a percentage of total volume (low loading will typically raise energy use per tonne of product)
- The mass of material being moved during the comminution process, and the extent to which this motion is against gravity (cylindrical crushers\(^{27}\) are relatively efficient, partly because they do not raise a heavy ball charge and feed against gravity; similarly, vertical mills operate like ball mills but give lower energy consumption because only the internal part of the mill rotates).\(^{28}\)

As noted in Section 3.2, theoretical approaches to analysing comminution energy use are useful for modelling the effects of process changes or comminution circuits. Such modelling is also useful for gauging the sensitivity of energy use to changes in process and material parameters. Laboratory and/or field trials will generally be necessary to confirm theoretical predictions.

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27 Similar principles apply to high-pressure grinding rolls.
28 Università di Bologna, Macinazione (see note 26).
4 MATERIALS HANDLING: RESOURCE EXTRACTION, EXCAVATION AND HAULAGE SYSTEMS

Materials handling in mine sites involves three distinct phases:

- **Resource extraction.** Defined as operations that dislodge resources from the resource deposit.
- **Excavation.** Operations that pick up and transfer these dislodged materials into the haulage stage.
- **Haulage.** The movement of excavated materials to the resource processing area of the mine.

Sections 4.1 to 4.4 discuss how a systems-engineering approach can be used to develop an effective EMB process that accounts for interactions between successive stages of materials handling operations.

4.1 EXAMINING THE BASELINE PERFORMANCE OF EXCAVATION AND HAULAGE SYSTEMS

Establishing the baseline energy use and material flows required for an EMB essentially involves collating fuel consumption data for the trucking fleet and excavators over a sufficient period of time to account for variations in fuel use and loading rates. For resource extraction systems, electricity consumption data may also be required.

Potential sources of variation include climatic conditions, which can affect operating hours, road surfaces and load density, changes in haulage routes and gradients, and any regular seasonal changes in market demand. An effective EMB process would produce an energy model that enables energy use forecasts to be adjusted so that the savings from opportunities can be estimated accurately. Section 1.3 of the *Energy Savings Measurement Guide* discusses adjustment of the opportunity baseline in more detail.

4.2 MODELLING ENERGY AND MASS FLOWS

Resource extraction (Section 4.2.1), excavation and mucking equipment (Section 4.2.3) have different requirements from haulage trucks, which are discussed in Section 4.2.4.

4.2.1 Resource extraction

Resource extraction encompasses the broad range of operations that remove the resource from the original deposit. The specific equipment and techniques required for different resource types and mine layouts will differ, but approaches to energy analysis may be considered analogous.

When considering the energy requirements of this stage of operations, a systems engineering approach is useful to compare the energy efficiency of different extraction techniques and machinery. Boundaries for the subsystem analysis may consider the energy required to remove the material from the deposit, and move it to the point where it can be excavated or transported. However, the condition of the extracted material (size distribution, density and material composition) affects energy use in excavation, haulage and comminution. For example, larger particles will require more energy during comminution. Taking a systems engineering approach to an EMB incorporating these interactions can minimise materials handling energy use. Variations in the grades and distributions of ore deposits complicates this systems engineering task.

4.2.2 Example of resource extraction principles

Consider an ore mining operation that has been operating for a number of years, where a new ore deposit is discovered and engineers are considering how to most efficiently extract this material. Since the mine is mature, there are two separate resource extraction machines already available on site that could be used.

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29 Fundamental theories in this section have been taken from Chapter 9 of the SME Mining Handbook (see note 9).
Option 1—blasting
By using estimates of the size and shape of the new deposit, engineers can determine a drilling pattern which allows estimates of total drilling distance required. The energy required to drill these holes can then be estimated using tabulated estimates from industry publications combined with on-site measurement and survey data. Since the mass of explosive is known, the energy content can be calculated. Since blasting operations are difficult to control, the parameters of the resource at the boundary of this system include variables to describe the size distribution of dislodged particles, but also a term describing the distribution of these particles through the materials being blasted. Further, as the particle size distribution widens, account could be taken of the increased energy requirements in the comminution stages, as described by Equation 1 in Section 3.2.1.30

Option 2—shearing
From earlier operations a shearing machine is available that would be suitable for the task. This machine generates material for excavation with a higher specific energy (measured in joules per tonne of material), but with more uniformly small particles and with less scattering of material than blasting.

Energy use comparison
Using energy and material flow data it is then possible to compare the energy intensities of the two operations. In each case, this will be the sum of the energy use per tonne of extraction and excavation and haulage, plus the energy use through comminution. Overall energy use will vary greatly for different sites, deposits and equipment, so as with comminution field trials would be needed to confirm theoretical predictions.

4.2.3 Excavation and mucking equipment
To understand how energy is used in excavation requires analysis of the material that is being loaded and how this determines the force required to scoop, lift and transfer loads. Blasting methods will affect both energy use and mass transfer rates by changing the density of the material that is moved, its hardness and its resistance to the forces applied by the teeth of the shovel. In turn, blasting will also affect wear rates by changing the size and shape of the shovelled material.

For large items of excavation equipment it may be worth developing an energy use model that analyses the dynamic forces required to move loads in relation to the angles of the shovel arms, rotation angles and the movement of the shovel base. The use of such analysis, possibly combined with direct measurement of forces on shovel teeth using load cells, may suggest potential changes to blasting techniques. Analysing the forces applied to the shovel may also provide useful data for maintenance purposes.31

4.2.4 Haulage trucks
In open pit mining operations, the trucking of overburden and ores is one of the major energy uses, and is dependent on the geology of the site, the density of the load, road surfaces and gradients. Although the Energy–Mass Balance: Transport guidance document developed by the EEO program discussed vehicle models in general, the surfaces, gradients, safety constraints and loading patterns in mining operations require specific consideration.

Haulage truck energy efficiency will depend on scheduling and loading rates, vehicle efficiency (design and maintenance), driving practices, and the gradient and surface features of haul roads. Energy use will also be affected by the nature of the material that is loaded. For example, irregularly sized and shaped overburden will tend to cause variation in load densities and energy use per tonne of overburden transported. Loading management and scheduling are an important component of energy efficiency for haulage operations. Section 4.3 presents a simplified energy–mass balance model for a mining haulage truck.

30 Using classifiers can potentially reduce energy requirements in these circumstances; SME Mining Handbook, ch. 25 (see note 9).
4.3 SIMPLIFIED ENERGY USE MODEL FOR A MINING HAULAGE TRUCK

Energy use should be examined separately for each model of truck, as performance will vary. This section discusses a first-pass approach that can be used to estimate energy use for a typical mining truck, using data for a Caterpillar 789C truck\(^\text{32}\) with a dual slope body, assumed to be carrying a material with an average density of 2.5t/m\(^3\). Having an energy use model, even a simple one, enables energy efficiency opportunities to be investigated relatively easily. If the energy use model estimates that a project will have significant benefits, field trials and/or additional data analysis may be warranted. Energy use models for mine haulage can potentially be developed as part of a representative assessment approach.

Table 3: Estimating the energy used by a haul truck for an average loading/unloading cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross machine operating weight</td>
<td>Maximum operating weight (Manufacturer specifications)</td>
<td>317.50</td>
<td>t</td>
</tr>
<tr>
<td>Vehicle weight</td>
<td>Chassis Weight + Body Weight + Liner + sideboards + tail extension = 102.3t + 27t + 11.5t</td>
<td>140.8</td>
<td>t</td>
</tr>
<tr>
<td>Load</td>
<td></td>
<td>175.00</td>
<td>t</td>
</tr>
<tr>
<td>Loading capacity</td>
<td>Manufacturer specifications, struck</td>
<td>73.00</td>
<td>m(^3)</td>
</tr>
<tr>
<td>Gross vehicle weight (GVW)</td>
<td>Vehicle Weight + (Loading Capacity x Density) = 141t + (73m(^3) x 2.4t/m(^3))</td>
<td>316.00</td>
<td>t</td>
</tr>
<tr>
<td>Weight on rear axle (loaded), W_{rl}</td>
<td>67% of GVW (Manufacturer specifications)</td>
<td>211.72</td>
<td>t</td>
</tr>
<tr>
<td>Weight on rear axle (unloaded), W_{ru}</td>
<td>53% of GVW (Manufacturer specifications)</td>
<td>167.48</td>
<td>t</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>Tabulated value, whereby 10 kg/t equals 1%. Assume a relatively smooth, maintained and watered dirt road</td>
<td>3.5%</td>
<td></td>
</tr>
<tr>
<td>Traction coefficient</td>
<td>Firm earth, tabulated</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Percentage gradient</td>
<td>Rise / Length = 72/1600</td>
<td>4.5%</td>
<td></td>
</tr>
<tr>
<td>Effective gradient</td>
<td>Actual Percentage Grade + Rolling Resistance</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>Angle of ascent (θ)</td>
<td>tan(^{-1}) (percentage gradient)</td>
<td>4.57 degrees</td>
<td></td>
</tr>
<tr>
<td>Hauling time</td>
<td>Time taken to transport the load to the dumping point, determined from speed and distance</td>
<td>360</td>
<td>secs</td>
</tr>
<tr>
<td>Loading time</td>
<td>Time taken for the excavator to load the truck</td>
<td>90</td>
<td>secs</td>
</tr>
<tr>
<td>Manoeuvring and dumping time</td>
<td>Time taken to position the truck and unload</td>
<td>27</td>
<td>secs</td>
</tr>
<tr>
<td>Return time (empty)</td>
<td>Time taken to transport the load to the dumping point, determined from speed and distance</td>
<td>138</td>
<td>secs</td>
</tr>
<tr>
<td>Cycle time</td>
<td>Hauling + Loading + Manoeuvring and Dumping + Return Time</td>
<td>615</td>
<td>secs</td>
</tr>
<tr>
<td>Power required</td>
<td>GVW x Effective Gradient</td>
<td>25.28</td>
<td>t</td>
</tr>
<tr>
<td>Rimpull (R)</td>
<td>See Figure 5 and notes for explanation of this step</td>
<td>25.28</td>
<td>t</td>
</tr>
<tr>
<td>Usable rimpull (R_{us})</td>
<td>R x W_{rl} x cosθ, where θ is the angle of the slope from the horizontal</td>
<td>16.88</td>
<td>t</td>
</tr>
<tr>
<td>Usable power</td>
<td>W_{rl} x Traction Coefficient</td>
<td>116.45</td>
<td>t</td>
</tr>
<tr>
<td>Torque at wheels</td>
<td>Rimpull x gravity x wheel radius</td>
<td>281.28</td>
<td>kNm</td>
</tr>
</tbody>
</table>

\(^{32}\) While the example uses a specific haulage truck, the fundamentals of this section will apply to any haulage truck.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>From gradeability graph (see Figure 5)</td>
<td>16</td>
<td>km/hr</td>
</tr>
<tr>
<td>Power required</td>
<td>Formula 5.1, p. 122</td>
<td>654.27</td>
<td>kW</td>
</tr>
<tr>
<td>Wheel rotations/second</td>
<td>Vehicle velocity ([\text{m/s}] / [\pi \times \text{wheel outside diameter}])</td>
<td>0.416</td>
<td>radians/second</td>
</tr>
<tr>
<td>Power from wheel torque</td>
<td>(2\pi \omega \times (\text{Torque at Wheels [kNm]}))</td>
<td>735.38</td>
<td>kW</td>
</tr>
<tr>
<td>Power from rimpull</td>
<td>(= \sqrt{\text{(km/hr)} \times \frac{1000}{3600} \times \frac{\text{m/s}}{\text{km/hr}} \times R \times 1000 \times \frac{\text{kg}}{\text{t}} \times g \times \frac{\text{m}}{\text{s}^2} \times \frac{1}{1000} \times \frac{\text{kW}}{\text{W}}})</td>
<td>735.38</td>
<td>kW</td>
</tr>
<tr>
<td>Engine output power</td>
<td>Power from rimpull/0.95, assuming 95% transmission efficiency</td>
<td>774.08</td>
<td>kW</td>
</tr>
<tr>
<td>Fuel input power, (P_f)</td>
<td>Power/0.25, assuming 25% efficiency at wheels</td>
<td>2941.51</td>
<td>kW</td>
</tr>
<tr>
<td>Fuel input per second</td>
<td>Assuming a calorific value of 38.6MJ/L, Fuel Input</td>
<td>0.076</td>
<td>L diesel/s</td>
</tr>
<tr>
<td>Fuel consumption (loaded cycle)</td>
<td>Fuel Input Per Second (\times) Haul Cycle Time</td>
<td>27.434</td>
<td>L diesel</td>
</tr>
<tr>
<td>Fuel consumption (loading)</td>
<td>Fuel Input Per Second (\times) Loading Cycle Time</td>
<td>3.060</td>
<td>L diesel</td>
</tr>
<tr>
<td>Fuel consumption (dumping)</td>
<td>Fuel Input Per Second (\times) Dumping Cycle Time</td>
<td>2.058</td>
<td>L diesel</td>
</tr>
<tr>
<td>Fuel consumption (unloaded return)</td>
<td>Recalculated model using gradeability curve, with an effective gradient of 2% (rolling resistance reduces effective gradient on descent) rimpull of 1.9 t, velocity of 44 km/h</td>
<td>2.02</td>
<td>L diesel</td>
</tr>
<tr>
<td>Fuel consumption, total cycle</td>
<td>Sum of fuel consumption over the four cycles</td>
<td>34.57</td>
<td>L diesel</td>
</tr>
<tr>
<td>Fuel tank capacity</td>
<td>(\text{Fuel Tank Capacity/Fuel Consumption per Cycle})</td>
<td>3222.00</td>
<td>L diesel</td>
</tr>
<tr>
<td>Number of cycles per tank</td>
<td>(\text{Fuel Tank Capacity/Fuel Consumption per Cycle})</td>
<td>93.12</td>
<td>cycles</td>
</tr>
<tr>
<td>Aero resistance</td>
<td>(= \frac{1}{2} C_d \rho A v^3 \times \frac{1}{1000} \times \frac{\text{[kW]}}{\text{W}})</td>
<td>2.24</td>
<td>kW</td>
</tr>
<tr>
<td>KPI: L/t</td>
<td>(= 0.2)</td>
<td>0.2</td>
<td>L/tonne</td>
</tr>
<tr>
<td>KPI: L/100km</td>
<td>(= 2160.6)</td>
<td>2160.6</td>
<td>L/100km</td>
</tr>
<tr>
<td>KPI: L/100km per tonne of GVW</td>
<td>(= 6.84)</td>
<td>6.84</td>
<td>L/100km/tonne of GVW</td>
</tr>
</tbody>
</table>

Data for this table are from Caterpillar, 789C Mining Truck, available from [www.cat.com](http://www.cat.com); C Bise, Mining engineering analysis, 2nd edition, Society for Mining, Metallurgy and Exploration Inc. (SME), Littleton, 2003, ch. 9; R Tatiya, Surface and underground excavations: methods, techniques and equipment, Taylor & Francis, 2005, ch. 7.
Calculations in Table 3 rely on a number of critical assumptions, including the overall fuel to wheel energy efficiency, the density of the load, and transmission efficiency. Acceleration and deceleration during the cycle are neglected, and the energy used when descending unloaded has been estimated using gradeability curves (Figure 5). This model could be refined to take into account acceleration, deceleration, braking, gear ratios and the torque and power curves for the specific truck engine.\footnote{33} While this simple model assumes constant engine efficiency, in practice efficiency will vary depending on engine speed and load.\footnote{34}

\textbf{Figure 5: Gradeability/speed/rimpull curve (CAT 789C Mining Truck)}


To use this graph, the first step is to find the point where the gradient line and the gross vehicle weight meet. This height, transposed to the left-hand axis, gives the rimpull.

To determine vehicle speed, a horizontal line is drawn from the rimpull value to its intersection with the curve representing the highest gear. The point on the bottom axis directly below this intersection will give the vehicle speed.


\footnote{34} Engine combustion efficiency analysis is discussed in Bosch, Automotive handbook, 7th edn, Robert Bosch GmbH, Plochingen, 2007. This volume also contains information on transmission systems, vehicle components, hybrid drives, sensors and measurement systems.
In some cases the most practical way to improve a vehicle model may be to refine the underlying assumptions and data. Some of the missing data may be available from manufacturers. Analysis of an organisation’s existing energy records and transport tasks records may help to fill some of the gaps in the vehicle energy model, or to check and refine answers derived from other methods.

Fuel use in haulage is impacted by many factors. As a result, determining the effect on energy use of one particular factor is likely to require taking account of other influences, using methods such as regression analysis, controlled experiments or in-service trials.

Data which may be available and useful for quantifying and refining the vehicle energy model may be available from several sources, including:

- fuel supplier invoices and electronic data files
- paper records
- vehicle on-board management systems (engine management systems, downloaded in real time or when a vehicle is at a depot)
- on-board load cell measurements
- telematic devices (that transmit vehicle management system and GPS data in real time).

### 4.4 POTENTIAL ENERGY SAVING MEASURES

Using the model provided in Section 4.3 enables the benefits of various types of energy saving opportunities to be conveniently estimated, as discussed in sections 4.4.1 to 4.4.5.

#### 4.4.1 Reducing vehicle weight

Looking at the parameters of the model in Table 3, it is apparent that more than 40% of the GVW is the weight of the vehicle itself. This means that there is the potential to improve fuel efficiency by reducing vehicle bodyweight from the current 141 tonnes. Using the model, it can be estimated that a theoretical reduction in the weight of the 27 tonne body [tray] by 25% (by using thinner, higher strength steel, for example) could provide energy savings of around 2.3%.

#### 4.4.2 Payload management

Haulage trucks are most efficient when fully loaded. Optimising loading can provide significant efficiency improvements. Reducing loading to 80% of the maximum and increasing speed according to the gradeability curve increases fuel use per tonne by 20%. Loading the truck at 90%, the model suggests that fuel use is still 9% greater per tonne than with a full load. Table 4 presents the results of some basic sensitivity analysis performed using the model and gradeability curves, which suggest that limiting trucks to the maximum loaded velocity on the hauling leg could reduce the sensitivity of fuel use to loading.

<table>
<thead>
<tr>
<th>Loading, % of maximum</th>
<th>Load, t</th>
<th>Load, % of GVW</th>
<th>Fuel use, L/t of load, allowing speed increase</th>
<th>Increase in L/t, c.f. full load, higher speed</th>
<th>Fuel use, L/t of load, at full load speed</th>
<th>Increase in fuel use in L/t, c.f. full load, full load speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>140</td>
<td>50</td>
<td>237</td>
<td>20%</td>
<td>224</td>
<td>13%</td>
</tr>
<tr>
<td>85</td>
<td>149</td>
<td>51</td>
<td>226</td>
<td>14%</td>
<td>216</td>
<td>9%</td>
</tr>
<tr>
<td>90</td>
<td>158</td>
<td>53</td>
<td>215</td>
<td>9%</td>
<td>209</td>
<td>6%</td>
</tr>
<tr>
<td>95</td>
<td>166</td>
<td>54</td>
<td>207</td>
<td>5%</td>
<td>203</td>
<td>3%</td>
</tr>
<tr>
<td>100</td>
<td>175</td>
<td>55</td>
<td>198</td>
<td>0%</td>
<td>198</td>
<td>0%</td>
</tr>
</tbody>
</table>
Figure 6 illustrates this result, showing that, based on this simple model, fuel use per tonne of load is considerably less sensitive to loading rates if vehicle speed is constrained. Given that kinetic energy is proportional to the square of velocity this result from the simplified model makes intuitive sense. However, since engine efficiency varies with engine speed, load and gearing, this result would require confirmation from more detailed analysis or field trials. Productivity effects of this change should also be taken into account. Note that more consistent haulage speeds could also reduce queuing at the loader, potentially providing productivity benefits.

**Figure 6: Sensitivity analysis: Effect of velocity constraints on fuel intensity**

Optimisation of excavation and loading will typically provide both energy efficiency and productivity gains. At the very minimum the number of trucks per loader should be determined so as to avoid queuing at the loader while keeping the excavator employed:

\[
\text{Number of trucks} = \frac{\text{Cycle time}}{\text{Loading time}}
\]

Due to changing vehicle weight, cycle times will vary with loading unless a strict speed limit is followed on the haulage leg. An average value should therefore be used to determine the number of trucks required. Rounding up the result to a higher number of trucks will tend to raise productivity at the expense of some queuing.\(^{35}\)

If blasting procedures produce inconsistently sized fragments, then this will affect load density and therefore truck loading. In-pit primary crushing may help to make the load density more consistent in some circumstances, facilitating load management. Where loads are of relatively consistent density, adjusting shovel dimensions to truck capacity may help to accelerate loading times.\(^{36}\)

Scheduling of mining haulage systems must also take into account safety, blasting schedules, traffic levels on haul roads and maintenance needs. Models for scheduling of loading and haulage have been developed that are significantly more complex than what can be presented here. Computerised simulations can also be employed to optimise load management and improve the consistency of operation.\(^{37}\)

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\(^{35}\) See D Asfahl, C Moore et al., *Construction equipment management for engineers, estimators, and owners*, CRC Press, 2006, ch. 5.

\(^{36}\) Asfahl, Moore et al. (see note 38).

4.4.3 Operational improvements: maintenance, tyres and driver training

Vehicle utilisation and driving practices can provide fuel efficiency benefits that are equivalent to, and sometimes greater than, improved engine technologies, often at lower cost. For example, transport research suggests that aggressive driving can raise fuel consumption by around 30%, poor tuning increases fuel consumption by 4–40%, while suboptimal tyre inflation and clogged air filters can raise fuel consumption by up to 3% and 10% respectively. These principles are equally applicable to mine haulage.

Suboptimal maintenance procedures can significantly affect the safety and energy efficiency of haulage trucks. An obvious example is that poorly maintained brakes will tend to encourage additional engine braking, increasing fuel consumption and causing additional wear on the transmission system. Optimised lubrication will tend to reduce friction losses within the engine and transmission while reducing unscheduled downtime.

Driver training has been estimated to improve fuel economy by up to 30% in freight operations, as noted above. The energy use model in Section 4.3 suggests that training of both drivers and shovel operators so as to optimise loading could yield energy savings of around 10%. In addition, training to encourage more consistent haulage speeds could provide further energy savings. Driver training for energy efficiency could also help to reduce maintenance and spare parts costs. Energy efficient driving tends to reduce rapid changes in velocity, thereby lowering stresses on vehicle components.

Tyre inflation levels can change the amount of rolling resistance and the traction coefficient. Maintaining tyre pressures at the correct level for existing haulage roads can provide significant benefits which can potentially be estimated using an energy use model. Truck manufacturers may be able to provide advice on tyre selection and inflation under different conditions.

4.4.4 Vehicle selection and haul road design

Developing an energy use model for haulage can help to evaluate alternative designs when purchasing new trucks. For example, a model can be used to objectively estimate the benefits of lighter body designs, larger payloads or more advanced payload or fleet management systems. Energy models may also help to evaluate the benefits of hybrid drive systems. As mines dig deeper pits to exploit more marginal resources, haulage roads could potentially become steeper. Hybrid trucks could provide significant advantages on steep haul routes by capturing some of the energy losses on descent.

When establishing new pits or expanding existing ones, haul road design and maintenance can potentially provide energy savings. An energy use model can also be used to predict the change in fuel consumption as a pit deepens, including the effect of increased distance, potential changes in gradient and any changes in road surface. For example, watering of haul roads will affect rolling resistance and energy consumption as well as reducing airborne dust particles. Potential savings can be estimated using an energy model, though paybacks from improved road design and maintenance may be relatively long for established sites.

4.4.5 Aerodynamic resistance considerations

Aerodynamic resistance is proportional to the cube of vehicle velocity, so at the loaded velocity of 16 km/h from the gradeability curve aerodynamic resistance represents an estimated 2.2 kW, only 0.3% of estimated engine power. By comparison, at the maximum loaded speed of 65 km/h, aerodynamic resistance would rise to an estimated 150 kW, 11% of maximum engine power output for this truck, assuming a drag coefficient of 0.9. During the cycle modelled in Table 3, aerodynamic resistance is a major source of energy losses only on the downhill return leg, where this resistance is desirable as it counteracts gravitational acceleration. Note that aerodynamic effects have not been included in the fuel use calculation, but have been calculated for reference.

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39 Hybrid drive systems are described in the Bosch Automotive handbook (see note 37).
40 For a discussion of the aerodynamic efficiency of mining haulage trucks, see Ghojel (note 36).
5 COMPRESSED AIR SYSTEMS

Compressed air systems are an important source of power for mining operations. They have been used to blast coal and are also used to operate stopers, mucking machines and other equipment requiring pressured air flows in both coal and mineral ore mining applications. Section 5.1 provides an overview of air compressor types for staff who are unfamiliar with these systems.

5.1 TYPES OF AIR COMPRESSORS

There are two broad types of air compressors used in industrial applications. Positive displacement air compressors achieve compression by admitting successive volumes of air into a closed space and then decreasing the volume. Dynamic air compressors achieve compression by the mechanical action of rotating vanes or impellers imparting velocity and pressure to the air.

Positive displacement air compressors are suitable for applications where a large pressure increase, but a smaller volume of gas, is required and dynamic compressors are suitable for applications in which a higher volume of compressed air, but smaller pressure increase, is required.

Reciprocating and rotary screw compressors use a change in volume to achieve compression and are the two most common types of positive displacement compressors. In mining applications the reciprocating compressor is the most common type of air compressor used. Most reciprocating compressors are single acting machines that use a piston action to compress air. Advantages of reciprocating compressors include their high efficiency and excellent part-load performance, as well as the large range of sizes and pressures available.

Centrifugal compressors are the most common form of dynamic air compressor, which use velocity change, acceleration, followed by deceleration and static pressure recovery to achieve air compression. The key advantages of centrifugal compressors are that they offer simplicity of design, few moving parts, large clearances and minimal vibration. However, they do exhibit poor part-load performance and are best used in base-load applications.

Sections 5.2 and 5.3 present a basic discussion of how to measure compressor efficiency, measure compressor performance and investigate opportunities for compressed air systems.

5.2 MEASURING COMPRESSOR EFFICIENCY

The baseline energy efficiency of an air compressor can be measured using the free air delivery test. Using the experimentally derived efficiency values allows comparison with the manufacturer’s design or standard values.

The test is based around the properties of expanding air as it passes through a nozzle and uses the test circuit shown in Figure 7.

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43 Petchers, ch. 30 (see note 45).
45 Petchers, ch. 30 (see note 45).
46 Kreith, Timmerhaus, Lior, Shah, Bell et al. (see note 47).
47 Petchers, ch. 30 (see note 45).
Once the test equipment is in place, the compressor can be run until steady-state is reached, with stable temperature and receiver pressure. Once the system is stable, measurements for the variables listed in Equation 2 can be recorded. It is recommended to run the compressor at part-load settings as well, to observe and graph the relationship between energy use and compressor loading. Although the relationship between compressor loading and energy efficiency is well known and often defined in compressor documentation, these tests may still improve the energy manager’s understanding of the specific compressor system and its condition. In general, compressor curves describe the compressor operation under ideal, controlled conditions. Further testing while connected to the other parts of the compressed air system may reveal operational flat spots that would not be resolved through theoretical analysis alone.

Used in conjunction with equations 3 and 4, the volumetric flow rate equation can be used to model a number of different system parameters and potential energy savings from changes to initial conditions.
5.2.1 Volumetric flow rate—Equation 2

Equation 2 calculates the volumetric flow rate.

\[
Q_f = \frac{k\pi}{4} d^2 \frac{T_1}{p_1} \left[ \frac{2(p_3 - p_4)(p_3 R_a)}{T_3} \right]^{\frac{1}{2}}
\]

Equation 2. Volumetric flow rate

Where:

- \(Q_f\) = free air delivered, in cubic metres per hour
- \(k\) = flow coefficient, assumed equal to 1
- \(d\) = nozzle diameter in metres
- \(T_1\) = inlet temperature in kelvin (K)
- \(p_1\) = inlet pressure in pascals
- \(p_3\) = pressure before nozzle in pascals
- \(T_3\) = temperature before the nozzle
- \(p_3 - p_4\) = pressure drop across the nozzle
- \(R_a\) = gas constant: 287 J/kg.K

The isothermal power required to deliver a specific pressure and flow rate can be calculated using Equation 3. This theoretical result can then be compared to observed energy use (by metering the compressor) to determine the compressor efficiency.

5.2.2 Isothermal power—Equation 3: example

\[
P_{iso} = p_1 Q_f \ln r
\]

Equation 3. Isothermal power in kilowatts

Where:

- \(P_{iso}\) = isothermal power (theoretical power required in kilowatts)
- \(p_1\) = absolute intake pressure (kPa)
- \(p_2\) = receiver pressure (kPa)
- \(Q_f\) = free air delivered (m³/s⁻¹)
- \(r\) = pressure ratio \((p_2/p_1)\)

Using this relationship, where:

- \(p_1 = 101.3\) kPa (atmospheric)
- \(p_2 = 506.5\) kPa (equipment requirement)
- \(Q_f = 0.4\) m³/s⁻¹ (equipment requirement)
- \(r = p_2/p_1 = 506.5/101.3 = 5\)

Gives:

\[
P_{iso} = 101.3\ kPa \times 0.4\ m^3/s^-1 \times \ln (5)
\]

\[
= 65\ kW
\]

Equation 3 represents the theoretical minimum power required to generate compressed air at the required flow rate and pressure. By manipulating this relationship it is possible to determine how changes in pressure and flow requirements can reduce energy consumption. As an example, items of equipment with lower air flow requirements can be substituted and the effects on power requirements can be modelled.
To compare the isothermal efficiency to the actual efficiency, the electricity use of the motor can be metered. Measured values can then be adjusted for the motor efficiency:

\[ P_{\text{motor}} = \text{compressor power (voltage x current across the motor terminals in kilowatts)}. \]

\[ P_{\text{motor}} = 100 \text{ kW}. \] If motor efficiency (\( \eta_{\text{comp}} \)) is 85% (consult manufacturer information) then compressor power (\( P_{\text{comp}} \)) is 85 kW. Motor efficiency could potentially be adjusted based on manufacturers’ curves.

5.2.3 Compressor efficiency—Equation 4: example

Then, compressor efficiency (\( \eta_{\text{comp}} \)) is given as:

\[ \eta_{\text{comp}} = \frac{P_{\text{iso}}}{P_{\text{comp}}} \times 100 \]

Equation 4. Compressor efficiency

\[ \eta_{\text{comp}} = \frac{65 \text{ kW}}{85 \text{ kW}} \times 100 = 76\% \]

5.2.4 Equation 2—variables in energy savings

Using this relationship, in conjunction with the test equipment detailed in Figure 7, it is possible to determine the flow rate from the compressor.

In energy efficiency terms, however, the most valuable outcome from this relationship is the ability to model how changes in variables influence energy requirements.

Substituting Equation 2 into Equation 3:

\[ P_{\text{iso}} = \ln \left( \frac{k \pi d^2 T_1}{4} \right) \left( \frac{2(p_3 - p_4)(p_3 R_4)}{T_3} \right) \]

Equation 5. Relationship between receiver pressure, inlet temperature and isothermal power

By altering the variables in Equation 5 it is possible to model their influence on energy use. The examples below model the influence of ambient (inlet) temperature on compressor energy use and the effect of reducing inlet air temperature on isothermal power requirements.

Figures 8 and 9 illustrate the relationship between the variables that can be controlled by a compressed air system manager and the power consumption by the air compressor.

In both cases, (inlet air temperature and receiver pressure) modifications that lower these values will reduce the overall energy use.

Modifications that lower inlet temperature could include:

- shielding the compressor housing from direct sunlight
- ensuring adequate ventilation and heat rejection from compressor housings.

Compressed air system operators are also able to alter the receiver air pressure, with significant changes to energy efficiency as a result. The relationship between receiver air pressure and isothermal energy use is modelled in Figure 9. All other variables remain fixed.

However, while lowering receiver air pressure will also lead to energy savings, care must be taken to ensure that equipment operation is not impacted by these changes.
5.2.5 Energy efficiency opportunities—variable speed drives

Variable speed drives (VSD) are electromechanical devices used to control the speed of electric motors. VSDs offer a number of advantages over traditional speed-controllers, particularly energy efficiency advantages.

For air compressors, most energy savings benefits will be realised through better management of partial loads and reduced in-rush current at start-up. Actual energy savings will vary between applications, but these can be estimated by observing compressor operations and using the drive-curve supplied by the manufacturer.
5.2.6 Variable speed drives energy savings example—start-up

An estimate of the energy savings of installing a VSD can be derived by estimating the available energy savings per start-up, then multiplying this by the average number of start-ups per unit time. A current and voltage data logger placed across the terminals of the motor will supply the necessary information. In a time series, start-up operations will appear as spikes in current. The curve for each start-up can then be compared to the curve supplied by the VSD manufacturer. The difference between the integrals of current over time (the area under the current versus time curve) multiplied by voltage for each of the curves will estimate the energy savings of each start-up operation.

Figure 10: Comparison of VSD and fixed speed drive start-up power

In Figure 10 above, the energy saving is represented by the area between the curves with and without a VSD.

For more detail on calculating energy savings from time series data, see Section 9.1, which describes how to estimate areas under curves using the trapezoidal rule.

5.2.7 Compressor maintenance

All compressors contain moving parts operating in a hostile environment of intermittent loading, elevated and changing temperatures and very high pressures. As such, compressor energy use can be minimised by adhering to recommended maintenance schedules.

As engine oil wears, the viscosity increases beyond the designed range and suspended solids increase. Both of these mechanisms contribute to tribological49 losses by increasing the internal friction of the compressor, which reduces the overall cycle efficiency. Further, impediments on either the inlet or outlet side of the compressor will decrease overall efficiency. On the inlet side, air filters will need to be replaced as per the manufacturer’s recommendations. Outlet restrictions and chokes in pipework and hoses can also decrease system efficiency.

It is recommended to inspect valves regularly for wear and sticking, and to inspect outlet manifolds for scaling and oil deposits that can increase system backpressure. Details on these procedures can be obtained by reviewing the manufacturer’s documentation and seeking specialist advice when necessary.

49 Tribology is the study of lubrication and wear.
5.3 MEASUREMENT TECHNIQUES FOR COMPRESSED AIR SYSTEMS

Due to the relationship between compressor pressure and energy use, one simple energy saving measure is to ensure that only the required pressure is being supplied.

Each machine will have a recommended pressure and flow rate for optimal performance. The first step is to determine where each machine is located in the network. In general, the lowest pressure in the system will be at the point furthest from the compressor receiver. An ideal system would therefore be designed so that the equipment with the lowest pressure requirements is located furthest from the receiver whenever possible. Measurements along the network can determine pressure drops through the network more accurately than estimates, and potentially indicate restrictions in the network. Locating places in the network where the rate of pressure drop per metre is greater than others may reveal efficiency opportunities.

5.3.1 Measuring and fixing air leaks

Repairing air leaks from compressed air reticulation networks is a simple, yet effective, way to reduce energy losses. Further, there can be occupational health and safety benefits from reducing leaks as the sound created by escaping air poses a sound pressure hazard.

Air leaks can be detected either by inspection or by using specialised equipment, such as ultrasonic detectors. In either case, it is recommended to perform the inspections while the site is relatively quiet. Leaks should be located and clearly tagged for later repair. In many cases there may be benefit in prioritising which leaks are to be repaired first. Priority should be given to high-pressure and large holes over low-pressure or small leaks.

The methods to quantify energy savings due to repaired air leaks are complex and may require specialist assistance. In cases where there is a need to estimate the energy savings from repairing air leaks, the Energy efficiency best practice guide: compressed air systems, produced by Sustainability Victoria can be a useful starting point. To improve the accuracy of these measurements, it is further recommended that the tests be repeated and compared.

5.3.2 Multiple compressor systems

Since air compressors are most efficient when operating at or near their full load, appropriate compressor sizing can be an important energy efficiency measure to consider.

The efficiency of compressed air operations is often improved by using compressors of different sizes. Energy efficiency is optimised when all but one air compressor unit is operating at full load, with a relatively small unit or VSD brought on line when required to deal with demand peaks. This situation correlates to the fourth compressor load profile, shown in Figure 11. One compressor has been designed to run at full load all the time so as to cover base-load demand, with a smaller secondary air compressor only being brought online when base-load demand is exceeded. If a system has several distinct operating regimes, it may be appropriate to use more than two smaller compressor units to run optimally in each of these regimes.

To evaluate the most effective compressor configuration, the load profile of the compressor needs to be determined, preferably by electrical data logging. Once this profile is determined, Figure 11 can be used to determine the most appropriate configuration.

It is useful to consider ways that the demand profile can be flattened, such as deferring intermittent processes to later times where possible or increasing the cycle time of constant processes. In general, the goal should be to remove peaks from the load profile, to both minimise compressor start-ups and place the compressor in the optimum performance band.

52 Petchers, ch. 30 (see note 45).
Figure 11: Overview of the relationship between compressor size and demand profile

6 VENTILATION SYSTEMS

Mine ventilation systems are essential for removing hazardous gases and dust from mine workings so that employees can work safely in mine shafts. With these objectives in mind, ventilation systems should deliver sufficient pressure and air flow to ventilate effectively without raising too much dust.53

6.1 MEASURING BASELINE ENERGY USE

Ventilation fans are almost always electrically powered, so in principle it is relatively simple to establish the energy inputs for a given system configuration from electrical measurements. Electric power is consumed by the motor, the transmission and losses on the fan impeller to produce ‘air power’, the power imparted to the air by the fan system. This power is required to overcome the static and dynamic pressure resistance and to impart kinetic energy to the mass of air driven by the fan. Section 6.2 discusses ways to estimate system resistance and air flows.

Velocity measurements can be made with anemometers, while pressure can be measured with digital manometers or pitot tubes. An understanding of the dynamics of fluid flows is essential for ensuring accurate measurements. For example, flow measurements should be taken at various points in the flow cross-section to obtain an appropriate average, avoiding turbulence. Obstructions should also be avoided.54 Other measurements that are typically needed are air temperatures and humidity, as these affect the density and viscosity of the working fluid. Adjustments can also be made for the effects of natural ventilation.55

Ideally, mine ventilation systems could be fitted with data loggers and connected to a site-wide energy management system covering the various ancillary items of equipment (ventilation, dewatering systems, compressed air, lighting, and comminution systems).

6.2 MODELLING VENTILATION SYSTEM ENERGY USE

Air flows in mine shafts are driven by the pressure difference between the intake shaft and the exhaust, which is provided by the fans in the ventilation system. Fans operate under similar principles to pumps, with gases rather than liquids as the working fluid. Pressures are typically measured in ‘head’ (metres of water), but can also be expressed in units of pressure, pascals (Pa).56

6.2.1 Flow resistance

Flow and pressure requirements should be considered at the outset for new mine shafts to ensure sufficient system capacity. As with ventilation systems in general, mine ventilation systems have pressure losses due to friction as air passes through ventilation shafts, and ‘shock’ losses due to obstructions and changes in flow direction.57

53 See, for example, Bise, ch. 9 (see note 44).
55 These adjustments are outlined in the SME Mining Handbook (see note 9).
56 The pressure exerted by a column of fluid in pascals equals ρgh, the product of density (kg/m$^3$), the acceleration due to gravity (9.81 m/s$^2$) and the height of the fluid column in metres.
57 Shock losses in mine shafts are analogous to minor pipe flow losses in piping systems.
Static pressure head required in pascals can be estimated from:

\[ H_s = \frac{KLOV^2}{A} \]

**Equation 6.**

Where:
- \( K \) = friction coefficient in \( \text{Ns}^2/\text{m}^4 \)
- \( L \) = length of a shaft (m)
- \( O \) = shaft perimeter (m)
- \( V \) = air velocity (m/s)
- \( A \) = shaft cross-sectional area (m\(^2\)).

Caution should be taken with the units for the \( K \) value in this equation, since the equivalent imperial unit measure is substantially different.

Since the volume of air flow, \( Q \), equals the product of area (m\(^2\)) and velocity, static pressure head can also be expressed as:

\[ H_s = \frac{KLOQ^2}{A} \]

**Equation 7.**

Defining the static ‘resistance factor’ \( R \) as \( KLO/A \) gives \( H = RQ^2 \).

In addition to meeting the required static pressure, fans must also overcome the velocity resistance or **velocity head**, given by:

\[ H_v = \sum X \frac{\rho V^2}{2} \]

**Equation 8.**

where \( X \) represents the shock loss coefficients, which account for flow disturbances due to changes in direction or cross-sectional area.\(^{58}\)

One of the basic mine ventilation design principles is that the pressure developed by the system should offset friction losses and shock losses. There is a square law governing the relationship between volumes and pressures, so that doubling flow volumes requires four times the pressure. If the airflow leaves one common point, is split among several conduits and is returned to a common point, the pressure drop for each split will be equal, independent of the air flows in each split. This law is used to determine flow resistances in shaft networks.\(^{59}\)

Once the static pressure that fans must generate at a particular mine has been determined, this pressure can be plotted against the volumetric flow rate to give the system characteristic curve\(^{60}\), shown with dashed lines in Figure 12. The operating point for a fan is found at the intersection of the system characteristic curve with the fan characteristic curve produced by the manufacturer from experimental results and design features.

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\(^{58}\) Equations in this subsection can be found in the SME Mining handbook, ch. 11 (see note 9).

\(^{59}\) Bise (see note 44).

\(^{60}\) In mining, the system characteristic curve is sometimes termed the ‘mine characteristic curve’.
Performance curves can be used to estimate the change in flow rates, pressures and power requirements when the system configuration changes or fan characteristics are changed. For example, Figure 12 shows the effect of an increase in flow resistance, which reduces the flow rate to $Q_2$ and raises the required fan pressure from $P_1$ to $P_2$. Reducing fan speed from $N_1$ to $N_2$ would move the fan characteristic curve, reducing the fan pressure and flow rate for any given system characteristic curve. The power in watts required to overcome static pressure resistance is the product $PQ$ in the performance curve figure.

The air power, $P_{air}$ (kW) produced by a fan is given by:

$$P_{air} = \frac{H_l Q}{1000},$$

Equation 9.

where $H_l$ equals the sum of static pressure, velocity pressure and the pressure due to changes in elevation (the latter being relatively insignificant for air, given its low density). This power represents only part of the electric power supplied to the fan motor, due to losses in the motor, power transmission and belts, and aerodynamic losses in the fan impeller:

$$P_{air} = \eta_{motor} \eta_{transmission} \eta_{impeller} P_{el}$$

While it is possible to estimate the efficiency of a fan using the principles of fluid dynamics applied to a specific impeller design alone, the analytical effort required may not be justified. The efficiency can be calculated relatively easily using flow measurements. Some fan manufacturers may supply efficiency curves in addition to fan characteristic curves, which simplifies efficiency optimisation.

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61 The theoretical estimate developed is based on simplifying assumptions, as presented in M Potter & D Wiggert, (2002), Mechanics of fluids, 3rd edn, Brooks/Cole, ch. 12.
For marginal changes in fan configuration, the following fan laws can be used to estimate the change in fan performance:

\[
\frac{Q_1}{Q_2} = \frac{N_1}{N_2}
\]

Equation 10. Fan Law 1

\[
\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2
\]

Equation 11. Fan Law 2

\[
\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3
\]

Equation 12. Fan Law 3

For example, the first fan law indicates the change in flow rate for a change in fan r.p.m., for known values of \(Q_1\) and \(N_1\). If \(Q_1\) equals 5 m\(^3\)/s and \(N_1\) is 1500 r.p.m., then changing the fan speed to 1200 r.p.m. would produce a new flow rate of around 4 m\(^3\)/s. If the system characteristics change, the accuracy of calculations made using fan laws will decline.\(^{62}\)

### 6.3 POTENTIAL ENERGY SAVINGS MEASURES

Ventilation systems are seldom run at optimal efficiency, so for most mines there will be opportunities to improve ventilation system efficiency and find energy savings. Even if a ventilation system has been well designed at the outset, changes in mine shaft layouts may lead to suboptimal operation. Given that mine ventilation is safety-critical, mine shafts are typically overventilated rather than underventilated, resulting in excessive energy use.\(^{63}\)

#### 6.3.1 Lower cost opportunities

Maintenance improvements can provide significant efficiency gains. Fan impellers or blades should be regularly cleaned to avoid fouling in dusty environments, which causes static pressure losses. Similarly, fan housings should be cleaned to reduce friction. Misaligned drive belts, or belts that are worn or poorly tensioned, will require significantly more energy than well-maintained belts. Worn bearings cause friction losses that can also be significant. Indicators of bearing wear include increased noise output and higher operating temperatures.\(^{64}\)

Ensuring that ventilation systems are well maintained will also reduce downtime, prolong the life of ventilation equipment and safeguard air quality in the mine.

#### 6.3.2 Matching supply to demand

Mine ventilation systems are subject to changing system characteristic curves as the workings move. This means that a system that is initially optimised will deviate from this optimum over time.

Fan pressures and flow rates can be adjusted to changes in system characteristics by using regulators, fan inlet or outlet vanes, or varying fan output with variable speed drives and/or adjustable pitch fan blades. In some instances it may be possible to change fan speed by changing the sheaves or pulleys on the drive. Energy savings can then be estimated using the performance curves.\(^{65}\)

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63 Bise (see note 44).

64 Grobler & Vorster (see note 65).

65 Grobler & Vorster (see note 65).
Passive flow control using regulators creates flow restrictions, increasing frictional losses and energy use. Similarly, inlet and outlet vanes create a degree of turbulence which affects fan output. In most cases, installing VSDs will be the most energy efficient flow control option, because flow is controlled by reducing power inputs. Further information on VSDs is available in sections 5.2.5 and 5.2.6.

When investigating opportunities to reduce ventilation system energy use, the costs and benefits of installing VSDs may be worth considering. VSDs can be retrofitted to existing fans and housings. The natural frequency of the fan system should be considered in the retrofit process to avoid excessive vibration and damage to the fan system. Fan manufacturers may be able to advise if in doubt.

Energy efficiency and performance for a VSD-equipped fan will be maximised if it is fitted with an automated control system. Fan performance simulation software is also available to assist in optimising mine ventilation systems.

In some instances it may be possible to optimise ventilation system energy use by using multiple smaller fans rather than using a single larger one. This enables a single fan to be used for low load periods where applicable. Performance curves for different pumps can be combined in such cases:

- for parallel flow, the flow rates are summed for all the fans
- for fans in series, by contrast, the heads are summed.

6.3.3 Other equipment replacement or retrofit options

Major retrofits or equipment replacement can be costly, but may be justifiable if the existing system is inefficient. If the existing fan or motor is oversized, replacement with a lower capacity motor may be desirable. Older, less efficient fan units could potentially be replaced with newer, more efficient units. Impeller replacement may be an appropriate option if the existing impeller design has low efficiency. Even for systems with variable speed drives, installation of an automated control system can increase efficiency significantly.

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67 Papar, Szady et al. (see note 69).
68 Grobler & Vorster (see note 65).
7 PUTTING THE EMB TOGETHER

Once the energy and mass flows for the individual systems within a mine site have been determined, it will be possible to bring together the EMB for the entire site. Documenting the outcomes of the EMB may involve the tabulation of data, or a report combining the outcomes of the analysis conducted on the various subsystems at the site. As outlined in Section 1.1, the assumptions, calculations, equations used and decision processes should all be documented and kept for at least seven years.

Because many of the outflows from one system within mining operations also represent inflows for other systems (e.g. mass flows from haulage operations represent a mass inflow into crushing and grinding circuits), separating the documentation or tabulation of energy and mass flows by energy-using systems will simplify the analysis and ensure that values are not double-counted.

Table 3 presented a summary of the energy use model based on an average loading/unloading cycle for a haul truck, illustrating one possible method for capturing and displaying the energy use data that arises from detailed energy modelling. Using this detailed information for each subsystem, energy managers can then determine priorities for the site as a whole. For example, in some mining operations improved blasting can reduce the amount of energy required for comminution, but may change load density for the haulage process.

The EMB can cover every aspect of site operations. Figure 13 shows a high level process mapping of a mine site, which has been analysed as part of an EMB exercise. Using this mapping EMBs can be performed on each area of energy use. Then, each of the process-specific EMBs can be collated to form an EMB for the whole site. It is through this process of analysing broad trends, then drilling-down into the detail of specific subsystems that the most effective opportunities are found.

One example of how an EMB can be used to examine interactions between different subsystems and ambient energy and mass flows is dewatering. Figure 14 shows energy and mass flows for a dewatering operation at an open pit mine site, showing interactions between energy using systems and other site factors, such as the height of the water tank relative to the pump. Dewatering process flows could be integrated with other subsystem EMBs to investigate interactions such as the effect of road watering levels on haulage truck rolling resistance, using the model in Section 4.
Figure 13: Energy and mass flows for a dewatering operation

- **Energy flow**
  - Electricity: 5,736,278 kWh (20,658 GJ)
  - Automotive Diesel Oil: 3,403,194 L (130,863 GJ) and 2,723 T

- **Mass flow**
  - Potable Water (from borefield and RO plant): 24,775 kL (24,775 T)
  - Process Water (from rainfall/surface runoff/mine dewatering): 917,920 kL (917,920 T)
  - Lubricants: 130 kL (104 T)
  - Tyres: 144 T
  - Spares/Consumables (e.g., Drills, rock bolts, mesh, gaskets, brake pads, etc.): 22 T
  - Explosives: Anfo 767 T (3,069 GJ), Emulsion 67 T (220 GJ)
  - Cement: 144 T

- **Energy and mass flow losses**
  - Waste Heat: 95,609 GJ
  - Combustion Exhaust Gases: 11,983 T
  - Process water (lost via evaporation): 438,000 kL (438,000 T)

- **Ore**
  - Surface ore: 499,988 T
  - Underground ore: 122,865 T

- **Ore to treatment plant**
  - Ore: 622,853 T

- **Recyclable outputs**
  - Used tyres to off site recycle: 115 T
  - Used lubricants to off site recycle: 104 kL (83 T)

- **Waste mass flows**
  - Mullock/Waste/Dust: 1,851,224 T
  - Waste to landfill: 151 T
  - Waste to incineration: 1 T
  - Waste water (sewage): 302 kL (302 T)
  - Mine water: 479,920 kL (479,920 T)

External Influences on Energy Use:
- Weather
- Regulations and Standards
- Market Demand
- Mine design and characteristics
- Equipment Selection
- Employee attitudes and training

Sections 5–6 examine the energy use in compressed air and ventilation systems.
Section 4 examines excavation and mucking equipment.
See section 3 for analysis of energy use in crushing and grinding.
Section 4 analyses energy use in haulage operations.
Figure 14: Energy and mass flows for a dewatering operation
8 CONCLUSION

The development of an EMB is an iterative process that provides a deeper understanding of the energy and mass flows through a site or process. The initial version of an EMB will assist in identifying areas for improvement in data collection and analysis. Initial EMBs will also identify some low-cost, easily implemented opportunities, with subsequent improvements to data and analysis refining the understanding of energy usage. Further iterations of the process will produce a final, comprehensive EMB, providing for a more thorough analysis of components within the system, and the identification, detailed investigation and evaluation of specific opportunities. If prepared as part of an approved representative assessment approach, EMBs for a sample of mining operations, such as a haulage fleet, may be applied across the entire portfolio.

This document was developed to provide guidance on the key considerations involved in conducting an EMB on a mine site. In particular the document identifies some key energy-using systems within an operation and associated mass flows that the analysis should focus on, and discusses typical energy efficiency opportunities for these key systems.
9 APPENDICES

9.1 INTEGRATING DATA USING THE TRAPEZOIDAL RULE

For any mathematical function $f$, the area under the curve plotted against time is given by the integral:

$$\int_{t_0}^{t_1} f_2 dt$$

which is often difficult to evaluate.

In the example below (Figure 15) the energy savings from installing a VSD are determined by finding the area under the curve, from time zero ($t_0$), to a time in the future ($t_1$). This can then be compared to the area under the ‘Without VSD’ curve, over the same time period. Expressed mathematically:

$$\text{Energy Saved} = \int_{t_0}^{t_1} f_2 dt - \int_{t_0}^{t_1} f_1 dt$$

Where:

- $f_2$: start-up curve for ‘Without VSD’ test
- $f_1$: start-up curve for ‘With VSD’ test
- $t_0$: test start time
- $t_1$: test finish time

Start and finish times for both tests must be identical for the comparison to be accurate. One method to achieve this is by starting the timer, in both instances, when the machines are switched on. For the finish time, longer runs will provide greater accuracy, but only until both curves reach an identical steady-state.

Figure 15: Comparison of start-up power for a VSD and a non-VSD system

If the integral is difficult to evaluate, the trapezoidal rule provides an adequate estimation tool. Integrals of experimentally derived data, for example, can be estimated using the trapezoidal rule. This method approximates the area under a curve by adding the areas of a series of vertical trapezoids and is particularly useful for calculating the area under a curve that is not easily described by an algebraic
function. This estimation is based on adding the areas of a number of vertical trapezoids, as shown in Figure 16. Estimation accuracy can be increased by using smaller time differences for each trapezoid, which will reduce the difference between the integral and the trapezoidal estimate, shown by the shaded areas in Figure 16.

**Figure 16: Application of the trapezoidal rule**

![Figure 16: Application of the trapezoidal rule](image)

Looking at Figure 16, the expression to determine the area of the first trapezoid is given by:

\[
A = (x_2 - x_1) \left( \frac{y_2 + y_1}{2} \right)
\]

Note that this relationship is only true while \( y \geq 0 \).

This base relationship can then be applied to the data set to determine the total energy use throughout the test period. While this analysis appears complex, the data manipulation within a program such as Microsoft Excel is relatively straightforward. Details of this are beyond the scope of this document.