The Measurement & Verification of Energy Conservation Measures at a Coal-fired Power Plant

Prepared by:

Richard Larmour

LRMRIC001

Energy Research Centre, Department of Mechanical Engineering

University of Cape Town

Supervisor:

Ms Mascha Moorlach

Co-supervisors:

Professor Kevin Bennett, Mr Andrew Hibberd

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Declaration

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To Emily, Amy & Jake

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Nomenclature

ABMA	American Boiler Manufacturers Association
ACEEE	American Council for an Energy Efficient Economy (USA)
AD	Air dried (sometimes stands for ‘As determined’)
AEEE	Alliance for an Energy Efficient Economy (India)
AEPCA	Australasian Energy Performance Contracting Association (Australia)
AER	Applied Economic Research
AF	As fired
AGO	Australian Greenhouse Office
AH	Air heater
AI	Abrasion index
ANOVA	Analysis of variance
AR	As received
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers (USA)
BEE	Bureau of Energy Efficiency (India)
BFP	Boiler feed pump
BFPT	Boiler feed pump turbine
BMS	Building management system
BTU	British thermal units
C&I	Control & instrumentation
CCS	Carbon capture & storage
CEP	Condensate extraction pump
CF	Capacity factor
CO2	Carbon dioxide
CPP	Clean Power Plan (USA)
CRS	Congressional research service (USA)
DB	Dry basis
DCS	Distributed control system
DECC	Department of Energy & Climate Change (UK)
DOF	Degrees of freedom
DSM	Demand side management
DSS	Daily start-stop
ECM	Energy conservation measure
EE	Energy efficiency
EM&V	Energy measurement & verification
EPA	Environmental Protection Agency (USA)
EPC	Energy performance contracting / Energy savings performance contracting
EPRI	Electric Power Research Institute (USA)
ESP	Electrostatic precipitation
FD	Forced draft
FEMP	Federal Energy Management Program (USA)
FGD	Flue gas desulphurisation

FW	Feed water
FWH	Feed water heater
GDC	Gross Dependable Capacity
GEC	General Electric Company
GHG	Greenhouse gas
H2O	Water
HFO	Heavy fuel oil
HGI	Hardness grindability index
HHV	Higher heating value
HP	High pressure
HR	Heat rate
HR_G	Gross heat rate
HR_N	Net heat rate
HV	Heating value
ID	Induced draft
IEA	International Energy Agency
IM	Inherent moisture
IP	Intermediate pressure
IPMVP	International Performance Measurement & Verification Protocol
kW	Kilowatt
kWh	Kilowatt-hour
kT	Kiloton (10^3 metric tons)
LHV	Lower heating value
LP	Low pressure
M&T	Monitoring & targeting
M&V	Measurement & verification
MCR	Maximum continuous rating
min	Minute
MMBTU	British thermal units (Millions)
MPa	Megapascal
MW	Megawatt
MWh	Megawatt-hour
NEMVP	North American Energy Measurement & Verification Protocol
NETL	National Energy Technology Laboratory
NO_2	Nitrogen dioxide
NO_X	Oxides of nitrogen
NPC	National Petroleum Council (USA)
NREL	National renewable energy laboratory (USA)
NRN	Net heat rate
NSW OEH	Office of the Environment & Heritage (New South Wales, Australia)
η	Efficiency symbol
O&M	Operation & maintenance
O_2	Oxygen
OFA	Over fire air
p.a.	Per annum

PA	Primary air
PAT	Perform, Achieve & Trade (India)
PC	Performance contracting
PF	Pulverised fuel
PD	Project developer
ROI	Return on investment
SANS	South African National Standard
SAWS	South African Weather Service
SCR	Selective catalytic reduction
SE	Standard error
SEE Action	State & Local Energy Efficiency Action Network
SO_2	Sulphur dioxide
SO_X	Oxides of sulphur
Std Dev	Standard Deviation
t	Metric ton (mass)
TM	Total moisture
TTD	Terminal temperature difference
UCT	University of Cape Town
UK	United Kingdom
UP	University of Pretoria
US	United States
USA	United States of America
VM	Volatile matter
VSD	Variable speed drive

Abstract

The aim of this dissertation was to use Measurement & Verification (M&V) to determine the improvements in net heat rate (HR) at a South African coal-fired power plant (CFPP) following an extensive refurbishment programme. The CFPP consisted of multiple subcritical pulverised fuel generating units and the refurbishment programme aimed to improve the overall net heat rate by 1%. The purpose of using M&V is to isolate the performance changes attributable to specific energy conservation measures from those changes brought about by other factors, or that would have occurred anyway for other reasons.

An extensive literature review was undertaken, firstly into M&V and secondly into CFPP design and performance. The conventionally accepted methods for determining plant performance are the 'direct method' in which a measurement boundary is drawn around the entire plant, and the 'components method' which evaluates the boiler, the turbine-condenser cycle and the auxiliary loads separately. Caution is drawn to the fact that plant performance may be expressed in many ways depending on how HR is defined and on which coal measurement base is used.

The physical factors affecting plant performance were classified as either fixed or variable. Fixed factors included vintage and design, size, condition of the major components (boiler, turbine and condenser), cooling water system type and pollutant controls. Variable factors included ambient conditions, flexibility of operations (such as running at part-load and load cycling) and the characteristics of the coal used including heating value, total moisture, hydrogen, ash, volatile matter, sulphur, hardness & abrasiveness. The literature indicates that the language used to describe flexible operations is inadequate and poorly defined. Other factors that may affect the calculated heat rate of a plant include coal weighing, stockpile surveys, length of assessment periods, changes to static stockpiles, measurement boundary selection and other assumptions.

The literature review was used as a basis to develop an M&V methodology for the specific CFPP involved in the case study. The energy conservation measures were described in detail as well as constraints regarding availability and resolution of plant data. Although all measurement boundary options were considered, the whole facility approach was chosen (Option C). This approach was mainly motivated by the lack of data available and a high potential for interactive effects. Another reason is the fact that assessments need to capture the overall performance which could include deterioration in one part of the plant and simultaneous upgrades in other parts. The primary data required to find heat rate is the electrical energy use (exported, imported and auxiliary), the mass of coal consumed and the coal higher heating value (HHV).

The M&V methodology included the development of a baseline adjustment model to adjust for changes in plant load, coal moisture and coal ash content. Ideally the model should have included changes in ambient conditions (temperature and relative humidity) but this was not possible as no ambient data was available and the assessment was done retrospectively. The absence of ambient data was mitigated by stipulating that assessment periods need to consist of a minimum of twelve consecutive months to account for changes in performance due to seasonal effects. The methodology also included a Monte Carlo analysis to quantify the combined uncertainties associated with electrical energy use, coal energy use, coal heating value and the adjustment model itself.

The methodology was used to assess the change in net heat rate of the plant used in the case study for two separate twelve month reporting periods. The calculated impacts of the energy conservation measures were not as favourable as originally anticipated. A brief analysis of the results is provided with a discussion of potential reasons for the underperformance. A whole facility approach does not allow the reasons for performance changes to be pinpointed. One possibility is simply that the energy conservation measures had not been implemented as originally planned. An important finding was that the performance changes could not be solely attributed to the exclusion of any independent variables from the baseline adjustment model (e.g. ambient conditions).

A more general discussion of the merits, shortcomings and limitations of the methodology is provided as well as some comments on the general interpretation of results. The baseline adjustment model is only applicable to the plant in the case study and is only valid for small changes in the independent variables. When calculating part-load operation, special attention must be given to generating units that have been derated. The application of a single part-load adjustment model to a multi-unit plant is discussed and found to result in conservative reporting. Factors which contribute to uncertainty, but which are unknown include staithe coal level changes, unknown stockpile dynamics, uncalibrated instruments, unrecorded coal movements and inaccuracy of aerial stockpile surveys.

The dissertation concludes that the original hypothesis is supported: that a credible M&V methodology may be developed and applied to determine the heat rate improvements resulting from the refurbishment programme at a coal-fired power plant.

Recommendations include an upfront agreement on which measurement reporting bases to use (both for heat rate and for coal), selection of a whole facility measurement boundary, a minimum assessment period of twelve months, installation of at least one accurate instrument to measure actual coal consumption (as opposed to coal delivered to the plant and then moved within the plant), sampling of coal, determination of heating value and collection of accurate ambient condition data from the start of the baseline period. Further recommendations are made to reduce uncertainty, determine static factors and to better interpret reported impacts.

Chapter 1 Introduction

1.1 Background

Coal remains the single most prevalent source of primary energy in the production of electricity worldwide, accounting for approximately 40.8% of all electricity generated in 2014 (International Energy Agency [IEA] 2016: 24). Globally the installed electrical generating capacity is 1700 GW and in the absence of new policies aimed at reducing this, the capacity is expected to continue increasing (IEA 2014a: 6).

Coal fired power plants (CFPPs) are normally designed for an operational life of 25 – 35 years although life extensions are common and some generating units have operated in excess of 50 years. The global average CFPP efficiency[1] is about 33% and is dominated by older, less efficient plants (IEA 2014a: 16,19). In the USA it is estimated that over the last five decades CFPP efficiencies have declined by several percent for reasons including reduced maintenance and upkeep, increased cycling operations, declining coal quality, decreased personnel levels and the installation of emission controls (Electric Power Research Institute [EPRI] 2014: 1.2, 1.3). There is good reason for utilities to recover some of this lost efficiency. The benefits of improving efficiency include reduced operating costs, reduced emissions, extending the life of coal reserves and potentially increasing power output (IEA 2010: 15).

A coal-fired power plant[2] (CFPP) in South Africa underwent an extensive refurbishment programme over several years with the aim of improving the plant heat rate (HR) by at least 1%. The programme consisted of multiple projects throughout the plant including major equipment repairs, replacements and refurbishments, operational optimisations and measures to reduce auxiliary power use. The utility required that the efficiency impacts of the projects be quantified using Measurement & Verification (M&V), a method which is commonly used for finding the impacts of demand side energy conservation measures (ECM).

The energy savings brought about by one or more ECM cannot be measured directly and needs to be calculated as the difference between the energy use before and after the implementation of an ECM. However the energy used by a system or facility is normally dependent on multiple factors and a reduction in energy use may not be the result of ECMs only. Likewise, an increase in energy use does not necessarily indicate that an ECM was ineffective, but rather that its impacts were outweighed by other influences.

For example, the power station may repair leaking boiler drum safety valves and thus save live steam, but then happen to operate during a period of severely high ambient temperatures, causing the condenser pressure to increase. If no overall change to the HR is detected then that is not necessarily an indication that the valve repair was a poor investment choice or that the repairs had no impact. On the contrary, an M&V analysis could yield that the investment was a very good one

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[1] CFPP performance is often expressed as a heat rate (HR) which is the heat input required per unit of electrical energy produced (e.g. MJ/kWh).

[2] The name of the plant is classified.

and provide an estimate as to what the performance would have been if the valves had not been replaced.

The purpose of M&V is to isolate the changes in energy use which are attributable to specific ECMs from changes due to other factors. This is achieved by constructing an adjustable energy baseline that characterises energy use as a function of significant energy-driving factors (independent variables), which makes it possible to estimate what the energy use would have been in the absence of any ECMs. CFPPs are large, complex facilities and there is no single universally accepted method for determining and expressing the real operational heat rate (IEA 2010: 15). Different methods use different assumptions, measurement bases, measurement boundaries and assessment periods.

1.2 Hypothesis

It is hypothesised that a credible M&V methodology may be developed and applied to determine the HR improvements resulting from the refurbishment programme at a CFPP.

1.3 Objectives

The objective of the study is to develop an M&V methodology to determine the HR improvements brought about as a result of the refurbishment investments at the power plant. This required an investigation into the following research questions.

1.4 Research questions

- What are the key principles of M&V and how should these be applied?
- What are the accepted methods for determining the HR of a CFPP and which method would be most suitable?
- What are the energy efficiency interventions and what are their expected impacts?
- What are the most important factors which influence the HR of a CFPP and can these factors be adequately characterised in order to perform valid adjustments to the baseline HR?
- What are the data requirements and how does data accuracy affect the uncertainty of the calculated impacts?
- Can the methodology developed be used universally or are there limitations and exceptions required for its application?

1.5 Benefits of this study

This study has the following benefits for the refurbishment programme and also for other similar programmes.

- It will allow the power plant operator to gain a quantitative indication of the real energy and power impacts of the refurbishment programme versus the theoretical impacts which were expected.
- It will provide the basis for a realistic cost benefit analysis which could serve as a guide for future investments.
- It reduces risk for the programme funder.
- It provides an audit that the ECMs were carried out as intended.
- It will add to the M&V literature an approach for M&V of supply-side ECMs.

1.6 Dissertation layout

Chapter 2 is a literature review which firstly examines M&V including its development, principles, methods and practical guidance. Secondly CFPPs are examined including basic operation, auxiliary power, methods of determining HR and the factors which affect HR. Chapter 3 develops an M&V methodology which is guided by the constraint of data availability. Chapter 4 presents the M&V results including uncertainty and sensitivity. Chapter 5 is a discussion of the method, the results and the limits of applicability to other CFPPs. The final chapter provides conclusions and recommendations.

Chapter 2 Literature review

This literature survey was carried out with the purpose of informing the development of a sound M&V methodology to determine the heat rate improvement resulting from various planned energy efficiency interventions at the power plant in question.

2.1 Measurement & Verification

2.1.1 An overview

M&V is the process of determining the performance of an energy[3] efficiency intervention[4] in an impartial manner. A definitive M&V document, The International Performance Measurement and Verification Protocol (IPMVP 2012: 4) expands on this and defines M&V as follows:

> ***"…the process of using measurements to reliably determine actual savings created within an individual facility by an energy management program. Savings cannot be directly measured, since they represent the absence of energy use. Instead savings are determined by comparing measured use before and after implementation of a project, making appropriate adjustments for changes in conditions."***

As the above definition mentions, savings cannot be measured and thus by necessity need to be calculated by finding the difference between the energy use before the ECM was implemented and the energy use afterwards. However any change in energy use between those two periods is not necessarily the result of the ECM alone and could have resulted from many other contributing factors. The ultimate aim of M&V is to determine how much of that change is attributable to the ECM alone, and how much of it would have occurred anyway, in the absence of the ECM. Adjustments are thus required in the calculation to account for those factors which affect energy use apart from the ECM (IPMVP 2012: 7).

Sometimes, the adjustments required may be based solely on measurements, while in other cases assumptions may be allowed for, but in either instance an element of uncertainty is introduced into the calculations (Australasian Energy Performance Contracting Association [AEPCA] 2004: 22). According to the Lawrence Berkeley online M&V Portal, M&V is not an exact science (Lawrence Berkeley National Laboratory, n.d.). Of course other methods could be used to estimate the savings brought about by an ECM, such as engineering calculations, equipment manufacturer data or case studies of similar projects, but M&V seeks to find the savings under real operational conditions as accurately as possible by using actual measured data (NSW Office of the Environment & Heritage [NSW OEH] 2012: 1).

In the surveyed literature, the terms "Evaluation, Measurement, and Verification (EM&V), "Energy Measurement and Verification (EM&V)" and "Monitoring & Verification (M&V)" all ostensibly carry the same meaning as "Measurement & Verification (M&V)" as described in this dissertation. These

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[3] Although M&V can be applied to find the savings of any resource, energy is the resource in this study.

[4] For the purpose of this study the terms "energy conservation measure (ECM)", "energy efficiency intervention" and "energy efficiency measure" have the same meanings.

terms however are not to be confused with the terms “Monitoring & Evaluation (M&E)”, “Monitoring & Targeting (M&T)” and “Monitoring, Reporting & Verification (MRV)”, the latter of which is specifically being developed in the climate change context.

2.1.2 Development of M&V

In 1977, the President’s National Energy Program in the USA stated “Conservation is the quickest, cheapest, most practical source of energy” (American Presideny Project [APP] n.d.). Much more recently, in March 2014, the American Council for an Energy Efficient Economy (ACEEE 2014: 40) reported that energy efficiency had been the cheapest energy resource over the preceding decade and suggests planners should regard it as a reliable “first fuel” choice. Apart from being a cost effective resource, energy efficiency has numerous other benefits which are driving investment into end-use efficiency. These include reduced fuel costs, reduced emissions and associated health impacts, reduction in water use, lower electricity costs, reduced need for new generation capacity and increased competitiveness among other benefits[5].

Although these are recognised benefits and drivers of energy efficiency, investors need the energy savings of an ECM to be accurately quantified in order to confidently know the return on investment (IPMVP 2012: 5; NSW OEH 2012: 1). Over the past four decades, M&V has been developed and used for assessing the performance of ECMs to inform future investment decisions (ACEEE 2014: 5). In some instances, the inability of project stakeholders to agree on how M&V should be performed has hindered long term project success (AEPCA 2004: 6).

Some DSM incentive schemes are based on guaranteed energy savings such as energy performance contracting (EPC or PC) where an ECM is installed at a facility with a guarantee of the energy savings it will bring about over an agreed period. These projects are typically financed such that the client is not liable for the upfront cost. Thorough and transparent M&V reporting is an integral part of these projects as it forms the contractual basis for performance-based payments (Eskom 2012a: 8; NREL 2013: 1–7). In Australia M&V is a requirement for government financed programmes (NSW OEH 2012: 1). Guidelines and methodologies for the M&V of PC projects have been developed in the USA, South Africa, Australia and India (AEEE n.d.; AEPCA 2000; Eskom 2012b; US DOE 2015) while the UK has promoted use of the IPMVP (Department of Energy & Climate Change (UK) [DECC] 2015: 23).

Another major factor driving energy efficiency is the need to reduce CO_2 emissions and demand-side efficiency has been recognised by the US Clean Power Plan (CPP) as an easily accessible, cost effective means of reducing emissions in the power sector (EPA 2015: 1). Some countries have imposed or planned a carbon tax to reduce CO_2 emissions and support energy efficiency (Carbon Tax Centre, n.d.). Under the CPP in the USA and under the PAT scheme in India, M&V is required for the issue of tradable carbon and energy savings certificates respectively (Bureau of Energy Efficiency (India) [BEE] 2012: 90; Peskoe, 2015: 3).

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[5] Other benefits that have been cited include, reduced number of disconnections, improved revenue collections, improvements in system reliability, increased stability of electricity prices, job creation, increase in property values, beneficial health impacts, improved safety and increased productivity (ACEEE 2015: v-40; SEE Action 2016: 2–34).

South Africa has introduced an energy efficiency income tax incentive for businesses and an entire M&V national standard was developed for performing the M&V for these tax rebate claims (South African Bureau of Standards, 2011; *Income Tax Act*, 2013).

M&V is an evolving discipline and the body of literature has grown in recent years (SEE Action 2012: 1–1; NREL 2013: 1–7; EPA 2015: 6). However, the IPMVP (2012) stands out as being the single most widely used text, both in practice and as the basis from which other literature is developed. Some texts are based on it directly while in others it is clear that the same principles are being applied (AEPCA 2004; SANS 2011). Other important contemporary M&V texts include Measurement of Energy, Demand and Water Savings (American Society of Heating Refrigeration and Air-Conditioning Engineers [ASHRAE] 2014) and M&V Guidelines: Measurement and Verification for Performance-Based Contracts 4.0 (DOE 2015).

The IPMVP is not prescriptive about exactly how to perform M&V in every situation or for every ECM type. Rather, it provides a broad generic M&V framework and presents the user with various options to suit the requirements of each specific ECM. This has the advantage of allowing flexibility and use in varied applications however it does mean that not all reported ECM impacts are necessarily directly comparable, even for efficiency measures which may have been identical. This has recently led to an effort to standardize the M&V methodology used for specific ECM and technology types, but many of these are still completely compatible with the M&V principles laid out in the IPMVP[6]. Other reasons for the emergence of standardised methods include the need to reduce M&V costs and to improve consistency in calculations so that similar projects in different locations may be directly compared (National Renewable Energy Laboratory, 2013US Environmental Protection Agency, 2015).

The purpose of this dissertation is to develop an M&V methodology for a specific application, but still remain within the broad M&V framework and principles already established in the IPMVP.

2.1.3 Key principles of M&V

M&V increases the credibility of reported savings and to this end should be underpinned by the following important principles as listed by the IPMVP (2012: 6) and other guides (AEPCA 2004: 22).

- **Accuracy**: Reporting should be as accurate as possible. There is usually a trade-off between accuracy and cost (See Section 2.1.11 on Uncertainty).
- **Completeness**: Reporting should ensure that all energy related parameters of the ECM are considered. Significant aspects should be measured while others may be estimated[7]. (See also Interactive effects)
- **Conformity**: M&V reporting must conform to the requirements agreed upon before the ECM is undertaken.
- **Conservativeness**: Energy savings should be stated conservatively. Thus the M&V methodology should be carefully planned so that savings are understated rather than overstated.

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[6] Certain instances which do not insist on any measurement at all are inconsistent with the IPMVP.

[7] An exception to this is ASHRAE (2014: 8) which stipulates that all parameters need to be measured. In some cases the IPMVP allows for assumptions to be made.

- **Consistency**: A consistent approach should be taken to determine savings. For example the same methodology should be used throughout all reporting periods of the life of an ECM project, allowing easy comparison from one period to the next. Terminology and definitions in reporting should also be used consistently.
- **Relevance**: This is closely related to "completeness" above. All relevant energy related parameters should be measured while less important ones may be estimated[7].
- **Repeatability**: Good measurement practices allow for repeatability of calculated results.
- **Traceability**: M&V should be undertaken in a systematic and organised way that allows for traceability of all elements which contribute to a calculated result. This enhances transparency as it permits a detailed scrutiny of results if required.
- **Transparency**: Each part of the M&V process should be available for scrutiny by all relevant parties.

2.1.4 M&V terminology

Although the well-known M&V texts share a great deal of commonality, the terminology and meanings used is not always consistent. The below M&V definitions and terminologies will be used throughout hereafter.

- **Energy conservation measure[8] (ECM)**: An intervention into an existing system or subsystem with the purpose of improving energy efficiency. The intention is for the system to produce the same useful output but with a lower input energy requirement than would have been the case in the absence of the intervention. An ECM can thus also reduce energy demand. Also known as "Energy efficiency measure (EEM)", "Energy savings measure (ESM)" or simply as a "Retrofit" (IPMVP 2012: 8,56; BEE 2012: 94; SEE Action 2012: A6).
- **Measurement boundary:** This is a notional boundary for measurement purposes which captures all the significant energy uses affected by an ECM. The boundary could be drawn around an entire facility or around just subsection of it and should be drawn with the specific intention of determining the savings brought about by an ECM. Also known as "Assessment boundary" (IPMVP 2012: 11; SEE Action 2012: A2).
- **Facility:** A building or an industrial site which contains multiple energy end-use systems. A subsection of such a building or site may also be considered to be a facility. (IPMVP 2012: 56)
- **Baseline period:** The period prior to the implementation of an ECM that is chosen to be representative of the original performance of a system or facility in terms of energy use. This period needs to be chosen to include the full spectrum of typical operating conditions of the facility or system. Also known as the "Pre-implementation period" or the "Pre-retrofit period" (IPMVP 2012: 55,82; Eskom 2012b: 4).
- **Reporting period:** The chosen period following the implementation of an ECM during which its performance is evaluated by means of M&V reporting. As with the baseline period, the reporting period must be chosen to include the full spectrum of typical operating conditions of the facility or system. The length of this period is ultimately determined by the parties requiring M&V reporting of the ECM. Also known as "Post-installation period", "Post-

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[8] Although there is debate about the meaning of ECM vs EEM, for this study, ECM is taken as a measure which includes primarily energy efficiency but also energy conservation.

implementation period”, “Performance assessment period” or the “Post-retrofit period” (IPMVP 2012: 57,72; SEE Action 2012: A-1; EPA 2015: C-6).

- **Independent variable:** A measurable, physical parameter which has a significant effect on energy use of a system or a facility in a predictable way and which is expected to change regularly, but not as a result of the intervention. The independent variables represent the conditions within the measurement boundary during the baseline and reporting periods. For example ambient air temperature could be an independent variable which has a significant effect on the energy used by an air-conditioning system. Also known as “Energy governing factor”, “Explanatory variable” or “Independent factor” (SABS 2011: 4; SEE Action 2012: A-8,A-13).
- **Adjustment model:** A model which characterises specific energy use of a system or facility as a function of one or more independent variables. This model is used to routinely adjust the baseline period energy use in order to objectively compare it to the reporting period energy use and thus may have either a positive or a negative impact on the savings. Also known as “Baseline model”, “Energy model” and “Regression model” (AEPCA 2004: 9; IPMVP 2012: 27; NSW OEH 2012: 8; SEE Action 2012: A-14; ASHRAE 2014: p5).
- **Routine adjustment:** An adjustment to the baseline energy use using the selected independent variables and the baseline adjustment model. This is routinely performed every time an ECM saving is calculated as it is always necessary that the baseline used represents what the energy use would have been, given the reporting period conditions, but in the absence of the ECM. Also known as “Normalisation” (BEE 2012: 124; ASHRAE 2014: 6).
- **Non-routine adjustment:** These are baseline energy use adjustments which are required less frequently if static factors affecting energy use change within the measurement boundary between the baseline period and the reporting period. Also sometimes known as “Baseline adjustment” (IPMVP 2012: 42; ASHRAE 2014: 5).
- **M&V Plan:** This is a document which specifies all aspects of the M&V methodology for a particular ECM and is agreed to by all interested parties before the ECM is implemented. It includes all key items including a thorough ECM description, expected savings, baseline period, measurement boundary, metering specifications, metered data requirements, handling of missing data, independent variables, adjustment model, non-routine adjustment handling, justified assumptions, reporting intervals, reporting uncertainty and may also include M&V costs (IPMVP 2012: 36).
- **Savings:** The independently calculated M&V reported savings of either energy or demand[9] brought about by an ECM. The savings reflect what the actual energy use was over a specific reporting period versus what the energy use would have been in the absence of the ECM, but under the same operational conditions present during the reporting period. The savings calculation is based upon measured data, independent variables and the baseline adjustment model and must be performed according to the M&V Plan. Savings need to be reported with a specified uncertainty. Also known as “Impacts”, “Evaluated savings”, “Avoided energy use”, “Reported savings”, “Actual energy savings” and “Ex-post savings” (IPMVP 2012: 57; SEE Action 2012: A-7; ASHRAE 2014: 2,3).

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[9] If the savings are related to demand, these are usually referenced to a specific time of day (Larmour, 2013: 3).

2.1.5 Savings calculations

In order to isolate the savings brought about by the ECM from those changes in energy use which would have occurred anyway, the following foundational equation is used. Equation 1 calculates energy but could equally be used to find demand savings.

Equation 1

$$E_S = E_B - E_R \pm Adj$$

Where E_S = *calculated energy savings*

E_B = *energy use during the baseline period*

E_R = *energy use during the reporting period*

Adj = *baseline adjustments (routine and non-routine)*

The adjustment term in Equation 1 includes both routine and non-routine adjustments. The selection of the most significant independent variables, the quality of the adjustment model and the application of non-routine adjustments are arguably the most important elements of an M&V savings calculation as the level of uncertainty that could potentially be introduced may far exceed the uncertainty associated with metered data. This may be overlooked in the interest of reducing the time and cost of M&V reporting but a poorly adjusted or an unadjusted baseline can lead to very misrepresentative reported savings (AEPCA 2004: 7; NSW OEH 2012: 6). Adjustments are addressed in Section 2.1.7. Figure 1 depicts the savings as the difference between adjusted baseline energy use and actual reporting period energy use. In this example, production is the chosen independent variable and this is seen to increase during the reporting period along with a resultant baseline increase. Figure 2 depicts the process and data requirements to determine ECM savings.

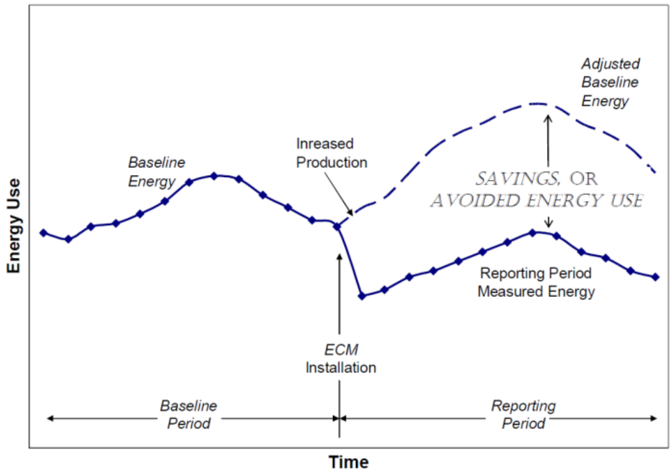

Figure 1: Hypothetical example of energy savings after an ECM showing an adjusted baseline (IPMVP 2012: 7)

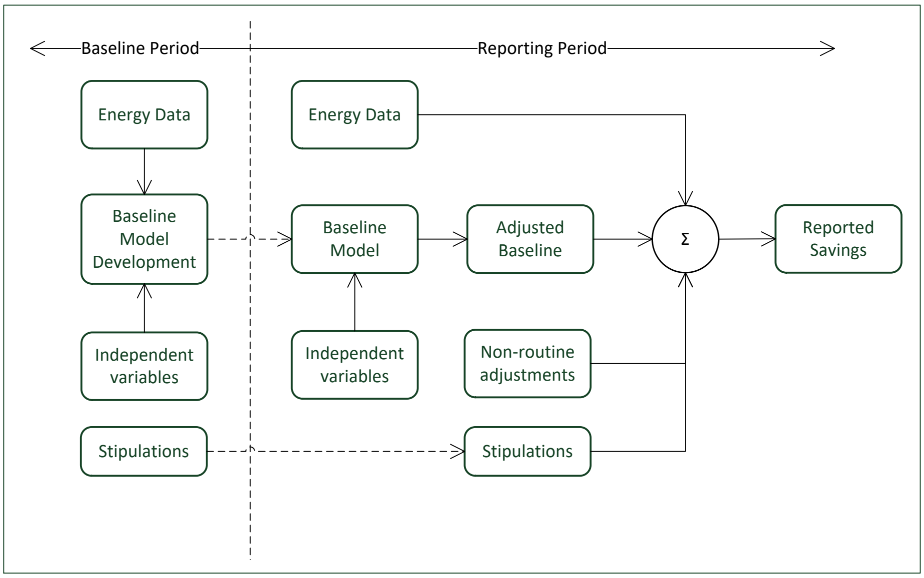

Figure 2: The M&V process, adapted from NSW OEH (NSW OEH 2012: 7)

2.1.6 Measurement boundary options

The literature reviewed typically followed the IPMVP by proposing four different options for measurement. The option chosen is stipulated in the M&V Plan and is largely determined by the expected ECM savings, the overall budget available for M&V and the level of acceptable uncertainty required for reported savings. Although the naming conventions for the measurement options vary slightly from one text to the next, the IPMVP naming is used to describe the options below (IPMVP 2012: 17,18). In all cases, measurement frequency could range from instantaneous spot readings to continuous measurements but needs to be determined by how often the measured parameter is expected to change.

a) Option A – Retrofit isolation: Key parameter measurement

In this option the placement of the measurement boundary is designed to isolate the specific system where the ECM has been implemented and nothing else. Energy use is determined by key variables being measured but allows for some independent variables to be estimated.

The values of estimated parameters need to be justified and this may include engineering modelling, historical data, manufacturer's data[10] or sound engineering judgement. Also, the impact that the estimation may have on reporting uncertainty needs to be quantified.

A typical example of this is a lighting retrofit where the pre- and post-implementation electrical demand for each retrofitted lamp is measured, but parameters such as supply voltage and operating hours may be estimated. Justifications may include historical data for the supply voltage and an automated lighting control system by means of a building management system (BMS).

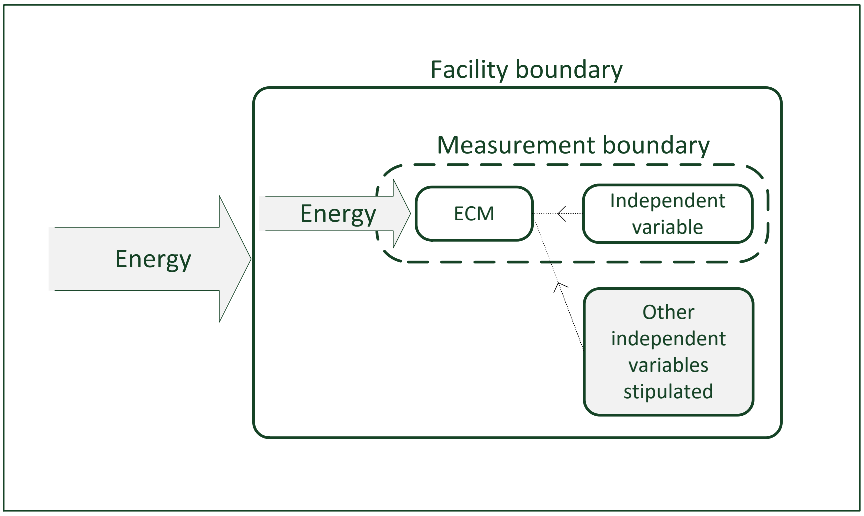

Figure 3: Measurement boundary for Option A: Retrofit isolation key parameters measured

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[10] SABS (2011: 12) stipulates that manufacturer data needs to be verified with actual tests.

b) Option B – Retrofit isolation: All parameter measurement

In this option the placement of the measurement boundary is designed to isolate the specific system where the ECM has been implemented and to measure the values of all the significant independent variables within that boundary as they relate to the affected ECM. Energy use is determined by using all of the measured variables.

This option may be preferable when a high degree of accuracy is required and where it is not justified to make assumptions about variable parameters which contribute towards energy use. However the more stringent measurement requirements of this option may increase M&V costs.

Continuing with the simple example from "Option A" above, in addition to the pre- and post-implementation electrical demand measurement for each retrofitted lamp, all other significant parameters would need to be measured, such as supply voltage and operating hours, if these were expected to vary in comparison to the baseline period.

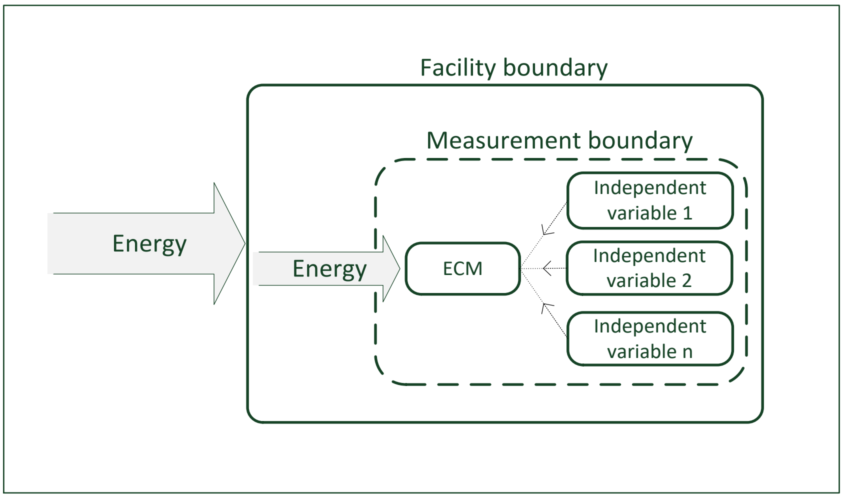

Figure 4: Measurement boundary for Option B: Retrofit isolation all parameters measured

c) Option C – Whole facility measurement

This option places the measurement boundary around an entire facility or a large subsection of a facility. All the energy use within the facility is measured at the boundary for each energy carrier. The most significant variables affecting energy use at the facility are also measured. The final reported savings reflect the net impacts of all the ECMs.

This approach may be selected when several ECMs have been implemented at a single facility, and particularly when there are interactive effects between the ECMs which are difficult to characterise. Very often billing class metering is already in place at large facilities, eliminating the need for new metering.

In order to successfully report energy savings, the IPMVP (2012: 25) only recommends this option in instances where the expected ECM impacts are in excess of 10% of the baseline energy usage. It also recommends this option only in cases where M&V reporting is likely to continue for a number of years. The reason given is that effects of short-term random and unexplained variations in energy use will be reduced through averaging over time.

A typical example where this measurement option might be appropriate would be a large industrial facility where multiple large ECMs have been implemented and are expected to significantly change the energy usage.

It is important to consider that for energy carriers others than electricity, billing invoices do not necessarily reflect the energy use for a particular period as stockpiling can take place, such as with coal or oil. Thus if invoices are to be used, they should be accompanied by carefully prepared estimates of changes to the stockpile inventory for the same period.

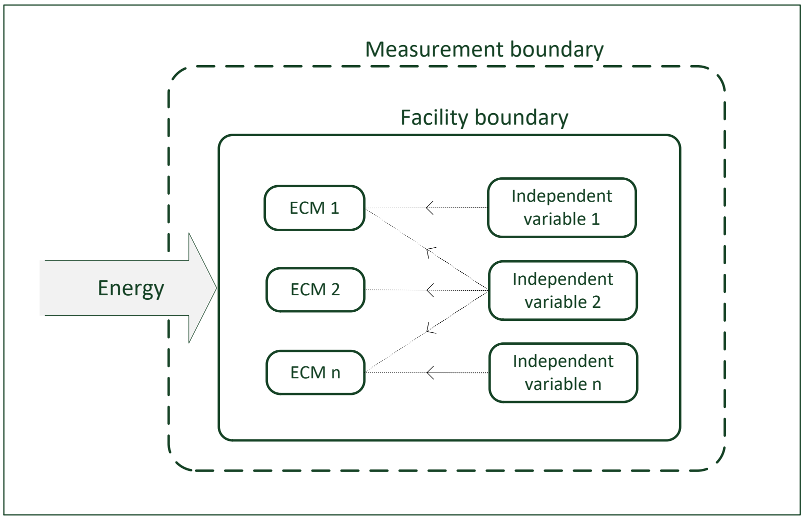

Figure 5: Measurement boundary for Option C: Whole facility measurement

d) Option D – Calibrated simulation

This option involves the use of a computer simulation model to predict the energy use at a facility. Some actual metering of various parameters is required to calibrate the model such that it reasonably predicts energy use within a specified degree of accuracy.

Unlike option C, the simulation model can distinguish the individual impacts of each ECM provided that the facility has been characterised in sufficient detail and provided metered data of each individual subsystem is available to calibrate the model. Option D is not suitable for all facility types, especially some with specific building design features such as large atriums, unusual exterior shapes and those with multiple different temperature control zones (IPMVP 2012: 29).

Motivations for using this option may include a lack of data for either the baseline or reporting periods, where large non-routine adjustments are expected or are very difficult to assess and where the individual impacts of multiple ECMs are required but where options A & B are deemed too difficult or too costly.

The model is required to simulate energy use in terms of both demand and total consumption. It is also suggested that the model is not made to be a black box computation, but be made publicly available for scrutiny by others. Calibration data consists of real energy use data, independent variables and static factors.

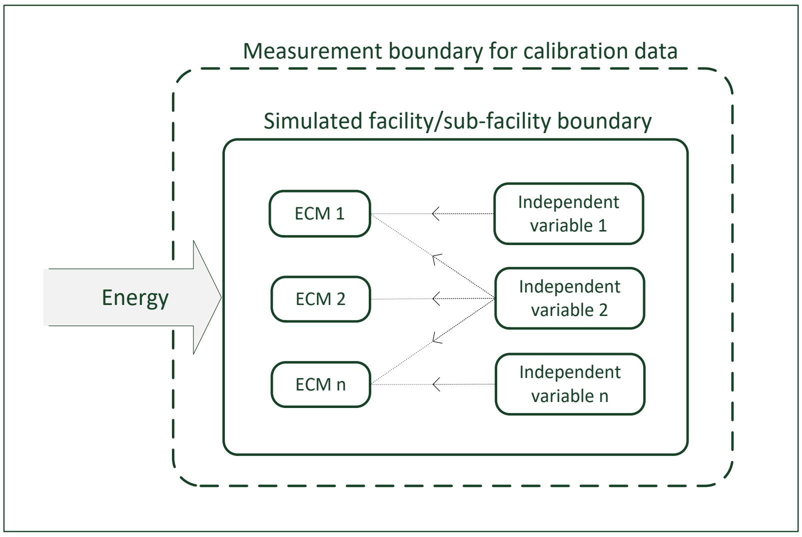

Figure 6: Measurement boundary for Option D: Post-retrofit parameters measured for model calibration

2.1.7 Adjustments

This section provides further details on routine adjustments (using an adjustment model) and non-routine adjustments.

a) Routine adjustments

Routine adjustments are made using an adjustment model to predict what the energy use would have been during the reporting period, but in the absence of the ECM. The literature is not prescriptive about exactly what form an adjustment model should take but rather provides broad guidelines and recommendations about developing a suitable model.

In general, an adjustment model is a mathematical relationship which expresses energy use as a function of one or more significant independent variables. A model is normally unique to a specific ECM at a particular facility and is built using energy data and independent variable data from the same periods prior to the ECM implementation (NSW OEH 2012: 4). However in the interest of reducing costs there is a trend towards using standard methods for ECMs involving common technologies (NREL 2013: 1–3).

It is normal to have some of the energy use explained by independent variables and some which remains unexplained; thus a model need not predict energy use perfectly, but the independent variables selected should be shown to have a significant effect on energy use. The model should use data which represents the full operating cycle of the system or facility affected by the ECM. This typically determines the length of time required to produce an adequate baseline, which may be up to 12 months for facilities where energy use is seasonal.

Routine adjustment models are broadly categorised as either empirical models (also called inverse methods) or engineering models as shown in Figure 7 (ASHRAE 2014: 12).

Empirical models use real-world data and do not necessarily require an in-depth knowledge of the underlying physical processes driving energy use. These models may include more than one independent variable and consist of the following types:

- **Regression**: These can consist of various functional forms, such as simple linear, polynomial, exponential, etc.
- **Linear change point**: These are models which characterise different portions of a facility's operating regime with piece-wise linear approximations.
- **Neural network**: These are software systems which involve computational learning and once 'trained' can be used for predictions.

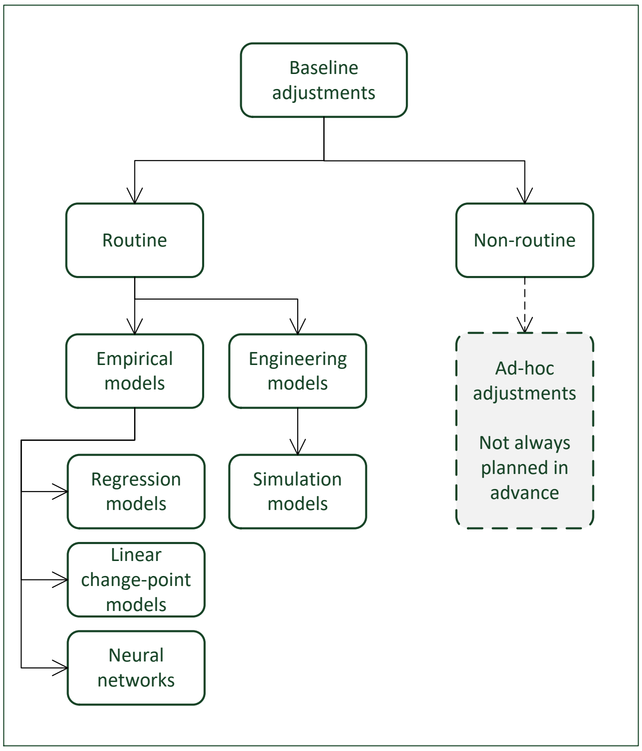

Figure 7: Tree diagram showing baseline adjustment types

Engineering models are computational simulations of the physical processes between independent and dependent variables associated with energy use. Many simulation packages are available for modelling various types of facilities, systems and processes.

Below are some cautionary notes on the development of empirical models for routine adjustments.

- Models should be built with data which is available and will be easily accessible throughout the reporting period.
- Careful judgement is required when deciding whether to include outlier data points which form part of a data set but clearly do not represent routine operations (IPMVP 2012: 6,93).
- In multivariate models, the variables chosen must be independent of one another and should not exhibit covariance (IPMVP 2012: 94).
- Models should only be used to predict energy use using independent variable values which fall within the domain of the values originally used to derive the model (IPMVP 2012: 93).
- The independent variable data from the baseline period should be applied to the model and the resulting energy predictions should be compared to the actual energy used during the baseline period. This is known as a Net Determination Bias test and the result should not exceed 10% of the estimated savings (ASHRAE 2014: 12).

b) Non-routine adjustments

Non-routine adjustments are required for so-called static factors within the measurement boundary. These are factors which, if changed, would affect energy use, but are not expected to change in the normal course of business at the facility (ASHRAE 2014: 12).

For instance, suppose Option C (Whole facility measurement) is being used for the M&V of a certain ECM. If that facility was either expanded or if a large subsection of it was shut down, a non-routine adjustment may be required. The reason is that such a change would generally only occur quite seldom during the reporting period, but is very likely to affect energy use. Other examples of instances which could require non-routine adjustments are changes to equipment and changes in operations. The adjustments could be permanent or temporary (SABS 2011: 8; ASHRAE 2014: 12).

The methods used to perform non-routine adjustments are not necessarily known at the start of M&V reporting as the potential changes to static factors are far more difficult to predict than the routine changes associated with independent variables (ASHRAE 2014: 12).

2.1.8 Interactive effects

Interactive effects (sometimes referred to as leakages) refer to unintended changes in energy use outside of the measurement boundary brought about as a result of the ECM and can either be favourable or unfavourable. These effects may be accounted for or ignored but their potential magnitude should always be quantified and discussed with relevant stakeholders. Interactive effects may be treated differently depending on the measurement option chosen.

For retro-fit isolation (option A or B), the effects may be challenging to quantify without further measurements. If the entire facility being measured (option C), interactive effects are automatically accounted for if they affect the same energy carrier. When option D is used (simulation), accounting for these effects may introduce extra complexity to the simulation model.

2.1.9 Additionality of multiple ECMs

In some instances, multiple ECMs may be planned for the same facility. The combined saving of multiple ECMs is not simply the sum of the expected savings from each ECM if they had been implemented independently without the other ECMs, i.e. the savings are non-additive. This can occur when multiple ECMs are implemented in parallel with overlapping measurement boundaries and so part of the energy available to be saved is effectively split between the ECMs (NSW OEH 2012: 30).

As an example consider an air-conditioned building with potential for energy savings from two separate ECMs. The first measure might be to install more energy efficient fans and motor speed controls and the second measure might be to improve the thermal insulation of the building. When evaluated individually, each of these two measures would each have a certain savings potential. However if the two were implemented simultaneously, the total savings would not equal the sum of the savings achievable from either one ECM if implemented alone. If the building insulation was implemented first, then the system load would be reduced and the impact of installing new fans and speed controls would need to be evaluated against the new reduced load and not against the original scenario.

In order for savings not to be overstated, the overlaps and influences between the various ECMs needs to be well understood. There are various methods for handling additionality problems but they all have the aim of avoiding double-counted savings (NSW OEH 2012: 30).

- The measurement boundary of each ECM may be adjusted so that there is no overlap, allowing each one to be reported on individually.
- The measurement boundary may be expanded to include all of the ECMs involved as a single intervention. This could lead to a revised baseline and require further independent variables.
- The ECMs could be implemented sequentially so that the savings of the first project are reflected in a lower baseline for the second project, and so on.

2.1.10 Missing data

In reality, data sets are very seldom perfect, but small omissions should not hinder M&V reporting from taking place. Rather, a method for handling missing or erroneous data should be documented clearly so that the savings calculation may be replicated independently if required. The missing data should be detailed in all savings reports in terms of the missing quantities of each parameter. Missing independent variable data may be derived from the full range of data in adjacent time intervals. Missing dependent variable data may be derived from the full range of independent variable data from the missing time interval. However, in all cases, the data set used to derive the missing data should be at least an order of magnitude larger than the derived data (ASHRAE 2014: 12).

2.1.11 Uncertainty

The energy saved by an ECM can never be stated with absolute certainty and so should always be expressed as an estimate which falls within a given range of precision at a specified level of confidence. From a statistical point of view, a saving is not deemed valid unless it is at least twice the size of the standard error of the adjusted baseline (IPMVP 2012: 88). The uncertainty of an ECM saving is an important risk factor from an investment standpoint, and it could also play a very important role if the ECM savings were challenged in court (ASHRAE 2002: 102).

However, a thorough and rigorous uncertainty analysis may be very complex and can significantly increase the costs of M&V (ASHRAE 2002: 106) as illustrated in Figure 8 (DOE 2015: 5–4). One of the most important, albeit challenging aspects of M&V is that it to keep costs low while achieving an acceptable range of uncertainty (DOE 2015: 5–3). The incremental cost increases need to be justified by the value added by improved uncertainty and assumptions to simplify uncertainty calculations may be warranted (ASHRAE 2002: 13,20). One rule suggests that M&V costs should be within 2-5% of expected annual cost savings resulting from the ECM and this is one way of informing the effort spent on improving uncertainty (DOE 2015: 5–4).

The main sources of quantifiable uncertainties are listed below.

a) Measurement

Metering accuracies are published by the manufacturers, although these are usually at full-scale measurement, so meters should not be oversized. Poor meter placement can introduce errors, for example a poorly placed flow meter in a pipe. The environmental conditions where a meter is installed could exceed the design limitations and the accuracy of sensors also naturally drift over time. In order to mitigate these risks meter installations should always follow best practice, meters should be of a high quality and fit for purpose, and drift can be managed through a calibration programme.

b) Sampling

Sampling can be used in a spatial sense where only a portion of the total number of units under study are measured, and also in a temporal sense where measurements are only taken for some of the total time being analysed. Care is needed to sample randomly to avoid data bias. Sampling is used primarily to reduce costs and the uncertainty it introduces is well understood from statistics.

c) Modelling

Modelling is likely to introduce the most significant component of uncertainty in an M&V calculation (ASHRAE 2002: 106). Energy use regression models never perfectly explain energy use as a function of the independent variables. Some important variables may have been excluded, less important ones included, the model could be of the wrong form or the data set could be poor (IPMVP 2012: 93).

The accuracy of a model can be tested statistically using the following tests, all of which are shown in Appendix A.

- **Coefficient of determination (R^2)**: This ranges from 0 – 1 and some texts suggest that an $R^2 \geq 0.75$ implies that the model is reasonable predictor, although in isolation this test is insufficient to validate the model (IPMVP 2012: 95).
- **Coefficient of variation of the root-mean square error (CV_{RMSE})**: Used in conjunction with the above R^2 value, it has been suggested that a $CV_{RMSE} < 7\%$ implies a reliable model (Eskom 2007: 12).
- **Mean Bias Error (MBE)**: It has been suggested that an absolute value of the MBE < 7% indicates an acceptable model (Eskom 2007: 12).

However, ASHRAE (2002: 106) has questioned the above model criterion as they seem to be arbitrarily chosen limits which cannot guarantee a specific level of final reporting uncertainty. It is argued that an acceptable fractional uncertainty in the savings should rather be chosen beforehand which would then dictate the model accuracy requirements.

Some errors are not quantifiable and need to be evaluated subjectively. These errors may include human error, random error, poor estimation of interactive affects, poor technique and poor assumptions. The impact of these random unexplained errors is minimised as the period of assessment lengthens (ASHRAE 2002: 108; IPMVP 2012: 25).

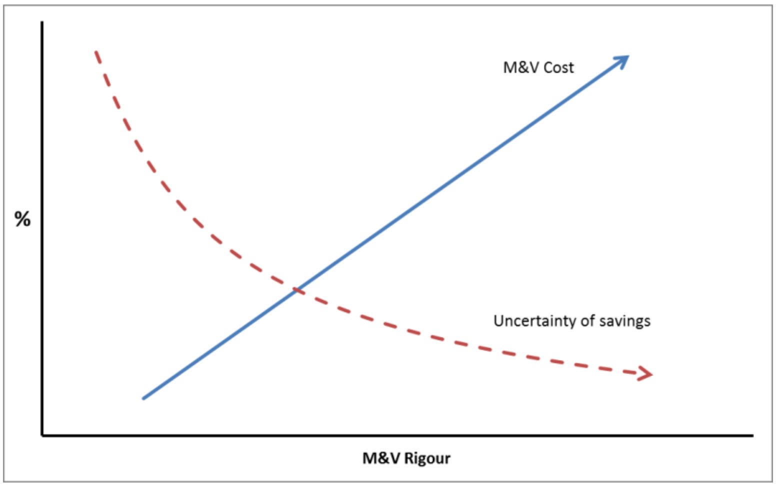

Figure 8: Trend of savings uncertainty vs M&V costs adapted from DOE (DOE 2015: 5–4)

2.1.12 M&V Plan

The M&V Plan is the reference document which specifies all aspects of how the M&V will be undertaken and is agreed before the ECM is implemented. It is usually written in consultation with technical staff at the facility and the engineers who designed the ECM. It forms an upfront agreement by all parties and must include at least the following information (IPMVP 2012: 36; NSW OEH 2012: 12).

- A thorough description of the facility.
- The scope of the intended ECM and the expected savings.
- Specification of measurement equipment, which could include responsibility for purchase and commissioning of meters.
- Minimum data requirements for the duration of the baseline and reporting periods, including energy data and independent variable data.
- The measurement option and the measurement boundary chosen, considering additionality issues which could arise in the case of multiple ECMs.
- The methodology for performing routine baseline adjustments including the actual planned adjustment model.
- Details of static factors and provision for non-routine baseline adjustments.
- The duration of the baseline and reporting periods.
- The reporting requirements in terms of format, content, distribution and expected dates of issue.
- Description and justification of any assumptions that are to be used.
- The methodology used to derive missing data.
- Details of planned site visits before and after the ECM implementation.
- Treatment of reporting uncertainty.
- Method of handling foreseen interactive effects.
- Records of reference materials used in compiling the M&V plan.
- In the case of a simulation being used (Option D), the software type, version and calibration data details need to be provided.
- Provision for how the M&V methodology may be revised should the actual ECM deviate from that which was planned.

2.2 Coal fired power plants

2.2.1 The ideal Rankine cycle

CFPPs employ steam as the working fluid which operates on the Rankine cycle, consisting of the following four idealised stages shown in Figure 9 and Figure 10 (Cengel & Boles, 2008: 567–569). The cycle shown here is said to be subcritical as the fluid pressure & temperature never exceed the critical point of the saturation curve. (Most modern plants employ a reheat cycle but this is not featured in the CFPP of this study, thus the focus here is on the simple ideal Rankine cycle).

- **1-2: Isentropic compression**. The fluid (feedwater) pressure is increased to the boiler pressure in a boiler feed pump (BFP).
- **2-3: Constant pressure heat addition**. Heat from burned fuel is transferred to the fluid as it passes through the boiler until it is superheated.
- **3-4: Isentropic expansion**. The superheated steam expands through a turbine which drives an electrical generator.
- **4-1: Constant pressure condensation**: The fluid leaving the turbine exhaust is condensed by transferring its latent heat to a cold heat sink.

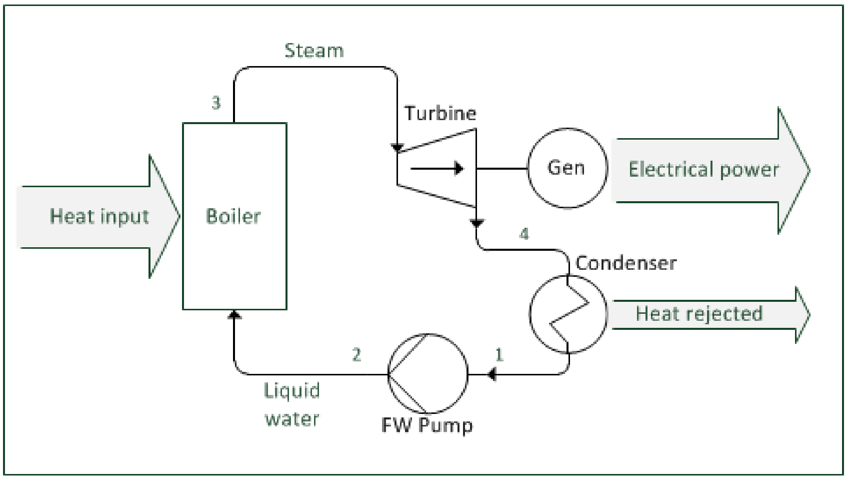

Figure 9: The major components of a steam power plant.

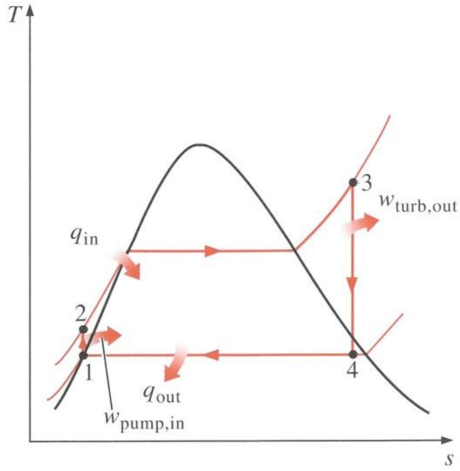

Figure 10: A Temperature-Entropy diagram of the ideal Rankine cycle (Cengel & Boles, 2008: 567).

2.2.2 Real Rankine cycles

In reality these stages are negatively affected by several factors which cause the cycle to deviate from the ideal as explained below (Cengel & Boles, 2008: 571–572).

- Fluid friction in the piping causes pressure drops in and between the various plant components. This is shown in Figure 11 as dashed lines 2-3 and 4-1.
- Heat is lost to the surroundings due to imperfect insulation.
- The real behaviour of the turbine and the BFP is not isentropic. This is shown as a characteristic deviation in Figure 11 as dashed lines 1-2 and 3-4.
- The condensate formed in the condenser is intentionally cooled to slightly below the minimum temperature required for complete condensation. This is done to prevent cavitation at the intake of the condensate extraction pump (CEP).

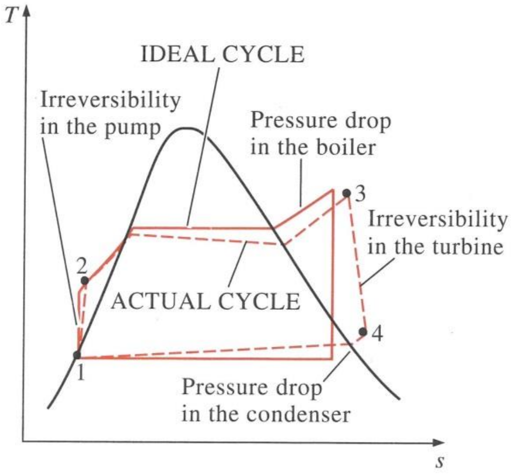

Figure 11: Deviations of a real cycle from an ideal one (Cengel & Boles, 2008: 572).

2.2.3 Design improvements for efficiency

Before any equipment inefficiencies have been accounted for, the theoretical efficiency of this cycle can be improved by increasing the boiler pressure, reducing the condenser pressure, increasing the maximum temperature of the superheated steam and reheating the steam using a second superheater pass through the boiler; however this is not used in all older designs (Cengel & Boles, 2008: 574–575).

Another method of improving CFPP efficiency which is employed universally is the use of feedwater heaters (FWHs). This uses a small amount of steam from various stages of the turbines (bleed steam) to heat the condensed feedwater before it enters the boiler. Some superheat and all of the latent heat from the bleed steam is transferred to the feed water rather than rejected in the condenser (Cengel & Boles, 2008: 582).

2.2.4 Auxiliary power use

Not all of the power generated by a steam power plant is available for export as some power is required to run major pieces of plant equipment. This is usually called auxiliary power[11] and is quoted as a percentage of gross power generated. A 'unit' is an entire generator set from boiler through to turbo-generator with all its own auxiliary equipment which could operate as a standalone unit.

Auxiliary power needs range from 5% - 10% for older plants and from 7% - 15% for newer plants. The higher demand for newer plants is due to the power needs of flue gas cleaning equipment and higher BFP demands in supercritical plants (Gellings, 2013: 389). Figure 12 below shows the breakdown of major auxiliary loads for a typical CFPP. Table 1 from another study is more detailed and shows typical ranges for plant auxiliary loads (Gellings, 2013: 390).

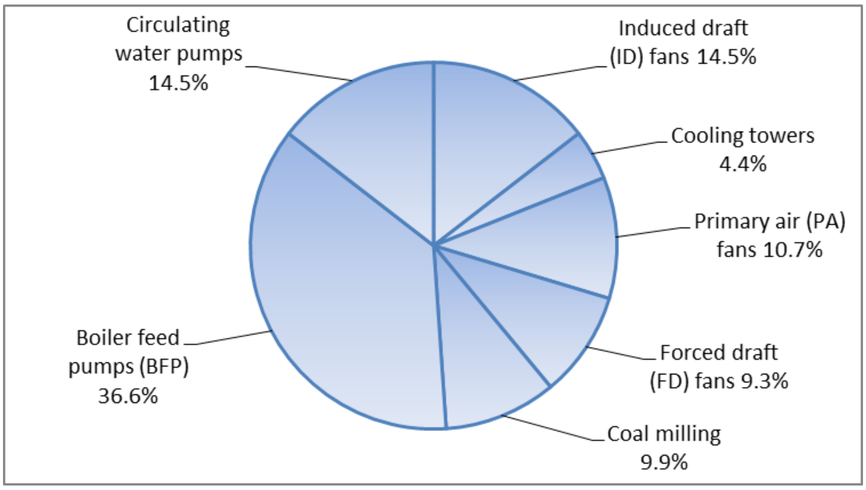

Figure 12: Typical breakdown of major auxiliary loads (Gellings, 2013: 390)

Table 1: Breakdown of auxiliary power consumption (Gellings, 2013: 390)

Subsystems	**Contribution to Auxiliary Power**
Draft System (forced draft (FD) fans, primary air (PA) fans and induced draft (ID) fans)	~ 30 %
Feed Water System (Condensate extraction pumps (CEPs), LP Heaters, Deaerator, Boiler feed pumps (BFPs), HP heaters and Economisers)	25 – 35 %
Milling system (Mills or pulverisers)	6 – 7 %
Circulating Water (CW) System (cooling water pumps and cooling towers)	9 – 17 %
Coal Handling Plant (CHP)	1.5 – 2.5 %
Ash Handling System (ash water pumps and ash slurry series pumps)	1.5 – 2 %
Compressed Air System (instrument air compressors (IAC) and process compressors (PAC) and air drying units)	1 – 1.5 %
Air Conditioning System	0.5 – 1 %
Lighting System	0.8 – 1 %

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[11] This is also sometimes referred to as "Parasitic power" or "Works power".

2.3 Heat rate definition

The heat rate (HR) of a coal-fired power plant (CFPP) is the quantity of thermal input energy required to produce a unit of useful electrical output energy and is inversely related to plant energy efficiency as shown in Equation 4 (IEA 2010: 31). HR and efficiency are equally useful measures of performance and although some countries have a convention of using one term or the other, the terms are sometimes used together (IEA 2010: 24,91,109). The units for HR used here are (kJ/kWh) but it could also be expressed in other units such as (Btu/kWh) (Power 2015: 54).

Equation 2 $$\eta = \frac{E_{OUT}}{E_{IN}}$$

Where $\eta = \text{Plant thermal efficiency}$

$E_{OUT} = \text{Useful electrical energy output (kJ)}$

$E_{IN} = \text{Total thermal energy input (kJ)}$

Equation 3 $$E_{IN} = m \times HV$$

Where $E_{IN} = \text{Total thermal energy input (kJ)}$[12]

$m = \text{mass of coal consumed (kg)}$

$HV = \text{Coal heating value (kJ/kg)}$

Equation 4 $$HR = \frac{3600}{\eta}$$

Where $HR = \text{Plant heat rate (kJ/kWh)}$

$\eta = \text{Plant efficiency}$

These definitions alone do not fully specify plant performance. Any quoted HR, or change in HR, needs to specify the basis on which it has been calculated including: gross or net electricity produced; higher or lower fuel heating values; moisture base and whether percentage changes to performance are referring to HR or to efficiency.

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[12] Some plants may include startup fuel in this calculation but others may consider it negligible.

2.3.1 Gross vs Net heat rate

As described in Section 2.2.4, some of the generated power is needed on site to drive auxiliary equipment. Although the plant supplies electricity to the grid, it also has a supply from the grid which provides auxiliary power when the plant is initially started. It is also possible that some of the auxiliary equipment could be powered permanently by imported electricity[13].

Gross HR (HR_G) uses the total electricity generated whereas Net HR (HR_N) uses only the net electricity sent out to the grid. HR_N is often considered the more important performance indicator as it accounts for the entire CFPP including the performance of all auxiliary systems and equipment (EPRI 2014: 1–1). To find HR_G or HR_N, E_{OUT} is found using Equation 5 and Equation 6 respectively.

Equation 5

$$E_{OUT} = E_G$$

Equation 6

$$E_{OUT} = E_N = E_G - E_A - E_I$$

Where E_N = Net useful electrical energy output (MWh)[14]

E_G = Electrical energy generated within the plant (MWh)

E_A = Auxiliary electrical energy (MWh)

E_I = Imported electrical energy (MWh)

2.3.2 Coal measurements

National and international standards exist stipulating the methods for sampling, handling, preparation and laboratory analysis of coal. These are listed in Appendix B.

a) Heating values[15]

The heating value of coal is its most important characteristic and is found by burning a unit mass of sampled coal in a bomb calorimeter under carefully controlled conditions (IEA 2002: 12, IEA 2010: 45). The typical combustion products are ash, CO_2, SO_2, N_2 and H_2O. The Higher Heating Value (HHV) is determined by allowing the water produced to condense and thus includes the latent heat of condensation. The Lower Heating Value (LHV) is the value of heat released if all the water produced remains in the vapour state (Babcock & Wilcox [B&W] 1972: 5–16). Various conversion formulae

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[13] This is the case with the power plant related to this study.

[14] In some plants which produce electricity and heat, this term may also include the useful heat exported (IEA 2010: 27).

[15] The terms HHV and LHV are also known as Gross Calorific Value (GCV) and Net Calorific Value (NCV) respectively, however these terms have intentionally not been used here to avoid confusion with the terms Net and Gross related to HR.

exist to find LHV using the HHV together with the results of proximate or ultimate coal analyses (IEA 2010: 47).

When the coal is burned in a boiler the latent heat of condensation is very rarely recovered and is normally exhausted in the flue gas. Although this represents a loss, one of the reasons for this is to avoid the formation of corrosive acids in the flue gas (IEA 2010: 54). There are arguments to be made both for using LHV and HHV and there is no strict standard when determining overall plant HR. HHV is used very widely internationally but there are exceptions, including Germany (IEA 2010: 98).

Using either HHV or LHV will cause an apparent difference in the calculated thermal efficiency of a plant. Efficiency will appear higher if the LHV is used and vice versa.

b) Moisture measurement base

The moisture content of coal found during laboratory analysis is known as total moisture and is the sum of the surface moisture and inherent moisture. Surface moisture exists on the outer exposed surfaces of the coal whereas inherent moisture exists in the porous organic structure of the coal[16] (IEA 2005: 6). Once the coal has been sampled, the sample is sealed until the time of analysis as the surface moisture is affected by changes in ambient temperature and humidity.

The sample is received by the laboratory on an ‘as received’ (AR) basis. At that point both surface moisture and inherent moisture are present and an immediate analysis will yield the total moisture. In order to determine the inherent moisture the analysis is carried out on an ‘air dried’ (AD) sample where the bulk of the surface moisture is first allowed to evaporate (IEA 2002: 14). The surface moisture is then found as the difference between the total moisture and the inherent moisture. The inherent moisture is also used to convert the coal sample properties to a ‘dry basis’ (DB). It should be noted that an analysis of a sample on an AD basis could yield different results at different laboratories purely owing to differing ambient conditions.

When quoting coal properties the base of measurement should always be specified. In the literature, sometimes AD refers to ‘as determined’ rather than ‘air dried’. ‘As determined’ refers to the total moisture content obtained at the time of analysis (Elliott, Chen & Swanekamp, 1997: 1–14). This evidently has the same meaning as AR above, leaving potential for confusion. ‘As fired’ (AF) reflects a sample being taken just prior to combustion.

2.3.3 Note on percentages

A clarification is warranted here on percentages as percentages and percentage-points are commonly confused when referring to HR and efficiency of a CFPP (IEA 2010: 76).

Efficiency is already quoted as a percentage and thus a “% change” is understood to be a “%-point change.” For example, a 1% improvement to an efficiency of 30% implies a new value of 31%, not 30.3%. However, this is not so with HR. A 1% improvement to a HR of 10,000 (kJ/kWh) would imply a new value of 9900, (kJ/kWh) (IEA 2010: 76).

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[16] Some moisture in the form of water of crystallisation in the mineral matter is not measured in standard analyses. This water varies with inorganic content and can account for up to 2% of the sample mass (IEA 2002: 14).

At a HR of 12,000 (kJ/KWh), a 1% HR improvement equates roughly to a 0.3%-point improvement in efficiency.

Table 2 shows the permutations of factors mentioned which would result in twelve different calculated HR values for a particular plant, none of which would be incorrect. However, for a fair comparison of one HR to another there must be consistency between the two calculations.

Table 2: Potential permutations of calculation variables which have an apparent effect on Heat Rate

	Lower Heating Value (LHV)	**Higher Heating Value (HHV)**
Net Heat Rate (HRN)	As received (AR)	AR
	Air dried (AD)	AD
	Dry basis (DB)	DB
Gross Heat Rate (HRG)	AR	AR
	AD	AD
	DB	DB

2.4 Methods of determining whole plant heat rate

This section describes and briefly compares two methods of determining CFPP HR which are in common use internationally (Australian Greenhouse Office [AGO] 2006: 48–51; IEA 2010: 101,109). These methods seek to establish the actual operational HR under real world conditions rather than a theoretical value or that which was found during acceptance testing, so neither method provides the best potential performance. If either method is used on a single unit rather than an entire plant, care needs to be taken that the auxiliary power measured is only supplying auxiliary equipment related to that particular unit (IEA 2010: 33).

2.4.1 The direct method[17]

This is the simpler of the two methods and draws the measurement boundary around the entire plant or unit. Rearranging the equations of Section 2.3, HR_N is obtained as follows.

Equation 7

$$HR_N = \frac{3600 \times m \times HV}{E_N}$$

$Where\ \ HR_N = Net\ plant\ heat\ rate\ (MJ/MWh)$

$m = mass\ of\ coal\ consumed\ (kg)$

$HV = Average\ coal\ heating\ value\ (MJ/kg)$

$E_N = Net\ useful\ electrical\ energy\ output\ (MWh)$

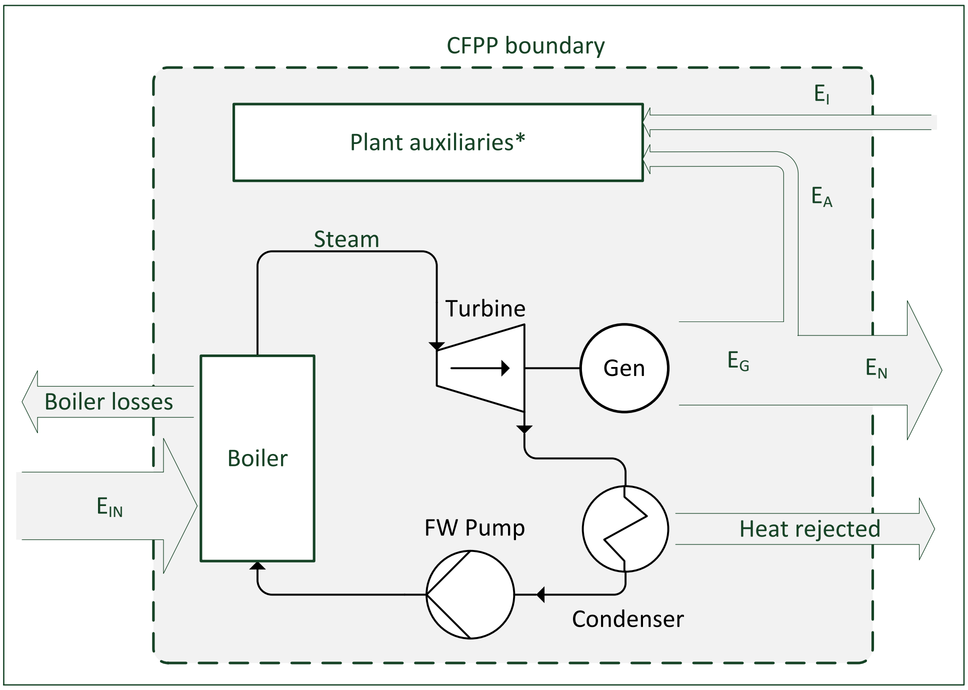

Figure 13: Measurement boundary for the direct method

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[17] Also known as the "Input/Output method". These terms are also used to refer to methods for finding boiler efficiency, however in this context they refer to whole plant efficiency.

The variables in Equation 7 all refer to a specified time period for which the HR is being determined and the period should always be quoted as well to provide context for the HR. Performing this calculation on an annual basis is recommended as that accounts for seasonal variations in ambient conditions, cooling water temperature and capacity factor. It will also tend to reduce the impacts of short-term operating problems (IEA 2010: 29).

Test standards

The use of standards is valuable as it provides some degree of consistency and the IEA has considered two standards for use in analysing whole plant performance. These are the US ASME PTC46-*Performance Test Code on Overall Plant Performance*, and the German standard VDI 3986 *Determination of Efficiencies of Conventional Power Stations*.

However the main aim of these standards is to perform short term tests to determine whether contractual requirements have been met. Importantly, these standards are not highly prescriptive and do not guarantee consistency. In particular, the VDI 3986 standard allows for deviations in the methodology used provided these are agreed to by the contract parties (IEA 2010: 31).

a) Relative merits of the direct method

Advantages

- It can be applied to either an entire plant or a single generating unit.
- There is no need to try and track internal energy flows within the plant.
- It is very simple.

Disadvantages

- It is not possible to pinpoint where in the plant inefficiencies may exist.
- The uncertainty associated with this method is directly affected by the accuracy of the measurement equipment. Measurement equipment needs to be maintained and regularly calibrated (IEA 2010: 29). The mass of coal burned also requires estimates of changes to coal stockpiles, which introduce further uncertainty.

Comments

The IEA estimates that for a well-managed plant the direct method can yield a HR with an accuracy of ±1%, but only ±5% for a poorly-managed plant (IEA 2010: 29). Others however argue that the measurement inaccuracies mentioned negate the credibility of this method altogether (Nowling, 2015: 54).

2.4.2 The components method[18]

This method divides the plant into three major subsystems and evaluates the efficiency of each of them separately. Then these are combined to find the overall plant efficiency. The major components are the boiler, the turbine-condenser cycle and the balance of the plant auxiliary loads. This method is typical of testing the performance of plants where the major components are all from different vendors and have different performance targets. Figure 14 below shows an example of the boundaries that may be used (Nowling, 2015: 55).

Equation 8

$$\boldsymbol{HR_N = \frac{1}{\eta_B} \times \frac{3600}{\eta_{TG}} \times \frac{E_G}{E_N}}$$

Where $\eta_B = \text{Boiler efficiency } (\%)$

$\eta_{TG} = \text{Overall turbo-generator cycle efficiency } (\%)$

$E_G = \text{Generated electrical energy } (MWh)$

$E_N = \text{Net useful electrical energy output } (MWh)$

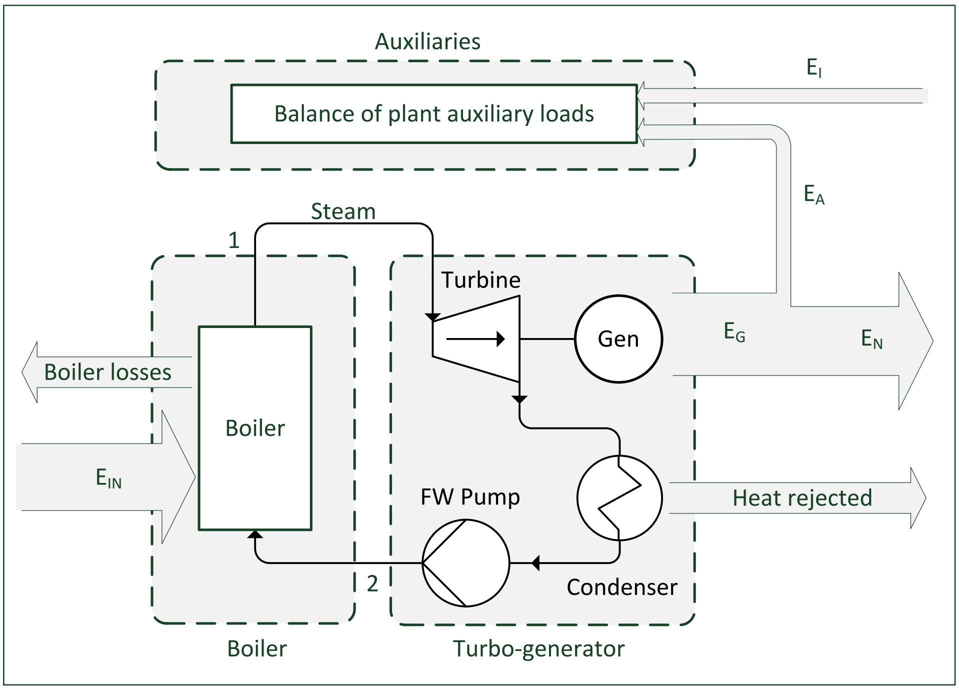

Figure 14: Boundaries of the boiler, turbine-condenser cycle & auxiliaries used in the components method

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[18] Also known as the "Indirect method" or "Heat-loss method". These terms are also used to refer to methods for finding boiler efficiency, however in this context they refer to whole plant efficiency. When using this method for plant efficiency, the efficiency of the boiler may be found either directly or indirectly.

The following sections explain the typical methods of finding the efficiency of each of these major plant components. Two different ways of finding boiler efficiency are explained. Although the two methods should yield the same results, the heat-loss method is often viewed as superior as it avoids the need for very accurate fuel and steam flow measurements. However the method selected should be based on the availability and accuracy of data rather than the fact that one method is seen as superior to the other (Gay, Palmer & Erbes, 2004: 369).

a) Boiler efficiency (Heat-loss method)

The efficiency of a pulverised fuel (PF) boiler is found by measuring the heat energy entering the boiler as pulverised coal and accounting for all of the losses incurred in the production of steam (Gay, Palmer & Erbes, 2004: 368; AGO 2006: 50).

Equation 9

$$\eta_B = \left[1 - \frac{\sum L_i}{HV}\right] \times 100$$

Where η_B = Boiler efficiency (%)

L_i = Boiler specific losses per kg of fuel burned (kJ/kg)

HV = Heating value of the coal (kJ/kg)

The boiler losses are categorised and discussed below. Whenever the “Flue gas temperature” is referenced, this really is referring to the temperature of the flue gas directly after the final heat exchanger where any more heat could be extracted from it, rather than the temperature at which the gas leaves the stack and is exhausted to the atmosphere.

Flue gas losses

These losses are associated with the net rise in temperature of the products exiting the boiler with respect to the initial temperature of the reactants. These represent the most dominant of all the boiler losses and are inevitable as the flue gas temperature is intentionally kept above the dew point to prevent the formation of corrosive acids (IEA 2010: 54).

Dry air losses

All of the N_2, CO_2, SO_2, O_2, and other gases which leave the stack at an elevated temperature represent sensible heat lost to the atmosphere (B&W 1972: 6–10). Typically excess air of 15-20% is used to try and ensure that as much carbon as possible is burned[19]. For boilers where the combustion takes place at below atmospheric pressure, air in-leakage is another source of excess air which decreases efficiency (B&W 1972: 6–10; Gay, Palmer & Erbes, 2004: 370). A common rule of thumb used in industry is that a 40°F (22.2°C) increase in flue gas temperature results in a 1% decrease in boiler efficiency (Gay, Palmer & Erbes, 2004: 370).

Equation 10 accounts for theoretical losses to each individual gas type found in the flue gas. However, sometimes in practice this calculation is simplified by treating the flue gas as a single gas

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[19] Excess air is extra air introduced into the boiler to attempt complete combustion of all the carbon into CO2. It is expressed as a percentage of the theoretical stoichiometric amount of air required.

type and using a mean specific heat available from tables for different fuel types (B&W 1972: 6–12; Gay, Palmer & Erbes, 2004: 377; AGO 2006: 49).

Equation 10 $$L_{DA} = \frac{1}{100} \times \sum_i^n x_i \times c_i \times (T_F - T_I)$$

Where L_{DA} = *Dry flue gas loss per kg of coal burned (kJ/kg)*

x_i = *Fractional mass of each flue gas type per kg of coal burned (%)*

c_i = *Specific heat of each flue gas type (kJ/kg.K)*

T_F = *Flue gas temperature (°C)*

T_I = *Inlet temperature of the combustion air (°C)*

Air moisture losses

The moisture in the air which enters the boiler leaves in the flue gas at an elevated temperature which is sensible heat lost to the atmosphere (B&W 1972: 6–12; Gay, Palmer & Erbes, 2004: 379).

Equation 11 $$L_{MA} = m_V \times m_A \times (h_{g@T_F} - h_{g@T_I})$$

Where L_{MA} = *Flue gas moisture losses per kg of coal burned (kJ/kg)*

m_V = *Mass of water vapour per kg of combustion air (kg/kg)*

m_A = *Mass of combustion air per kg of coal (kg/kg)*

$h_{g@TI}$ = *Enthalpy of water vapour at the inlet temperature (kJ/kg)*

$h_{g@TF}$ = *Enthalpy of water vapour in flue gas (kJ/kg)*[20]

Coal moisture losses

These are the sensible and latent heats lost during temperature increases and vaporisation of the surface and inherent moisture present in the coal at the time of burning (B&W 1972: 6–12; Gay, Palmer & Erbes, 2004: 378).

Equation 12 $$L_{MC} = \frac{M_C}{100} \times (h_{g@T_F} - h_{f@T_I})$$

Where L_{MC} = Losses due to moisture in the coal (kJ/kg)

M_C = Fractional mass of total coal moisture per kg of coal burned (%)

$h_{f@TI}$ = Enthalpy of liquid-state water in the coal (kJ/kg)

$h_{g@TF}$ = Enthalpy of water vapour in flue gas (kJ/kg)[20]

Losses due to water formed from hydrogen in the coal

These are the sensible and latent heats lost during temperature increases and vaporisation of the water formed as a result of combustion of hydrogen in the coal (B&W 1972: 6–12; Gay, Palmer & Erbes, 2004: 379).

Equation 13 $$L_{HC} = \frac{9H_C}{100} \times (h_{g@T_F} - h_{f@T_I})$$

Where L_{HC} = Losses due to water formed due to hydrogen in the coal (kJ/kg)

H_C = Fractional mass of hydrogen in the coal per kg of coal burned (%)

9 = Approximate molecular weight ratio of H_2O:H_2

$h_{f@TI}$ = Enthalpy of liquid water formed at the inlet temperature (kJ/kg)

$h_{g@TF}$ = Enthalpy of water vapour in flue gas (kJ/kg)[20]

Ash heat losses

Ash is the residue of combustion and consists mainly of thermally decomposed and oxidised inorganic mineral matter which was originally present in the coal such as silicates, carbonates and disulphides (IEA 1993: 21, IEA 2002: 10). Both the fly ash and the bottom ash exit the boiler at a higher temperature than the coal which was burned and thus carry sensible heat which is not recovered.

Fly ash

This ash remains in suspension in the flue gas and can constitute between 30% and 80% of the total ash produced. The bulk of it is typically removed with cleaning equipment such as an ESP or bag filter (B&W 1972: 12–3).

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[20] This enthalpy corresponds to the partial pressure of the water vapour at that temperature.

Bottom ash

This ash accumulates below the furnace and depending on the furnace design it is removed either as dry ash from the bottom hopper, or it is tapped off as liquid slag (IEA 1972: 12–6).

Equation 14

$$L_{HA} = \frac{A_C}{100} \times \sum_i^n x_i \times c_A \times (T_F - T_I)$$

Where L_{HA} *= Losses due to sensible heat in the ash per kg of coal burned (kJ/kg)*

A_C *= Fractional mass of ash produced per kg of coal burned (%)*

c_A *= Specific heat of the ash (kJ/kg.K)*

T_{AF} *= Temperature of the ash exiting the boiler (°C)*

T_{CI} *= Inlet temperature of the pulverised coal (°C)*

Unburned combustible losses

These losses consist of the carbon and volatiles in the fuel which fail to oxidise and represent inefficiencies as this fuel was supplied to the boiler but did not produce the requisite heat for steam production. These losses are influenced by excess air, fuel volatility and fuel fineness (Nowling, 2015: 56).

Unburned carbon

This can occur even where good mixing and excess air is used and it leaves the boiler in the ash (B&W 1972: 6–12).

Equation 15

$$L_{CA} = \frac{A_C}{100} \times \left[\frac{C_A}{100 - C_A}\right] \times HV_C$$

Where L_{CA} *= Losses due to unburned carbon in the ash (kJ/kg)*

A_C *= Fractional mass of ash in the coal (%)*

C_A *= Fractional mass of unburned carbon in the ash (%)*

HV_C *= Heating value of the carbon char in the ash (kJ/kg)*

Unburned carbon monoxide

In a PF boiler the carbon is mainly oxidised in two steps: firstly as C + ½O_2 → CO, and then secondly CO + ½ O_2 → CO_2 (IEA 2005: 19). The second step is crucially important as it accounts for approximately 72% of the total heat released in the two-step reaction (B&W 1972: 6–4). However sometimes this second step is not completed and the flue gas contains carbon monoxide.

Equation 16

$$L_{CO} = M_{CO} \times (HV_{CO2} - HV_{CO})$$

Where L_{CO} = *Losses due to incomplete combustion of carbon flue gas (kJ/kg)*

M_{CO} = *Mass of CO in the flue gas per kg of coal burned (kJ/kg)*

HV_{CO2} = *Heating value of* CO_2 *(kJ/kg)*

HV_{CO} = *Heating value of CO (kJ/kg)*

Radiation and convection losses

These are heat losses due to the exposed outer hot surfaces of the boiler and increase percentage-wise with decreasing boiler size. These losses are also negatively affected by part-load operation, low ambient temperatures and wind. These losses are normally estimated using charts published by the ABMA and typically range from 0.2 – 10% of the gross heat supplied to the boiler (B&W 1972: 4–19,20).

Unknown losses

These losses are not measured or explicitly accounted for in any of the preceding major categories and usually range from 0.5% – 2% (Nowling, 2015: 56).

Summary of losses

The Sankey diagram in Figure 15 provides a visual idea of the order of magnitude of the typical losses associated with a bituminous coal boiler (Energy Research Institute (ERI) n.d.: 80; B&W 1972: 6–14).

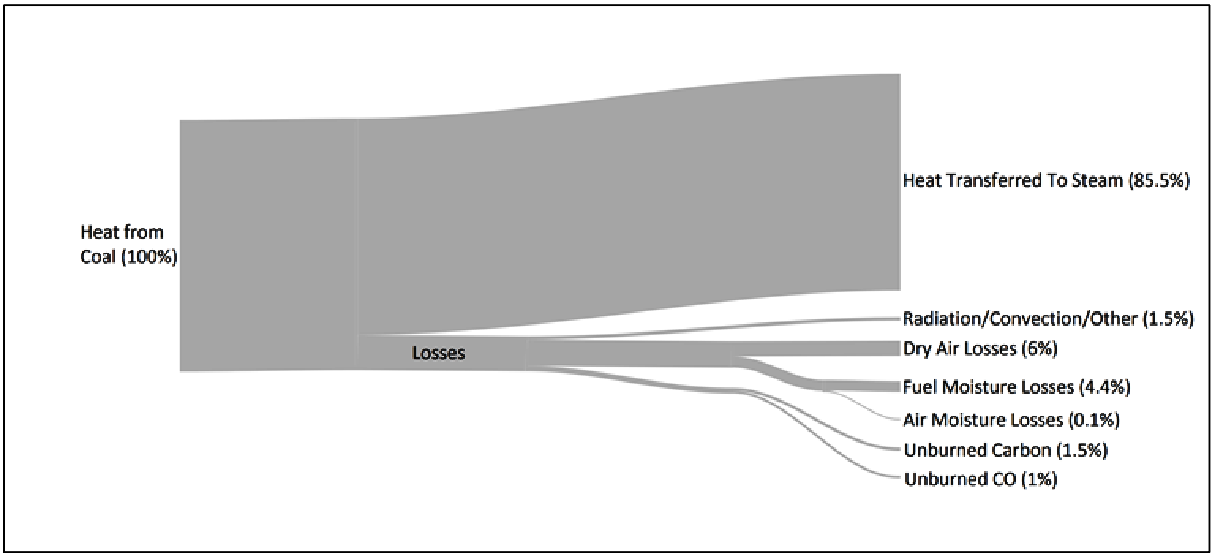

Figure 15: Approximate magnitudes of the losses typical of a bituminous coal boiler (www.sankeymatic.com n.d.)

Boiler credits

Gay (2004: 381) recommends that all electrical power inputs to the boiler should also be accounted for. These inputs include power to the PA fans, FD fans, ID fans and coal pulverisers. However these could also be accounted for in the total plant auxiliary power use as in Equation 6. The same principle applies to the BFP in Equation 18.

Test standards

Numerous standards exist for formally evaluating boiler performance under test conditions. However these standards are not all consistent. In order for performance tests on the same plant to be comparable, the same standard should be used in a consistent way with the same assumptions, system boundaries and agreed amendments. The IEA (2010: 30) suggests that these standards are not suitable for use under normal operating conditions. Some standards are listed in Appendix B.

b) Boiler efficiency (Direct method)

It is also possible to determine boiler efficiency by direct measurement of input and output energy.

Equation 17

$$\eta_B = \frac{m'_{FW} \times (h_S - h_{FW})}{m'_C \times HV}$$

Where η_B = Boiler efficiency (%)

m'_{FW} = Mass flow rate of HP feedwater to boiler (kg/s)

h_S = Enthalpy of superheated steam upstream of the HP turbine (kJ/kg)

h_{FW} = Enthalpy of HP feedwater supply to boiler (kJ/kg)

m'_C = Mass flow rate of coal burned (kg/s)

HV = Heating value of the coal (kJ/kg)

c) Turbine-Condenser cycle efficiency

The efficiency spoken of here is not the isentropic or even the real efficiency of the turbine as an isolated device, but rather the overall efficiency of the entire vapour power cycle.

Equation 18[21]

$$\eta_{TG} = \frac{P_G}{m'_{FW} \times (h_S - h_{FW})}$$

Where η_{TG} = Net turbo-generator cycle efficiency (%)

P_G = Gross generated electrical power (MW)

m'_{FW} = Mass flow rate of HP feedwater to boiler (kg/s)

h_S = Enthalpy of superheated steam upstream of the HP turbine (kJ/kg)

h_{FW} = Enthalpy of HP feedwater supply to boiler (kJ/kg)

This is a single efficiency indicator which automatically accounts for the steam cycle losses from the point the steam exits the boiler to the point of re-entry. These include the equipment and system inefficiencies inherent in the original design, as well as losses due to performance degradation. Losses include rejected heat, turbine and generator inefficiencies, steam leaks, condensate sub-

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[21] In the case of a cycle which employs reheat, this equation would need to include the energy added to the steam during the reheat phase.

cooling, feedwater heater losses, condenser and cooling tower losses, piping frictional losses and air in-leakage (AGO 2006: 51; Nowling, 2015: 56,57).

Turbo-generator credits

Nowling (2015: 56) recommends that the BFP power should also be accounted for in the turbine cycle. However this could also be accounted for in the total plant auxiliary power use as in Equation 6. The same principle applies to the boiler fans and coal pulverisers in Equation 9.

Test standards

Selected steam turbine performance testing standards are listed in Appendix B.

d) Balance of plant auxiliary loads

The components method avoids the need for sub-metering by grouping all the balance of plant auxiliary loads together as a single factor represented by E_G/E_N. Generator efficiency at all loads is automatically accounted for.

The energy used by auxiliary loads includes inefficiencies due to operating practices, for example if the coal conveyors are running when they are not required.

It is important that imported electricity also needs to be accounted for.

On-site energy use for transport is normally a very small fraction and is thus neglected.

e) Relative merits of the components method

Advantages

- Although this method cannot pinpoint inefficiencies, it does offer some advantage in identifying where these might exist.
- If the heat-loss method is used to evaluate the boiler, the uncertainties associated with measuring coal consumption can be avoided.

Disadvantages

- This method is typically used to evaluate short term plant performance rather than over extended periods at various loads (IEA 2010: 30).
- In terms of metering and calculations, it is far more onerous than the direct method.
- Sub-metering could be required for the BFP, boiler fans and pulverisers.

Comments

It has been argued that splitting the plant into three major subsystems and using the heat-loss method for the boiler is superior because of the typical measurement inaccuracies of coal consumption (Nowling, 2015: 54). However, given that even strict testing standards cannot guarantee better accuracies than ±3% for the boiler and ±2% for the turbine, the IEA (2010: 30,31) has suggested that it may not ultimately offer an accuracy advantage over the direct method.

2.5 Factors affecting heat rate

The calculated HR of any specific CFPP is affected by a multitude of different factors and this section examines the most significant ones. These factors have been broadly categorised into those which are fixed and those which are variable. This is somewhat subjective as not all of the factors fall strictly into only one category. For example fuel type is not strictly a fixed factor as fuel switching is always theoretically possible, but may never be a realised because of practical constraints (IEA 2010: 19). However categorising these factors has value for this particular M&V study when considering the need for baseline adjustments. Some texts categorise these factors as either controllable or uncontrollable constraints (IEA 2010: 42), but once again, whether a factor is controllable or not may vary in practice from one plant to the next.

2.5.1 Fixed factors

a) Plant vintage & design

Older plants were not designed to operate as efficiently as newer plants. This has mainly been brought about by improvements in materials which allow elevated temperatures and pressures, and efficiency gains brought about by new designs (Elliott, Chen & Swanekamp, 1997: 2.14; Cengel & Boles, 2008: 575). The average global CFPP efficiency is approximately 33%, compared to 45% achievable with modern units (IEA 2014a: 16).

One NETL (2010: 4) study compared the average efficiency of a subcritical bituminous coal generating fleet (48 units) to a supercritical fleet (79 units) using the same rank of coal. The subcritical fleet operated at steam pressures between 12.4 – 17.9 MPa, whereas the supercritical fleet operated above 23 MPa. On average the supercritical fleet operated 2.4%-points more efficiently than the subcritical fleet. Unit 3 at the Nordjylland Power Station in Denmark (1998) is a supercritical unit which uses steam at 29MPa and 582°C and boasts a net electrical efficiency of 47%[22] (Turner, 2016).

Another important consideration is the coal type which the original design was based upon. Boilers are designed and operated to minimise unburned carbon in the ash and also to minimise the formation of slag due to ash fusion (IEA 1993: 47–52). In some cases where coals have been switched in order to reduce operating costs or to satisfy environmental requirements, this has had a negative impact on performance (Elliott, Chen & Swanekamp, 1997: 2.46).

The auxiliary systems of older plants may be less efficient than newer plants which incorporate VSD motor speed controls for pumps, fans and conveyors.

b) Plant size

Larger plants tend to be more efficient than smaller plants as the fixed losses of the boiler and turbine are a smaller component of the total losses (Campbell, 2013: 18).

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[22] Calculated on an LHV basis

c) Plant condition

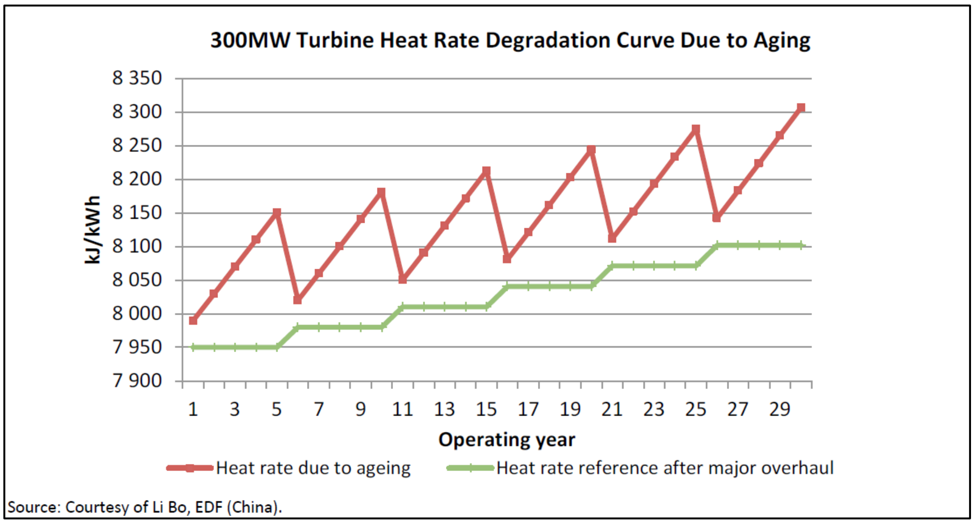
CFPP efficiency losses occur with age and the original as-commissioned efficiency level is never fully regained despite routine maintenance (IEA 2010: 22). Added to this is the fact that many plants operate well beyond their original life expectancy of 25-30 years, with some plants operating more than 50 years (IEA 2014a: p18). An increase in unit HR of 1% over 4-5 years is not unexpected and can increase as much as 10% over 30 years (National Renewable Energy Laboratory [NREL] 2012: 33).

Boiler

Boiler performance deteriorates with time due to fireside and waterside depositions. On the fireside, ash deposition leads to slagging (in the radiative zones) and fouling (in the convective zones). Both of these impede heat transfer and gas flows and in turn can lead to increased flue gas losses and an off-design temperature profile throughout the boiler. Ash-induced corrosion and erosion are also sources of boiler outages. Despite regular sootblowing, not all of the design heat flux is recovered (IEA 1993: 49–53). On the waterside of the boiler tubes, scale build-up can significantly impede heat transfer (B&W 1972: 4–16). Older boilers may also not operate optimally due to outdated and unreliable instrumentation and controls (Bhatt & Jothibasu, 1999: 466).

Steam turbine

The heat consumption rate of a steam turbine may deteriorate at 0.25% between overhauls and up to 2% could be lost in the first two years of operation (IEA 2010: 22). An NREL study (2012: 33) found that between overhauls, turbine efficiencies can decline from 88-91% down to the low 80%'s. Figure 16 shows the typical HR of a steam turbine over time. It can be seen that although HR improves after each overhaul, some HR is never recovered and the general trend is for HR to increase with time (IEA 2014a: 36).



Source: Courtesy of Li Bo, EDF (China).

Figure 16: Typical deterioration in HR over time of a steam turbine (IEA 2014a: 36)

Condenser

Condenser condition has a direct impact on plant performance and even small increases in condenser operating pressure can have a seemingly disproportionately negative impact on plant heat rate (IEA 2010: 24). Condenser CW tubes are prone to the fouling caused by insoluble scale build-up and microbiological deposits which both negatively affect heat transfer. Plants with closed loop evaporative cooling systems are especially prone to increased ion concentrations (Putman & Harpster, 2000: 2). Also, failed tubes may have been removed from service (plugged) reducing heat transfer surface area (IEA 2010: 26). The steam side (shell) of a CFPP condenser operates well below atmospheric pressure and leaks draw in ambient air. This degrades heat transfer of the steam to the CW and, unless properly removed, increases the condenser pressure (Lakovic et al., 2010: 55).

General

Maintenance carried out in an emergency situation can have a negative effect where the plant is restored to working condition but with a performance penalty. For example, if a turbine blade is defective, the entire row of blades could be removed as the lead time in obtaining a replacement part may be too long. This results in a unit de-rating and a degraded efficiency. Elsewhere in the plant other sources of deterioration could include leaks, wear, fouling, distortions, instrumentation faults and drift in calibrations (IEA 2010: 22).

d) Cooling water system type

The temperature of the CW at a CFPP has a significant influence on plant HR (Lakovic et al., 2010: S54). Plants that have once-through cooling water systems supplied from a cold source such as the sea or a cold river will be more efficient than the same plant situated inland with a closed system using wet cooling towers. The extreme case in water-scarce areas would be a dry closed cooling system where efficiency would suffer the most (IEA 2010: 52). Cooling water temperature is also affected by the general prevailing climatic conditions where the plant is located (Campbell, 2013: 18).

e) Pollutant controls

Pollutant control systems increase the auxiliary load which causes performance to deteriorate in terms of HR_N. The most important of these systems are Selective Catalytic Reduction (SCR), Flue Gas Desulphurisation (FGD) and Electrostatic Precipitation (ESP) or Bag Filters to control NO_X, SO_X and particulate matter (PM) emissions respectively. Carbon capture and storage (CCS) is used to limit CO_2 emissions but is not yet widely used.

Table 3 below compares the impacts on efficiency of pollutant controls from various sources in the literature. Although these all stated differently, they are within the same order of magnitude (National Petroleum Council [NPC] 2007: 8; IEA 2010: 53, IEA 2014a: 16).

Table 3: Comparison of efficiency impacts of pollutant controls from the literature

Pollutant control	**HR correction factor** (IEA 2010: 53)	**%-point increase in aux power** (NPC 2007: 8)	**%-point decrease in overall thermal efficiency** (IEA 2014a: 16)
FGD (Wet)	1.02	2%	1%
FGD (Dry)	1.01		
SCR	1.005	1%	"Relatively small"
Bag Filter	1.005	-	"Relatively small"
LNB / OFA[23]	1.005	-	-

2.5.2 Variable factors

a) Ambient conditions

Apart from the longer term degradation of the condenser mentioned before, the condenser pressure is affected in the short term by changes to the CW temperature. All closed circuit CW system performances deteriorate with increasing ambient air temperature but wet cooling systems are particularly negatively affected by increased relative humidity (RH) (Elliott, Chen & Swanekamp, 1997: 3–35; Lakovic et al., 2010: 54). In a wet cooling tower, the lower limit to which CW can be cooled is the ambient wet bulb temperature. Changes in ambient conditions are both seasonal and diurnal (IEA 2010: 25). Once-through CW systems are also susceptible to similar effects and can have wide seasonal variations in CW temperature. One such example has a seasonal range of 4 – 28°C (Lakovic et al., 2010: 57).

This trend was examined by (Mirjana, Slobodan & Miloš, 2012: S380) in a simulation study of a 110 MW CFPP with induced-draft wet cooling towers. In Figure 17, the temperature of the CW exiting the cooling tower is shown as a function of ambient temperature and RH, with the CW flow rate held constant. Figure 18 (from the same study) then shows simulated condenser pressure as a function of CW temperature (2012: 383).

Although a rise in condenser pressure from the design value leads to a worse HR, the reverse is not true. HR can also deteriorate if the condenser pressure decreases below the point where the LP turbine exit flow becomes choked, in which case subcooling occurs (Putman & Harpster, 2000: 2).

An increased ambient temperature does have a positive effect on the boiler performance as radiation losses are reduced and combustion air enters at a higher temperature, although these effects are outweighed by the deterioration in the cooling system performance. Accounting for these two opposite effects, an increase in HR of 0.15% per 1°C temperature rise has been suggested by the (IEA 2010: 53), however it is not stated the temperature range over which this is valid.

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[23] LNB = Low NOx burner; OFA = Over-fire air.

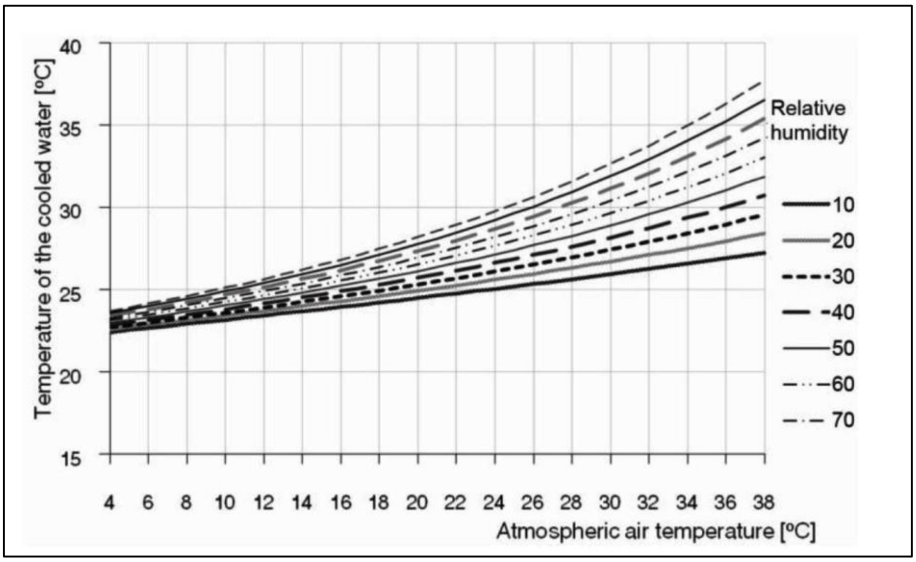

Figure 17: Wet cooling tower CW temperature as a function of ambient temperature and RH (Mirjana, Slobodan & Miloš, 2012: 380)

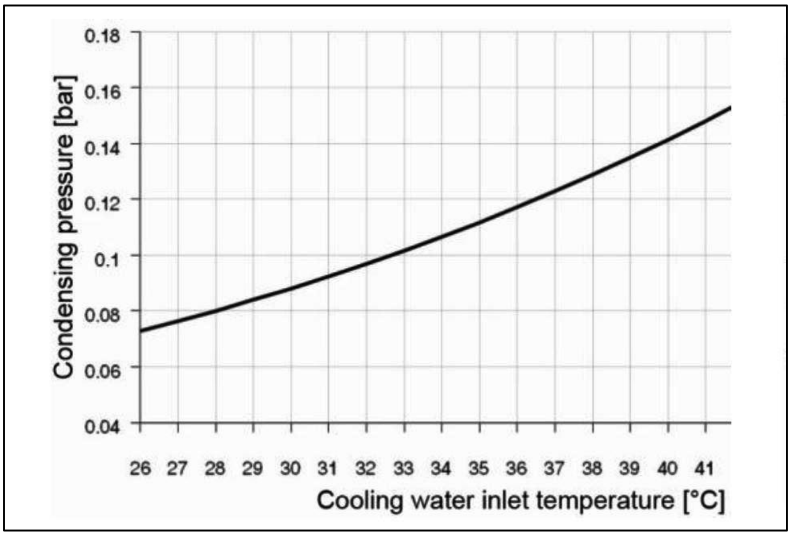

Figure 18: Condenser pressure as function of CW temperature (Mirjana, Slobodan & Miloš, 2012: 383)

b) Flexible operation

Conventional power plants which were designed for baseload operation are being required to operate in a flexible manner and older subcritical CFPPs have been particularly affected. This is attributed to changing demand due to economic factors such as recessions, changing fuel prices and an increasing penetration by intermittent renewable sources which typically have despatch priority. This has led to load-following, lower minimum loads, two-shifting, frequent starts & stops and increased ramp rates[24] (Hesler, 2011: 1,2).

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[24] These terms are defined by the IEA as described in Appendix C.

One of the consequences of sub-MCR and cyclical operation is an increased HR. One EPRI study found that despite large capital investments to improve efficiency, the plant HR actually deteriorated due to cycling and part-load operation (EPRI 2014: 3–7).

Terminology

An industry-wide EPRI study (2002: 6–1) found that the terminology for describing flexible operations is not consistent and not precise enough to express mathematically. In some cases all non-baseload conditions are described by the term cycling (IEA 2011: 35), but in other instances cycling refers to more extreme changes in output such as starts & stops and high ramp rates (Van den Bergh & Delarue, 2015: 70).

A term commonly used by to describe plant utilisation is capacity factor[25] (CF) as shown in Equation 19, (Eskom, 2013: 23,24). However CF needs to be distinguished from the average operating load. Figure 19 shows two profiles, each having a CF of 50% and which could both be described as cycling. Profile “A” shows load-following at part-load while “B” shows two-shifting at almost 100% MCR when running (high average operating load). Plant “A” would suffer from the inefficiencies associated with part-load operation whereas plant “B” would experience the losses associated with fast ramping and multiple starts and stops.

Equation 19

$$CF = \frac{E_N \times 100}{E_P}$$

Where E_N = *Net actual useful electrical energy produced (MWh)*

E_P = *Net useful electrical energy which could have potentially been produced (MWh)*

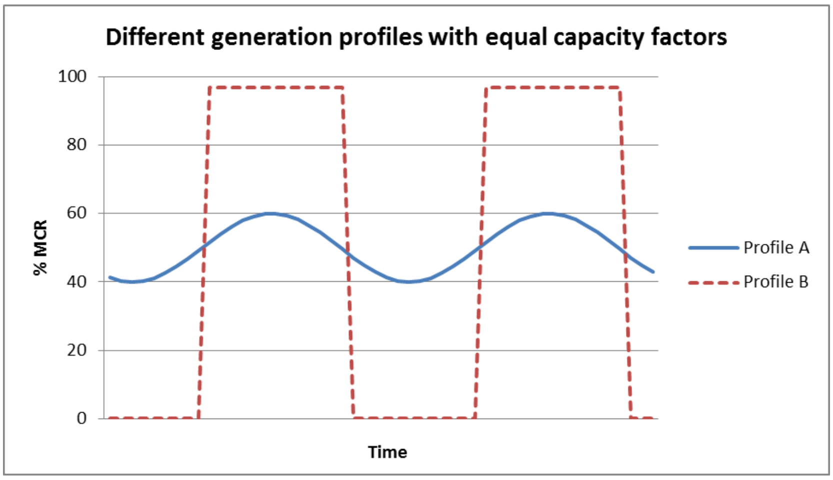

Figure 19: Example of different generation profiles with the same capacity factors

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[25] Also known as “Load factor” or “Generation load factor”

In order to better describe flexible operation EPRI (2002: 6–1) has defined a cycle as a pattern of load levels repeated on a weekly basis and further categorised cycles as either “On/Off Cycles” or “Load Cycles”.

Load cycles[26]

AER (EPRI 2002: 6–1) has empirically developed fourteen prototypical operating cycles for fossil steam generating units. These are categories of observed typical load patterns where the percentage load is plotted radially as a function of time which proceeds clockwise over a seven day period.

An example is shown in Figure 20 of a plant in category “Cycle 4C – Load Follower, Intermediate: Max Load Daily, Min Load (30%) Nightly”. Figure 21 then shows a plot of the corresponding HR as a function of gross load for the same period. The exact impact of operating at part load differs from one plant to the next but it is possible to establish the trend of HR as a function of load (de Groot, 2016: 16). Figure 22 shows this trend as a % deviation in HR_N for generic subcritical and supercritical CFPPs (IEA 2010: 20). When expressed as a %-deviation the increased HR at low loads is more pronounced. For a specific plant this relationship would need to be derived either from a reliable data set or by simulation.

The rate at which the power output of a generating unit can change is limited by the control system to avoid contact between moving parts and stationary parts in the turbine caused by differential expansion (IEA 2014b: 26). When power output is ramped up or down fast, steam may need to be dumped to the condenser via a turbine bypass system (IEA 2014b: 37) instead of producing useful work in the turbine and this has a negative effect on HR. However, in the context of HR changes due to ramping, ramp rates are generally not well defined.

NREL (2012: 34) has brought some distinction by classifying load following cycles as either “shallow” or “significant”. Cycles with a greater MW range than 15-20% of gross dependable capacity (GDC) are considered to be significant and all others are considered to be shallow. It was found that the impact of cycling on unit heat rate is dependent on multiple factors including the unit itself, the control systems, previous spending on measuring and maintaining HR and the depth, ramp rate and time spent during the cycle. Lew et al (2012: 5) found that the CFPP emissions (and thus HR) are not significantly affected by ramp rate. Oates and Jaramillo (2013: 4) noted that hourly data is not well suited to analysing ramp rates.

Apart from the instantaneous impacts on HR, cycling also has long term impacts. NREL (2012: 33) found that much of the HR loss which cannot be recovered by overhaul is attributable to cycling.

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[26] This includes part-load operation and load following

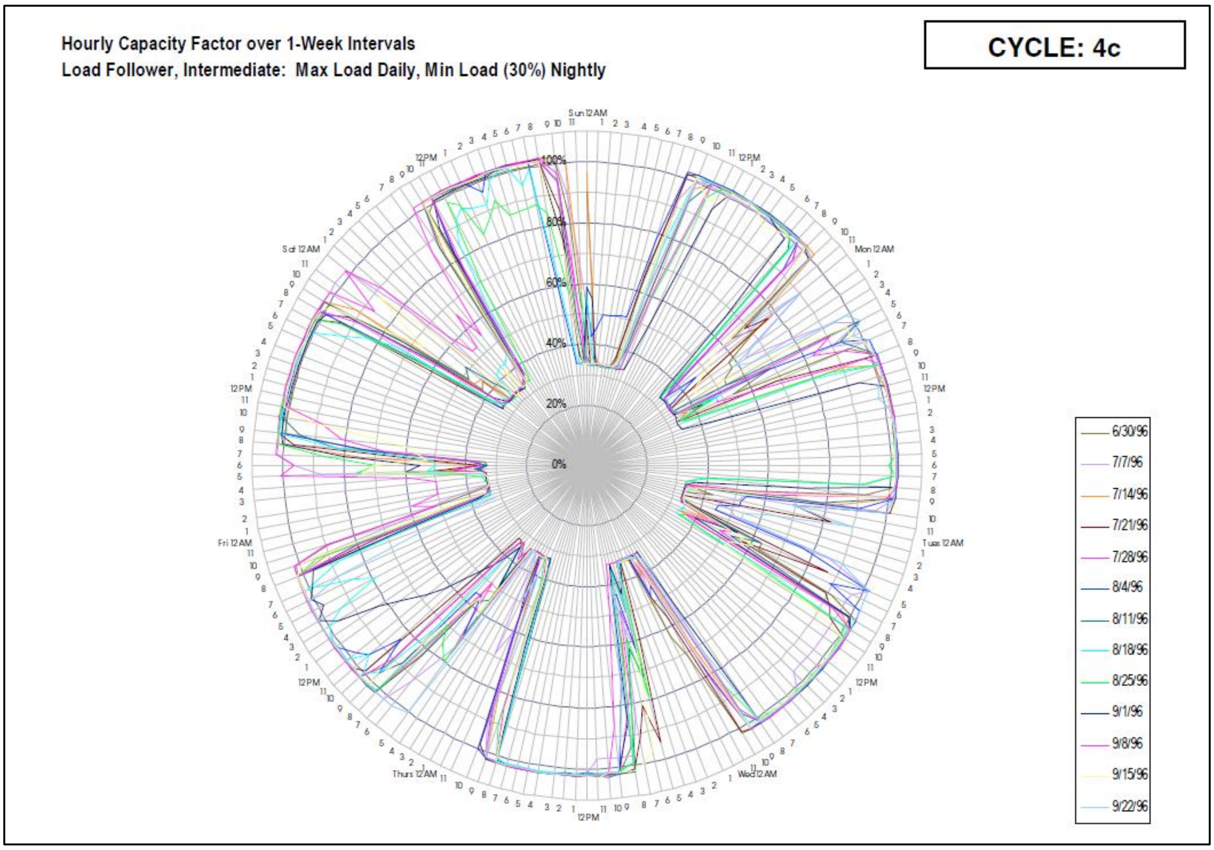

Figure 20: Prototypical weekly cycle 4C (Load Follower, Intermediate) (EPRI 2002: A-14)

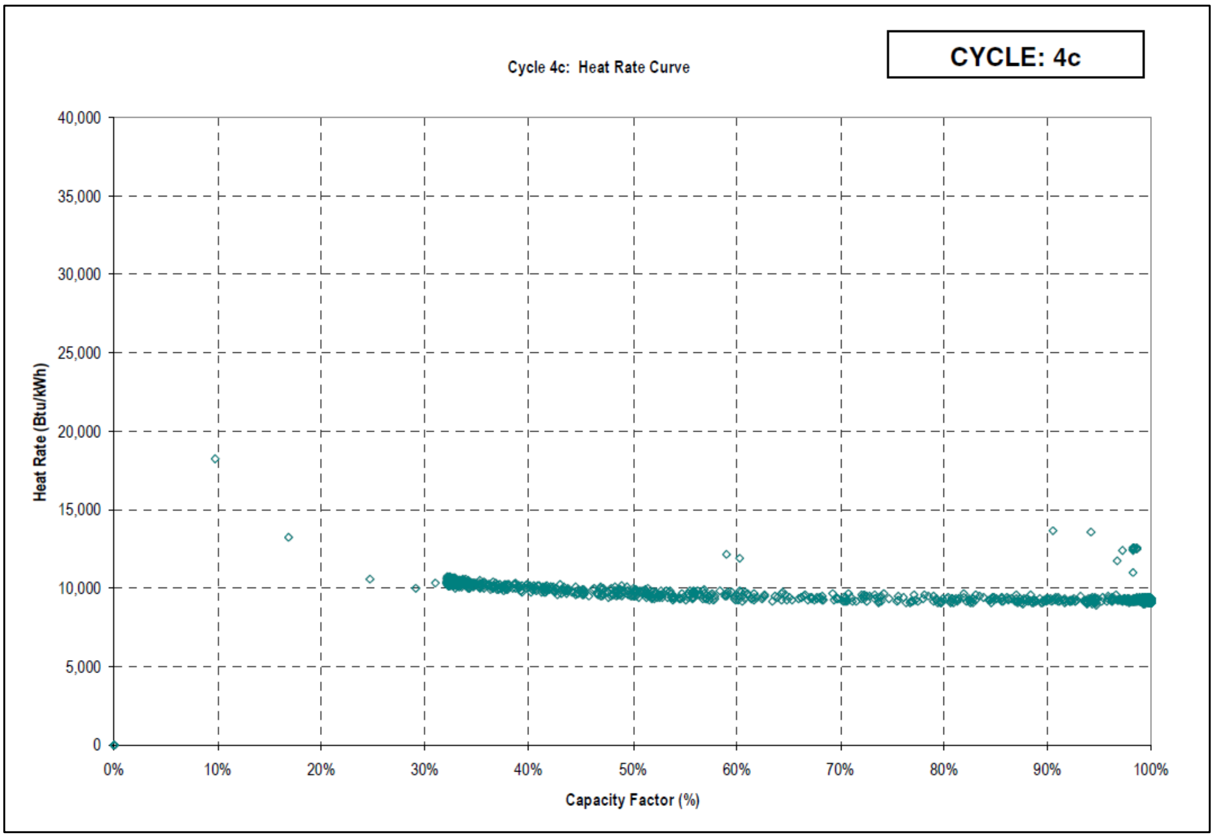

Figure 21: Gross Heat Rate as a function of load (EPRI 2002: A-25)

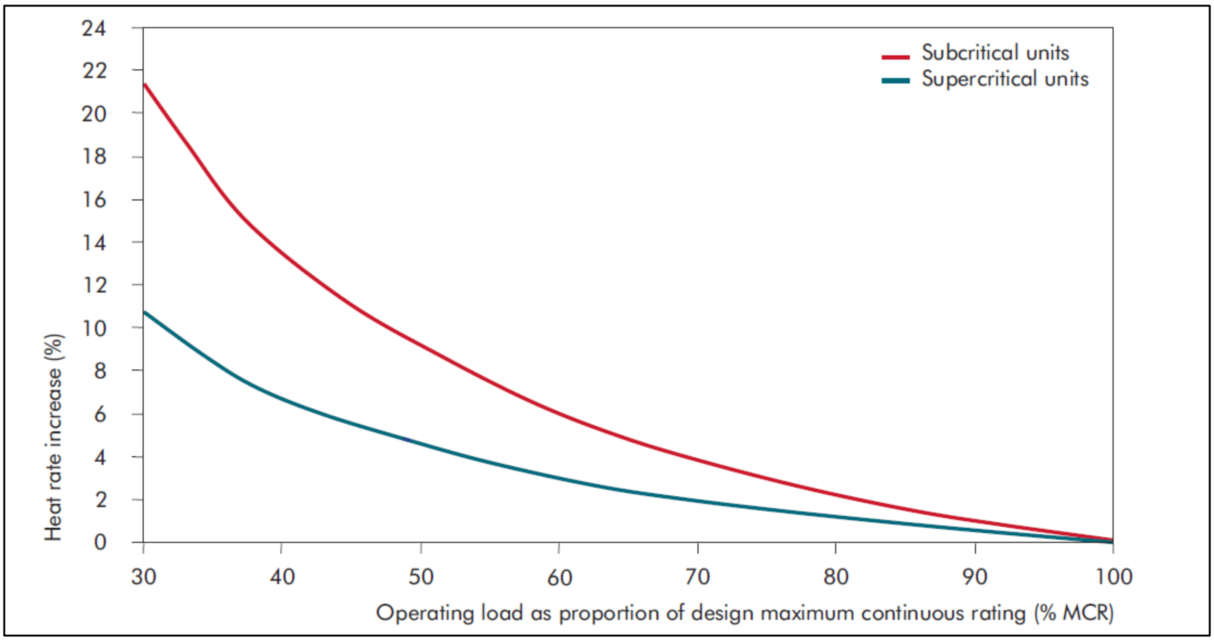

Figure 22: HR % deviation as a function of unit % MCR (IEA 2010: 20)

On/Off Cycles

On/Off cycles (i.e. plant start/stop cycles) occur due to large changes in demand and bring about significant energy losses. These losses increase with stoppage time as the subsequent start of a cold unit takes longer to minimise thermal stresses. Supercritical units are especially vulnerable to large startup losses (IEA 2010: 21).

Repeated On/Off cycling not only incurs losses but also affects the plant condition and leads to a degraded efficiency. In order to compare the performance of various plants, the IEA (2010: 21) has suggested three broad categories of on/off cycling with total energy adjustments for each category as seen in Table 4. This provides some idea of on/off cycling energy but is too vague to calculate small changes to HR.

Table 4: IEA suggested energy adjustments for on/off cycling (IEA 2010: 21)

On/Off cycling category	**Adjustment to total energy use to account for on/off cycling (%)**
Base load	0.5 %
Transitional	1.5 %
Marginal/Peaking	5 %

Plant starts are generally divided into three categories, namely cold, warm and hot, although these are not strictly defined as shown in Table 5. NREL (2012: 30) have empirically quantified startup fuel per MW of unit capacity for each start type and for different categories of CFPP as shown in Table 6.

Table 5: Comparison of cold, warm and hot start definitions from the literature

Start type	**Time offline** (Lefton & Hilleman, 2011: 3)	**Time offline** (Leǐzerovich, 2008: 194)
Hot start (from standby)		t < 2-3h
Hot start	t < 5h	t < 8-10h
Warm start	5h < t < 40h	10h < t < 72h
Cold start	t > 40h	t > 72h

Supposing all other factors remain constant, the expected change in HR between two assessment periods may be inferred from changes to the number of starts as shown in Equation 20. It must be noted that this change is only relevant if the total fuel used in a HR calculation includes startup fuel such as HFO.

Table 6: Startup fuel for various start types and plant categories (NREL 2012: 30)

	CFPP Startup fuel (MMBTU/MW) / (MJ/MW)		
Start type	**Subcritical Small (35 – 299 MW)**	**Subcritical Large (300 – 900 MW)**	**Supercritical (500 – 1300 MW)**
Typical hot start	5.00 / 5275	7.50 / 7913	10.10 / 10656
Typical warm start	6.67 / 7037	10.00 / 10551	17.10 / 18041
Typical cold start	9.33 / 9844	14.00 / 14771	20.10 / 21207

Equation 20

$$\Delta HR = \frac{3600 \times \Delta n_i \times Q_j \times P}{E_N}$$

$Where\ E_N = Net\ actual\ useful\ electrical\ energy\ produced\ (MWh)$

$\Delta HR = Change\ in\ Heat\ Rate$

$\Delta n = Change\ in\ number\ of\ starts\ between\ assessment\ periods$

$i = Start\ type\ (Cold/Warm/Hot)$

$Q = Startup\ fuel\ quantity\ (MJ/MW)$

$j = Unit\ type\ (Sub/supercritical)$

$P = Unit\ size\ (MW)$

To gain a sense of the magnitude of startup energy requirements Table 7 shows an example where startup energy is expressed as equivalent hours at 100% MCR for a 200MW subcritical unit[27].

Table 7: Startup energies expressed as fuel masses and equivalent time at 100% MCR

Start type	**Startup energy (GJ)**	**HFO (t)**	**Coal (t)**	**Equivalent time at 100% MCR**
Typical hot start	1055	25	48	26min
Typical warm start	1407	33	64	34min
Typical cold start	1969	46	89	48min

c) Coal characteristics[28]

The heating value of the coal is the most important characteristic of the coal (IEA 2002: 12) and is found as described in Section 2.3.2. Other coal characteristics are normally obtained by either proximate analysis or ultimate analysis. Proximate analysis is the simpler of the two methods and provides a percentage breakdown of the coal in terms of moisture, volatile matter (VM), ash and fixed carbon. Ultimate analysis is used to find the fractional composition of the main elements which are carbon, hydrogen, oxygen, nitrogen and sulphur (IEA 2002: 17). Some of the below properties of coal have been mentioned as factors which affect boiler efficiency.

Heating value

Since heating value is a specific quantity, any changes to it should not affect HR. For instance if the heating value decreases, then theoretically the plant should simply be able to increase the firing rate to produce the same electrical power, but in practice this is not the case. Even if the LHV is being used, the plant HR is not likely to remain exactly the same. A coal with a lower LHV may for instance contain more ash which would degrade heat transfer, increase boiler losses and increase the auxiliary power of fans, mills & conveyors.

Moisture

The coal HHV indicates the total heat available once all of the latent heat of water vapour has been recovered after combustion. However, most PF CFPP boilers do not recover this energy and the latent heat is lost to the atmosphere. Thus LHV is a better indicator of actual heat available in a unit mass of fuel burned in a PF boiler. In order to maintain the same output, an increase in moisture requires a proportional increase in firing rate. Thus HR can be affected by changes in moisture when evaluated using LHV. An IEA (1993: 86) statistical study of CFPPs in the USA found a HR increase of 7.4 kJ/kWh for each %-point increase in coal moisture.

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[27] Assumptions: Coal HHV = 22MJ/kg; HFO HHV = 43 MJ/kg; Unit Net HR = 12.3 MJ/kWh; 1BTU = 1.055056kJ

[28] This section should be read in close conjunction with Sections 2.3.2 and 2.4.2a) which describe coal moisture and boiler heat losses respectively.

Hydrogen

An increase in hydrogen also increases latent heat vapour losses in the flue gas as more water is produced during combustion. However hydrogen content is not determined during routine proximate analysis, so detecting short term changes may present a challenge.

Ash

An increase in ash content reduces the heating value of the coal and also negatively affects HR in several ways. The boiler is affected by lower flame temperatures, increased flue gas losses, slagging and poorer heat exchange. The resulting poor heat distribution can then necessitate increased steam attemperation (IEA 1993: 73). Attemperation is the controlled injection of liquid water into the steam to reduce the temperature to an acceptable level before it enters the turbine. Auxiliary power demand for the FD, ID and PA fans increases as well as auxiliary steam use needed for extra soot blowing (Bhatt, 2006: 30). A decrease in ash fusion temperature is also associated with increased slagging and fouling in the boiler and a statistical study of CFPPs in the USA found a HR increase of 12.7 kJ/kWh for each %-point increase in ash content (IEA 1993: 56,86).

A study by Bhatt (2006: 37) of 30 CFPPs ranging from 30MW – 500MW found that overall net plant efficiency declines with increased ash content as shown in Figure 23. It also should be noted that the ash yielded during a proximate coal analysis is different from that yielded during actual boiler combustion due to the higher temperatures and heating rates in the boiler (IEA 2002: 16).

Combustion characteristics

This describes the rate that the coal progresses through each stage of combustion with the volatile matter (VM) released first burning quickly and then the carbon char releasing heat more slowly later. This combustion profile determines the way heat is distributed throughout the different sections of the boiler and any deviation from the profile the boiler is designed for negatively affect plant HR. However the combustion characteristics cannot be accurately predicted from the information in a standard proximate analysis (IEA 1993: 47,48).

Sulphur

In general higher sulphur coals will cause FGD systems to consume more auxiliary power (IEA 1993: 73).

Hardness

The coal hardness grindability index (HGI) indicates the coal’s resistance to pulverisation, with low indexes being harder and high indexes being softer. Pulverising mill specific energy use (kWh/t) is higher for low HGI values and vice versa. Hardness can affect plant output as a drop of 15 HGI units can cause a 25% decrease in pulverising mill capacity (IEA 1993: 24,72).

Abrasiveness

The abrasion index (AI) is an indicator of how abrasive the coal is and this is particularly affected by ash containing a high content of quartz and pyrite. Highly abrasive coals increase the wear rate of the pulverising mills, degrade the performance of the boiler fans air heaters by increasing the rate of fan erosion and heaters leaks respectively (IEA 1993: 42,44).

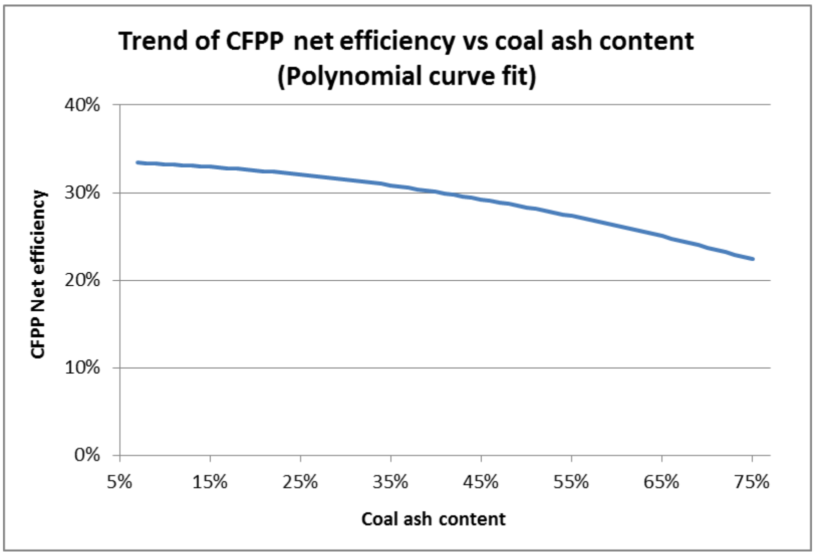

Figure 23: Trend of net efficiency of 30 CFPPs as a function of coal ash content (Bhatt, 2006: 37).

2.5.3 Other factors

Several other factors may also contribute to a calculated HR, or to the uncertainty thereof.

a) Coal weighing

Various methods can be used to measure coal purchased that enters the power station including conveyor belt scales, weigh bridges, hopper weighers and rail weighers. These scales need to be calibrated at least annually, and in some cases more frequently (AGO 2006: 33). In South Africa scale accuracies need to comply with the requirements of the Legal Metrology Act (Act 9 of 2014).

Ideally, for accurate HR assessments, the coal entering the boiler of each unit should be measured continuously, but this is not always the case. An industry rule-of-thumb is that these measurements are only accurate to within ±2% for gravimetric scales and ±5% for volumetric scales and experience has shown that the actual error may be as high as 10% (Nowling, 2015: 54).

b) Stockpile surveys

Where coal entering the boiler is not measured directly it must be estimated from purchase receipts and changes to the site stockpiles. In one case the potential error in the coal use was estimated to be as high as 25% (Nowling, 2015: 54). Stockpile surveys should always include both a volume survey and a measurement of stockpile bulk density. However these surveys are rather inaccurate mainly due to the difficulties in measuring bulk density. Survey inaccuracy also increases with stockpile size (AGO 2006: 34).

c) Changes to static stockpiles

Stored coal is vulnerable to weathering, which is the loss of some of its heating value due to natural oxidation with the atmospheric air. This loss can be from 1-3% in the first year, depending on coal rank. Also, the mass of stockpiled coal can physically decrease as surface dust is removed by wind and during transport. This problem of dusting is exacerbated if the coal moisture content drops below a critical value, depending on coal type (IEA 1993: 36).

d) Boundary selection

When measuring sent-out, imported and auxiliary electrical power, meters should be positioned to include transformer losses, otherwise these would need to be estimated (AGO 2006: 83; IEA 2010: 18).

e) Assessment period

HR assessments over short periods under idealised conditions may yield better results than over longer periods where conditions are more representative of normal commercial operation. Annual assessments also tend to represent the full range of typical seasonal demands and ambient conditions (IEA 2010: 29).

f) Assumptions

When HR is calculated some assumptions may be required where measured data is not available, not credible or where the expense of that data is not justified. For example startup fuel energy might be assumed to be negligible in comparison to overall energy use. In the UK, short term HR assessments include a large number of assumptions that are known to introduce errors (IEA 2010: 21,107).

2.6 Chapter summary

This first part of this chapter provided an introduction to M&V and the general principles of determining ECM savings including boundary selection, savings calculations, baseline adjustments, interactive effects, key project documents, uncertainty and cost.

The second part gave an overview of CFPPs, starting with the Rankine cycle, auxiliary power use and the definition of plant efficiency and HR. Then the major factors affecting HR were examined, all of which are either, fixed or variable, controllable or uncontrollable, real or apparent. The fixed factors included plant vintage, design, size and condition. The variable factors included ambient conditions, flexibility of operations (CF, load cycles, On/Off cycles) and coal characteristics. The factors which are apparent relate to the measurement bases used in coal analysis and HR definitions.

The next chapter uses this information, together with data availability constraints, to develop a credible M&V methodology for determining the HR improvements brought about by a series of ECMs introduced at a CFPP over several years.

Chapter 3 Development of an M&V Plan

3.1 Introduction

The objective of this chapter is to develop an M&V Plan as described in Section 2.1.12 to determine the HR impacts of the proposed ECMs. A description of the power plant and coal supply is provided and the methodology employed to develop the M&V Plan is that recommended in the IPMVP.

3.2 The power plant

The CFPP is a PF subcritical baseload plant consisting of multiple non-reheat generating units and is several decades old. Each generating unit has a single-flow HP turbine and a double-flow LP turbine in a tandem-compound configuration. Steam conditions are approximately 10.8 MPa / 538°C. Heat rejection is provided by natural draft wet cooling towers. The plant supplies electrical power at 50Hz into the South African national grid. Figure 24 shows a partial aerial view of the plant.

3.3 The energy conservation measures

The details of the refurbishment programme are described in Table 8 to Table 11. This information was provided as a set of detailed appraisal documents for each proposed ECM. In each case, where possible, the estimated impacts are provided as either an annual coal saving, or a MW power saving with the MW values stated as either absolute or relative. The absolute values remain the same irrespective of unit load, whereas the relative values are proportional to unit load. (The ECMs as well as the estimated impacts were developed by the utility in conjunction with STEAG[29]).

Table 8: Proposed ECM list for the Primary Energy Work Stream

ECM Identifier	**1.01**
ECM Title	**Online coal analyser installation to monitor the coal entering the station**
Details of system inefficiency	The coal from the neighbouring colliery is analysed but imported coal is not. Thus average quality of total coal entering the station is not known and combustion conditions cannot be optimised accordingly. This causes clinkering in the ash hoppers affecting combustion and heat transfer. Unplanned boiler shutdowns are required to effect repairs which reduces unit availability.
ECM Description	2 online coal analysers are to be installed on the conveyors supplying the staithes. The online coal analysis will be used for combustion optimisation which should reduce clinkering.
Estimated impacts	Relative demand saving 1.6 MW.

ECM Identifier	**1.02**
ECM Title	**Improve light-up time (Cold-start)**
Details of system inefficiency	Boiler light ups take too long. This is affected by steam-air heaters being out of commission on some units. No Steam-Air heaters are available on the remaining units.
ECM Description	Improve light up time from 12-15h to 8h. Review light-up procedures and light up team. Install and commission steam-air heaters. Investigate using economiser recirculation valves. Retrofit burner tips with larger ones. Modify chemistry sampling points on burners. (Currently sampling takes place at superheater steam outlet).
Estimated impacts	Absolute demand saving of 3.4 MW.

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[29] STEAG is a German energy engineering consultancy of international repute.

Table 9: Proposed ECM list for the Boiler Work Stream

ECM Identifier	**2.01**
ECM Title	**Replace boiler drum and superheater safety valves**
Details of system inefficiency	Valves should be lagged but are not. Torsion bar stiffness has deteriorated and valves pass high grade steam to the atmosphere.
ECM Description	Replace existing torsion bar valves with Helical Spring Valves. Lag valves according to revised maintenance procedures.
Estimated impacts	Absolute coal savings 16.7 kT p.a.

ECM Identifier	**2.02**
ECM Title	**Boiler tube alignment and skin casing inspection and repair**
Details of system inefficiency	Boiler efficiency is affected by 1) Improper lagging, 2) Tube misalignment causing hot spots and 3) Air ingress.
ECM Description	Apply lagging to affected areas to reduce skin temp to < 50deg C. Replace misaligned boiler tubes. Ensure observation doors are closed when operating.
Estimated impacts	Gains are uncertain. Rough estimate is 60kW per boiler.

ECM Identifier	**2.03**
ECM Title	**Install online O2 analysers after the air heater (AH) and CO analyser before the AH**
Details of system inefficiency	Suspected air heater (AH) leakages could be causing poor combustion. There are no CO Analysers before AH) nor O_2 analysers after AH.
ECM Description	Install CO and O_2 sensors. Feedback to DCS and operators to optimise combustion and detect AH leaks. O_2 change over AHs < 12%. CO currently not measured. Changes are to be proved on one unit first.
Estimated impacts	Improved Combustion. No coal or electrical savings estimates have been quantified.

ECM Identifier	**2.04**
ECM Title	**Replace/refurbish attemperator spray valves to improve steam temperature control**
Details of system inefficiency	Attemperator control valves and isolation valves passing. Water injection takes place when not required causing up to 5deg C drop in steam temp (Unit dependant). Possibility of blade damage if wet steam enters turbine. Currently steam entering turbine is < 538 °C. Consultant estimates losses at 1MW per 5 °C although this is uncertain.
ECM Description	Repair and replacement of spray water valves. Achieve 540deg C steam from boiler outlet & 538deg C steam to enter turbine. Revise spray valve maintenance procedure.
Estimated impacts	Improvement in turbine efficiency as a result of better quality steam supply. No coal or electrical savings estimates have been quantified.

ECM Identifier	**2.05**
ECM Title	**Ensure calibration and accuracy of all C&I instrumentation**
Details of system inefficiency	There are discrepancies between water flow and steam flow even when blow-down has been accounted for as orifice measurements are inaccurate. This results in inaccurate heat rate reporting.
ECM Description	Critical boiler field instruments are to be recalibrated. This includes steam & water flow, temperatures & pressures. Clean boiler impulse lines. Replace orifices where needed.
Estimated impacts	This measure will increase confidence in plant heat rate reporting. No savings are expected.

ECM Identifier	**2.06**
ECM Title	**Replace or refurbish boiler drum and superheater drain valves**
Details of system inefficiency	Boiler drum and superheater drain valves which should operate periodically only are leaking but the losses are not known.
ECM Description	Repair or replace culprit drain valves as required. Review and revise drain valve maintenance procedures.
Estimated impacts	Coal savings 1.9 kT p.a. Reduced demineralised water losses.

Table 10: Proposed ECM list for the Turbine Cycle Work Stream

ECM Identifier	**3.01**
ECM Title	**Improve and maintain condenser performance**
Details of system inefficiency	The condenser is a primary component in a vapour-liquid power cycle. Internal pipe & heat exchanger scaling has severely degraded condenser heat transfer & condenser vacuum due to reduced flow rates. (Condenser vacuums currently > 10 kPa.) This has caused losses in efficiency. The probable cause is poor CW chemistry due to unavailability of lime plant, clarification plant & performance of Taprogge system.
ECM Description	Acid clean condensers to remove deposits of calcium carbonate & silicates (Improve condenser vacuum to 7-8 kPa). Review operation & maintenance of lime plant to improve availability. Repair water sealed valves. Review operation & maintenance of Taprogge system & consider a system improvement. Monitor condenser performance.
Estimated impacts	Absolute demand saving 81.8 MW.

ECM Identifier	**3.02**
ECM Title	**LP and HP heater refurbishment / replacement**
Details of system inefficiency	Most LP heaters have malfunctioning vents. Heaters may be under-designed. Steam velocities which are too high may be causing wear. Poor LP and HP feed water heater performance results in losses estimated at 0.3 - 1.5 MW per unit. Boilers require more coal to heat feedwater to required temperature at the economiser stage.
ECM Description	Inspect & repair LP heater inlet domes and inspect & repair bypass valves. Replace HP heaters which are damaged or are being bypassed. Maintain and replace vent systems on LP & HP heaters. Find root causes of poor LP heater performance. Investigate LP heater replacement. Investigate cause of heater level control problems. Targets are i) TTD of <= 4deg C on HP and LP heaters. ii) Final LP condensate temp >=83deg C. iii) Final feedwater temp >= 221deg C.
Estimated impacts	Relative coal saving. 12.9 kT p.a.

ECM Identifier	**3.03**
ECM Title	**CW system refurbishment**
Details of system inefficiency	Currently poor condition of system includes i) Damaged Poly-Grid splash packs, ii)No acid dosing tank on the South side, iii) Centrewell debris leading to blockages in ducting, iv) Passing isolation valves, v) Lime plant unavailability & vi) Clogged and damaged CT Ham sprayers.
ECM Description	Replace Poly-Grid splash packs with new design. Move an acid dosing tank from the North side to the South side. Remove $CaCO_3$ scaling in CW ducts. Replace isolating valves. Increase size of CT screen collecting bin. Replace Ham sprayers. Install individual CT distribution isolation valves. Upgrade Lime plant (see ECM 3.01). Modify routing of recovered station drain water via clarifier.
Estimated impacts	Absolute coal saving 18 kT p.a.

ECM Identifier	**3.04**
ECM Title	**HP turbine modular spare project and LP rotor replacement for all units.**
Details of system inefficiency	Turbine inner efficiency has deteriorated on all units due to plant age. One unit has been de-rated by 30MW (LP 1st stage cropped). Another unit has been de-rated by 5MW (HP 12th stage cropping).
ECM Description	Replace LP rotor on former unit. Replace LP rotor on each unit where required in order of criticality. Replace HP Rotor on latter. Both units to return to design spec MW rating. (Rotor replacements to carry performance guarantees)
Estimated impacts	Absolute demand saving 35MW. Absolute coal saving 41.9 kT p.a.

ECM Identifier	**3.05**
ECM Title	**HP turbine efficiency testing with calibrated instrumentation. Improve station online C&I for future monitoring.**
Details of system inefficiency	Cylinder efficiency tests yielded results which were worse than expected or else did not make sense. Accuracy of instrumentation is suspect. Instrumentation required for unitised CT flow rates, post-governor valve temperature and pressure. Real-time performance of CTs cannot be established due to lack of weather station.
ECM Description	Install local weather station for real-time CT performance. Integrate into DCS for operational optimisation. Check for presence of water in impulse line. Repeat turbine centreline efficiency tests (all units). Fix vacuum leakages. Re-institute steam ejector tests. Re-institute vacuum performance monitoring. Address defects during outages.
Estimated impacts	Improved confidence in turbine efficiency reporting. Real-time performance analysis of cooling towers.

ECM Identifier	**3.06**
ECM Title	**Improve availability of BFPTs on all units**
Details of system inefficiency	BFPTs have poor availability. Damaged labyrinth seals causing steam leaks into pedestals. Units are operating with high oil and water content.
ECM Description	Improve BFPT availability to > 95% thereby reducing electric feed pump usage. Inspect repair & modify rotor blades. Repair and modify gland boxes.
Estimated impacts	Absolute electrical saving of 2.8 MW.

ECM Identifier	**3.07**
ECM Title	**Improved feedwater drum level control**
Details of system inefficiency	Boiler feed water flow rate is automatically controlled by regulating valve (throttling) which represents a power loss due to poor control philosophy.
ECM Description	Bypass BFPT throttling valves. Control boiler feed water by BFPT speed control. Pressure loss over throttle valves should reduce from 2.2 MPa to <0.5 MPa.
Estimated impacts	Relative coal saving of 7.9 kT p.a.

Table 11: Proposed ECM list for the Electrical Work Stream

ECM Identifier	**4.01**
ECM Title	**Replace air heater packs and repair of draught group ducting.**
Details of system inefficiency	Air heater packs and ducting are worn due to high AI of coal. Heat transfer is poor causing poor boiler efficiency. Resultant maintenance outages are too frequent. FD and ID fan motor loads are increased due to air ingress.
ECM Description	Replace worn out air heater packs. Adjust seals. Repair/replace worn out draught group ducting. Maintain air heater packs and seals more frequently including monitoring O_2 leakage via online monitoring. (see ECM 2.03) Aim for air heater outlet temperature target of 235 °C.
Estimated impacts	Relative electrical saving of 1.5 MW. Relative coal saving of 18.2 kT p.a.

ECM Identifier	**4.02**
ECM Title	**Reduce number of CW pumps in operation**
Details of system inefficiency	CW requirements may decrease once condensers have been cleaned. Presently all pumps operate continuously regardless of ambient temp. 1 pump per side may be switched off during cold winter months.
ECM Description	Reduce CW pumps in operation in winter by 1 on both the north and the south sides. Automate this via DCS-based on condenser back pressures. Use a non-unitised CW pump scheme.
Estimated impacts	Absolute electrical saving of 0.5 MW.

ECM Identifier	**4.03**
ECM Title	**Complete installation of the efficient lighting project**
Details of system inefficiency	Contractor offices on site are yet to have efficient lighting fitted.
ECM Description	Install energy efficient lighting in contractor offices on site. 45W lamps to be replaced by 28W lamps. Retrofits to take place during weekly lighting maintenance.
Estimated impacts	Absolute electrical saving of 0.1 MW

ECM Identifier	**4.04**
ECM Title	**Replace epoxy glass wedges with magnetic wedges on ID fan motors (Certain units only)**
Details of system inefficiency	Original motor magnetic wedges were of poor quality and caused frequent motor failure. These were retrofitted with epoxy glass wedges which decreased motor efficiency and caused high running temperatures.
ECM Description	Replace epoxy glass wedges with durable magnetic wedges.
Estimated impacts	Absolute demand saving of 0.4 MW.

Figure 24: An aerial view of the power plant (Google Earth)

3.4 Measurement boundary selection

This section evaluates the merits of each M&V measurement option and provides motivation for selecting "Option C – Whole facility measurement" as the most appropriate. Throughout this discussion the prime consideration is the objective of M&V to determine the HR improvement of the whole plant.

3.4.1 Option A or B – Retrofit isolation

Using either Option A or B (both retrofit isolation) would require evaluating each ECM individually and would have the advantage of being able to attribute specific savings to each measure. In theory, this would allow for better investment decisions based on the results of particular ECM performance. However in practice this may not be the case as multiple measures may be implemented simultaneously on the same system.

For example, suppose that a unit's combustion is optimised, the air heater packs and ducting is repaired, the boiler tubes are realigned and skin casing repaired (see ECM 1.01, 2.02, 2.03 & 4.01). It would then be difficult to determine the share of the gains that should be attributed to each measure. It is in fact the case that when a unit is taken out of service, as much as possible is performed simultaneously so that the unit can be speedily returned to service.

Either of the retrofit isolation options would also require instrumentation and measurements for each ECM. Although a lot of plant process data is captured, the accuracy of the instrumentation has been questioned, as confirmed by ECM 2.05 which aims to calibrate all instrumentation. This means that equipment-level baseline data obtained before implementing ECM 2.05 would be suspect.

A CFPP with multiple units contains complex processes and energy flows and evaluating each ECM in isolation could overlook important interactive effects and non-additive savings (EPRI 2014: 5–1). This is not to say that retrofit isolation is not appropriate for any of the measures. In some cases it may be the most appropriate, such as for the lighting retrofit project (ECM 4.03).

One of the challenges with isolating each ECM is that the M&V reporting requirement is to find the change in plant HR. If the ECM is relevant only to a particular unit, then it is not possible to determine the improvement in HR for that unit as coal consumption is not measured per unit.

3.4.2 Option C – Whole facility

It is possible that while one unit is being repaired, the HR performance of another unit may be deteriorating. Figure 25 shows an example of the rate at which condenser pressure at the plant can deteriorate after acid cleaning. An important question is whether M&V should only be reporting on improvements, or on overall performance, where the improvements in one part of the plant could be offset by deterioration in another part.

This problem, as well as all interactive effects and potential ECM additionality problems are taken care of by using option C. There are also instances where gains would be captured which may otherwise have gone unmeasured. For instance the passing steam valves (see ECM 2.01 & 2.06) could potentially produce secondary energy savings by reducing the load on the demineralised water plant.

The IEA (2010: 37,43) recommends that CFPP performance analysis should be on a whole plant basis rather than as individual units as this simplifies the analysis, removes all arguments about internal power flows, and also avoids having to find the performance of individual components. This implies a measurement boundary which covers receipt of fuel all the way to the point where power is sent out into the grid.

A problem associated with selecting option C is the magnitude of the savings. The IPMVP (2012: 25) recommends that the expected ECM savings should exceed 10% of the baseline energy if the reporting period is less than two years. In this case the total anticipated coal saving and the increased power output of all of the ECMs across all units improves the heat rate by approximately 10%. This assumes that every ECM performs exactly as planned. However, even if that was the case, the collective impacts would only be seen over the overall execution period of 3 years. This further assumes that when the final project is completed, the projects that were implemented 3 years prior to that are still performing optimally. Using option C would not allow for the impacts of each ECM to be measured individually.

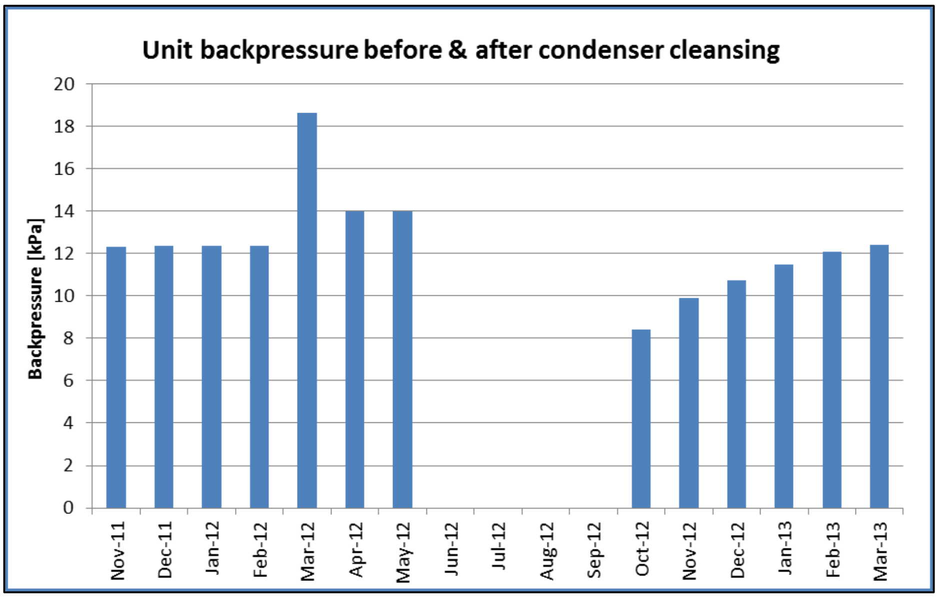


Figure 25: Monthly average condenser pressure before and after acid cleansing

3.4.3 Option D – Calibrated simulation

Option D requires the use of a sophisticated plant simulation package which is calibrated to match actual plant performance. The utility did acquire such software which was subsequently evaluated for performing M&V.

As with the retrofit isolation options, the primary drawback with this approach is that it requires large amount of accurate data from multiple sensors and detailed performance on an individual component level. Because the software is able to simulate one generating unit at a time, this would make model calibration very difficult as the coal consumed per unit is not known.

3.4.4 Summary

The primary reason for selecting the option C as the measurement boundary is data availability. Even at the level of the entire bounded facility, the daily and monthly coal used is estimated. It would therefore make no sense to attempt to resolve heat rate impacts on a per-unit basis. When reporting on net HR, it would also not make sense to perform the calculation on a unit level as there is no way of apportioning the total auxiliary power to individual units.

It could be argued that this boundary is not an optimal choice because the impacts of relatively small projects may not be identifiable. However, as projects are completed with time, their effects on heat rate will be cumulative and are less likely to go undetected. The whole facility approach also ensures that only sustained impacts are likely to be reported.

Option C means that the “Direct method” will be used rather than the “Components method” as described on p28 and p30 respectively. The method is routinely used internationally to determine power station performance and it satisfies the programme financier’s M&V requirement.

3.5 M&V Calculations

The aim of M&V for the plant is to determine the change in HR as a result of multiple ECMs. Given the choice of measurement option C, the principal M&V calculation (Equation 1) is adapted as shown in Equation 21. Figure 26 visually maps the data required for the principal M&V calculation of HR, for the adjustments and for the quantification of uncertainty. The rest of this section addresses each of these in turn.

Equation 21

$$\Delta HR_N = HR_{BP} - HR_{RP} \pm Adj$$

Where $\Delta HR = \text{change in plant heat rate}$

$HR_{BP} = \text{plant heat rate during the baseline period}$

$HR_{RP} = \text{plant heat rate during the reporting period}$

$Adj = \text{baseline heat rate adjustments (routine \& non-routine)}$

For clarity, Equation 6 (p25) & Equation 7 (p28) are repeated here as Equation 22 and Equation 23. In Equation 23, E_N is expressed in MWh so the factor of the 3600 (MJ/MWh) is excluded.

Equation 22

$$E_N = E_G - E_A - E_I$$

Where $E_N = \text{Net useful electrical energy output (MWh)}$

$E_G = \text{Electrical energy generated within the plant (MWh)}$

$E_A = \text{Auxiliary electrical energy (MWh)}$

$E_I = \text{Imported electrical energy (MWh)}$

Equation 23

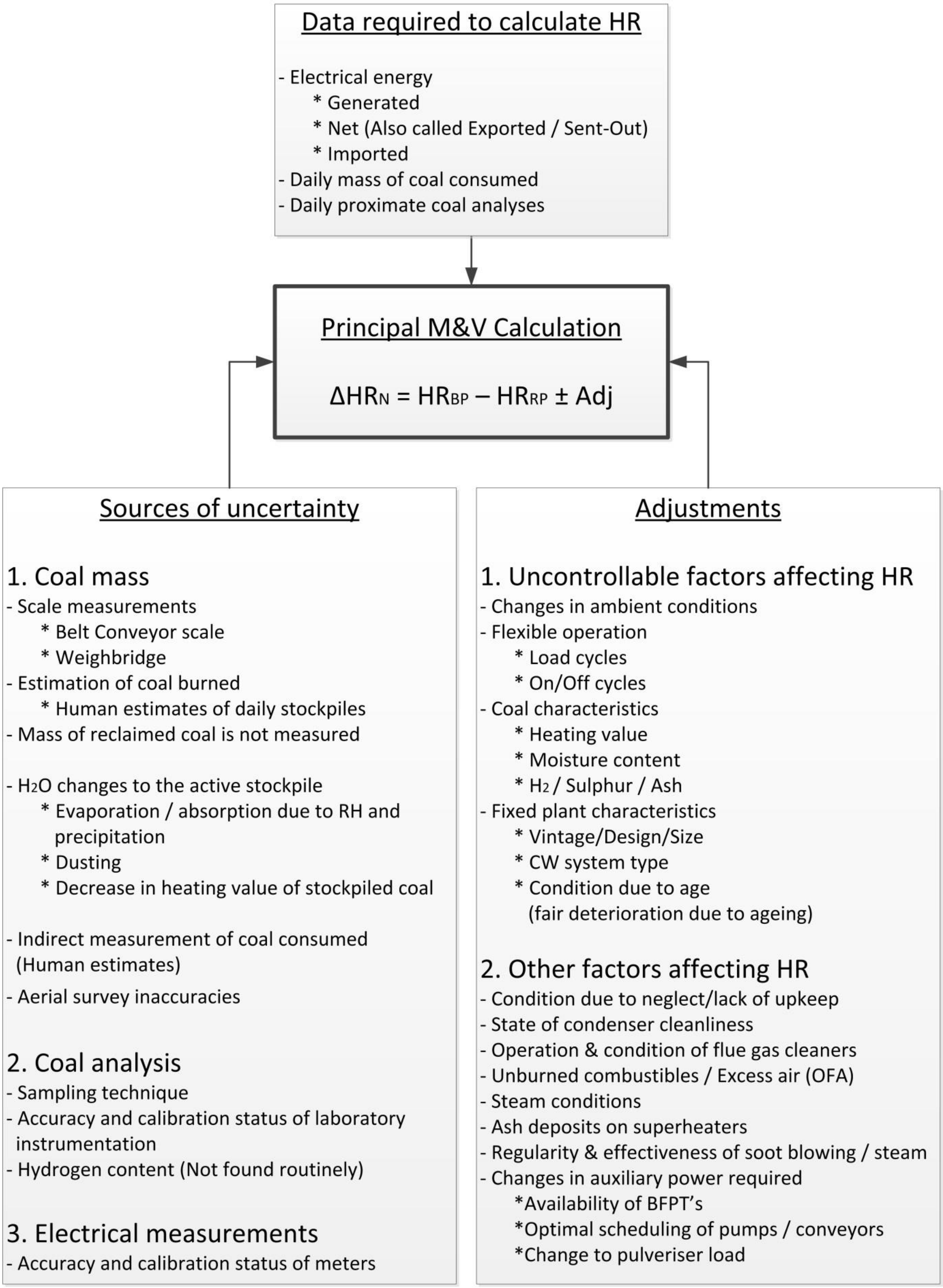
$$HR_N = \frac{m \times HV}{E_N}$$

Where $HR_N = \text{Net plant heat rate (MJ/MWh)}$

$m = \text{mass of coal consumed (kg)}$

$HV = \text{Average coal heating value (MJ/kg)}$

$E_N = \text{Net useful electrical energy output (MWh)}$



Data required to calculate HR

- Electrical energy
  - * Generated
  - * Net (Also called Exported / Sent-Out)
  - * Imported
- Daily mass of coal consumed
- Daily proximate coal analyses

Principal M&V Calculation

$$\Delta HR_N = HR_{BP} - HR_{RP} \pm Adj$$

Sources of uncertainty

1. Coal mass

- Scale measurements
  - * Belt Conveyor scale
  - * Weighbridge
- Estimation of coal burned
  - * Human estimates of daily stockpiles
- Mass of reclaimed coal is not measured

- H_2O changes to the active stockpile
  - * Evaporation / absorption due to RH and precipitation
  - * Dusting
  - * Decrease in heating value of stockpiled coal

- Indirect measurement of coal consumed (Human estimates)
- Aerial survey inaccuracies

2. Coal analysis

- Sampling technique
- Accuracy and calibration status of laboratory instrumentation
- Hydrogen content (Not found routinely)

3. Electrical measurements

- Accuracy and calibration status of meters

Adjustments

1. Uncontrollable factors affecting HR

- Changes in ambient conditions
- Flexible operation
  - * Load cycles
  - * On/Off cycles
- Coal characteristics
  - * Heating value
  - * Moisture content
  - * H_2 / Sulphur / Ash
- Fixed plant characteristics
  - * Vintage/Design/Size
  - * CW system type
  - * Condition due to age (fair deterioration due to ageing)

2. Other factors affecting HR

- Condition due to neglect/lack of upkeep
- State of condenser cleanliness
- Operation & condition of flue gas cleaners
- Unburned combustibles / Excess air (OFA)
- Steam conditions
- Ash deposits on superheaters
- Regularity & effectiveness of soot blowing / steam
- Changes in auxiliary power required
  - *Availability of BFPT's
  - *Optimal scheduling of pumps / conveyors
  - *Change to pulveriser load

Figure 26: A summary of the data requirements for the M&V ΔHR calculation

3.5.1 Data required to calculate HR

a) Electrical energy measurements

The plant is able to supply data for the gross (generated) and net (exported/sent-out) MW power for each generating unit on an hourly basis. Figure 27 shows the gross power generated and the net power sent out from one unit on a summer weekday in January 2011. Each data value represents the average demand for the preceding hour and since the interval is hourly, the sum of all of the values in any period is equal to the energy for the period in MWh (see Equation 24).

The electrical energy imported into the plant is available as MWh value on a monthly basis and it is roughly two orders of magnitude smaller than the sum of the hourly generated values for any given month.

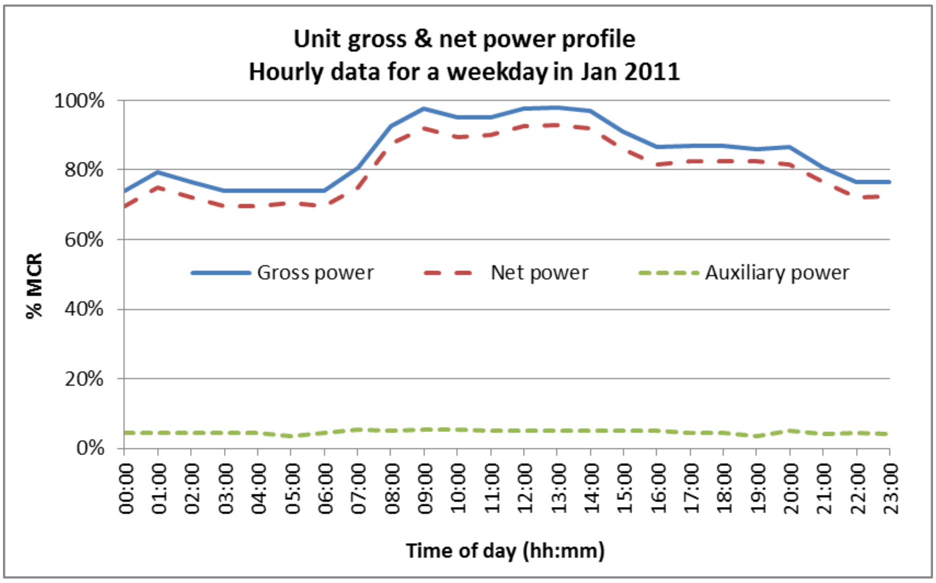


Figure 27: Unit generation profile as a % of MCR for a summer weekday

Equation 24

$$E_N = \sum_1^i [P_{Gi} - P_{Ai}] - E_I$$

Where E_N = *Net useful electrical energy output for the month (MWh)*

P_{Gi} = *Total plant hourly average power generated (MW)*

P_{Ai} = *Total plant hourly average auxiliary power (excl imports) (MW)*

E_I = *Monthly total electrical energy imported (MWh)*

i = *hours of the month*

b) Coal consumption

Finding the HR_N requires both the mass of coal consumed as well as its average heating value for the period (IEA 2010: 40). It is important to note that the mass of the coal burned is not directly measured at either a unit level, or at a plant level, but is a calculated value. Also, in order to find a reasonable average heating value of the coal burned during a given period, certain assumptions are required. This section describes the plant's coal supply, logistics, accounting and analyses in order to indirectly determine the heat input to the plant.

Coal supply & logistics

A neighbouring colliery (Supply "A") supplies about 80% of the plant's coal needs and this coal is transported into the plant precinct by conveyor belts. After being weighed by conveyor scales, the bulk of the coal is delivered to the staithes, then conveyed to the bunkers and finally to the pulverisers. Coal from this mine which has a moisture content greater than 10% or which is not required at the staithes is diverted to a live stockpile by another conveyor and weighed enroute.

The remaining coal needs of the plant, about 20%, are supplied by road imports from other coal mines (Supply "B"). These imports are measured by a weighbridge and then transferred directly to one of the stockpiles.

The stockpiled coal is divided into three areas, namely the live stockpile, the strategic stockpile and the 5-day emergency stockpile. However for coal accounting purposes these are collectively referred to simply as "the stockpile". The total amount of coal which is stockpiled, when added to the coal stored in the staithes and bunkers is referred to as "total coal stock" which includes all the coal on site. Occasionally coal is reclaimed to the stockpile from the staithes and the mass of coal moved in this operation is estimated as it is not weighed.

Coal that enters the plant is not burned immediately but has either a short delay at the staithes and bunkers, or an indeterminately longer delay at one of the stockpiles. It is estimated by plant staff that coal which enters the staithes is burned approximately two days after arrival. Figure 28 is a schematic flow chart which shows the coal handling and stockpiling flows within the plant.

Coal accounting

All coal movements on site are recorded on a daily basis and consolidated in a monthly coal accounting spreadsheet. The letters in square parentheses [] in Figure 28 each represent a column in the coal accounting spreadsheet.

The coal mass in the staithes and bunkers is estimated by a highly experienced plant engineer who performs a weekly stock survey. After each survey, the calculated burn rate of the coal is subject to minor adjustments as shown in Figure 28. The burn rate is a plant performance indicator which is used internally and has units (kg/kWh). Aerial surveys of the stockpile are undertaken on a quarterly basis after which the plant may be instructed to adjust the stockpile inventory, which in turn affects the estimated burn rate for the period. Between the staithes and the bunkers are a set of inclined scales although these are not deemed to be accurate and as a result they are not used.

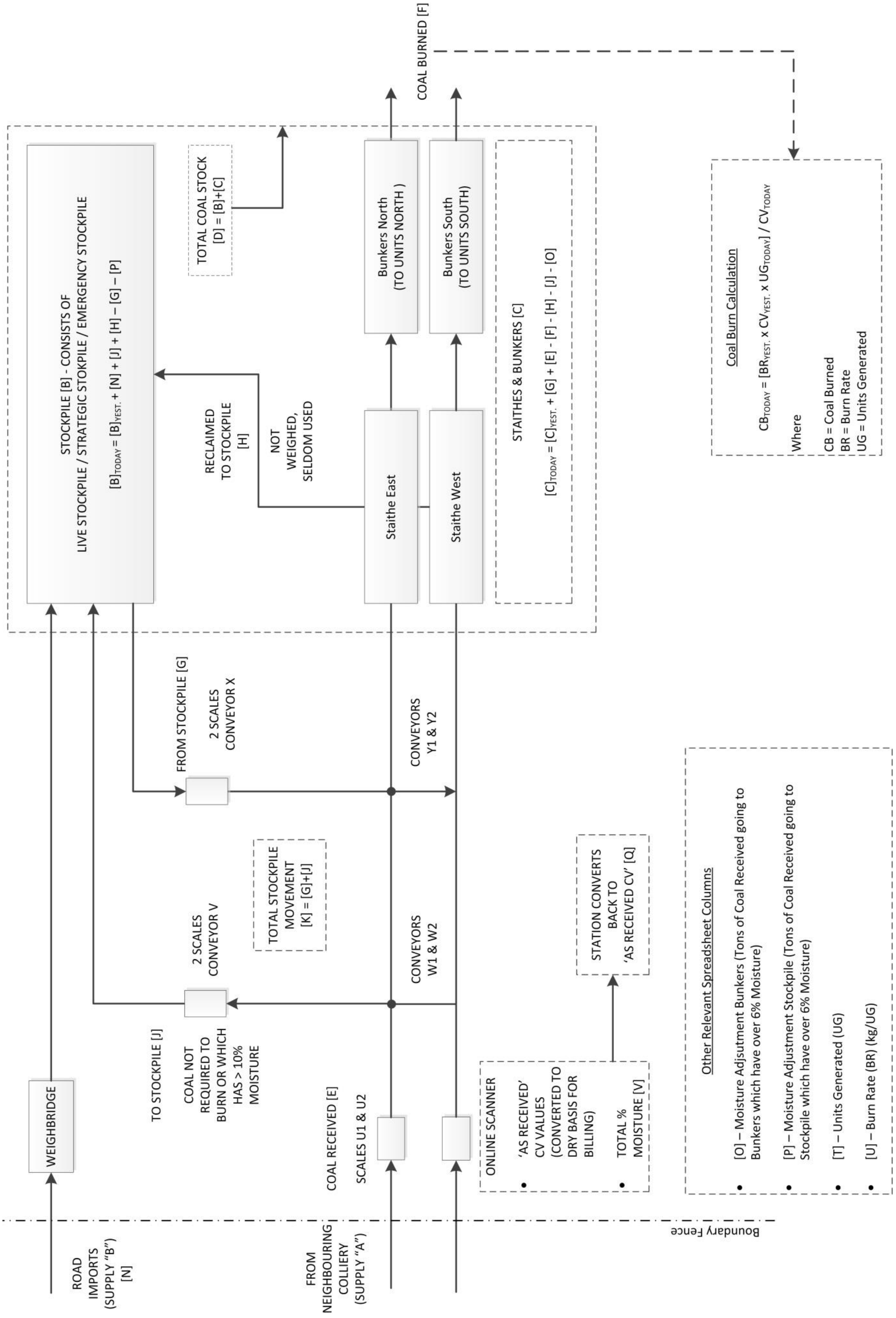


Figure 28: Schematic flow of coal in the plant showing supply, stockpiling & consumption

c) Coal analysis

The coal entering the plant by conveyor is sampled every 2 hours for proximate analysis by two separate laboratories, one at the power plant and one at the supplying colliery. That incoming coal is also analysed by a third method which is an online coal analysis device located on the conveyor.

Online monitoring eliminates the need for coal sampling and preparation and also has the advantage of detecting changes in coal quality in real-time (IEA 2002: 19). However plant engineers have reported that the online analyser is prone to drift and requires frequent recalibration, a tendency which is confirmed in the literature (IEA 2002: 20). The daily results from the three analyses are recorded together for each calendar month. Table 12 shows the coal parameters which are measured daily by each analysis.

The coal which is imported to the plant by road is not included in either the laboratory or the online analyses but is purchased on a “pre-certified” basis. The supplier builds up a stockpile and then takes a sample under the supervision of a plant representative. An independent laboratory analyses the coal sample and if it meets the contractual specification, it is dispatched by road to the plant.

The standards applicable to sampling, laboratory analysis and online analysis of the coal are listed in Appendix B. A composite coal sample is sent to a laboratory for ultimate analysis on a monthly basis.

Table 12: Coal parameters measured daily from laboratories and plant online analyser

Parameter	**Units**	**Basis**	**Laboratory (At the plant)**	**Laboratory (At the colliery)**	**Online analyser**
Total moisture (TM)	% Mass	AD (Lab), AR (Online)	•	•	•
Inherent moisture (IM)	% Mass	AD	•	•	
Higher Heating Value (HHV)	MJ/kg	DB (Lab), AR (Online)	•	•	•
Ash	% Mass	DB (Lab), AR (Online)	•	•	•
Volatile matter (VM)	% Mass	DB (Lab), AR (Online)	•	•	•
Sulphur	% Mass	DB	•	•	
Hardgrove grindability index (HGI)	HGI	DB	•	•	
Abrasiveness index	mgFe/kg	DB	•		

The daily coal analysis data from the three different sources needs to be combined to provide the most credible values. It is not expected for any of the three values to be identical as none of the analyses are performed on exactly the same coal sample and all are found using different equipment. The power plant uses only the values from the online analyser to calculate HR, but this is because of a stipulation in the coal supply contract rather than because it is necessarily the most accurate.

Figure 29 shows a typical month of daily HHV and it is evident that the data from the two laboratories have a far higher degree of mutual correlation than either of them has with the online analyser. The same is true of total moisture values seen in Figure 30. Table 13 shows the better mutual correlation of the laboratories. For this reason the online analyser data has been excluded and the various daily coal parameters have been found by averaging the two laboratory values.

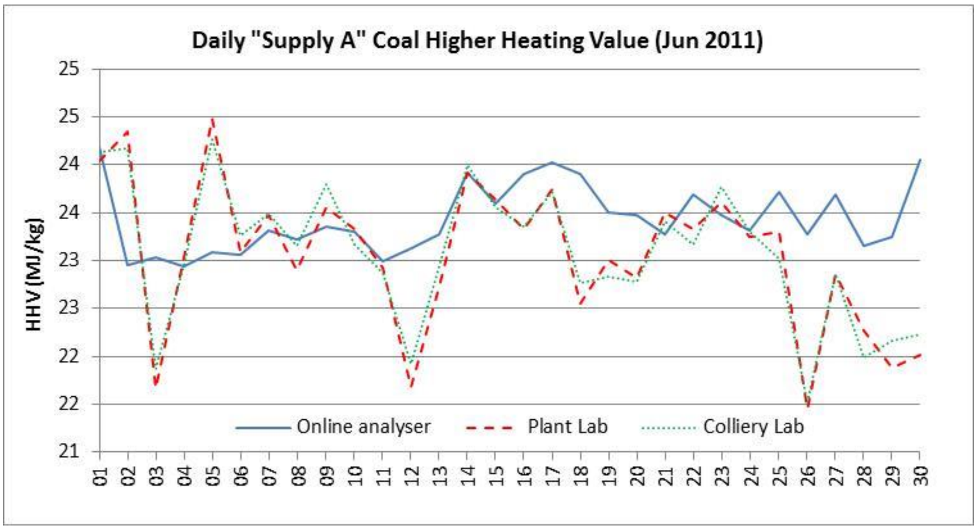


Figure 29: Comparison of different analyses of HHV for “Supply A” coal (Jun 2011)

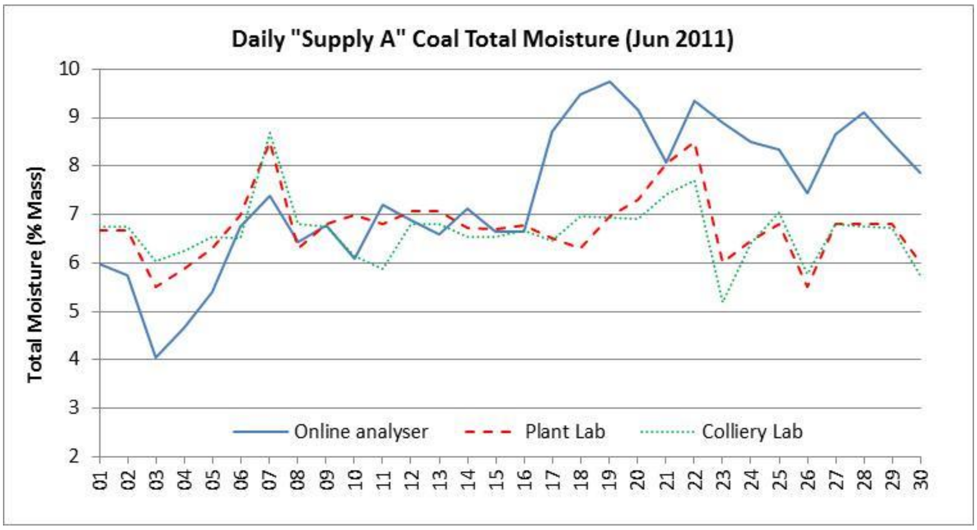


Figure 30: Comparison of different analyses of Total Moisture for “Supply A” coal (Jun 2011)

Table 13: Comparison of daily coal HHV from three sources for 2011

Source comparison	Average daily absolute difference (%)	Correlation coefficient (%)
Online analyser vs Plant laboratory	2.19	50.6
Online analyser vs Colliery laboratory	2.16	53.1
Plant laboratory vs Colliery laboratory	0.65	97.2

Higher heating value vs Lower heating value

As Table 12 shows, only the HHV of the coal found by proximate analysis is used routinely. Thus for this study, HHV has been selected for use in Equation 23 to find HR. It could be argued that the LHV is the correct value to use, as the latent heat of condensation of the moisture in the flue gas is not recovered but is lost to the atmosphere. However the choice to use HHV is justified by the following considerations.

- The IEA (2010: 45) recommends that the data collected and analysed should be readily available.
- It is standard convention to use HHV in many countries including Australia, Canada, India, Japan, South Korea, Russia and the USA (IEA 2010: 91–110).
- Although empirical models exist to convert HHV to LHV (IEA 2010: 47), the dataset used to derive the models may not represent the local coal well.
- Most important is that the M&V calculation in Equation 21 finds a *difference* in HR; it finds a change *relative* to the baseline HR. Therefore if the difference between HHV and LHV remains constant during both the baseline and the reporting periods, percentage change in HR will be identical, regardless of whether LHV or HHV has been used to find HR.

Stability of key coal characteristics over time

Figure 31 to Figure 33 show the trends in selected key coal parameters for coal from “Supply A” for the period 01 January – 31 December 2011. From the trend lines and formulas shown, it can be seen that these characteristics were relatively stable over this 12 month period.

Figure 34 to Figure 36 show the trends for the same coal parameters over that period from coal “Supply B”. The parameters are not quite as stable as from “Supply A” although this is to be expected given that the “Supply B” coal is not necessarily always sourced from the same mine.

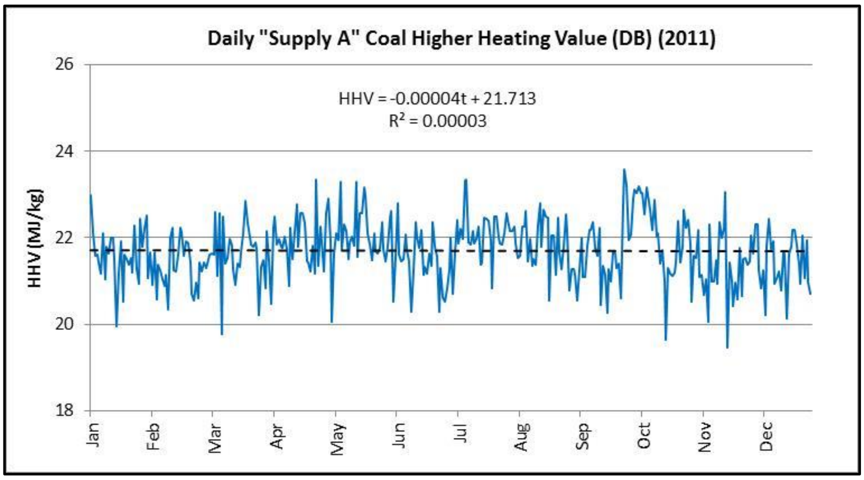


Figure 31: "Supply A" coal daily HHV for Jan – Dec 2011

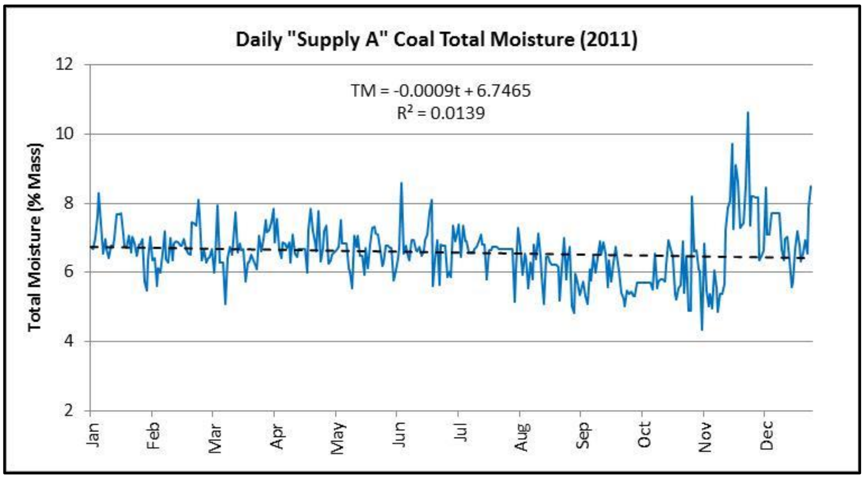


Figure 32: "Supply A" coal daily Total Moisture for Jan – Dec 2011

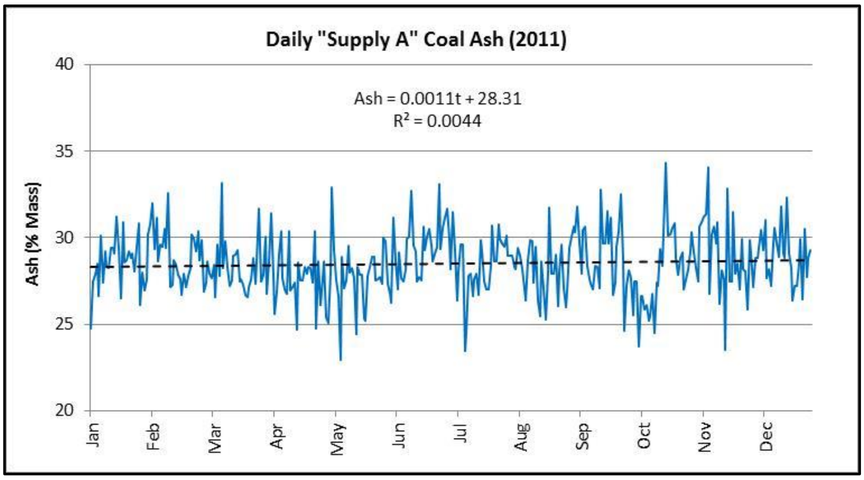


Figure 33: "Supply A" coal daily Ash for Jan – Dec 2011

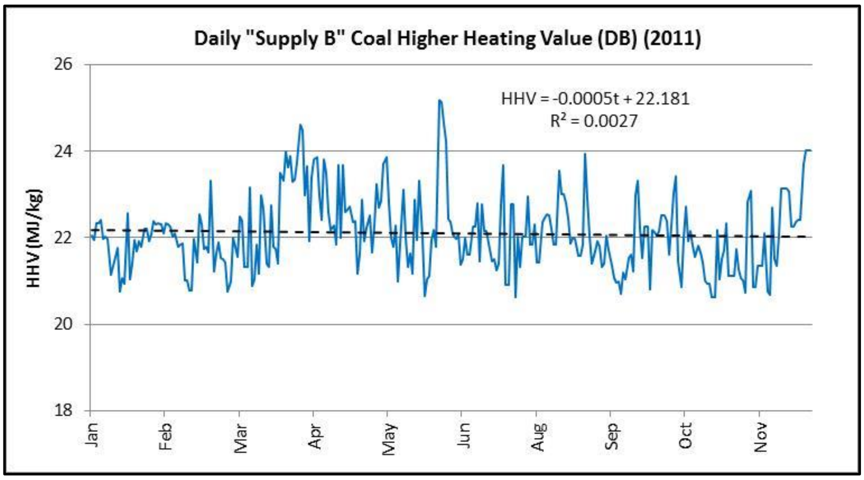


Figure 34: “Supply B” coal daily HHV for Jan – Dec 2011

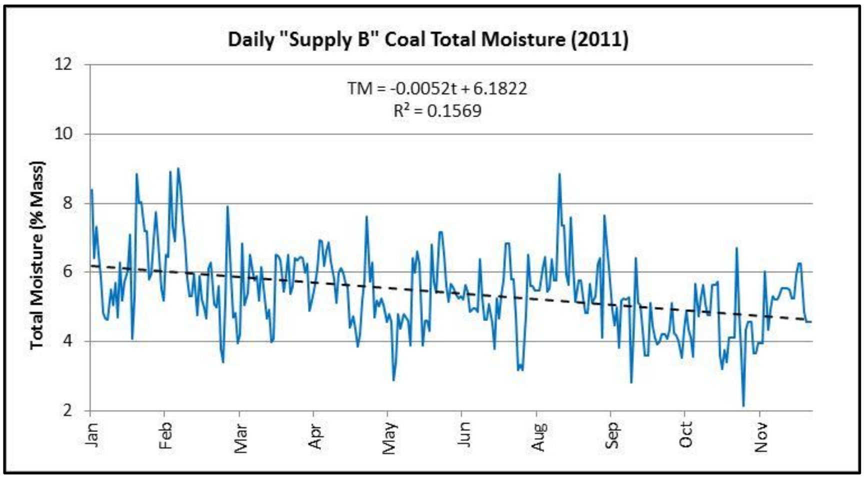


Figure 35: “Supply B” coal daily Total Moisture for Jan – Dec 2011

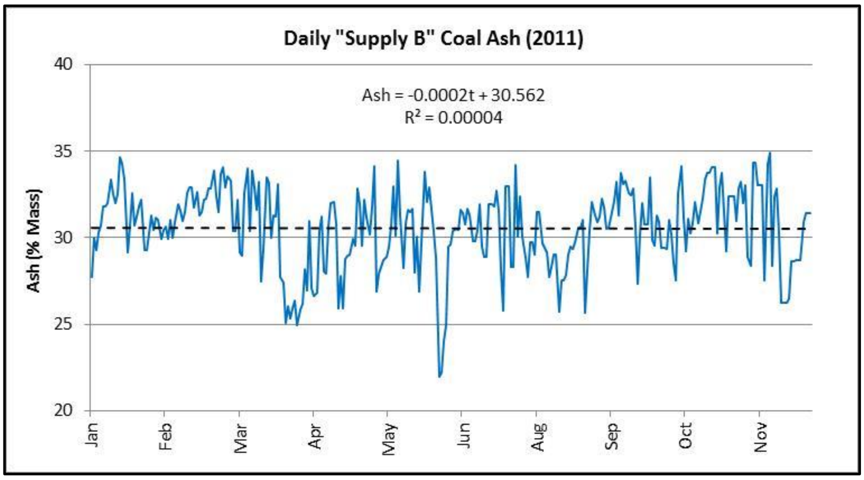


Figure 36: “Supply B” coal daily Ash for Jan – Dec 2011

General determination of a weighted average coal HV

Figure 37 below shows a simplification of the coal flows within the plant (derived from Figure 28). In the diagram, **$\alpha \cdot m_A$** represents the fraction of “Supply A” coal which travels directly to the staithes, and **$(1-\alpha) \cdot m_A$** represents the remaining fraction which is stockpiled. The value of **α** fluctuates on a daily basis and the annual average also varies from year to year. However all of the “Supply B” coal is always first stockpiled. The coal which is subsequently drawn from the stockpile on conveyor X is thus comprised of coal from both sources and the HV assigned to it needs to reflect that. Equation 25 below shows the coal energy delivered to the staithes in terms of HV of “Supply A” coal (HV_A) and stockpiled coal (HV_S). A proposed means of finding HV_S is shown in Equation 26.

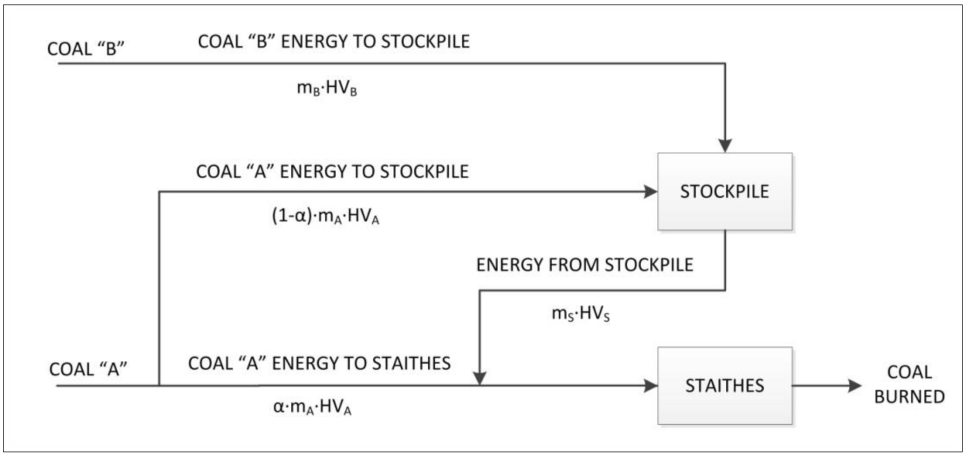


Figure 37: Simplified coal flow within the plant

Equation 25

$$m \cdot HV = \alpha \cdot m_A \cdot HV_A + m_S \cdot HV_S$$

Where m = *Total annual mass of coal burned (kg)*

HV = *Annual weighted average HHV of coal burned (MJ/kg)*

α = *Fraction of “Supply A” coal sent directly to staithes (%)*

m_A = *Total annual mass of “Supply A” coal purchased (kg)*

HV_A = *Annual mean HHV of “Supply A” coal (kJ/kg)*

m_S = *Total annual mass of coal drawn from the stockpile (kg)*

HV_S = *Annual mean HHV of stockpiled coal (kJ/kg)*

Equation 26 $$HV_S = \frac{(1-\alpha)\cdot m_A \cdot HV_A + m_B \cdot HV_B}{(1-\alpha)\cdot m_A + m_B}$$

Where $HV_S = HHV\ of\ stockpiled\ coal\ (kJ/kg)$

$\alpha = Fraction\ of\ \text{“}Supply\ A\text{”}\ coal\ sent\ directly\ to\ staithes\ (\%)$

$m_A = Total\ annual\ mass\ of\ \text{“}Supply\ A\text{”}\ coal\ purchased\ (kg)$

$HV_A = HHV\ of\ \text{“}Supply\ A\text{”}\ coal\ (kJ/kg)$

$m_B = Total\ annual\ mass\ of\ \text{“}Supply\ B\text{”}\ coal\ purchased\ (kg)$

$HV_B = HHV\ of\ \text{“}Supply\ B\text{”}\ coal\ (kJ/kg)$

It is possible that the mass of coal delivered to the stockpile exactly equals the coal removed from it during in any given period (i.e. $m_S = (1-\alpha)\cdot m_A + m_B$). In this case no net stockpile changes would occur. Although this would simplify the above two equations, it is not likely to occur and thus the general form of the equations is preferred.

The mass flow of coal through the plant, together with the sampled coal heating values may be analysed either on a *time* basis or a *mass* basis and these two approaches are discussed below.

Time-based method

This method treats the coal laboratory results as a time series. This means that for either source of coal, the laboratory HV found on any specific day is applied to the entire mass of coal obtained from that source for that day. Thus with reference to Figure 37, the annual total coal energy consumed is found according to Equation 27.

Equation 27 $$m \cdot HV = \sum_{i=1}^{365} (\alpha_i \cdot m_{Ai} \cdot HV_{Ai} + m_{Si} \cdot HV_S)$$

Where $m = Total\ annual\ mass\ of\ coal\ burned\ (kg)$

$HV = Annual\ weighted\ average\ HHV\ of\ coal\ burned\ (MJ/kg)$

$\alpha_i = Daily\ fraction\ of\ \text{“}Supply\ A\text{”}\ coal\ sent\ directly\ to\ staithes\ (\%)$

$m_{Ai} = Daily\ mass\ of\ \text{“}Supply\ A\text{”}\ coal\ purchased\ (kg)$

$HV_{Ai} = Daily\ HHV\ of\ \text{“}Supply\ A\text{”}\ coal\ (kJ/kg)$

$m_{Si} = Daily\ mass\ of\ coal\ drawn\ from\ the\ stockpile\ (kg)$

$HV_S = Annual\ mean\ HHV\ of\ stockpiled\ coal\ (kJ/kg)$

Equation 28 $$HV_S = \frac{\sum_{i=1}^{365}[(1-\alpha_i)\cdot m_{Ai}\cdot HV_{Ai}+m_{Bi}\cdot HV_{Bi}]}{\sum_{i=1}^{365}[(1-\alpha_i)\cdot m_{Ai}+m_{Bi}]}$$

Where HV_S = Annual mean HHV of stockpiled coal (kJ/kg)

α = Daily fraction of "Supply A" coal sent directly to staithes (%)

m_A = Total daily mass of "Supply A" coal purchased (kg)

HV_A = Daily HHV of "Supply A" coal (kJ/kg)

m_B = Total daily mass of "Supply B" coal purchased (kg)

HV_B = Daily HHV of "Supply B" coal (kJ/kg)

Assigning the daily heating value to the entire daily mass entering the plant is not unreasonable as coal sampling procedures are followed specifically so that a small sample accurately represents a much larger population.

A disadvantage of this method is that for each day, or for each batch of coal delivered, only one or two laboratory heating values are obtained. Annually, this results in a single total value of coal energy entering the plant, but does not provide any insight into the precision or the degree of confidence in that value. Also, this method may not adequately consider the significant amount of mixing that occurs between various batches of coal, particularly on the stockpile.

Mass-based method

This method treats the coal supplied to the plant annually as a large mass which is spatially sampled. Characterisation of the coal in this way provides an average heating value for an assessment period, as well as an HV probability density distribution. Since it is the same data set, the number of samples is identical to the time-based method.

One way of determining the total probable coal energy consumed is to use the coal HV probability density distributions in a randomised Monte Carlo simulation. It could be argued that this type of simulation better predicts the actual composition of coal consumed as delivered batches are inevitably split up and mixed. This method is well suited to an uncertainty analysis, which is required for M&V.

Provided the empirical coal HV data closely matches a normal distribution, it can be reasonably characterised by a normal distribution with the same average and standard deviation. A spreadsheet random number generator is then used over multiple iterations to simulate a likely HV probability density distribution for the weighted mix of coals from multiple sources. This occurs firstly at the stockpile (mix of coal from "Supply B" with a fraction from "Supply A") and secondly at the staithes (mix of stockpiled coal with remaining fraction from "Supply A"). Each iteration of this calculation is expressed as pseudo-code in Equation 29. In Figure 38 the subscript "R" has been added to indicate that for each iteration, a probable HV is assigned randomly.

In the interest of conservative M&V reporting, the mass-based method is preferred as it will naturally yield a greater range of uncertainty.

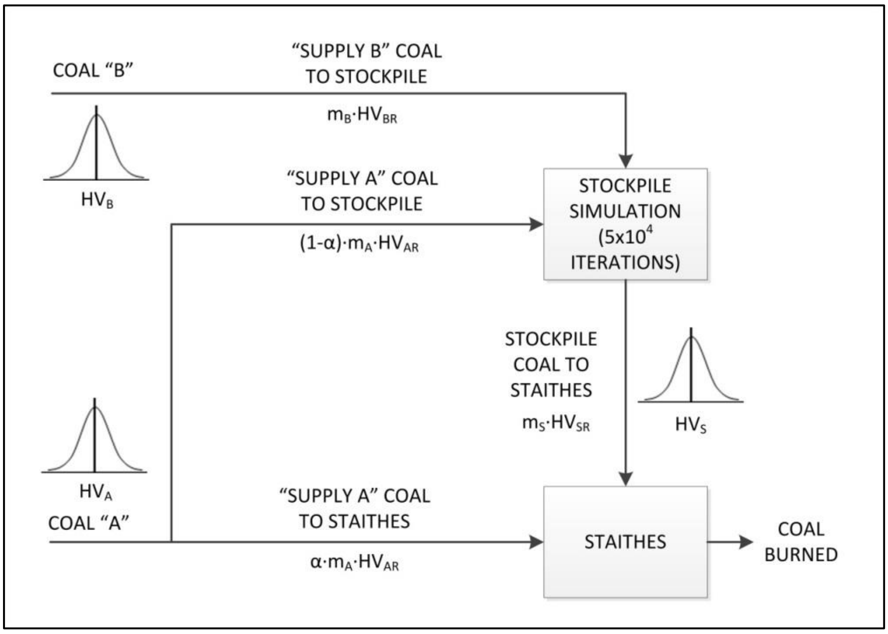


Figure 38: Outline of mass-based Monte Carlo simulation method

Equation 29

$$HV_S = \frac{m_A \cdot InvNrmRnd(\mu_A,\sigma_A) + m_B \cdot InvNrmRnd(\mu_B,\sigma_B)}{m_A + m_B}$$

Where HV_S = *Weighted average HHV of stockpiled coal (MJ/kg)*

m_A = *Total annual mass of "Supply A" coal supplied (kg)*

m_B = *Total annual mass of "Supply B" coal supplied (kg)*

InvNrmRand = Spreadsheet random inverse normal function

μ = *Average HHV of sampled coal (InvNormRand argument)*

σ = *Std Dev of HHV of sampled coal (InvNormRand argument)*

Stockpile composition assumption

Before the start of an assessment period, the stockpile was already in existence, so it is assumed that the stockpile composition was similar to that of the assessment period. This assumption is reasonable provided that routine operations and coal sourcing have been in a steady state for some time. This assumption is required regardless of whether the stockpile HV is characterised on a time basis or a mass basis.

3.5.2 Baseline adjustments

This section discusses the significant variable factors affecting HR and develops a baseline adjustment model. The treatment of each of these factors could well differ from one plant to another so the model proposed here is not universally applicable.

a) Ambient conditions

The primary barrier to characterising HR with ambient conditions is a lack of weather data. CW temperature is affected by both ambient air temperature and humidity, but neither of these is available for the plant during the baseline period. ECM 3.05 (p55) includes installing a local weather station.

An attempt was made to find changes in local temperature by interpolation of SAWS weather data for surrounding weather stations. The distance of the three closest stations ranged from 38km – 67km from the plant, however these data sets were incomplete. The closest station had 71% missing data for the baseline period and was discarded. The furthest station had 21% of the data missing for the baseline period and 14% missing for the reporting period. The third station had in excess of 90% usable data, but its use was considered limited as the altitude between the station and the plant differed by about 300m.

An ambient model would be important if the plant HR was evaluated over short periods such as monthly or quarterly, although this is less important if evaluated annually as seasonal effects are largely accounted for.

b) Flexible operation

The plant operation closely matches the EPRI prototypical cycle of “Baseload: Minor Load Following” (Categories 5a, 5b) (EPRI 2002: A-15, A-16) as shown in Appendix D. Cycling is typically shallow and is not characterised by regular On/Off operation, deep cycles or regular fast ramp rates. Provided this typical operation pattern does not change from the baseline period to the reporting period, adjustments associated with deep cycling are not necessary. A comparison of the number of On/Off cycles between the two periods will be made to verify this. Given these patterns, the changes in performance due to part-load operation may be based on the plant capacity factor (CF) (p44).

Figure 22 (p47) shows the generic trend of HR deterioration for a generating unit under part-load operation. At the CFPP in question, the coal flow to individual generating units is not measured so it is not possible to build such a part-load model empirically. However, a simulation model has been used to characterise the part-load performance of one of the units. The model shown in Figure 39 was generated using VirtualPlant™ modelling software produced by GPStrategies® (previously General Physics®).

The model has been calibrated using real plant data and validated by comparison to the original unit heat balance (see Appendix E). This model is not an exact predictor of performance, but is the best available means of predicting a *relative change* in HR (ΔHR) based on average operating load for two assessment periods. The model was used to generate HR values at various loads and these data points were then characterised using a single variable polynomial regression. This adjustment model predicts a % HR deviation from 100% MCR as a function of average plant load as shown in Equation 30.

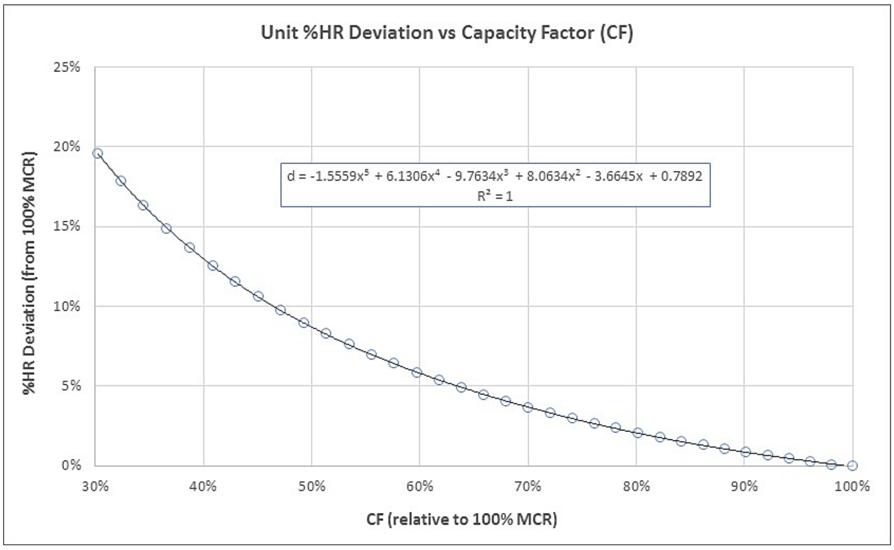


Figure 39: Regression model for unit HR deviation at part-loads

Equation 30 $$d = 0.7892 - 3.6645x + 8.0634x^2 - 9.7634x^3 + 6.1306x^4 - 1.5559x^5$$

Where $d = \%\ Deviation\ in\ HR\ (from\ 100\%\ MCR)\ (\%)$

$x = Average\ plant\ operating\ load\ for\ an\ assessment\ period\ (CF)$

c) Coal characteristics

Heating value (HV)

The higher heating value (HHV) of the coal is the data which is readily available and is quoted on a "Dry basis" (DB). The daily total moisture (TM) values are then added back to obtain the HHV on an "As received" (AR) basis. Provided that other coal parameters do not change very much, small changes in HHV should not affect the plant HR as coal mass flow can be altered proportionally.

Total moisture (TM)

Changes in TM directly affect the difference between the coal LHV and HHV and this has two separate effects on HR.

Firstly, if the coal TM increases, the LHV decreases. In order to maintain the same electrical output, the coal mass flow can be increased. If calculated on an LHV basis, the HR would remain unchanged, provided that the TM changes are small and that the plant was not already operating at 100% MCR. However, if calculated on an HHV basis, the HR would increase. This increase does not represent a real performance change, but an apparent change brought about by the use of HHV rather than LHV. Secondly, as explained in the "Moisture" section (p49), empirical evidence has shown that actual HR does deteriorate slightly as TM increases. The sum of these two effects has been estimated for a set of reference conditions as shown in Figure 40.

This model is developed by assuming that for small changes in TM, the plant maintains output by adjusting the coal flow slightly. Suppose that TM increases from 6.3% to 7.9% (an increase of 1.6%-pt), the coal LHV decreases by 0.2%[30]. In order to maintain plant output, the coal mass flow is increased by 0.2%. If calculated on a LHV basis, the plant HR would go unchanged, but if calculated on a HHV basis, the HR would increase by approximately 0.2% due to the increased coal consumption. This apparent change in HR is not performance related and the baseline HR would need to be adjusted up by 0.2%.

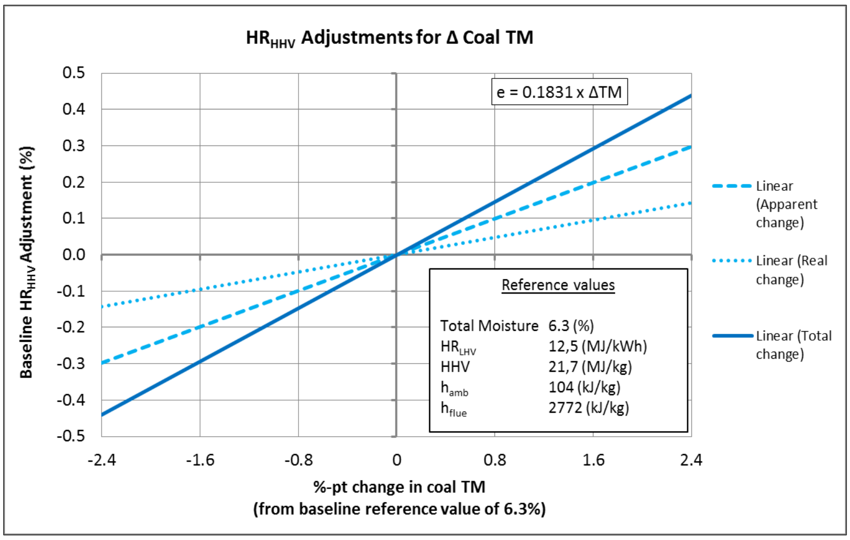


Figure 40: Baseline adjustment model for small changes in coal total moisture

Equation 31

$$e = 0.1831 \times \Delta TM$$

Where $e = HR\ adjustment\ for\ changes\ to\ coal\ total\ moisture\ (\%)$

$\Delta TM = Change\ in\ coal\ TM\ (\%\text{-}pt\ from\ baseline\ value\ of\ 6.3\%)$

Ash

Increased coal ash content causes HR to increase for multiple reasons. The boiler is most affected by lower flame temperatures, increased slagging, poorer heat exchange and increased losses. Auxiliary plant loads tend to increase and coal HV is also negatively affected (see “Ash” on p50).

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[30] This model assumes coal moisture enters the plant at 25°C and leaves in the flue gas at 175°C. This represents an enthalpy rise from 104 kJ/kg to 2,772 kJ/kg.

In the absence of empirical plant data, the ash adjustment model is based on an IEA (1993: 56,86) study which found a HR increase of 12.7 kJ/kWh for each %-point increase in ash content. This has been used to create a baseline HR adjustment model shown in Figure 41 and Equation 32[31].

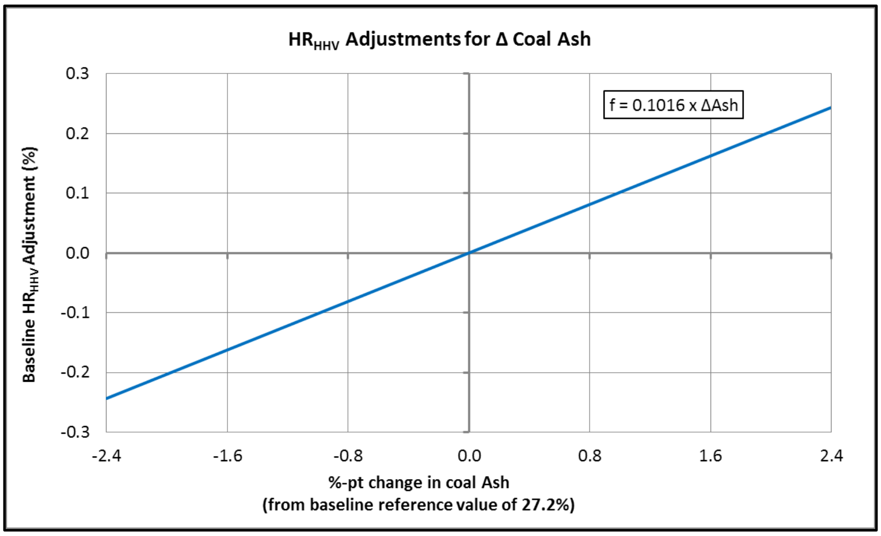

Figure 41: Baseline HR adjustment model for changes in coal ash

Equation 32

$$f = 0.1016 \times \Delta Ash$$

$$Where\ \ f = HR\ adjustment\ for\ changes\ to\ coal\ ash\ content\ (\%)$$

$$\Delta Ash = Change\ in\ coal\ ash\ (\%\text{-}pt\ from\ baseline\ value\ of\ 27.2\%)$$

Other factors

The following assumptions have been made for other coal characteristics and unknown factors.

- The hydrogen content of the coal is not found during routine proximate analysis and ultimate analysis data was not available. This is assumed to remain reasonably constant.
- Changes in sulphur content and coal hardness have been ignored.
- The coal is not present on the stockpile for long enough for the HV to be significantly affected by natural atmospheric oxidation.
- The moisture in the coal is not measured again after delivery so the real value just prior to combustion is unknown.
- The coal mass lost to the atmosphere during wind and onsite transport is unknown.

---

[31] The reference conditions for this model are a baseline ash content of 27.2% and a HR of 12.5 MJ/kWh

d) Routine adjustment model

Of the major factors which affect HR, the average plant operating load or capacity factor (CF) and the total coal moisture (TM) have been selected as the independent variables. These are the primary HR determinants for which reliable data is available. The HR adjustment formulas are shown in Equation 33 and Equation 34.

The part-load performance model is non-linear and the %-HR deviations predicted are referenced to the performance at 100% MCR. Neither the baseline, nor the reporting period average loads are likely to be at 100% MCR. Thus the adjustment uses the ratio of deviations from 100% MCR for both the baseline and reporting periods.

Equation 33

$$HR_{ABP} = HR_{BP} \times A$$

Where HR_{ABP} = Adjusted baseline heat rate (MJ/MWh)

HR_{BP} = Baseline heat rate (MJ/MWh)

A = Baseline adjustment factor

Equation 34

$$A = \frac{(1+e)(1+f)(1+d_{RP})}{(1+d_{BP})}$$

Where A = Baseline adjustment factor

e = HR adjustment for changes to coal total moisture (%)

f = HR adjustment for changes to coal ash content (%)

d_{RP} = Deviation in HR (from 100% MCR) at baseline period load (%)

d_{BP} = Deviation in HR (from 100% MCR) at reporting period load (%)

e) Non-routine adjustments: static factors

Below are listed various major factors which certainly affect the plant HR, but which either are fixed or are not expected to change throughout the baseline and reporting periods. In the case of any changes, appropriate adjustment methods would need to be developed.

- Plant vintage, design and size.
- Plant equipment: It is assumed that major parts of the plant remain the same. These parts may undergo repairs and maintenance but are not retrofitted entirely with more modern systems and continue to be operated in the same way. Some of these plant parts include boilers, steam turbines, condensers, CW system and pollutant controls.
- Fuel type: It is assumed that the fuel sources remain the same. It is given that the coal characteristics vary with time but these do not constitute fuel switching (e.g. natural gas) or major changes such as co-firing with biomass.
- If the plant began using an entirely different fuel, such as gas or co-firing with biomass.

3.5.3 Uncertainty

This section examines the uncertainties listed previously in Figure 26 (p62) and proposes a method of quantifying the combined effect of these.

SABS (2017: 24) recommends a Monte Carlo simulation for evaluating the combined uncertainties from different sources. In cases where an uncertainty calculation is dominated by one component, then less significant elements may be excluded. According to SABS (2017: 23), if the effect of the most significant component is four times larger than the effect of the next smallest component, then the smaller components may all be disregarded.

It should be noted that the final uncertainty statement of confidence and relative precision refers to the impacts and is thus a function of the magnitude of the those impacts. As the magnitude of the impact decreases relative to the baseline, the relative precision of the impact deteriorates (Carstens, Rawlins & Xiaohua, 2017: 3).

a) Metering precision: General

It can be assumed that meter precisions are quoted at a 95% confidence level, unless stated otherwise (SABS 2017: 10). It is important to note that some meter precisions are quoted as a percentage of the full-scale (maximum) measurement specification of the device. If a measured value is well below the quoted full-scale, then the precision will likely be much worse than the stated value (IPMVP 2014: 12). According to the IPMVP (2014: 17), meters which are used for billing purposes may be taken to be 100% accurate, provided that required calibrations have been performed.

b) Electrical energy

According to SABS (2009a: 12), electrical energy meters measuring loads in excess of 100MVA are required to be "Class 0.2S" (Relative precision of ±0.2%) (SABS 2009a: 12) and the required calibration interval is five years (SABS 2009a: 22). Calibration certificates for the electrical meters were not available. The uncertainty of the electrical energy includes both sent-out and imported measurements.

c) Coal mass

According to calibration certificates obtained for the conveyor scales, the relative precision of scales required for trading coal is ±0.5% (Exact Calibration Services, 2014: 2). The conveyor scales and the weighbridge for road deliveries are routinely calibrated but the conveyor scales measuring coal flow within the plant are not formally calibrated. Internal checks are done from time to time using deadweights.

d) Coal heating values

Sampling

Measurement of coal HV involves sampling and is affected by issues such as fuel variability, number of samples taken, mass of samples taken and the number of increments into which each sample is divided (SABS 2001: 6). Sampling according to standardised methods and best practice ensures that sample bias is minimised. On this basis, the sample average heating value ($\overline{HV}$) and the sample standard deviation (s) are assumed to be unbiased estimators of those parameters for the entire population.

Distribution of coal heating values

The actual coal HV probability density distributions during the baseline phase are shown in Figure 42. Each data set has been approximated by a superimposed normal distribution with the same average ($\overline{HV}$) and standard deviation (s). Deciding whether a data set can be approximated by a normal distribution is subjective, although some guidelines have been suggested (ResearchGate, 2014). In this case a visual inspection is taken as sufficient to support this assumption. Moreover, even in cases where normality of a population cannot be assumed, the sampling distribution (distribution of means) may still be assumed to be normal (Walpole, Myers & Myers, 1998: 217) and it is the sampling distribution which is of prime importance in this case. The data for coal “Supply B” is slightly right-skewed. In this case the median (M) is used rather than the average to generate the normal approximation.

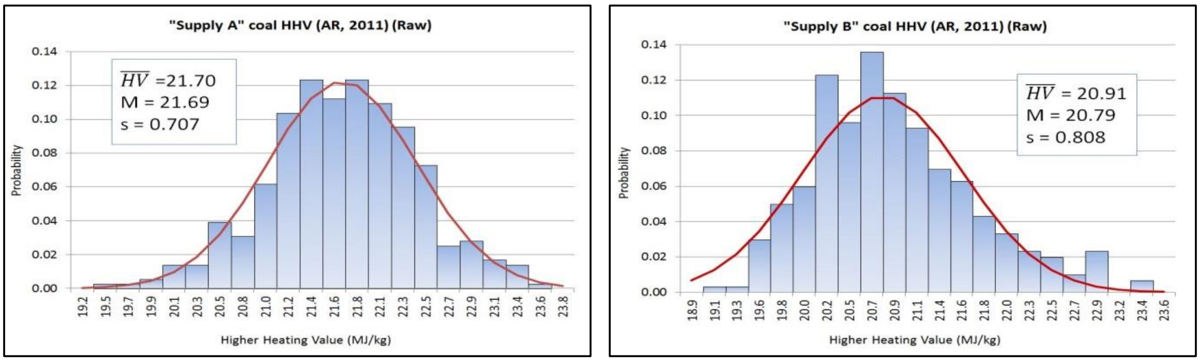

Figure 42: Actual and idealised baseline coal HHV probability density distributions

Laboratory performance

The coal analysis equipment at both laboratories is periodically calibrated by SANAS-accredited inspection bodies. Regular internal checks are also undertaken every few weeks to verify that calorimeters are performing within specified limits. The laboratories also partake in collaborative exercises with other laboratories to assess performance by all testing the identical material using a standard measurement method (SABS 2009b: 4). However given that coal is a heterogeneous substance, even properly prepared samples cannot be expected to yield identical results at various laboratories.

Table 14 shows an example of the variability of results between laboratories obtained during such an exercise. This indicates that each individual coal HV data point has a 95% probability of being within ±2.16% of the average.

Table 14: Summary of results from “Round-Robin” exercise (24 coal analysis laboratories)

Sample Parameter	Value	Unit
n	24	-
Minimum	26.69	kJ/kg
Maximum	28.05	
Median	27.13	
Average	27.14	
Std Dev (s)	0.2994	
Lower bound (95% Conf)	26.56	
Upper bound (95% Conf)	27.73	
Relative range (containing 95% of samples)	Average ± 2.16 %	

e) Uncertainty of the adjustment model

The HR deviation model R^2 value of 0.999 indicates that 99.9% of the HR deviation is explained by the model. An ANOVA (Analysis of variance) spreadsheet function is used to determine the model standard error (SE) and to find the statistical significance of each of the polynomial coefficients.

The model SE ($SE\ d_{BP}$) is given as 0.0415. Then the overall uncertainty of the baseline HR adjustment factor A (see p79) is found using Equation 35. For an A value of unity and HR deviations of roughly 2.5%, this yields a baseline adjustment factor relative precision of ± 0.12% at a confidence level of 95%.

Equation 35

$$\frac{SE\ A}{A} = \sqrt{\left[\frac{(SEd_{BP})}{(1+d_{BP})}\right]^2 + \left[\frac{(SEd_{RP})}{(1+d_{RP})}\right]^2 + \left[\frac{(SEe)}{(1+\mathrm{e})}\right]^2 + \left[\frac{(SEf)}{(1+\mathrm{f})}\right]^2}$$

$Where\ \ A = Baseline\ adjustment\ factor$

$d_{BP} = Baseline\ period\ \%\ deviation\ of\ plant\ CF\ from\ 100\%$

$d_{RP} = Reporting\ period\ \%\ deviation\ of\ plant\ CF\ from\ 100\%$

$e = HR\ adjustment\ for\ changes\ to\ coal\ total\ moisture\ (\%)$

$f = HR\ adjustment\ for\ changes\ to\ coal\ ash\ content\ (\%)$

Table 15 shows all of the ANOVA coefficient “t-stat” values significantly exceed the critical “t-value” of 2.04 for 95% confidence and 33 degrees of freedom (DOF). Thus all of them are considered to be statistically significant (IPMVP 2014: 17).

Table 15: Evaluation of regression uncertainty

Term	Coefficient	"t-stat" Absolute value (ANOVA)	Critical "t-value" (DOF=33)
Constant	0.7892	49.49	2.04
x	-3.6645	26.06	
x^2	8.0634	16.91	
x^3	-9.7634	12.53	
x^4	6.1306	9.96	
x^5	-1.5559	8.25	

f) Assumptions and exclusions

The following aspects of uncertainty are considered to be insignificant.

- It is assumed that over the course of an assessment, the error of the laboratory results are random and thus have an unbiased probability of being above or below the true values. Errors have also been reduced by taking the daily HV as the average of the daily results from the plant laboratory and the colliery laboratory. It so happens that in the collaborative exercise, the plant laboratory HV was above the mean and the colliery HV was below it. In that instance the potential error was reduced by 1.66 %-points.
- The uncertainty associated with the HR adjustment for moisture changes is taken to be insignificantly small.
- The uncertainty associated with the quarterly aerial surveys has not been accounted for due to lack of data.
- The mass of coal reclaimed from the staithes to the stockpile is not measured and no estimates are available. However this apparently only occurs very seldomly.
- The estimated two day lag from coal entering the staithes to being burned is considered to be insignificant.

g) Magnitudes of component uncertainty

Table 16 below shows the uncertainty that each parameter contributes to the calculated HR. All the components are similar in magnitude and thus all need to be considered.

Table 16: Potential uncertainty effects of various parameters on calculated HR

Uncertainty parameter	Relative precision (at 95% confidence)
Coal mass	± 0.5 %
Coal heating value (HV)	± 0.4 %
Electrical energy	± 0.2 %
Adjustment model	± 0.07 %

h) Uncertainty of the impact

The uncertainty of the final calculated impact incorporates the HR uncertainties of both the baseline and the reporting periods as shown in Figure 43 and Equation 36. The final ΔHR and its precision can be stated either in absolute terms or in relative terms as shown in Equation 37 & Equation 38 respectively. In both cases, the “t-value” of 1.96 corresponds to a 95% confidence level (IPMVP 2014: 3,4,17).

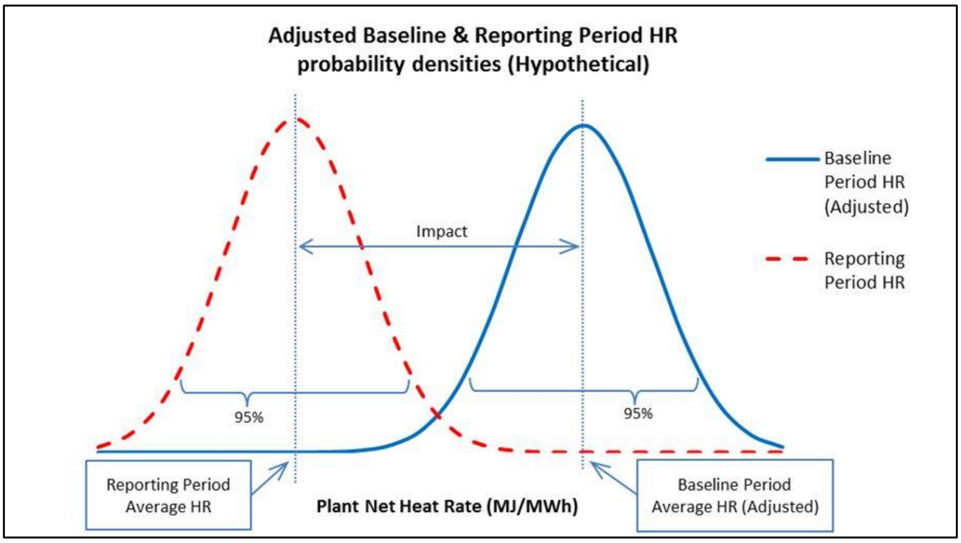

Figure 43: Hypothetical HR probability distributions for baseline and reporting periods

Equation 36
$$SE_I = \sqrt{{SE_{ABP}}^2 + {SE_{RP}}^2}$$

Where SE_I = Standard error of the impact ΔHR (MJ/MWh)

SE_{ABP} = Standard error of the adjusted baseline HR (MJ/MWh)

SE_{RP} = Standard error of the reporting period HR (MJ/MWh)

Equation 37
$$\Delta HR = HR_{ABP} - HR_{RP} \pm 1.96 \times SE_I$$

Equation 38
$$\Delta HR_{\%} = \frac{HR_{ABP} - HR_{RP}}{HR_{ABP}} \pm \frac{1.96 \times SE_I}{HR_{ABP}}$$

Where ΔHR = HR Impact (absolute) (MJ/MWh)

$\Delta HR_{\%}$ = HR Impact (relative) (% ± %-pt)

HR_{ABP} = Adjusted baseline HR (MJ/MWh)

HR_{RP} = Reporting period HR (MJ/MWh)

SE_I = Standard error of the impact ΔHR (MJ/MWh)

3.5.4 ΔHR calculation summary

Figure 44 summarises the HR calculations for any assessment period. By convention, the adjustment step for part-load operation is only applicable to the baseline period.

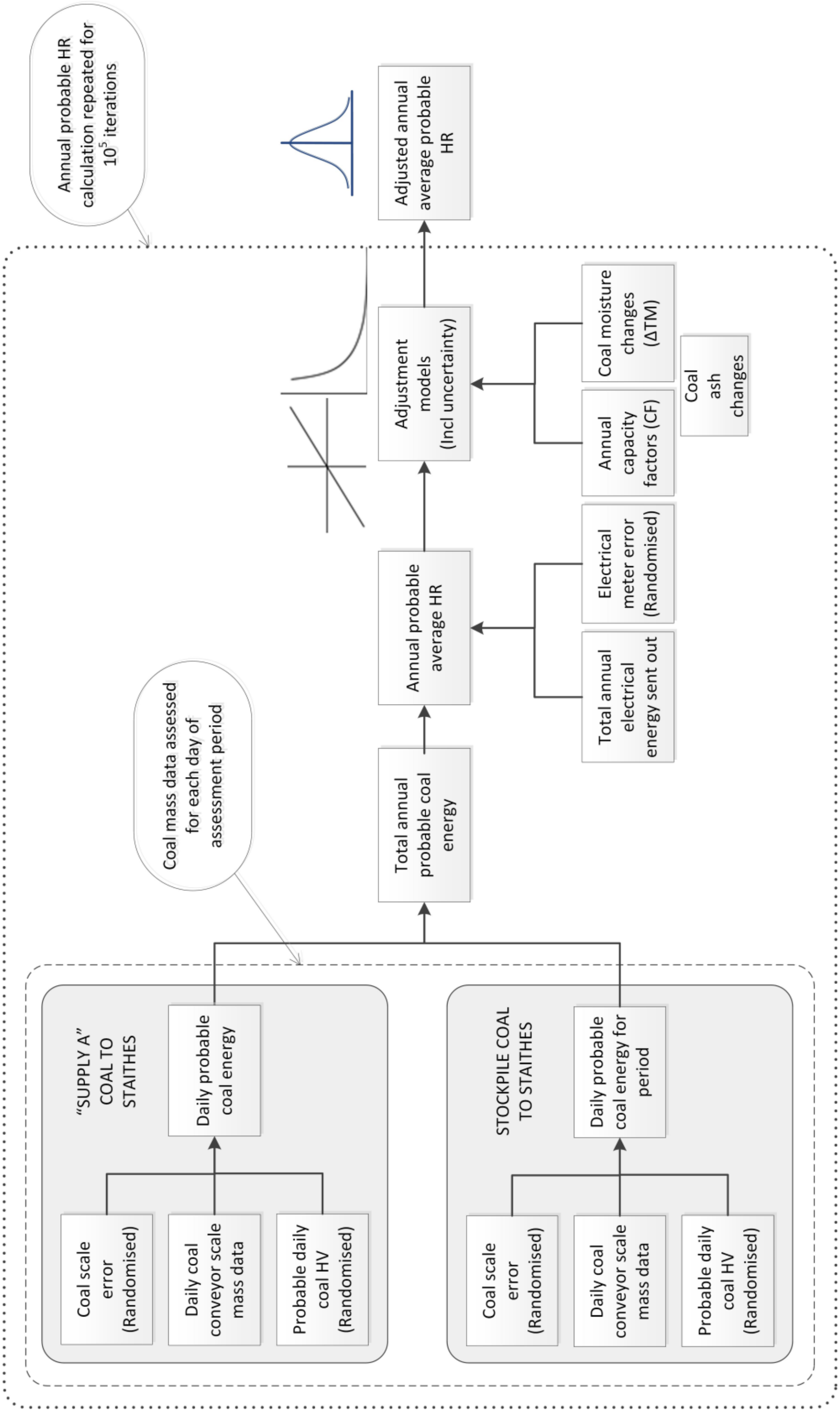

Figure 44: Schematic summary of statistical HR calculation

3.5.5 Other details

a) Measurement equipment

All data requirements are provided by the plant using existing meters and instrumentation. No new metering is to be installed for the purposes of M&V.

b) Data checks

Data needs to be inspected for obvious errors and rogue data points. These include:

- Data which is clearly out of range, e.g. the power output of a unit far above its maximum rated capacity.
- Parts of a data series which are very unlikely to occur in real data sets such as long periods of an identical value or of perfectly uniform rates of change.
- Instances where copying errors have obviously occurred during manual transfer of data prior to it being supplied, e.g. if a coal daily HHV entry is an order of magnitude different due to the omission of the decimal point.
- Anomalies found in cases where double checks are possible, e.g. it could be the case that the sum of masses from two scales should equal the mass measured by a third scale.

c) Data derivation

If any data is missing, details of all derived data points must be detailed fully. This applies to both data required for the HR calculation, the independent variables required for adjustments and any data upon which assumptions are based.

d) Assessment periods

All assessment periods are a minimum of 12 months. The baseline period is selected as the calendar year of 2011 as this was the year before any ECM implementation on any of the generating units.

e) Site visits

Ideally site visits should take place before and after ECM implementation to verify that the planned measures have taken place, been commissioned and are fully operational. Site visits are also an opportunity to identify the potential need for non-routine adjustments.

f) Calculation tools

All data storage, calculations, graphing and analysis are performed using Microsoft Excel 2010. The part-load routine adjustment model was developed using VirtualPlant™ developed by GPStrategies® (previously General Physics®).

3.6 Chapter summary

This chapter provided an overview of the plant and described each ECM. “Option C” (Whole facility) was chosen as the measurement boundary and this was used to define the data requirements and assessment period length. In order to isolate the changes in HR_N which are due to the ECMs only, an adjustment model was developed to adjust the baseline HR_N to what it would have been in the absence of any ECM implementation.

A method for quantifying ΔHR_N uncertainty was developed using Monte Carlo analysis which included uncertainty related to coal mass, coal HHV, electrical energy and also the uncertainty of the adjustment model itself. Other aspects addressed in this chapter include data checks, data derivation, and site visits. The information in this chapter has been used to calculate the changes in plant HR_N which are presented in Chapter 4.

Chapter 4 M&V Results

This chapter uses the methodology developed in Chapter 3 to determine the changes in HR_N between the selected baseline period and two separate consecutive twelve month reporting periods.

4.1 Reporting periods

Table 17 below shows the dates selected for the baseline period and for the two reporting periods. After the baseline year of 2011, two years were allowed for the progressive rollout of ECMs across multiple generating units and the auxiliary plant as allowed for by shutdown periods.

Table 17: Dates of the baseline and reporting periods

Baseline period	Reporting Period 1	Reporting Period 2
01 Jan 2011 - 31 Dec 2011	01 Apr 2014 - 31 Mar 2015	01 Apr 2015 - 31 Mar 2016

4.1.1 Baseline HR_N data

Table 18 below summarises the data used to determine the HR_N for the baseline and reporting periods. Most of the absolute values of data from the plant such as coal used and electrical energy generated are indicated as “Classified” in order to protect the plant identity.

Table 18: HR calculation data for each assessment period (mainly classified)

	Baseline period	Reporting Period 1	Reporting Period 2
Average HHV of coal consumed (MJ/kg)	21.49	21.05	21.63
Total coal consumed (t)	**Classified**		
Total electrical energy sent-out (MWh)			
Total electrical energy imported (MWh)			
Baseline HR_N (MJ/kWh)			

4.2 Routine baseline HR adjustments

Section 3.5.2 described the key independent variables affecting plant HR and used these to develop a routine baseline adjustment model (see p75-80). These are mentioned again here briefly for clarity. The variables included in the adjustment model are the plant capacity factor (CF), the coal total moisture (TM) content and the coal ash content. The ambient conditions (temperature and relative humidity) should also be accounted for but could not be adequately modelled due to a lack of reliable historical weather data. The effect of excluding the ambient conditions was mitigated by only using assessment periods of at least twelve consecutive months to account for seasonal changes.

Further factors affecting HR are listed below which were also excluded from the routine baseline adjustment model. In some cases insufficient data was available to model the impacts on plant HR and in other cases no data was available at all.

- Coal hydrogen content.
- Coal sulphur content.
- Coal volatile matter (VM) content.
- Coal hardness.
- Changes to HV of stockpiled coal (due to natural atmospheric oxidation).
- Changes to total moisture (TM) of stockpiled coal (due to ambient conditions, precipitation).
- Changes to operation of the flue gas cleaning system (bag filters).
- Coal dust losses (due to wind, onsite transportation).

4.2.1 Plant capacity factor (CF)

Table 19 shows the whole plant CF for each assessment period. During the baseline period the plant produced 81.7% of the electrical energy which it could potentially have produced, during the hours it operated, based on its nameplate rated capacity. Relative to the baseline period, the CF was 1.3%-pts lower during the first reporting period (80.4%) and 4.1%-pts lower during the second reporting period (77.6%).

The CF adjustment model (see p75) has been used to estimate the %-deviation of the plant HR_N for each period as a result of part-load operation. During the baseline period the part-load HR penalty was 1.8%, and so on. As expected, it is evident that a lower CF incurs a greater performance penalty.

Table 19: Plant CF baseline adjustments

	Baseline period	Reporting Period 1	Reporting Period 2
Average plant capacity factor (CF) (%)	81.7	80.4	77.6
HR_N deviation from 100% MCR (%)	+1.8	+2.0	+2.4
Baseline HR_N adjustment (%)	N/A	0.17	0.57

During the reporting periods, some of the steam turbines were derated, either as a precautionary measure based on blade fatigue or following instances of actual blade failure. These derating measures affected the total generation capacity of the plant and this was accounted for in the CF calculation for each period.

Plant operational patterns also include start and stop cycles. These cycles only affect the use of startup fuels, which have been deemed insignificant for this study. For completeness however, Table 20 shows the %-change in total unit On/Off cycles for the entire plant during each reporting period in comparison to the baseline period. In both cases, the change was less than 9%.

Table 20: Changes in plant On/Off cycles

	Reporting Period 1	Reporting Period 2
Change in plant On/Off cycles relative to baseline period (%)	+8.5	-8.5

4.2.2 Coal total moisture (TM)

Table 21 summarises the baseline adjustments due to changes in coal TM for each assessment period. The average TM content of the coal is shown as a %-mass on an as-received (AR) basis. These are annual weighted averages which account for the daily masses of coal consumed from each coal source. The change in TM relative to the baseline period is an increase of 0.77%-pts and 0.48%-pts for the first and second reporting periods respectively.

A change in coal TM has two separate effects on HR_N. The first is an apparent effect brought about by the use of HHV rather than LHV. The second is a real effect brought about by changes to auxiliary loads resulting from changes in TM. The total amounts by which the baseline HR needs to be adjusted to account for these two effects is 0.14% for the first reporting period and 0.09% for the second reporting period. Although only the total adjustment is shown, the magnitude of the apparent component is roughly half the magnitude of the real component. This TM adjustment model is thoroughly described in Section 3.5.2.

Table 21: Coal TM baseline adjustments

	Baseline period	Reporting Period 1	Reporting Period 2
Total Moisture (%) (AR)	6.28	7.05	6.76
Change in TM relative to baseline (%-pt)	N/A	+0.77	+0.48
Baseline HR_N adjustment (%)	N/A	0.14	0.09

4.2.3 Coal ash

Table 22 summarises the baseline adjustments due to changes in coal ash for each assessment period. The average ash content of the coal is shown as a %-mass on an as-received (AR) basis. These are annual weighted averages which account for the daily masses of coal consumed from each coal source. The change in ash relative to the baseline period is an increase of 0.05%-pts and a decrease of 1.36%-pts for the first and second reporting periods respectively.

Table 22: Coal ash baseline adjustments

	Baseline period	Reporting Period 1	Reporting Period 2
Total Moisture (%) (AR)	27.2	27.3	25.9
Change in TM relative to baseline (%-pt)	N/A	+0.05	-1.36
Baseline HR_N adjustment (%)	N/A	+0.01	-0.14

4.2.4 Final baseline HR adjustment factor

The final routine baseline adjustment factors account for changes in plant capacity factor (CF), coal total moisture (TM) and coal ash content, as shown in Equation 34 (p79). Table 23 shows these factors for both reporting periods along with the standard error (SE) for each.

It can be seen that for both reporting periods, the adjustment factor is greater than unity, meaning that the baseline HR is adjusted *upwards*. This means that in the absence of any ECMs, the plant HR_N would have been *expected to deteriorate*, provided all other factors affecting HR_N remained the same.

The standard errors shown represent the uncertainty of the adjustment factor for each period according to the "Empirical Rule". In the first reporting period, there is approximately a 68% probability that the adjustment factor "A" falls in the range A ± (1 x SE), that is 1.00320 ± 0.00020 (1.00299 – 1.00340). There is a 95% probability that "A" falls in the range A ± (2 x SE) (1.00279 – 1.00360), and a 99.7% probability that "A" falls in the range A ± (3 x SE) (1.00259 – 1.00381). The same can be applied to the second reporting period. These probabilities were accounted for in the numerical uncertainty analysis as explained in Section 3.5.3.

Table 23: Baseline HR adjustment factors for each reporting period

	Reporting Period 1	Reporting Period 2
Baseline HR_N adjustment factor A	1.00320	1.00524
Standard Error (SE) of A	0.00020	0.00034

4.3 Non-routine baseline HR adjustments

No changes occurred regarding the major plant static factors during either of the reporting periods, thus no non-routine adjustments were necessary. Static factors are explained on p80.

4.4 M&V results

This section presents the final results of the entire M&V process. The changes in performance are expressed as a change in plant HR_N (ΔHR_N) for each reporting period, together with an associated uncertainty. As mentioned in Section 2.1.11, a saving is not deemed valid unless it is at least twice the size of the standard error of the adjusted baseline (IPMVP 2012: 88). This is also true for a performance deterioration.

A $\Delta HR_N < 0$ represents a performance improvement and $\Delta HR_N > 0$ represents a performance deterioration. In all cases, ΔHR_N is expressed as a %-change relative to the adjusted baseline HR, rather than as an absolute value. The results for each of the reporting periods may be read in a standalone manner which means that some explanations are repeated.

4.4.1 Reporting period 1

The M&V results for the first twelve month reporting period (01 Apr 2014 - 31 Mar 2015) are shown in Figure 45. The left-most curve represents the probable HR_N of the original unadjusted baseline. The adjusted baseline is situated at the origin on the x-axis as that is the point from which changes in performance are measured. The actual performance, relative to the adjusted baseline, is represented by the dotted curve on the right. The positive shift of 3.65% shows a marked deterioration in performance for the period, despite the fact that the baseline was also adjusted in a positive direction.

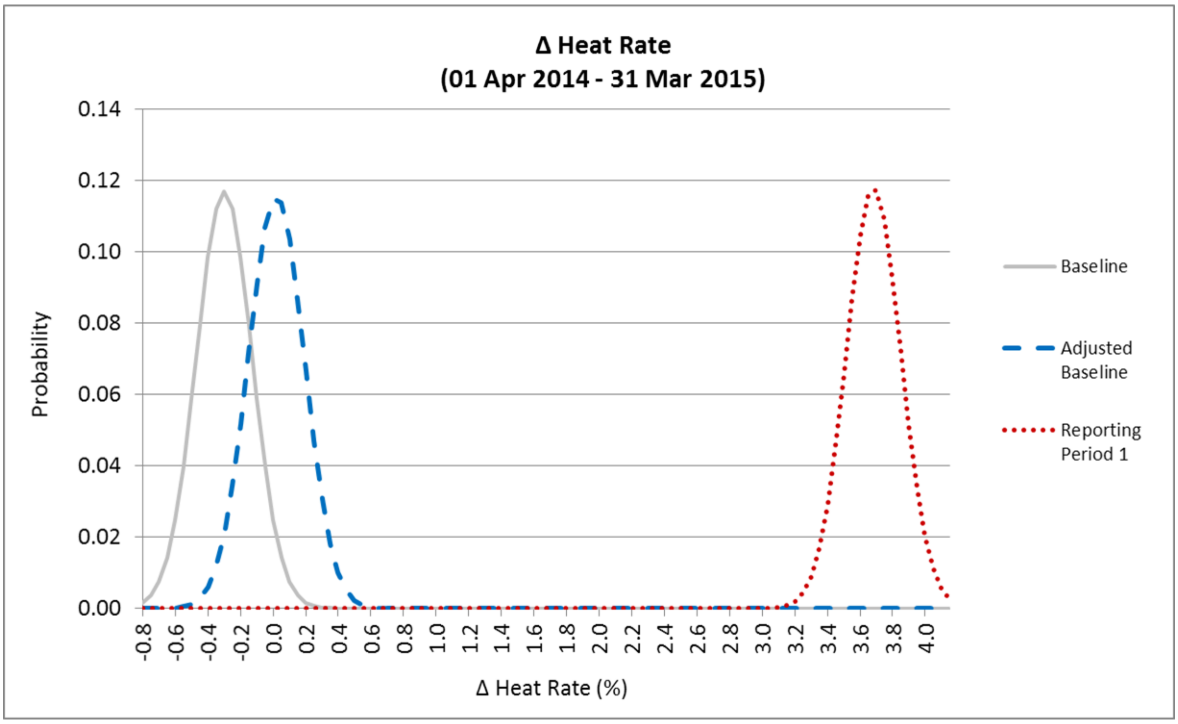

Figure 45: Probable change to HR_N for the period 01 Apr 2014 – 31 Mar 2015

Since the measurement boundary was "Option C" (Whole facility), it is not possible to pinpoint the reasons for the change in performance, however some potential causes may be speculated. One possibility is that the planned ECM rollout was not implemented on schedule. A delayed rollout of critical maintenance measures could have brought about a continued downward trend in performance.

Another possibility is that a critical factor affecting HR was excluded from the baseline adjustment model. For example, during the reporting period the ambient temperature may have been extraordinarily high. This may be tested using the suggested increase in HR of 0.15% per 1°C ambient temperature rise (IEA 2010: 53). If the exclusion of ambient temperature from the baseline adjustment model was the sole cause of the apparent drop in performance, this would mean that the average ambient temperature during the reporting period increased by over 24°C relative to the baseline period. This impossible scenario is sufficient to rule out ambient temperature as the sole cause.

Other factors affecting HR_N, which were excluded from the baseline adjustment model, are also unlikely to be the cause. Other annual average coal characteristics such as sulphur and VM content did not change significantly relative to the baseline period as shown in Table 24 and Table 25. All values are shown as %-mass of the coal on a dry basis (DB).

Table 24: Coal "Supply A" sulphur and VM content

	Baseline period	Reporting Period 1
Average coal Sulphur (%)	0.91	0.91
Average coal VM (%)	23.0	22.8

Table 25: Coal "Supply B" sulphur and VM content

	Baseline period	Reporting Period 1
Average coal Sulphur (%)	0.72	0.67
Average coal VM (%)	21.0	20.8

Table 26 below shows the precision of the calculated ΔHR_N value for three different confidence levels, namely 50%, 80% and 95%. So for example there is a 95% probability that ΔHR_N was between 3.18% and 4.12%, and so on. Narrower ranges of ΔHR_N uncertainty have lower levels of confidence and vice versa.

Table 26: ΔHR_N uncertainty for the period 01 April 2014 – 31 March 2015

Confidence level	ΔHR_N (%) Estimate ± Range	Lower estimate (%)	Upper estimate (%)
50%	3.65 ± 0.16	3.49	3.81
80%	3.65 ± 0.31	3.34	3.96
95%	3.65 ± 0.47	3.18	4.12

4.4.2 Reporting period 2 (01 Apr 2015 - 31 Mar 2016)

The M&V results for the second twelve month reporting period (01 Apr 2015 - 31 Mar 2016) are shown in Figure 46. The left-most curve represents the probable HR_N of the original unadjusted baseline. The adjusted baseline is situated at the origin on the x-axis as that is the point from which changes in performance are measured. The actual plant performance during the second reporting period is represented by the dotted curve to the right of the adjusted baseline.

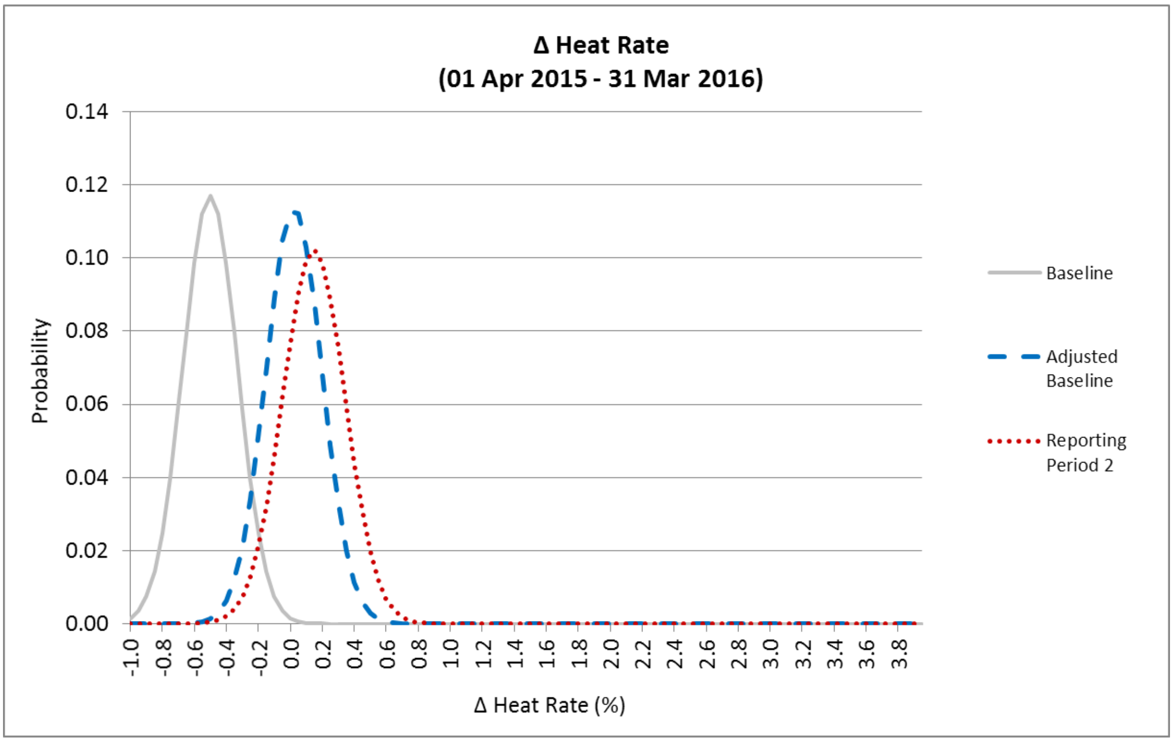

Figure 46: Probable change to HR_N for the period 01 Apr 2015 – 31 Mar 2016

Relative to the adjusted baseline, the performance deterioration for the period was +0.12%. However, when compared to the immediately preceding twelve months, that is the first reporting period, the performance shows a substantial improvement (see Figure 45). It could be argued that the performance improvement (over the first reporting period) was the result of the planned ECM implementation. However, as before, the measurement boundary was “Option C” (Whole facility) making it impossible to identify the exact reasons for the restored performance where there have been multiple ECMs.

Table 27 and Table 28 show that the annual average coal characteristics of sulphur and VM content did not change significantly relative to the baseline period. The slight change in performance is unlikely to be due to changes in these factors.

Table 27: Coal “Supply A” sulphur and VM content

	Baseline period	Reporting Period 2
Average coal Sulphur (%)	0.91	1.02
Average coal VM (%)	23.0	23.8

Table 28: Coal “Supply B” sulphur and VM content

	Baseline period	Reporting Period 2
Average coal Sulphur (%)	0.72	0.70
Average coal VM (%)	21.0	20.8

As is evident from Table 29 below, the minor performance change of +0.12% relative to the baseline period is not statistically significant at all. In fact, even at a confidence level of only 50%, it cannot be said that there was any change. The probable ranges of ΔHR_N are also shown for confidence levels of 80% and 95%.

Table 29: ΔHR_N for the period 01 April 2015 – 31 March 2016

Confidence level	ΔHR_N (%) Estimate ± Range	Lower estimate (%)	Upper estimate (%)
50%	+0.12 ± 0.17	-0.05	+0.30
80%	+0.12 ± 0.33	-0.21	+0.46
95%	+0.12 ± 0.51	-0.39	+0.64

4.5 Data derivation

There were some instances in which data derivation was required as summarised in Table 30 below. In all cases, derivations were performed using surrounding data as described in Section 2.1.10.

Table 30: Summary of data derivations

Derived parameter	Data resolution	Total derived %
Electrical energy	Hourly	2.7%
Coal HHV (MJ/kg)	Daily	1.1%
Coal TM (%)	Daily	2.5%
Coal Mass (t)	Daily	0.0%

4.6 Site visits

Prior to any ECM implementation, a single two day site visit was carried out to kick off M&V activities. Ideally this should have been followed up with further site visits to verify ECM implementation. Further visits would also have served to ensure that factors which had been classified as static did in fact remain unchanged.

Thus all information regarding the ECM rollout and static factors was provided by the plant staff electronically. This means of verification requires trust and itself introduces some uncertainty, although this is not quantifiable.

4.7 Chapter summary

This chapter presented the final results of the M&V process for two separate consecutive twelve month reporting periods. The baseline HR_N was adjusted for the plant CF and the coal TM relevant to each reporting period. In each case, the calculated ΔHR_N was presented as a probable range with an associated confidence interval. Each reporting period includes the collective impacts of all ECMs implemented since the end of the baseline period.

The results for each period were briefly discussed with speculative reasons for changes in performance. Where possible, for variables excluded from the baseline adjustment model, evidence was provided as to why their exclusion should not have had any significant impact on reported results. A brief summary of data derivation and site visits was also provided.

The following chapter discusses the merits and shortcomings of the M&V methodology as a whole.

Chapter 5 Discussion

5.1 Introduction

The purpose of this chapter is to provide an objective appraisal of the M&V methodology to identify and discuss its merits, shortfalls and limitations. The key aspects discussed are the measurement boundary selection, the selection of independent variables, the development and limitations of the baseline adjustment model, reasons for excluded independent variables and the general challenges associated with limited data.

5.2 Measurement boundary selection

The selection of a measurement boundary is often a compromise and may be affected by data availability, cost of new metering and instrumentation, the expected magnitude of the ECM impacts, the potential for interactive effects, the extent to which valid assumptions can be made, the length of assessment periods and the M&V funds available. The IPMVP (2012: 33,34) provides guidance on measurement boundary selection, but not every ECM or M&V project perfectly fits the selection criteria.

In this case the “Whole facility” option was chosen (“Option C”). Although the IEA recommends this boundary for determining CFPP performance (IEA 2010: 37,43), it was known that the expected ΔHR improvement would not exceed the 10% impact recommended by the IPMVP for the whole facility option. The “Whole facility 10% Rule” in the IPMVP is recommended as a means of decreasing reporting uncertainty due to unexplained random variations in energy use, when measured at the facility level over periods shorter than two years (IPMVP 2012: 25).

Yet there were further valid reasons for choosing this option. Firstly, many of the measures were likely to have complex interactive effects. Secondly, while the measures improved and restored performance in some parts of the plant, it is possible that the performance of other parts of the plant were simultaneously deteriorating. Similarly, a single ECM could be successful for a time and then become ineffective later. Thus from the perspective of ECM persistence and sustainability, the whole facility option is well-suited as it recommends long assessment periods and captures both positive and negative changes in performance. Apart from these reasons in favour of “Option C”, there were also reasons why the other available options were *not* ideal.

The “Retrofit isolation” options (“Option A” & “Option B”) require the measurement boundary to be around each individual ECM and would require data for the energy and independent variables within each of those boundaries. Given the number of different measures this would not only have greatly increased the burden of data collection, but would also have required new instrumentation. For example “ECM 2.01” (p54) states that “Valves should be lagged, but are not”. A retrofit isolation option would require monitoring the surface temperature of the valve and the ambient temperature to estimate the heat loss to the surroundings. Neither of these instruments was installed thus no baseline data was available, nor was there any M&V budget for such instrumentation. In general, an M&V methodology that is dependent on multiple data sources increases reporting risk in due to the potential of data failure. The IEA (2010: 45) recommends that data collected and analysed on a large scale should be readily available. This is specifically with reference to fuels but the principle has value for all data.

The “Calibrated simulation” (“Option D”) requires a sophisticated software model to simulate the vapour power cycle. Although such a simulation package was procured by the utility at the start of the M&V process, it is used to simulate the performance of a single generation unit, and thus requires accurate coal mass flow to each unit. As previously discussed, the coal flow at the plant is not measured to each individual generation unit, only the coal mass flow to entire plant is known.

Another factor against “Option D” was the availability of accurate calibration data. “ECM 2.05” (p54) stated “Ensure calibration and accuracy of all C&I instrumentation to increase confidence in HR reporting”. This ECM included calibration of instruments measuring temperatures, pressures, steam flow and water flow.

5.3 Evaluation of the baseline adjustment model

5.3.1 Included independent variables

As mentioned in Section 2.1.5, the selection of independent variables for the baseline adjustment model is arguably one of the most important aspects of an M&V calculation. Relevant independent variables are only those which explain, or partially explain, changes in energy use (IPMVP 2014: 7). An important consideration in the selection of variables is the extent to which a facility has control over those variables. Specifically for the purposes of this discussion the terms “controllable” and “uncontrollable” refer to whether the CFPP plant management has control over those variables.

For some independent variables it is clear that the plant management has absolutely no control over them. A case in point is that of ambient temperature. Changes in ambient temperature affect plant HR and it is obvious that such variables should be accounted for in baseline adjustments so that M&V results fairly reflect changes in performance brought about by ECMs. Thus ambient temperature can immediately be classified as uncontrollable. However, in other cases, it is not quite as clear and the reasons given for variables changing need to be considered. Some of these are discussed below.

a) Ambient conditions

Although ambient temperature is an important independent variable, it was excluded from the adjustment model due to lack of reliable baseline data.

A possible alternative was to use cooling water (CW) temperature as a proxy for ambient conditions. This is the temperature of the CW after it has passed through the cooling system and is returning to the condensers. An advantage of this is that it naturally accounts for changes in both ambient temperature and relative humidity (RH).

However the CW temperature is not only a function of ambient conditions. It is also dependent on flow rate (and thus internal pipe conditions) and the condition of the cooling towers (CTs). Wet CT performance can deteriorate due to broken splash packs and in the case of forced draft systems, poor fan blade condition.

For a given set of ambient conditions, low flow rates and poor heat transfer would result in higher CW return temperature. If this was used as a basis to adjust the baseline HR for ambient conditions, the plant would in effect be rewarded for poor maintenance. This would defeat the object of M&V which seeks to detect performance changes brought about by factors *within* the control of the plant, which would include maintenance of the cooling towers.

As a means of mitigating the exclusion of ambient temperature as an independent variable, it was stipulated that assessment periods should consist of at least twelve consecutive months to account for performance variations brought about by seasonality. Though no two twelve month periods are identical, this would at least go some way towards accounting for seasonality.

b) Condenser pressure

The reasoning provided above for not using CW temperature as an adjustment variable can also be applied to condenser pressure. The condenser pressure could be high for multiple reasons including scaling and fouling, high CW temperature, impaired CW flow rate and in-leakage of ambient air. Once again, if the reason for high condenser pressure is poor maintenance, then a baseline HR adjustment could be seen as rewarding that.

Although the IEA (2010: 24,25) suggests that condenser pressure may be used to adjust HR, this is typically in the context of comparing the performance of two plants which have different types of cooling water systems. For example, comparing a plant with a dry closed-loop cooling system to a plant with a once-through open-loop wet system.

c) Part-load operation

One of the reasons previously cited for flexible operations was the increasing penetration by intermittent renewable sources with despatch priority (Hesler, 2011: 1). If it is a national or state policy to procure renewable energy when it is available, then fossil-fired plants may be forced to throttle output back so that supply meets demand. From this perspective it would seem best to classify part-load operation as an uncontrollable factor.

However it is possible that plant output may be reduced for an internal reason. In that case it could be classified as a controllable factor and the performance penalty incurred from part-load operation would not be compensated for by adjusting the baseline. As an example, suppose that a boiler cannot produce its rated steam conditions due to excessive slag deposits. It could be argued that repairs should have taken place during planned maintenance outages and that this basis for part-load operation does not warrant a baseline adjustment.

A special case is where a steam turbine has been derated and can no longer be operated at full capacity. This could result from a preventive measure taken to avoid blade failure and prolong unit life, or due to a row of blades being cropped. For example, a steam turbine with a 100MW nameplate rating could be derated to a maximum output of 80MW, resulting in part-load losses in both the turbine and the boiler. After the derating, given that 80MW is the “new” (or “re-rated”) full load of that unit, a question that needs to be considered is whether 80MW or 100MW should be used as the full load in the CF calculation. In other words, if the new maximum unit output is 80MW, should this be expressed as 80% CF or as 100% CF?

If the re-rated value of 80MW is taken as the full load and CF is calculated as 100%, then this does not warrant any baseline adjustments for CF. Any deterioration in performance due to part-load operation or due to changes to the turbine blades would simply be reflected as an increased HR. If however, the original nameplate capacity of 100MW was used, then the CF would be calculated as 80%, and a baseline adjustment would be applied.

It would not make sense to perform a baseline adjustment in a case where the turbine derating was necessary due to long term neglect, as this would be rewarding the plant for poor maintenance. On the other hand, the plant could have been forced by the utility to delay critical maintenance, against the request of the plant management. In such a case a baseline adjustment may be warranted. The decision to apply a baseline adjustment requires professional judgement, depending on the reasons given for the turbine derating.

d) Coal total moisture (TM)

A CFPP may have some control over the moisture content of coal procured. However once the coal has been stockpiled in the open, the total moisture can increase during periods of heavy precipitation and excessive increases in moisture can lead to clogging of storage bunkers, conveyors and milling equipment. In some cases this has led to reduced plant output (Eskom 2016: 1), which would need to be considered under part load operation.

The coal TM values used in the adjustment model are weighted values representative of an entire assessment period, but it is important to note that these values are determined at the date of delivery and not at the date of consumption. By the time the coal is burned it could have been exposed to dry conditions, humid conditions or precipitation and any resulting changes in TM are not known.

The modelled HR deterioration as a function of TM was 7.4 kJ/kWh as stated by the IEA (1993: 86), but a later study suggested that the deterioration *could* be worse (IEA 2010: 50).

e) Coal ash

Coal procured under long-term supply contracts needs to meet certain specifications, including ash content so large fluctuations would not typically be expected. A linear model has been used for the small changes expected. Coal ash content values used in the adjustment model are weighted values representative of an entire assessment period.

5.3.2 Excluded independent variables

The following coal-related variables were excluded from the model primarily due to lack of data and in these cases assumptions were made. This section provides brief support for those assumptions.

a) Hydrogen

The hydrogen content of the coal for this study was not known and was assumed to remain constant for the reporting periods relative to the baseline period. An indicator of the hydrogen content is the carbon to hydrogen (C:H) ratio and the IEA (2010: 48) suggests that the coal volatile matter (VM) content is a reasonable predictor of C:H ratio. Over the assessment periods in this study, the average coal VM content remained quite stable at 24.6%, 24.8% and 25.6% for the baseline, first and second reporting periods respectively.

b) Combustion characteristics

Even if the coal VM content is known from the proximate analysis, the particular combustion characteristics of the coal cannot be derived on that basis (IEA 1993: 47,48), so modelling boiler performance as a function of these characteristics is not possible with the coal data available.

c) Sulphur, ash, hardness & abrasiveness

Although an increase in coal sulphur content does cause in increase in FGD power requirements (IEA 1993: 73), this was not considered as the plant was not equipped with an FGD system.

Although an increase in both coal hardness and abrasiveness are known to degrade plant performance, insufficient data was available to characterise this and no estimates were found in the surveyed literature.

5.3.3 Limitations of the model

a) Applicability

The application of the baseline adjustment model is limited to the power plant in question and is not generally valid for use with other plants. Firstly, the model used for part-load operation is plant-specific. Secondly, the component applicable to coal moisture adjustments is specific to the coal used during the baseline period of this study.

b) Domain of independent variables

Another limitation of the model is that it is only valid for small changes in the independent variables. For example, the moisture adjustment assumes that if coal moisture increases slightly, plant electrical output could be maintained by compensating with a slightly increased coal flow. This presumes that the coal processing equipment has the capacity to increase the coal flow and furthermore that the boiler has the capacity to handle the increased gas flows, heat absorption and ash production. Given that the actual operating capacity of the plant examined is very rarely close to 100%, this assumption is not unreasonable.

The calculated moisture losses used in the model are based on a set of reference conditions (see Figure 40, p77) and assume that these conditions are constant. For example, constant flue gas temperature.

c) A "single-unit" model for multiple units

The part-load operating model represents the part-load performance of a single generating unit, but it is being used to characterise the changes in performance of the entire plant which consists of multiple generating units. Thus at the level of the whole plant, different combinations of unit loads can result in the same station part-load value used by the model.

For example, suppose the plant had just two generating units and that over a given period both units were operating at a CF of 75%, then it is reasonable to apply the single unit model to the whole plant. However, suppose that over the same period, the same electrical energy had been generated, at an average CF of 75% for the whole plant, but with one individual unit operating well below 75% CF and the other operating well above 75% CF. It needs to be determined whether treating the whole plant as a single generating unit leads to conservative M&V results, or inflated results.

An examination of Figure 39 shows that over the domain of interest (0.3 < CF < 1.0), the model has an "upward concave" form. This means that for any two units operating at the same load (e.g. CF 75%), the adjustment factor applied will never exceed the combined effect of applying separate adjustments to the units individually, had one been operating below 75% CF, and the other above 75% CF. This is shown graphically in Appendix F for two generating units and by induction is true for cases where the number of units exceeds two.

5.4 Treatment of uncertainty

5.4.1 Monte Carlo analysis for known factors

The analysis of known uncertainties was handled using the recommended Monte Carlo method (SABS 2017: 24). This was used to combine the uncertainties associated with coal HHV (including sampling), coal mass measurement, electrical energy consumption, and the baseline HR adjustment model. These factors all have normal distributions which were either derived empirically or from standards and calibration certificates (SABS 2009b: 12, SABS 2017: 10; ECS 2014: 2). However certain assumptions were still required, for example the precision of the electrical and mass measurements is stated for full scale meter readings and the instrument performance below full scale is not known.

5.4.2 Unknown factors and assumptions

The following factors have all been mentioned previously but are discussed together here to justify the assumptions made in the context of reporting uncertainty.

a) Staithe coal level changes

The coal conveyed to the boilers is not directly measured, but the coal delivered to the staithes can be calculated using conveyor scale data. The assumption is that the coal delivered to the staithes during an assessment period is equal to the coal burned, which requires that the coal stock level in the staithes remains constant. The coal level in the staithes is not measured, but is estimated by experienced staff. Furthermore it is estimated that the coal delivered to the staithes is burned roughly two days later which introduces an error into the coal mass used in the HR calculation. The magnitude of the error is not dependent on the coal mass delivered over the last two days of an assessment period, but on the *difference* in mass delivered between the last two days and the same two days the previous year, which was considered to be negligible.

b) Steady-state stockpile dynamics

The coal mass, moisture and HHV data used to characterise the probable HHV distribution of the stockpile for any one of the assessment periods was only taken from that period. However, in reality the stockpile was already in existence at the start of any period. Although much of the coal delivered during the period would be consumed, it is only reasonable to assume that much of the coal burned in the period was also from pre-existing stockpiled coal contained in the stockpile prior the start of that period. This required the assumption that the stockpiled coal characteristics prior to the start of an assessment period were very similar to the characteristics *during* the period.

c) Uncalibrated instruments

Instrument calibration certificates were not available for some of the critical measurement instruments that provide data used to calculate HR. These included coal conveyor mass scales and electrical energy meters. The reason for these calibrations being unavailable could not be ascertained. It is possible that the calibrations had been carried out but that the certificates were simply not supplied upon request. Alternatively, it may be that the calibrations had not been carried out as required. The extent to which these instruments may have drifted due to lack of calibration is not known.

d) Unrecorded coal movements

Coal is occasionally reclaimed from the staithes back to the stockpile using earthmoving equipment, not on conveyor belts with weighing equipment. These events are not recorded and so the amount of coal moved this way is unknown but according to plant staff, it occurs very infrequently. The effect of this is to inflate the mass of coal conveyed to the staithes, as the same coal would be weighed more than once. If this occurred more during the baseline period than during the reporting period, the effect of this would be to inflate the baseline HR, leading to an inflated performance improvement. It has been assumed that the total coal mass shifted this way was negligible and did not change significantly during any of the assessment periods.

e) Aerial surveys

It was assumed that any errors in the results of the quarterly aerial stockpile surveys were random in nature and were not biased during any of the assessment periods.

5.5 Interpretation of results

Section 2.1.2 explained that M&V was developed in the context of energy efficiency and demand side management so it is normal to refer to ECM impacts as either energy or demand “savings”. The expected results from each ECM in this study were also originally specified as either “coal savings” or “MW savings”.

One of the questions asked by the utility was whether a reported performance improvement (ΔHR) could *always* be converted directly to a “coal saving”. Although this may be possible in many cases, in general it would not be recommended as it depends on the nature of the ECM. The following explanation is highly simplified and any real analysis would need to consider the operating conditions of the plant and the wider electrical grid.

In the first case, suppose that a generation unit is operating at 100% MCR, but at a poor HR_N due to a fouled condenser. Once the condenser is cleansed, the unit produces the same amount of electricity at a reduced rate of coal consumption. This is a case where an improvement in HR_N may be converted directly into a coal saving.

In a second similar case, suppose that a generation unit is operating at 100% MCR, once again with a poor HR_N, but which in this case is brought about by inefficient use of auxiliary power. If the auxiliary power consumption is reduced through efficiency measures, this also improves HR_N although if the unit remains at 100% MCR, there is no absolute coal saving, but rather the reduction in auxiliary power is simply exported to the grid. This would be a “MW saving”.

5.6 Calculated HR discrepancies

For any given period, the plant could report different ΔHR values than those found by the methodology explained in this study. There may be valid reasons for this as explained in the below two examples, which both relate to data.

5.6.1 Data interrogation

At some plants, HR reporting is automated and the data used is not necessarily subject to thorough interrogation. As an example, Figure 47 shows the hourly average power output of a generation unit for 19 days in January 2014. The period from the 12 – 22 January clearly contains erroneous values as the generated power (UGen) exceeds 100% of the unit capacity. There are also clear instances of this in the sent-out power (USO). In the latter part of the month, the values revert to what would typically be expected. If an automated HR reporting system was not programmed to detect such data errors, this would lead to overstated electrical energy generation and a deceptively good HR. M&V on the other hand requires data interrogation to detect such errors and also a means of deriving data for such periods.

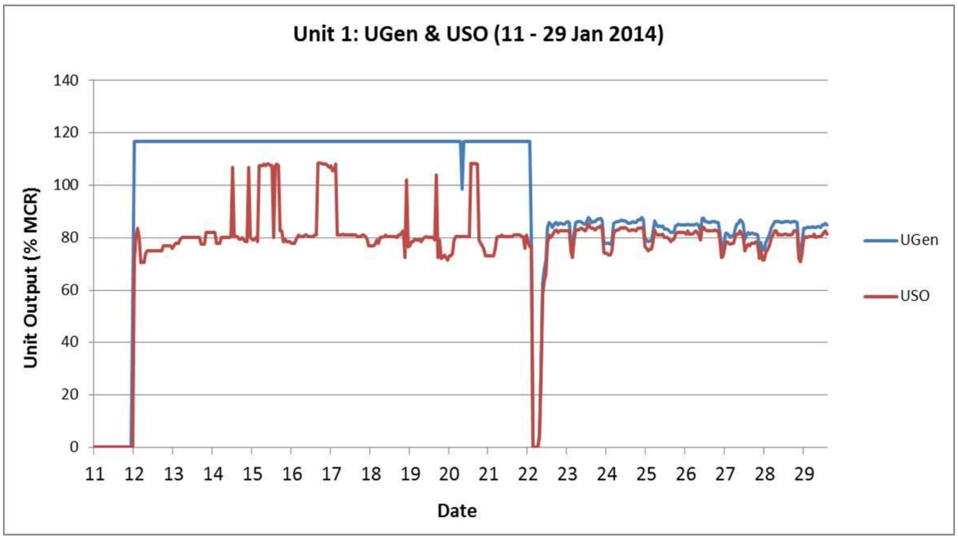

Figure 47: Erroneous electrical generation data for the period 11 – 29 Jan 2014

5.6.2 Contractual matters

Here reference is made to Figure 29 in Section 3.5.1c), on p67. It can be seen that the two daily coal HHV laboratory values are in close agreement compared to the values obtained from the online conveyor analyser. It was also explained that plant staff have reported drift in the accuracy of the online device which necessitates regular recalibration.

For this study, these factors were used to justify the use of the average daily HHV of the two laboratory values as the best estimate for daily HHV of coal delivered. However, the plant is contractually bound to measure coal energy procured based on the results of the online coal analysis device. Thus the plant’s own HR calculations will naturally differ from those which use the laboratory HHV.

Chapter 6 Conclusion & Recommendations

6.1 Conclusion

In essence, the HR_N of a CFPP is a simple calculation using the energy carriers crossing the facility boundary. However, challenges are introduced by the uncertainties associated with some of these key calculation inputs, most notably the mass of coal consumed. Further challenges include finding representative average values for the coal characteristics such as heating value (HV) and total moisture (TM). Furthermore, uncertainty is also introduced by the M&V baseline adjustment model itself.

At the start, Section 1.2 stated the hypothesis as follows: “It is hypothesised that a credible M&V methodology may be developed and applied to determine the HR improvements resulting from the refurbishment programme at a CFPP.” This hypothesis is supported. In principle there is no reason why M&V cannot be used to determine the impacts of a refurbishment programme on the HR of a CFPP. However M&V in this context does have some unique challenges and for this reason the recommendations in this chapter are made.

The factors affecting HR covered in Chapter 2 are applicable to all PF CFPPs, but the actual M&V methodology developed in Chapter 3 is applicable only to the plant in this case study. M&V of any other CFPP would need a plant-specific methodology based on the same principles.

6.2 Recommendations

6.2.1 Measurement bases and terminology

This section recommends that terminologies and measurement bases to be used are well defined, clarified and agreed upon at the start of the M&V process. Conventions vary between different countries and it would not make sense to impose a particular measurement base for M&V reporting which differed from that used by the local plant engineers. Examples of the different conventions that can be applied are listed below.

Firstly, overall plant performance can be specified either on a “gross” or a “net” basis[32]. Gross HR (HR_G) considers the total electricity generated only, whereas net HR (HR_N) accounts for the auxiliary[33] power required within the plant.

Secondly, the coal heating value can also be quoted on either a “gross” or a “net” basis as gross calorific value (GCV) or gross calorific value (NCV). To avoid confusion, it is recommended that the terms higher heating value (HHV) and lower heating value (LHV) are used to describe the coal energy content rather than GCV and NCV. In reality, most boilers do not recover the latent energy of the water vapour in the flue gas combustion products, so strictly speaking the coal LHV is the correct

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[32] In this dissertation, gross heat rate and net heat rate are described by the terms HR_G and HR_N respectively.

[33] Also called “works power” or “parasitic power”.

value to use. But it is the HHV that is found during routine laboratory analysis and as a result, it is often used directly to measure performance without converting it to LHV.

Thirdly, coal laboratory analysis results may be expressed in various ways depending on the sample preparation method. Results may be expressed as “As Received” (AR), “As Determined”[34] (AD), or on a “Dry Basis” (DB).

A note of caution is also advised when quoting performance changes as percentages. Performance may either be expressed as HR (MJ/kWh) or efficiency (%). Percentage changes in HR are found in the normal way, but percentage changes to efficiency need to be quoted as percentage-points. .” For example, a 1% improvement to an efficiency of 30% implies a new value of 31%, not 30.3%. However, a 1% improvement to a HR of 10,000 (kJ/kWh) would imply a new value of 9900, (kJ/kWh).

6.2.2 Measurement boundary

It is recommended that the IPMVP “Option C” (Whole facility) is used. From an M&V perspective this method accounts for all the plant interactive effects. It also automatically captures not only the performance improvements taking place due to ECMs, but also any performance deterioration in other parts of the plant. For an ageing plant, such as the one in this case study, a whole facility approach may be needed because coal supply is only measured at that level, but is not known for each generating unit. Also, from the perspective of CFPP performance, the IEA (2010: 37,43) recommends a whole facility approach.

However, choosing a whole facility approach does present a challenge as it requires that the impact of the ECM is at least 10% of the baseline value (IPMVP 2012: 25). M&V is typically used in the context of energy demand and end use. In that context, the impact of an ECM may be large in comparison to the baseline. Thus a whole facility measurement boundary may comfortably be selected. But that is not the case with a power plant. CFPPs are *conversion* facilities that convert heat to electricity and are designed and operated with efficiency as a priority. The impact of even a very large ECM programme at a CFPP is very unlikely to exceed 10% of the HR_N baseline. Moreover, the types of facilities where large impacts are likely are typically old plants where performance has substantially deteriorated and large programmes are undertaken to clawback lost efficiency. It is typically such large, costly programmes which could require M&V, yet it is those very ageing plants that could have unreliable or limited plant data for M&V, which could thus necessitate a whole facility approach.

Methods which find unit efficiency as a product of the major component efficiencies are not preferred (e.g. boiler, turbo-generator & auxiliaries) because these typically measure efficiency over short periods using special equipment and do not represent actual long term running conditions.

An “Option A” or “Option B” (Retrofit isolation) measurement boundary could be motivated if an ECM programme focused only on one part of the plant, which could be naturally isolated from the rest, such as the boiler. Still, instrumentation could be required for M&V which was not originally in place at the plant such as coal mass flow measurement for that individual boiler. Either of these

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[34] Sometimes in the literature “AD” indicates “air dried” rather than “as determined”.

options require special care to be taken regarding interactive effects outside of the measurement boundary.

"Option D" (Calibrated simulation) may also be a viable option if plant simulation software is available, but calibrating the model does require plant-wide accurate data at the level of individual flows and temperatures. This data is not always available. In this case study, it was known beforehand that much of the field instrumentation was not reliable and one of the ECMs specifically aimed to address this (see ECM 2.05 Table 9, p54).

Regardless of which measurement boundary is used, any electrical imports and transformer losses should be accounted for when finding the net electrical energy exported.

6.2.3 Assessment periods

Assessment periods should be a minimum of twelve months. This is suggested by both the IEA (2010: 29) and also the IPMVP (2012: 25). This is to minimise the measurement error and account for seasonal changes to energy demand and ambient conditions. Also, the baseline period should ideally begin *after* the M&V methodology (M&V Plan) has been written.

6.2.4 Instrumentation & data requirements

All instrumentation and measurement equipment should be serviced and calibrated before the start of the baseline period and should be kept calibrated throughout the baseline and reporting periods as required. For certain key data acquisition systems, installation of new equipment or at least ensuring the proper functionality of existing systems should be considered prior to the start of the baseline period. The following data sets deserve special attention.

a) Coal flow

It may be the case that older plants may not measure the coal flow to each individual generating unit as in this case study where only the daily coal mass flow to the staithes is measured. This introduces uncertainty in coal consumption due to stockpile level changes, first at the staithes and then at the bunkers. If it is not possible to install coal mass flow scales for each individual unit, even installing just one accurate scale at the discharge of the staithes would go some way to improving the accuracy of coal consumed across all units.

b) Coal heating value (HV)

Coal heating value should be obtained from laboratories which have current accreditation for the purpose. Laboratories should have records of daily calorimeter accuracy checks using standardised test samples and should also have records of collaborative exercises between groups of laboratories where to check for variance of results with respect to the group.

Coal sampling should also be performed in accordance with best practice and this may include adherence to regional or international standards. Coal sampling may be avoided if an online analyser is used to analyse the load of the incoming conveyor, although caution is advised. The accuracy of online coal analysis is questioned in the literature (IEA 2002: 20) and in this case study, the HHV results of an online coal analyser were seen to drift noticeably over short periods from the daily HHV obtained in two separate accredited laboratories (see Figure 29, p67).

c) Ambient conditions

In general, CFPP performance deteriorates with increased ambient temperature and relative humidity. Ideally, the impact of ambient conditions on HR_N should be derived empirically for any particular plant, based on accurate data collected during the baseline period. In the absence of a plant-specific empirical model, a literature-based model (such as the IEA one above) may be used, but this still requires accurate temperature data.

6.2.5 Baseline adjustment model

A baseline adjustment model is a function of one or more independent variables and is used to estimate what the plant performance would have been in the absence of any ECMs. This study concluded that the primary independent variables which affect HR_N of a CFPP are ambient conditions, flexible operations (load factor and types of load cycles) and coal characteristics (heating value, moisture, hydrogen & ash). Variables of secondary importance included coal volatile matter, sulphur, hardness and abrasiveness.

A model should ideally be derived from real empirical plant data acquired using accurate, calibrated instrumentation. If this is not available, then estimates may be made from a review of the literature. If no accurate benchmarks or generic models are available in the literature then a strategy should be adopted to mitigate the effect of an independent variable being excluded from the adjustment model. An example was that in this study no ambient data was available to model performance. The mitigation strategy was to stipulate a minimum assessment period length of twelve months to account for seasonal performance changes.

An important aspect of the adjustment model is the part-load performance and a distinction needs to be made between steady-state part load operation and flexible operation, which could include shallow or deep cycling. An indicator such as load factor does not fully capture or explain the dynamic aspects of cyclical operations. If fast ramp rates are to be analysed then hourly data is unsuitable and shorter time intervals are needed. This is important because some units not designed for flexible operations are being required to vary output to accommodate the integration of variable renewable sources.

6.2.6 Uncertainty

The final results of an M&V calculation should be stated with an accuracy range at a given level of confidence. For example a heat rate improvement might be stated as $\Delta HR_N \pm 1\%$ at 95% confidence. Given the number of variables involved, the combined uncertainties should be quantified using a Monte Carlo analysis. A very important aspect is that the stated uncertainty relates to the *impact*, not the baseline. As a percentage, the uncertainty range of the impact will always be higher than the uncertainty range of the baseline (Carstens, Rawlins & Xiaohua, 2017: 3).

The accuracy of M&V is not prescribed and is dependent on requirements set by the ECM stakeholders such as funders and clients. Requirements of small uncertainty ranges and high confidence levels typically drive M&V costs higher and some cost vs accuracy compromise may be required.

Efforts should be made before the start of the baseline period to improve the accuracy of coal consumption data. This could be achieved by adherence to a scheduled calibration programme of all coal mass scales with good record keeping and regular tracking of internal coal stockpile levels, either by installing new instrumentation or by keeping daily estimates.

The accuracy of electrical energy meters and coal mass scales are usually stated at a confidence level of 95%, but this is only for full-scale measurements and where possible, efforts should be made to characterise meter accuracy and performance below full-scale.

6.2.7 Static factors

In the same way that changes to independent variables are used for routine baseline adjustments, changes to static factors necessitate non-routine adjustments. Static factors within the measurement boundary are things which affect HR and which could change, but which are not expected to change. It is important that these are largely identified before the start of the baseline period and monitored to the end of the reporting period.

An example of a static factor might be the type of system for removing particulate matter from the flue gas: A system initially consisting of bag filters could be retrofitted with an ESP system. A more subtle variation of this could be a change to the routine maintenance procedures of the bag filters. Another example would be fuel blending such as a CFPP which begins a pilot project on one boiler co-firing biomass with the coal. Any major changes to equipment or operations outside of the listed ECMs should be considered for non-routine adjustments.

6.2.8 Interpretation of results

HR_N is dependent on coal flow, coal HV and electricity exported. In general it is not recommended that all reported HR_N improvements should be directly convertible to absolute coal savings. This is very dependent of the type of ECM which brought about the improved HR_N. In some cases, coal is saved but in other cases, the amount of electricity exported to the grid increases for the same amount of coal consumed. For this reason, the HR_N improvements that occur during any period should be associated with specific ECMs and ECM implementation and commissioning needs to be tracked.

There are legitimate reasons why a thorough M&V analysis could yield different ΔHR_N results to those obtained by CFPP routine reporting systems. The M&V process could involve a deeper interrogation of plant data and could detect errors that are otherwise not picked up by legacy automated performance reporting systems. Also, the M&V baseline HR adjustment model could produce a slightly different adjusted baseline to that obtained by the plant, which might use different correction factors for adjustments.

Appendix A Tests for evaluating regression models

a) Coefficient of determination

Equation 39 $$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}$$

b) Coefficient of variation of the Root-Mean-Square error

Equation 40 $$CV_{RMSE} = \frac{\sqrt{\frac{\sum(\hat{y}_i - y_i)^2}{n-p-1}}}{\bar{y}}$$

c) Mean Bias Error

Equation 41 $$MBE = \frac{\sum \hat{y}_i - y_i}{n}$$

Where R^2 = *Coefficient of determination*

CV_{RMSE} = *Coefficient of variation of the root-mean-square error*

MBE = *Mean bias error*

$\hat{y}_i$ = *Single regression predicted value for a single independent variable input*

$\bar{y}$ = *Mean of n observed values*

y_i = *Actual observed value*

n = *Number of independent variables in the regression model*

Appendix B Standards

a) Standards for sampling, handling, preparation and analysis of coal

ISO 18283:2006	Hard coal and coke – Manual sampling
ISO 9411-1:1994	Solid mineral fuels - Mechanical sampling from moving streams, Part 1: Coal
ISO 13909-X:2016	Hard coal and coke - Mechanical Sampling, Part 1 - 9
ISO 1171:2010	Solid mineral fuels – Determination of ash
ISO 562:2010	Hard coal and coke – Determination of volatile matter
ISO 540:2008	Hard coal and coke – Determination of fusibility
ISO 589:2008	Hard coal – Determination of total moisture
ISO 5074:2015	Determination of Hardgrove grindability index
ISO 1953:2015	Hard coal - Size analysis by sieving
ISO 1170:2013	Coal and Coke: Calculation of analyses to different bases
ISO 3310-1:2016	Test Sieves: Technical requirements and testing, Part 1: Test sieves of metal wire cloth
ISO 3310-2:2013	Test Sieves: Technical requirements and testing, Part 2: Test sieves of perforated metal plate
ISO 331:1983	Determination of moisture in the analysis sample – Direct gravimetric method

b) Standards for boiler performance testing (IEA 2010: 30)

BS EN 12952-15:2003	Water-tube boilers and auxiliary installations. Acceptance tests.
ASME PTC 4-2013	Fired steam generators
DIN 1942	Acceptance testing of steam generators (German) (Superseded)
BS 2885:1974	Code for acceptance tests on stationary steam generators of the power station type (Withdrawn)

c) Standards for steam turbine performance testing (AGO 2006: 52)

ASME PTC 6 – 2004	Steam turbines
ASME PTC 6S – 1988	Procedures for routine performance test of steam turbines
BS EN 60953-1:1996	Rules for steam turbine thermal acceptance tests. High accuracy for large condensing steam turbines.
BS EN 60953-2:1996	Rules for steam turbine thermal acceptance tests. Wide range of accuracy for various types and sizes.
BS EN 60953-3:2002	Rules for steam turbine thermal acceptance tests. Thermal performance verification tests of retrofitted steam turbines.

d) Standards for whole plant performance testing (IEA 2010: 31,32)

ASME PTC 46-1996	Performance test code on overall plant performance
VDI 3986	Determination of efficiencies of conventional power stations (German)
Technical Guidelines: Generator Efficiency Standards	Australian Greenhouse Office

Appendix C Description of various modes of operation

The following extract from the IEA (2011: 34,35) describes various modes of operation of a conventional CFPP as follows:

> ***"<u>Base load</u> – a base load power plant is one that generates at or near maximum output on a more-or-less continuous basis and is only shut down to undertake maintenance operations."***
>
> ***"<u>Peaking</u> – a peaking plant generates electricity only at periods of peak demand during the day. The extent of operation of some peaking plants can vary significantly throughout the year."***
>
> ***"<u>Load following</u> – a load following plant adjusts its power output as demand for electricity fluctuates throughout the day. Changes may be greater than 50% MCR (maximum continuous rating). Such a plant is often on for more than 48 hours at a time, but varies its output to follow the daily pattern of electricity demand."***
>
> ***"Load following plants often run during the day and early evening, and their output is curtailed during the night when electricity demand is lower."***
>
> ***"<u>Two-shifting</u> – here, the plant is started up and shut down once a day. There is also double two-shifting where the plant is started up and shut down twice a day. Economic two-shift operation requires that units are brought back on load and taken off load as quickly as possible to minimise off-load heat costs. Two-shifting is sometimes referred to as daily start/stop (DSS) operation. To be able to two-shift effectively, plants need to be 'flexible'."***
>
> ***"<u>On-load cycling</u> – in which, for example, the plant operates at base load during the day and then ramps down to minimum stable generation overnight."***
>
> ***"<u>Weekend shut-down</u> – in which the plant shuts down at weekends. This may be combined with load-following and/or two-shifting."***

Appendix D Generation profiles

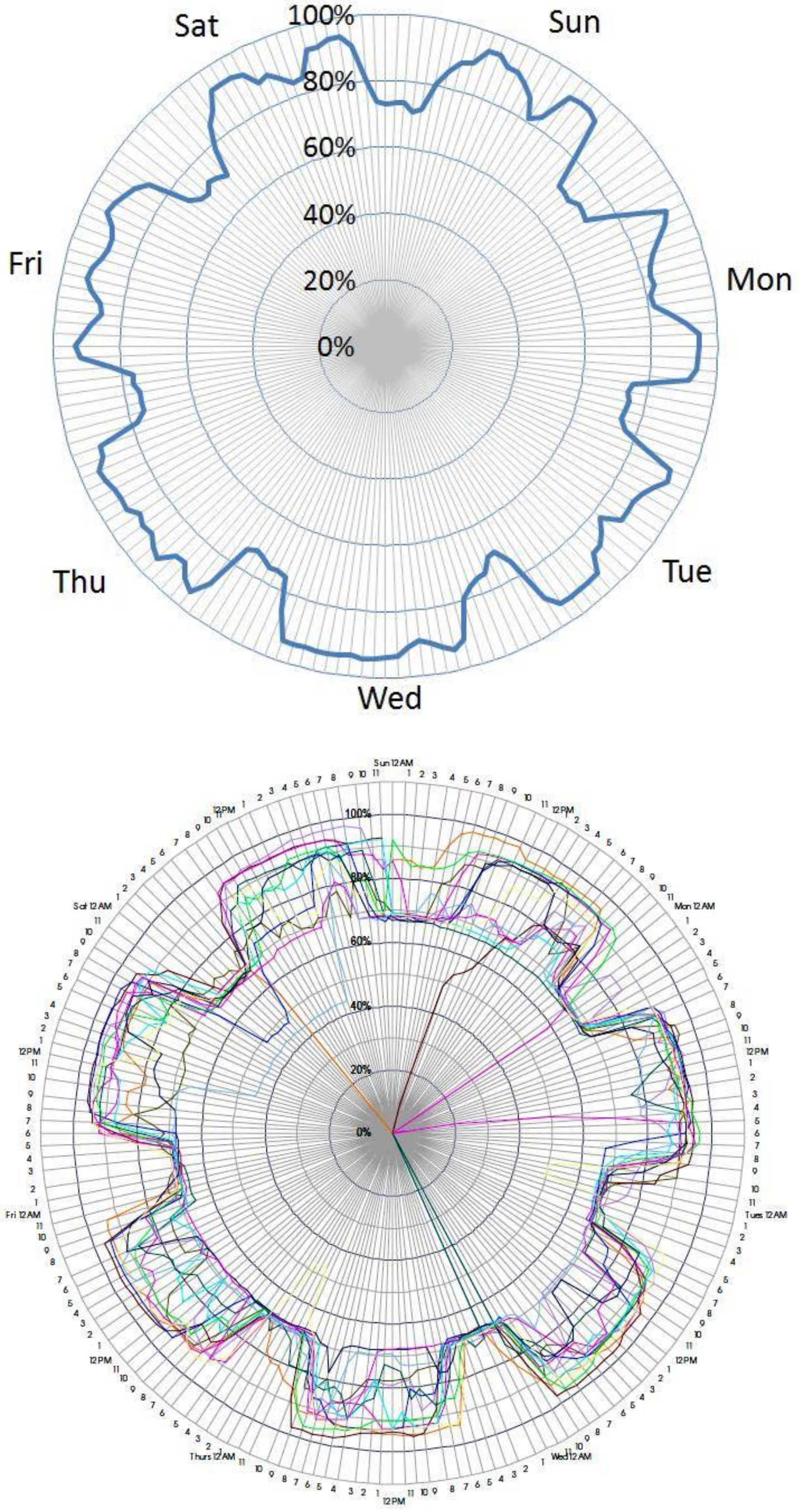

Figure 48: Visual comparison of actual plant load (top) vs EPRI Prototypical Cycle 5a (bottom) (EPRI 2002: A-15)

Appendix E Model validation

Validation of Virtual Plant™ model against actual plant heat balance.

Table 31: Comparison of key plant heat balance data against modelled values

"Virtual Plant" Result Variable Name	Description	Unit Type	Units	Model	Heat Balance	% Deviation
Boiler.StmWtrNode.ndFWInlet.enthalpy	Feedwater Inlet - enthalpy	Enth	kJ/kg	951.0	951.2	0.0%
Boiler.StmWtrNode.ndFWInlet.massflow	Feedwater Inlet - mass flow	Flow	kg/s	185.1	197.8	-6.9%
Boiler.StmWtrNode.ndFWInlet.pressure	Feedwater Inlet - pressure	Press	kPaa	11.6	12.2	-5.2%
Boiler.StmWtrNode.ndFWInlet.temperature	Feedwater Inlet - temperature	Temp	°C	221.0	221.0	0.0%
Boiler.StmWtrNode.ndSHOut.enthalpy	Superheater Outlet - enthalpy	Enth	kJ/kg	3465.3	3462.0	0.1%
Boiler.StmWtrNode.ndSHOut.massflow	Superheater Outlet - mass flow	Flow	kg/s	197.6	197.8	-0.1%
Boiler.StmWtrNode.ndSHOut.pressure	Superheater Outlet - pressure	Press	kPaa	10.4	10.8	-3.3%
Boiler.StmWtrNode.ndSHOut.temperature	Superheater Outlet - temperature	Temp	°C	537.9	538.0	0.0%
Steam Turbine, HP (Final Stage).StmWtrNode.ndOut.enthalpy	Exhaust - enthalpy	Enth	kJ/kg	2677.3	2677.0	0.0%
Steam Turbine, HP (Final Stage).StmWtrNode.ndOut.massflow	Exhaust - mass flow	Flow	kg/s	152.5	151.2	0.8%
Steam Turbine, HP (Final Stage).StmWtrNode.ndOut.pressure	Exhaust - pressure	Press	kPaa	0.3	0.3	-2.8%
Steam Turbine, HP (Final Stage).StmWtrNode.ndOut.temperature	Exhaust - temperature	Temp	°C	133.0	134.0	-0.7%
Steam Turbine, LP (Final Stage).StmWtrNode.ndOut.enthalpy	Exhaust - enthalpy	Enth	kJ/kg	2338.4	2252.9	3.7%
Steam Turbine, LP (Final Stage).StmWtrNode.ndOut.massflow	Exhaust - mass flow	Flow	kg/s	134.4	140.1	-4.2%
Steam Turbine, LP (Final Stage).StmWtrNode.ndOut.pressure	Exhaust - pressure	Press	kPaa	0.0	0.0	0.0%
Steam Turbine, LP (Final Stage).StmWtrNode.ndOut.temperature	Exhaust - temperature	Temp	°C	39.6	39.7	-0.3%
Condenser, Main.StmWtrNode.ndTrbStm0.enthalpy	Cond Zone 1 Turbine Steam - enthalpy	Enth	kJ/kg	2338.3	2096.7	10.3%
Condenser, Main.StmWtrNode.ndTrbStm0.massflow	Cond Zone 1 Turbine Steam - mass flow	Flow	kg/s	135.0	140.2	-3.9%
Condenser, Main.StmWtrNode.ndTrbStm0.pressure	Cond Zone 1 Turbine Steam - pressure	Press	kPaa	0.0	0.0	0.0%
Condenser, Main.StmWtrNode.ndTrbStm0.temperature	Cond Zone 1 Turbine Steam - temperature	Temp	°C	39.6	39.7	-0.3%
DA.StmWtrNode.ndFwOutlet.enthalpy	Feedwater Outlet - enthalpy	Enth	kJ/kg	533.0	532.8	0.0%
DA.StmWtrNode.ndFwOutlet.massflow	Feedwater Outlet - mass flow	Flow	kg/s	198.3	197.8	0.3%
DA.StmWtrNode.ndFwOutlet.pressure	Feedwater Outlet - pressure	Press	kPaa	0.2	0.2	0.2%
DA.StmWtrNode.ndFwOutlet.temperature	Feedwater Outlet - temperature	Temp	°C	126.9	126.8	0.1%
Steam Turbine, HP.StmWtrNode.ndExt0.enthalpy	HP Extraction #1 - enthalpy	Enth	kJ/kg	3095.3	3085.0	0.3%
Steam Turbine, HP.StmWtrNode.ndExt0.massflow	HP Extraction #1 - mass flow	Flow	kg/s	21.0	20.1	4.2%
Steam Turbine, HP.StmWtrNode.ndExt0.pressure	HP Extraction #1 - pressure	Press	kPaa	2.5	2.5	-3.0%
Steam Turbine, HP.StmWtrNode.ndExt0.temperature	HP Extraction #1 - temperature	Temp	°C	335.3	331.8	1.0%
Steam Turbine, HP.StmWtrNode.ndExt1.enthalpy	HP Extraction #2 - enthalpy	Enth	kJ/kg	2984.4	2972.0	0.4%
Steam Turbine, HP.StmWtrNode.ndExt1.massflow	HP Extraction #2 - mass flow	Flow	kg/s	9.7	9.7	0.6%
Steam Turbine, HP.StmWtrNode.ndExt1.pressure	HP Extraction #2 - pressure	Press	kPaa	1.5	1.5	-2.9%
Steam Turbine, HP.StmWtrNode.ndExt1.temperature	HP Extraction #2 - temperature	Temp	°C	275.9	271.3	1.7%
DA.StmWtrNode.ndExt.enthalpy	Extraction - enthalpy	Enth	kJ/kg	2712.5	2709.1	0.1%
DA.StmWtrNode.ndExt.massflow	Extraction - mass flow	Flow	kg/s	10.4	10.4	-0.4%
DA.StmWtrNode.ndExt.pressure	Extraction - pressure	Press	kPaa	0.2	0.2	0.2%
DA.StmWtrNode.ndExt.temperature	Extraction - temperature	Temp	°C	126.9	126.8	0.1%
Splitter (LP Ext 1).StmWtrNode.ndOutlet1.enthalpy	Outlet 2 - enthalpy	Enth	kJ/kg	2513.3	2456.0	2.3%
Splitter (LP Ext 1).StmWtrNode.ndOutlet1.massflow	Outlet 2 - mass flow	Flow	kg/s	6.9	6.8	0.5%
Splitter (LP Ext 1).StmWtrNode.ndOutlet1.pressure	Outlet 2 - pressure	Press	kPaa	0.1	0.1	-1.2%
Splitter (LP Ext 1).StmWtrNode.ndOutlet1.temperature	Outlet 2 - temperature	Temp	°C	86.4	86.7	-0.4%
LP HTR 2.StmWtrNode.ndExt.enthalpy	Extraction - enthalpy	Enth	kJ/kg	2544.4	2456.0	3.5%
LP HTR 2.StmWtrNode.ndExt.massflow	Extraction - mass flow	Flow	kg/s	7.2	7.1	0.3%
LP HTR 2.StmWtrNode.ndExt.pressure	Extraction - pressure	Press	kPaa	0.1	0.1	2.3%
LP HTR 2.StmWtrNode.ndExt.temperature	Extraction - temperature	Temp	°C	84.5	83.4	1.3%
Splitter (LP Ext 2).StmWtrNode.ndOutlet1.enthalpy	Outlet 2 - enthalpy	Enth	kJ/kg	2435.3	2355.1	3.3%
Splitter (LP Ext 2).StmWtrNode.ndOutlet1.massflow	Outlet 2 - mass flow	Flow	kg/s	3.9	4.3	-8.3%
Splitter (LP Ext 2).StmWtrNode.ndOutlet1.pressure	Outlet 2 - pressure	Press	kPaa	0.0	0.0	-3.3%
Splitter (LP Ext 2).StmWtrNode.ndOutlet1.temperature	Outlet 2 - temperature	Temp	°C	61.9	62.6	-1.1%
Steam Turbine, Auxiliary.StmWtrNode.ndIn.enthalpy	Inlet - enthalpy	Enth	kJ/kg	3095.3	3085.0	0.3%
Steam Turbine, Auxiliary.StmWtrNode.ndIn.massflow	Inlet - mass flow	Flow	kg/s	9.7	8.9	8.3%
Steam Turbine, Auxiliary.StmWtrNode.ndIn.pressure	Inlet - pressure	Press	kPaa	2.5	2.5	-3.0%
Steam Turbine, Auxiliary.StmWtrNode.ndIn.temperature	Inlet - temperature	Temp	°C	335.3	331.8	1.0%

Appendix F Application of the part-load adjustment model to multiple units

Figure 49 below shows the part-load HR deviation for two different scenarios. The x-axis indicates the total combined load of the two units in terms of CF. The domain shown is from 80% - 100% CF.

In the first case (Case 1), the solid curve indicates the mean combined HR deviation for two identical units operating at the same load. In the second case, the dashed line (Case 2) indicates the mean combined HR deviation for two identical units at different loads. The load on one unit is held constant at 100% CF and the load on the other is allowed to drop to 60% CF, such that the combined load is always equal to the load of the two units in the first case. It can be seen that the HR deviation for the two units at different loads is larger than when the units are at the same load. Since the baseline adjustment model treats all the units at the entire CFPP as a single large unit, the baseline adjustments are conservative.

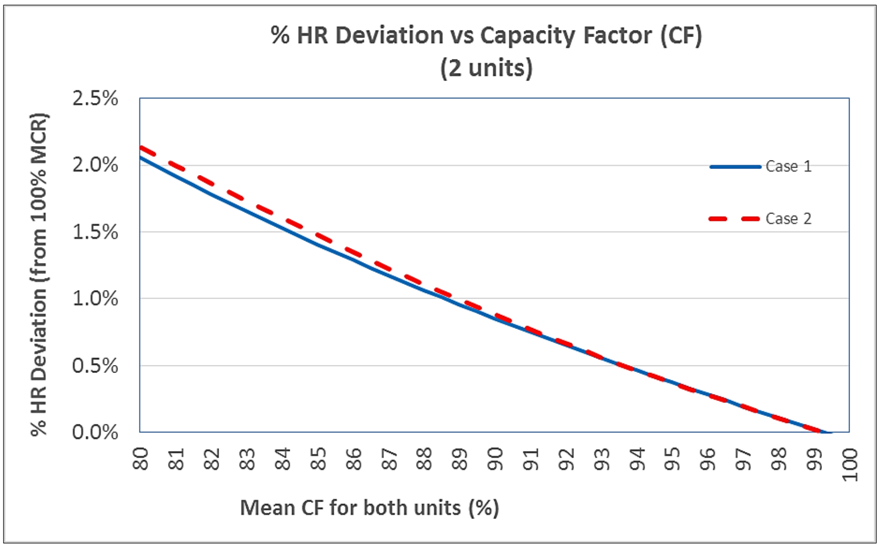

Figure 49: Part-load HR deviation for 2 units at the same load vs 2 units at different loads

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