

An improved energy management methodology for the mining industry

by

Michelle Levesque

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy (PhD) in Natural Resources Engineering

The Faculty of Graduate Studies  
Laurentian University  
Sudbury, Ontario, Canada

© Michelle Levesque, 2015

**THESIS DEFENCE COMMITTEE/COMITÉ DE SOUTENANCE DE THÈSE**  
**Laurentian University/Université Laurentienne**  
Faculty of Graduate Studies/Faculté des études supérieures

Title of Thesis Titre de la thèse	An improved energy management methodology for the mining industry		
Name of Candidate Nom du candidat	Levesque, Michelle		
Degree Diplôme	Doctor of Philosophy		
Department/Program Département/Programme	Natural Resources Engineering	Date of Defence Date de la soutenance	September 10, 2015

**APPROVED/APPROUVÉ**

Thesis Examiners/Examineurs de thèse:

Dr. Dean Millar  
(Supervisor/Directeur(trice) de thèse)

Dr. Marty Hudyma  
(Committee member/Membre du comité)

Dr. Helen Shang  
(Committee member/Membre du comité)

Dr. Monica Carvalho  
(Committee member/Membre du comité)

Dr. John Nyboer  
(External Examiner/Examineur externe)

Dr. Ubi Wichoski  
(Internal Examiner/Examineur interne)

Approved for the Faculty of Graduate Studies  
Approuvé pour la Faculté des études supérieures  
Dr. David Lesbarrères  
Monsieur David Lesbarrères  
Acting Dean, Faculty of Graduate Studies  
Doyen intérimaire, Faculté des études supérieures

**ACCESSIBILITY CLAUSE AND PERMISSION TO USE**

I, **Michelle Levesque**, hereby grant to Laurentian University and/or its agents the non-exclusive license to archive and make accessible my thesis, dissertation, or project report in whole or in part in all forms of media, now or for the duration of my copyright ownership. I retain all other ownership rights to the copyright of the thesis, dissertation or project report. I also reserve the right to use in future works (such as articles or books) all or part of this thesis, dissertation, or project report. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that this copy is being made available in this form by the authority of the copyright owner solely for the purpose of private study and research and may not be copied or reproduced except as permitted by the copyright laws without written authority from the copyright owner.

## **Abstract**

The focus for this work was the development of an improved energy management methodology tailored for the mining sector. Motivation for this research was driven by perception of slow progress in adoption of energy management practices to improve energy performance within the mining sector. Energy audits conducted for an underground mine, a mineral processing facility, and a pyrometallurgical process were reviewed and recommendations for improved data gathering, reporting and interpretation were identified.

An obstacle for conducting energy audits in mines without extensive sub-metering is a lack of disaggregated data indicating end use. Thus a novel method was developed using signal processing techniques to disaggregate the end-use electricity consumption, exemplified through isolation of a mine hoist signal from the main electricity meter data. Further refinements to the method may lead to its widespread adoption, which may lower energy auditing costs via a reduced number of meters and infrastructure, as well as lower data storage requirements.

Mine ventilation systems correspond to the largest energy demand center for underground mines. Thus a detailed analysis ensued with the development of a techno-economic model that could be used to assess various fan and duct options. Furthermore, the need for a standardized methodology for determination of duct friction factors from ventilation surveys was proposed, which included a method to verify the validity of the resulting value from asperity height measurements. A method was also suggested for determination of leakage and duct friction factor values from ventilation survey data.

Dissemination of best practice is a strategy that could be employed to improve energy performance throughout the mining sector, thus a Best Practice database was developed to

improve communication and provide a standardized reporting framework for sharing of energy conservation initiatives.

Demonstration of continuous improvement is an underpinning element of the ISO 50001 energy management standard but as mines extract ore from deeper levels energy use increases. Thus ensued the development of a benchmarking metric, with the use of appropriate support variables that included mine depth, production, and climate data, that demonstrated the benefit of implemented energy conservation measures for an underground mine.

The development of an ultimate energy management methodology for all stages of mineral processing from ‘Mine to Bullion’ is beyond the scope of this work. However, this research has resulted in several recommendations for improvement and identified areas for further improvements.

## **Keywords**

energy management; energy audits; mining industry; energy reporting; energy benchmarking;  
auxiliary mine ventilation; dissemination of best practice energy management; signal processing;  
electricity disaggregation;

## **Co-Authorship Statement**

The following includes a list of publications included within the thesis with the nature and scope of work from co-authors.

LEVESQUE, M.Y. and MILLAR, D.L., 2015. The link between operational practices and specific energy consumption in metal ore milling plants – Ontario experiences. *Minerals Engineering*, 71(0), pp. 146-158.

Levesque, M.Y. was responsible for conducting the data analysis and interpretation of the results whereas Millar, D.L. reviewed the work and participated in discussions that allowed the work to progress.

LEVESQUE, M., MILLAR, D. and PARASZCZAK, J., 2014. Energy and mining – the home truths. *Journal of Cleaner Production*, 84(0), pp. 233-255.

Data collection and analysis was conducted by Levesque, M., whereas Millar, D. and Paraszczak, J. reviewed the work and provided useful discussions and comments to improve the manuscript content and structure.

LEVESQUE, M.Y. and MILLAR, D.L., 2015-last update, Auxiliary mine ventilation cost assessment model [Homepage of Laurentian University], [Online]. Available: <http://dx.doi.org/10.14285/10219/2301> [02/10, 2015].

The model was developed by Levesque, M.Y. and the calculations were verified by Millar, D.L. who also provided suggestions for improving the structure of the model.

LEVESQUE, M., and MILLAR, D.L., 2013. A best practice database for energy management in the minerals industry. World Mining Congress, Montreal, Quebec, August 2013.

The database was developed and populated by Levesque, M. whereas Millar, D.L. reviewed the accompanying manuscript and suggested the development of the database.

## **Acknowledgments**

First I want to express my gratitude towards my supervisor Professor Dean Millar who provided me this amazing opportunity for personal and professional development. I believe that the experience I gained throughout my PhD studies was the key to the next step in my career path. I truly appreciate and enjoyed our discussions and I hope that we continue to collaborate in the future.

I am also grateful towards Vale for funding this research, without which I would not have been able to pursue. Special thanks go to Gregg Gavin, Jim Eddy, Ken Scholey, Lewis Oatway, and David Tomini, from Vale for your continued support and for providing me with the necessary data to conduct my work.

I would also like to acknowledge my colleagues at MIRARCO who have made this a memorable and enjoyable experience. I have met some wonderful individuals and I hope that we can maintain long-lasting friendships.

The auxiliary mine ventilation study would not have been complete without the collaboration of the staff from G+Industrial Plastics Inc., namely, Stephan Tapp, Pierre Trudel, Nina Dion, and Remi Desbiens. I am appreciative of our discussions and also for your support throughout this project. Furthermore, I am grateful for your request to further develop our ventilation model from which we enhanced our understanding of auxiliary mine ventilation systems.

I would also like to thank Ethan Armit for his help during the ventilation surveys conducted at MTI's test mine.



Finally, I would like to thank my family for their continued support and encouragement throughout this journey.

Thank you,

Michelle Levesque

## Table of Contents

Thesis Defence Committee .....	ii
Abstract .....	iii
Keywords .....	v
Co-Authorship Statement.....	vi
Acknowledgments.....	viii
Table of Contents .....	x
List of Tables .....	xiv
List of Figures .....	xv
List of Appendices .....	xviii
1 Motivation and objectives for research.....	1
1.1 Motivation .....	1
1.2 Energy use in mining.....	4
1.3 Objectives.....	12
1.4 Thesis outline .....	13
2 A critical review of energy management progress in the mining industry .....	17
2.1 Energy management timeline.....	17
2.2 1970's initiatives .....	22
2.3 Recent initiatives .....	28
2.4 Barriers to implementing best practice.....	34
2.5 Market drivers for energy management .....	41
3 A critical review of mining energy-related data reporting.....	45
3.1 Sustainability reporting guidelines.....	45
3.1.1 United Nations Global Compact.....	45
3.1.2 Global Reporting Initiative .....	46
3.1.3 International Council on Mining & Metals.....	49
3.1.4 Mining Association of Canada's Towards Sustainable Mining .....	51
3.1.5 Issues with current reporting guidelines .....	53
3.1.6 Demonstration of a need for reporting appropriate metrics – Musselwhite Mine case study.....	55
3.2 CIPEC Canadian benchmarking studies .....	59
3.3 US DOE study.....	64
3.4 Statistics Canada .....	65
3.5 Natural Resources Canada .....	68
3.5.1 Canadian Minerals Yearbook .....	68
3.5.2 Energy Use data Handbook Tables 1990-2010 .....	69
3.5.3 Comprehensive Energy Use Database Tables .....	72
3.6 Canadian Industrial Energy End-use Data and Analysis Center (CIEEDAC).....	73
3.7 Other sources.....	74
3.8 Issues with Canadian mining data.....	75
3.9 Proposed solution for improving reported energy- related data from the mining sector	77
4 A review of existing energy audit methodologies and guidelines .....	81
4.1.1 Top down energy audit .....	84
4.1.2 Bottom up energy audit.....	87

4.1.3	Hybrid top down / bottom up energy audit .....	91
4.2	Industrial energy audit guidelines .....	93
4.2.1	Energy Savings Toolbox .....	94
4.2.2	Industrial Energy Audit Guidebook – Guidelines for Conducting and Energy Audit in Industrial Facilities .....	99
4.2.3	Energy Efficiency Opportunities Energy Mass Balance: Mining.....	100
5	Key research questions arising in the context of ‘Mine to Bullion’ energy management..	103
6	Improved communication of best practice energy management .....	104
6.1	Continuous improvement and ISO 50001 compliance .....	104
6.2	Dissemination of best practice .....	107
6.2.1	Overview of existing frameworks.....	107
6.2.2	Methodology used to develop improved best practice database.....	110
6.2.3	Critical review of energy efficiency opportunities mining register .....	111
6.2.4	Structure of proposed improved mining industry energy management database .	119
6.2.5	Adopting the improved database .....	130
7	Improved auditing for mines – an example from Garson Mine.....	132
7.1	Background .....	132
7.2	Conducting the energy audit .....	133
7.3	Reconciling the data .....	136
7.4	An improved energy audit methodology for Garson Mine.....	139
8	Improved interpretation of energy consumption data - Energy management pertaining to auxiliary mine ventilation systems.....	149
8.1	Introduction .....	149
8.2	Ventilation survey methodology .....	150
8.3	Determination of friction factor .....	156
8.3.1	Friction factor calculations .....	156
8.3.2	Error analysis .....	159
8.3.3	Other quoted friction factor values for low friction ducts .....	161
8.3.4	Surface roughness .....	162
8.3.5	Friction factor of hydraulically smooth pipes.....	166
8.4	Techno-economic assessment of ventilation systems with various duct friction factors 169	
8.4.1	Capital costs of various duct materials .....	171
8.4.2	Development of ventilation system model .....	172
8.5	Hypothetical case studies using the ventilation model.....	179
8.5.1	Examination of scenarios with fixed-speed, fixed-custom speed, and variable-speed fans, for duct lengths up to 1200m.....	179
8.5.2	Flow variability .....	188
8.5.3	Potential energy savings .....	191
8.5.4	Capital cost versus energy savings .....	199
8.6	Examination of leakage effects on ventilation survey results .....	204
8.6.1	Series-parallel theory and resistances .....	204
8.6.2	Case studies of auxiliary ventilation systems with leaky joints.....	208
8.7	Discussion of auxiliary ventilation systems and friction factors.....	215
8.8	Conclusions of ventilation system analysis.....	222
9	A novel demand-side estimation of consumption.....	226

9.1	Existing disaggregation methods .....	226
9.2	Proposed top down electricity disaggregation method using time and frequency domain information.....	231
9.2.1	Signal processing background .....	232
9.3	Isolation of the electricity consumption of a mine hoist from a mine's total electricity meter data.....	246
9.3.1	Establishing the minimum sampling interval .....	246
9.3.2	Determining which activity to filter.....	248
9.3.3	Determination of probability of hoist operating state .....	253
9.3.4	Designing the filter .....	259
9.3.5	Applying the filter.....	263
9.3.6	Determination of hoist electricity consumption.....	267
9.3.7	Issues with the proposed disaggregation methodology and suggested future refinements.....	272
10	Improved energy audit and data interpretation and their impact on production patterns and profitability .....	276
10.1	Introduction .....	276
10.2	Clarabelle Mill flowsheet and process description.....	277
10.3	Electricity audit.....	280
10.3.1	Review of past audit.....	280
10.3.2	Converting collected data into energy values .....	281
10.3.3	Applying a top-down / bottom-up approach .....	283
10.3.4	Energy analysis .....	289
10.3.5	Part-load efficiency curve .....	290
10.4	Potential energy conservation at Clarabelle Mill .....	293
10.5	Demand charges in Ontario via 5CP billing.....	296
10.6	Potential demand savings in Ontario .....	298
10.7	Extension of analysis to other milling facilities in Ontario .....	301
10.7.1	Development of part-load curve .....	301
10.7.2	Savings estimate for flotation mills .....	307
10.8	Discussion of case study findings.....	309
10.9	Concluding remarks for case study .....	317
11	Using mass and energy balances with pinch analysis principles to identify energy savings from waste heat recycling: a case study from a pyrometallurgical mineral processing operation	319
12	Discussion .....	323
12.1	Improved energy audit and analysis guidelines.....	323
12.1.1	Recommendations for improved energy audits in the mining sector .....	323
12.1.2	A novel energy audit method.....	326
12.2	Improved communication of best practice energy conservation initiatives .....	327
12.3	Improved interpretation for enhanced energy savings and better communication... ..	329
12.4	Some final thoughts .....	334
13	Conclusions.....	336
13.1	Conclusions .....	336
13.2	Contributions .....	342
13.3	Future work.....	344

References .....	348
Appendix A – Frames extracted from different months of the aggregated signal to train Neural Network for identification of hoist operating probability .....	370
Appendix B – Summary of results from weekly data analyzed from all months (aggregated electricity signal, probability of hoist operation, filtered signal after extracting hoist electricity use, and hoist electricity consumption).....	383

## List of Tables

Table 1: Support variables and their effect on the mining and mineral processing stages .....	6
Table 2: Corresponding nomenclature between CANSIM tables for mining sub-sectors.....	36
Table 3: ICMM member companies' sustainability reporting performance (ICMM, 2015) .....	50
Table 4: Comparison of reported energy consumption from various sources .....	76
Table 5: Recommendations for improved reporting .....	79
Table 6: Relative cost and difficulty level definitions (Institute for Industrial Productivity, 2012) .....	123
Table 7: Recommended adjustments for reconciling energy audit data (Pawlik et al., 2001) .....	90
Table 8: Method used to obtain energy consumption from various end-uses at Garson Mine ..	134
Table 9: Variables that influence energy consumption in an underground mine .....	141
Table 10: Velocity measurement positions .....	153
Table 11: Resistance of ventilation system components .....	159
Table 12: Summary of friction factor simulation results .....	161
Table 13: Atkinson friction factors reported for plastic ducts .....	162
Table 14: Atkinson friction factor values calculated from asperity height measurements .....	166
Table 15: Friction factors for a smooth pipe at various Reynolds numbers .....	168
Table 16: Unit costs for various duct materials (1.2 m diameter) .....	172
Table 17: Input parameters for ventilation system analysis.....	182
Table 18: Common input parameters for all simulated ventilation systems with leakage .....	208
Table 19: Leakage model results for low leakage systems .....	212
Table 20: Leakage model results for high leakage systems.....	213
Table 21: Fourier transform categories.....	234
Table 22: Filter classification by type and purpose (S. W. Smith, 1997) .....	237
Table 23: Time and frequency of Garson Mine end-uses .....	247
Table 24: Lowpass filter design parameters for extraction of hoist electricity consumption .....	261
Table 25: Proportion of total electricity used by the hoist at Garson Mine for various periods.	271
Table 26: Data reconciliation issues and solutions .....	285
Table 27: Equipment excluded from 2008 audit.....	287
Table 28: Electricity allocation and reconciliation summary .....	288
Table 29: Potential savings from optimized TOU schedule and throughput - 2008 analysis.....	295
Table 30: Potential savings from optimized TOU schedule and throughput – 2012 monthly analysis.....	296
Table 31: Monthly GA amounts from 2011 to 2013 (IESO, 2014a) .....	298
Table 32: Coincident peaks for base period May 1, 2012 to April 30, 2013 (IESO, 2014b) .....	299
Table 33: Potential 2012 demand response savings for various sized facilities in Ontario.....	300
Table 34: Summary of Ontario milling facilities (numbers in brackets correspond to data sources – refer to bibliography) .....	302
Table 35: Potential savings from full-load operation for flotation mills in Ontario .....	308
Table 36: Energy savings from proposed waste heat recycling scheme.....	322

## List of Figures

Figure 1: Simplified overview of mining and mineral processing stages.....	3
Figure 2: Sankey diagram illustrating the energy consumption of the mining and processing stages.....	5
Figure 3: Canadian energy prices 1990-2012 - constant dollars (Natural Resources Canada, ca. 2014; Statistics Canada, 2015).....	7
Figure 4: Canadian mining industry energy consumption 1990-2012 (Natural Resources Canada, ca. 2014).....	8
Figure 5: Canadian metal and non-metal mining industry energy consumption 1990-2012 (Natural Resources Canada, ca. 2014).....	9
Figure 6: Canadian copper, nickel, lead, and zinc mines energy intensity 1990-2012 (Natural Resources Canada, nd).....	10
Figure 7: Chronology of crude oil prices and milestones relating to energy management in the mining industry. Source: Figure designed by the authors based on references related to the publications and initiatives cited in text.....	18
Figure 8: Historical annual costs for Canadian Metal Ore Mining (Natural Resources Canada, 2012a; Statistics Canada, 2013).....	37
Figure 9: Historical annual costs for Canadian Non-Metallic Mineral Mining and Quarrying (Natural Resources Canada, 2012a; Statistics Canada, 2013).....	38
Figure 10: Sustainability framework web.....	53
Figure 11: Specific energy consumption, expressed as kWh/tonne ore and kWh/oz of gold, for Musselwhite Mine.....	56
Figure 12: Specific energy consumption, expressed as kWh/(tonne ore•metre•HDD) and kWh/(oz Au•metre•HDD), for Musselwhite Mine.....	58
Figure 13: Energy intensity, expressed as MJ/\$2002 GDP for selected Canadian mining sectors (Natural Resources Canada, ca. 2013a).....	70
Figure 14: Energy intensity in MJ/tonne ore (metals) and MJ/tonne product (non-metals) for selected Canadian mining sectors (Natural Resources Canada, ca. 2013a).....	71
Figure 15: Continuous approach model from ISO 50001 standard (International Organization for Standardization, 2011b) Permission to use extracts from ISO 50001:2011 was provided by Standards Council of Canada. No further reproduction is permitted without prior written approval from Standards Council of Canada. ....	105
Figure 16: Screenshot of The Energy Efficiency Opportunities Mining Register (Australian Government Department of Resources, Energy and Tourism, 2011a).....	109
Figure 17: Energy Savings Measure Profile data entry template.....	120
Figure 18: Example to illustrate the form of cumulative energy savings curve in mining sector from 1980 to 2012.....	128
Figure 19: Energy savings by group.....	130
Figure 20: Energy audit phases (Capehart, Turner, & Kennedy, 2012; Doty & Turner, 2009) ...	83
Figure 21: Overview of top down energy audit (adapted from (Rosenqvist et al., 2012).....	85
Figure 22: Energy balance audit methodology (Pawlik et al., 2001).....	88

Figure 23: Sector and sub-sector classification from top-down method (Bennett & Newborough, 2001) .....	91
Figure 24: Screenshot of CUSUM analysis tool from Energy Savings Toolbox (Natural Resources Canada, 2009).....	96
Figure 25: Screenshot of Demand Profile Analysis tool from the Energy Savings Toolbox (Natural Resources Canada, 2009) .....	97
Figure 26: Energy flows at Garson Mine.....	135
Figure 27: Revised Sankey diagram for energy flows at Garson Mine .....	138
Figure 28: Proposed energy management methodology with continuous improvement approach .....	148
Figure 29: MTI Mine layout and ventilation survey measurement locations (inset illustrates a side view of the pressure measurement locations).....	151
Figure 30: Air velocity values for 8 point log-linear traverse at various fan speeds .....	154
Figure 31: Measurement location and sequence of 8 point log-linear traverse along the duct ..	155
Figure 32: 8 point velocity profile for new survey .....	156
Figure 33: Sample image with microscope focus on the material surface plane.....	164
Figure 34: Sample image with microscope focus on asperity peaks plane.....	164
Figure 35: Moody chart (Perry, Green, & Maloney, 1997) .....	167
Figure 36: Interaction matrix of mine ventilation system variables .....	170
Figure 37: Ventilation system of drift development with extending duct .....	174
Figure 38: Operation points of single fan and combined fans in series.....	177
Figure 39: Summary of annual cost versus final duct length for different duct types.....	180
Figure 40: Total and energy costs for ventilation systems of various duct materials and lengths .....	184
Figure 41: System resistance curves for a 200 m duct length of layflat PVC, steel and plastic duct .....	189
Figure 42: Supplied flowrate versus final duct length for fixed speed fan at 1800 rpm.....	190
Figure 43: Energy savings for fixed custom speed fan compared to fixed speed stock fan for 1 year project.....	191
Figure 44: Energy savings for variable speed fan compared to fixed speed stock fan for 1 year project .....	192
Figure 45: Energy savings from substitution of a layflat duct for a plastic duct for 1 year project .....	194
Figure 46: Energy costs from duct substitution and flowrate control for 1 year project .....	196
Figure 47: Energy costs from duct substitution and flowrate control for 3 year project .....	197
Figure 48: Energy costs from duct substitution and flowrate control for 5 year project .....	197
Figure 49: Potential energy savings from duct substitution and flowrate control .....	199
Figure 50: Annual costs from duct substitution and flowrate control for 1 year project.....	201
Figure 51: Annual costs from duct substitution and flowrate control for 3 year project.....	201
Figure 52: Annual costs from duct substitution and flowrate control for 5 year project.....	202
Figure 53: Schematic of series-parallel theory in an auxiliary ventilation system .....	205
Figure 54: Schematic illustrating the steps to calculate the equivalent resistance of a series-parallel ventilation system .....	207
Figure 55: Time and frequency domains .....	232
Figure 56: Time signals and frequency spectra of combined signals .....	233
Figure 57: Simplified method for signal disaggregation .....	236



Figure 58: Example of filter frequency response.....	238
Figure 59: Diagram illustrating 'sliding' frame by frame analysis.....	241
Figure 60: Diagram illustrating a frame by frame analysis .....	242
Figure 61: Overview of proposed top down electricity disaggregation method.....	245
Figure 62: Normalized aggregated electricity consumption at Garson Mine for the week of January 19 to 26 .....	248
Figure 63: Aggregate electricity consumption at Garson Mine for January 21.....	249
Figure 64: Segment of aggregate electricity use at Garson Mine for a 32 minute interval .....	250
Figure 65: Power / time diagram of cylindrical drum winder (S. C. Walker, 1988) .....	250
Figure 66: Hoist power and energy load signature curves for a 32 minute period .....	252
Figure 67: Frames extracted from January data to train Neural Network .....	254
Figure 68: Neural Network confusion matrix .....	256
Figure 69: Aggregated electricity signal and probability of hoist operating for January 19 to 26 .....	258
Figure 70: Comparison of synthesized hoist and actual hoist signals .....	260
Figure 71: Butterworth filter frequency response for Garson Mine hoist electricity extraction	262
Figure 72: Garson Mine electricity signal after hoist filter application overlaid on original aggregate electricity signal .....	264
Figure 73: Electricity signal at Garson Mine after hoist filter application for January 22 .....	266
Figure 74: Extracted hoist consumption signal from aggregate electricity signal at Garson Mine for January 19 to 26 .....	268
Figure 75: Extracted hoist signal from aggregate electricity signal at Garson Mine (32 minute segment).....	269
Figure 76: Butterworth frequency response for Garson Mine hoist electricity extraction .....	273
Figure 77: Comminution circuit flowsheet in 2008.....	278
Figure 78: Flotation circuit flowsheet in 2008 (Lawson & Xu, 2011) .....	279
Figure 79: Clarabelle Mill Sankey diagram for 2008 .....	290
Figure 80: Normalized average hourly electricity demand versus throughput expressed as % design capacity.....	291
Figure 81: Normalized specific energy consumption versus throughput expressed as % design capacity (hourly, monthly and annual data).....	293
Figure 82: Normalized specific energy versus throughput expressed as % design capacity for flotation mills in Ontario.....	306
Figure 83: Sankey diagram from a nickel laterite processing operation. (HSFO: High Sulphur Fuel Oil, HSD: High Speed Diesel, BWSTG: Steam turbine, DGB and MBDG: Diesel generators) (M. Levesque, 2011) .....	<b>Error! Bookmark not defined.</b>
Figure 84: Sankey diagram from a nickel laterite processing operation with waste heat recycling (M. Levesque, 2011) .....	321

## **List of Appendices**

Appendix A – Frames extracted from different months of the aggregated signal to train Neural Network for identification of hoist operating probability .....	370
Appendix B – Summary of results from weekly data analyzed from all months (aggregated electricity signal, probability of hoist operation, filtered signal after extracting hoist electricity use, and hoist electricity consumption).....	383

# **1 Motivation and objectives for research**

## **1.1 Motivation**

Mining constitutes an essential role to support the quality of life enjoyed by modern society in developed countries and to support economic development in developing countries. The mining sector produces a variety of minerals that are used in diverse applications. For example, metals are used for tools, currency, jewelry, transportation, and computers among other uses.

Nonmetallic minerals such as sand and gravel can be used for construction whereas potash is used for agricultural purposes as a fertilizer. A third category of minerals corresponds to fossil fuels which comprise coal, natural gas, and tar sands, which are used as energy sources (Hartman, Mutmanský 2002).

All of the above mentioned types of minerals are extracted from the ground via surface or underground mining methods. Once extracted, some minerals such as metals undergo further processing to convert the ore to high purity metal or bullion.

The mining process is essentially a materials handling process: ore is removed from the ground to a place where it can be processed or concentrated. To achieve this, size reduction is employed by blasting so that ore can be handled.

Mineral processing is essentially a concentration process where the valuable part of the ore is separated from the non-valuable part by physical and chemical means. This stage involves reducing the size of the ore material so that the valuable minerals are liberated. This step also aims to reduce the amount of material handled in subsequent stages of the process.

In the case of metallic commodities, a purification stage follows. The concentrate produced by the mineral processing stage is further purified by conversion, refining or smelting, which essentially constitutes melting the concentrate to separate the metal from the waste material in a thermal process. The high purity minerals produced during the concentration stage are then used in a marketing stage where manufacturers use these materials to fabricate various products (Hartman, Mutmanský 2002). Figure 1 shows a simplified overview of the mining stages used to produce bullion from ore. These are the stages in what we refer to as a 'Mine to Bullion' audit methodology.

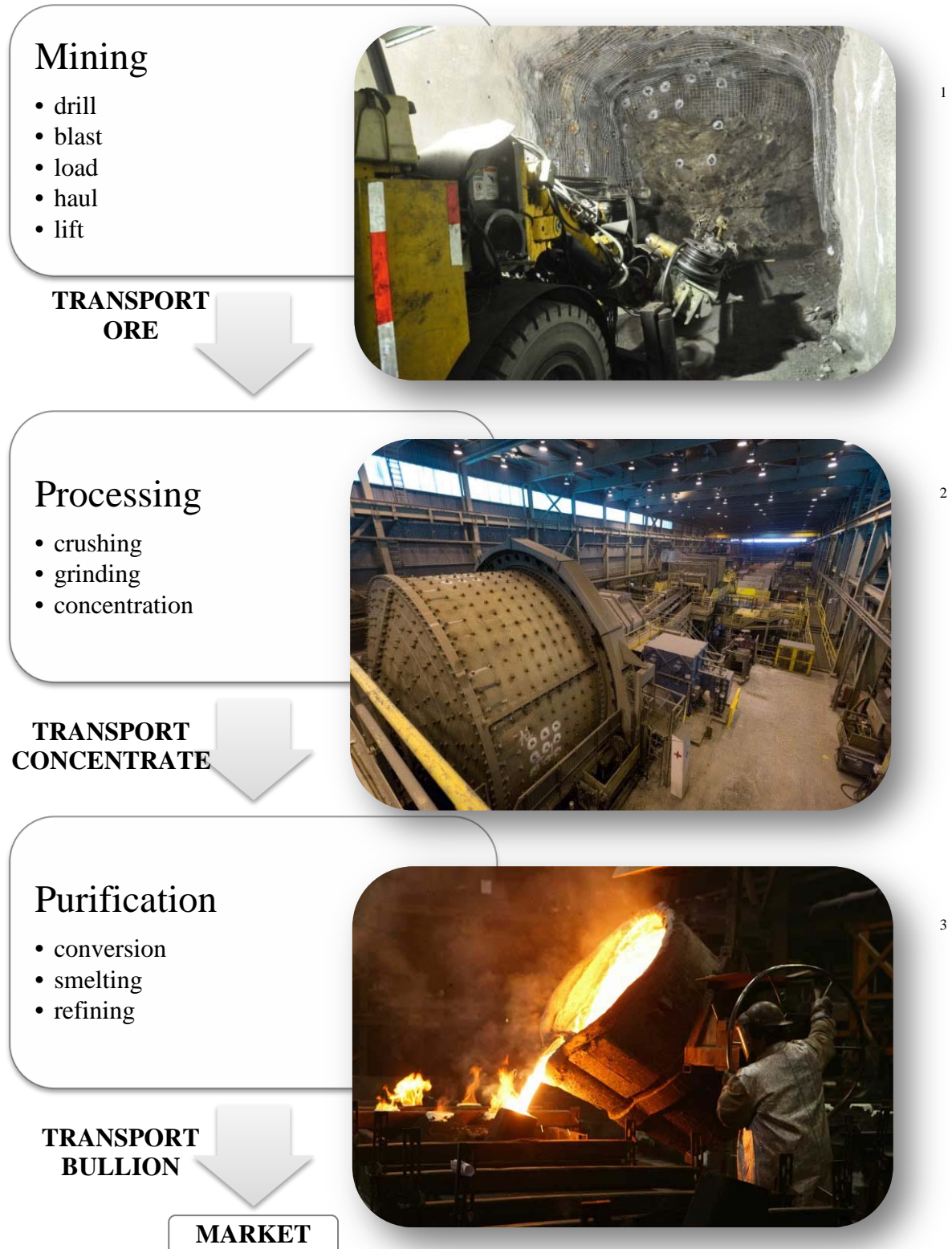


Figure 1: Simplified overview of mining and mineral processing stages

<sup>1</sup> Photo courtesy of Prof. Ismet Ugursal (Ugursal 2014)

<sup>2</sup> Photo courtesy of Vale and ABB (ABB 2014)

<sup>3</sup> Photo courtesy of FLSmidth (FLSmidth 2013)

In some cases the products of mineral production are basic necessities for human existence where population growth is a significant factor in the demand for the sector's commodities. However advances in technology and a desire for economic growth from developed and developing countries drive demand further. The basic economic equilibrium between supply and demand indicates that increases in demand will lead to a higher commodity prices if there is no corresponding change in supply (Frank, Bernanke et al. 2012b). Eventually, as ore bodies are mined out, mineral supply will decline and lead to further price increases. Conversely, lower operating costs associated with technological development may enable mining of ore bodies that were once considered uneconomical. Energy management is an area for technological development that may lead to lower operating costs, and thus allowing society to maintain or enhance current standards of living while keeping costs affordable.

## **1.2 Energy use in mining**

Mining is an energy intensive industry with substantial environmental impacts (Mudd 2010). Different energy sources are used during the various stages within the mining and mineral processing stages as illustrated in Figure 2 which was produced with actual data from Vale's Sudbury operations.

Six types of energy are used for these specific mining and processing stages; electricity is mainly used to for support activities in mines (ventilation, hoisting, pumping, compressed air, drilling) and for breaking ore in the processing stages, natural gas and propane are used as heating fuels (comfort or process heat), whereas gasoline and diesel are employed for transportation purposes, and coke is used as a reducing agent.

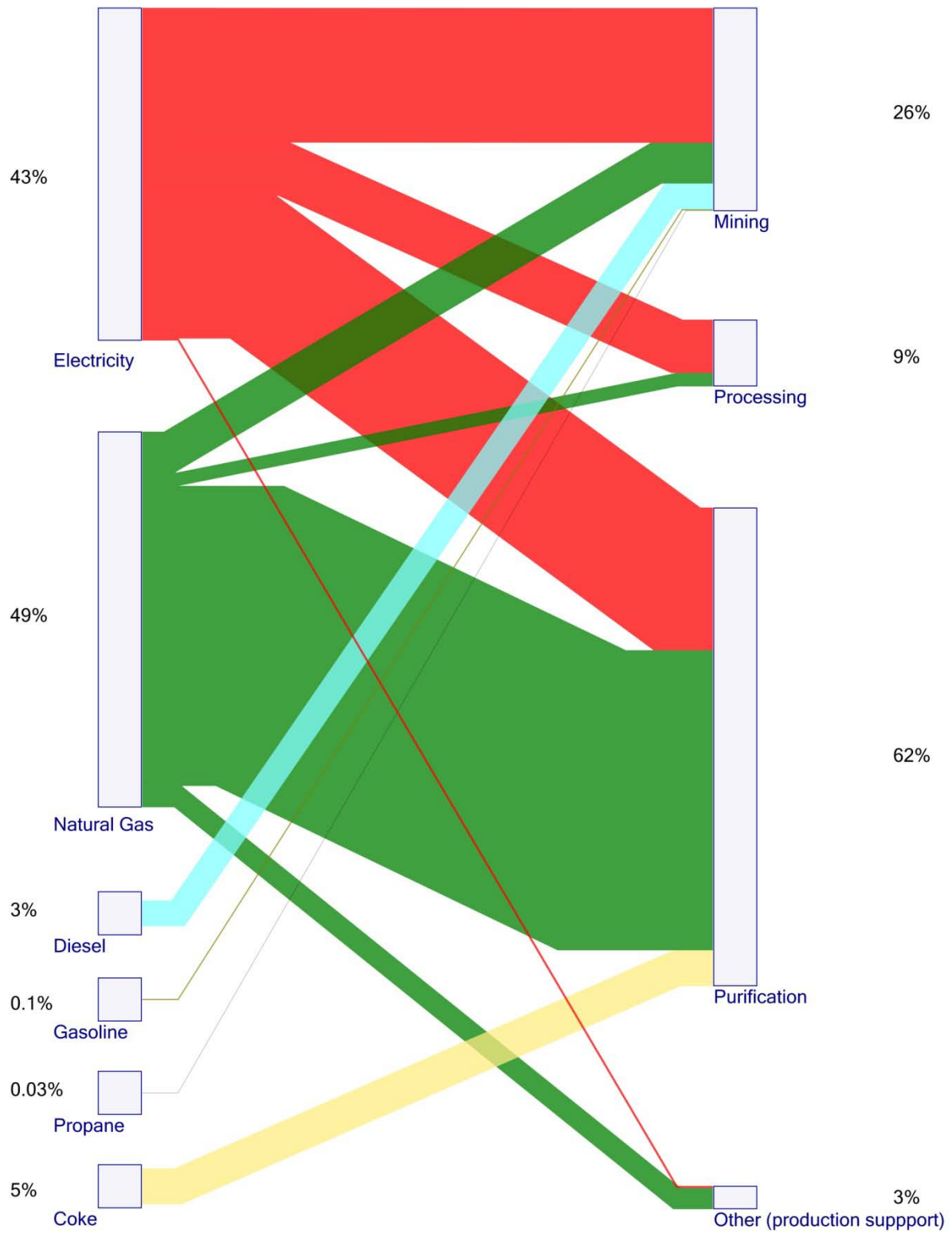


Figure 2: Sankey diagram illustrating the energy consumption of the mining and processing stages

The amount of energy used in the various stages of the process is influenced by different support variables as illustrated in Table 1. In addition to these, which are specific to the orebody, mine location can also affect energy use; more energy is used to heat buildings and mine ventilation air in colder climates whereas cooling is required in hot areas.

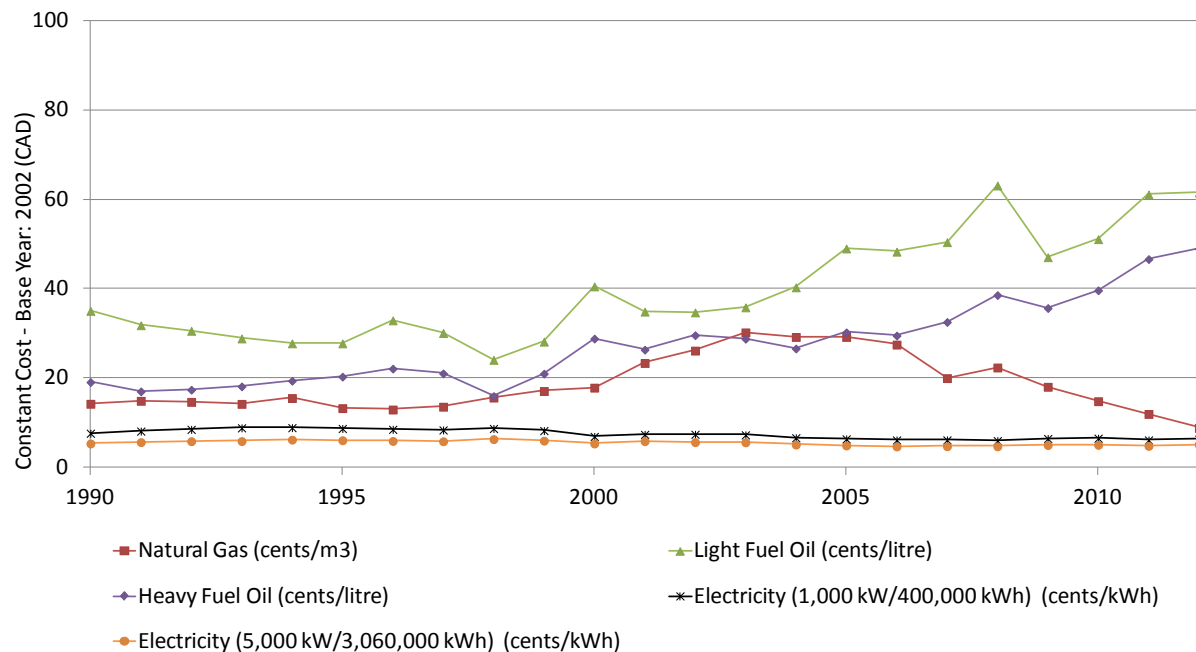
**Table 1: Support variables and their effect on the mining and mineral processing stages**

Stage	Effect on energy consumption
Mining	
drill and blast	harder ore needs more energy
load and haul	lower grade ore requires more material to be transported
lift	deeper ore bodies need more energy to bring ore to surface
Processing	
crushing and grinding	smaller minerals require more comminution, thus more energy to liberate, harder ores require more energy to break lower grade ores requires more material to be processed and transported per unit of mineral
concentration	lower grade ores requires more material to be processed and transported per unit of mineral
Purification	
conversion, smelting, refining	mineralogy affects the amount of energy required to 'melt' the material

In 2010, the proportion of total costs spent on energy averaged 15% and 19% for Canadian metal and non-metal mines respectively. Although energy corresponded to the smallest share of total



costs, it was the only category that has shown an increasing trend since 1961 (Natural Resources Canada 2012a, Statistics Canada 2013). It can be postulated that the proportion of total expenditure associated with energy in the mining sector is increasing due to a combination of factors such as rising energy rates or mines consuming more energy as they mine from deeper levels or process lower grade ores. Figure 3 illustrates the Canadian industrial energy prices from 1990 to 2012 in constant dollars (base year 2002). It shows that with the exception of natural gas, energy prices have stayed the same or increased. The most prominent increases are for fuel oils on which the sector depends.



**Figure 3: Canadian energy prices 1990-2012 - constant dollars (Natural Resources Canada ca. 2014, Statistics Canada 2015)<sup>4</sup>**

<sup>4</sup> Industrial energy price data published by Natural Resources Canada (ca. 2014) were provided using current dollar amounts however when comparing economic figures over time it is more appropriate to utilize constant dollars in order to eliminate the effect of inflation. Using consumer price index (CPI) for energy (Statistics Canada 2015), the current values were converted to constant values with a base year corresponding to 2002.

Figure 4 shows the Canadian mining industry energy consumption for the same period. The trend is clearly one of increase for the mining sector as a whole but this is mainly due to the petroleum sub-sector.

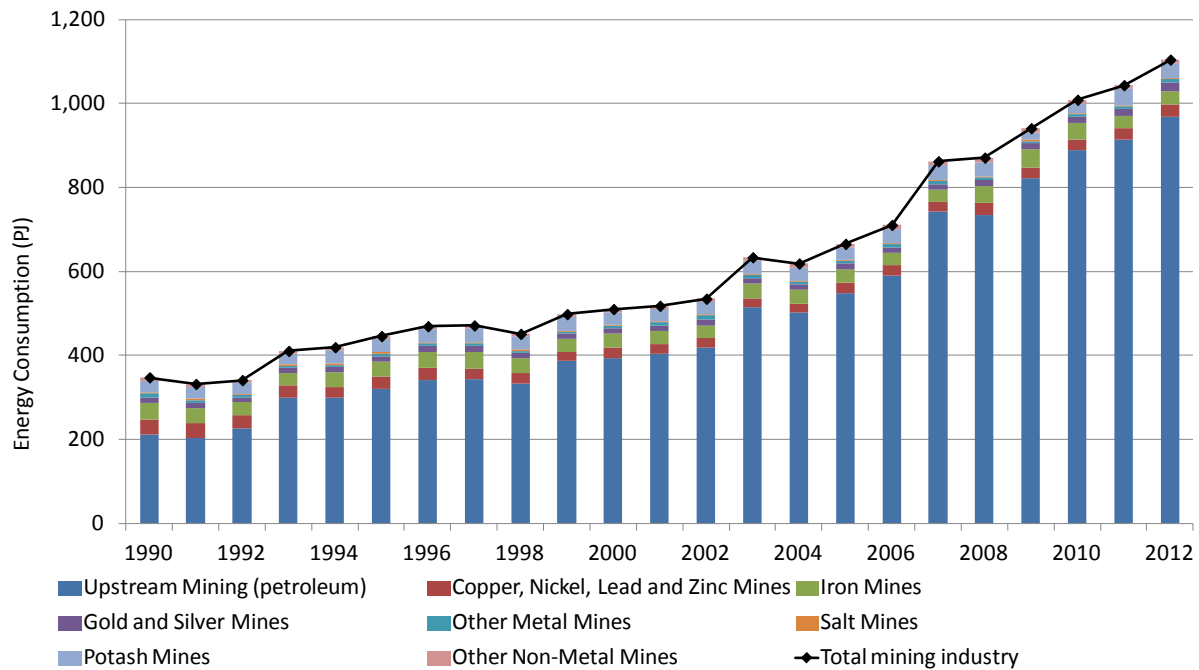
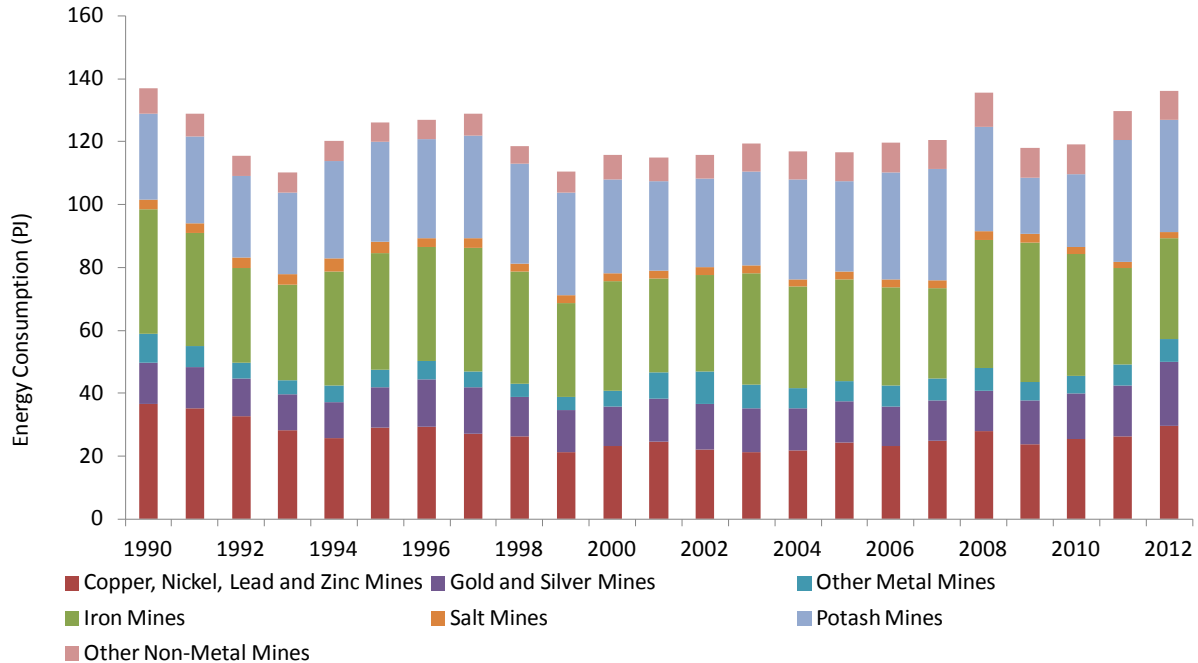


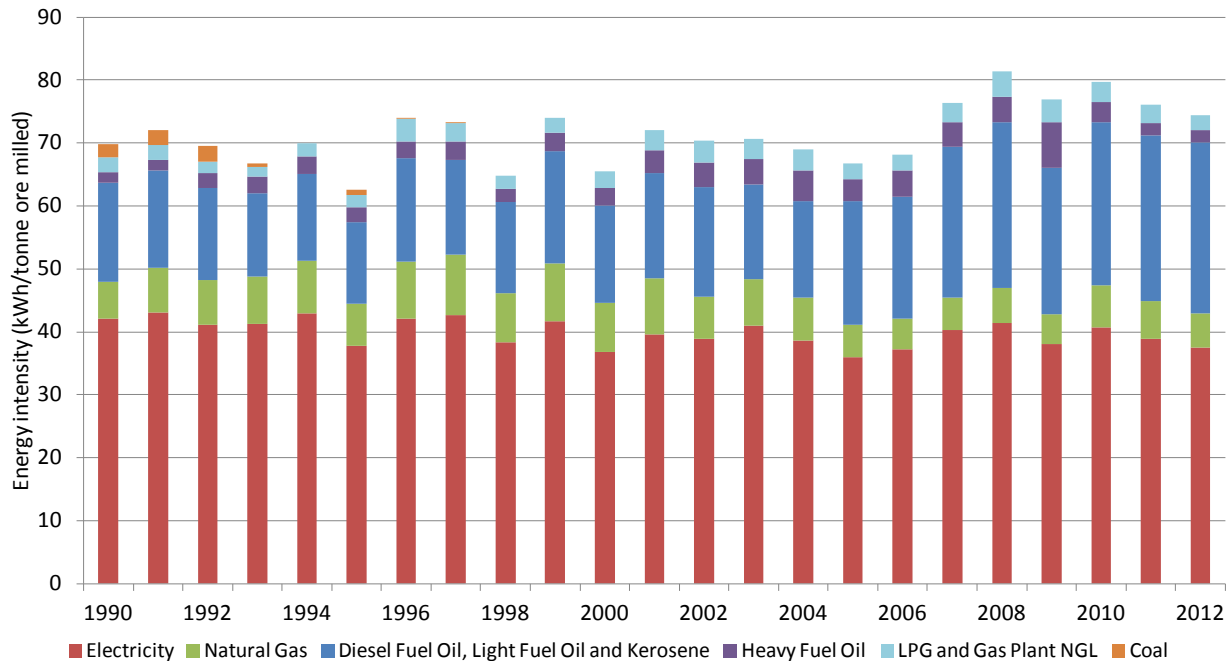
Figure 4: Canadian mining industry energy consumption 1990-2012 (Natural Resources Canada ca. 2014)



**Figure 5: Canadian metal and non-metal mining industry energy consumption 1990-2012 (Natural Resources Canada ca. 2014)**

Examination of the energy use from the Canadian metal and non-metal sub-sectors in Figure 5 reveals that energy use from 2000 to 2007 was relatively stable. In 2008 energy use increased, mostly influenced by the iron industry which may have increased production output as a response to high iron prices but in 2009 energy use returned to previous levels. An appraisal of the current energy situation in the mining sector is limited due to the most recent data published corresponding to 2012, but the trend from 2010 to 2012 suggests that energy use is on the rise due to increasing consumption from copper, nickel, lead and zinc mines, as well as potash mines.

Figure 6 presents a breakdown of the energy use per tonne of ore milled by energy type for the Canadian copper, nickel, lead, and zinc mines from 1990 to 2012. The data illustrates that from 2007 to 2012 more energy was consumed per tonne of ore milled.



**Figure 6: Canadian copper, nickel, lead, and zinc mines energy intensity 1990-2012 (Natural Resources Canada nd)**

It can be observed from Figure 6 that over the period natural gas and electricity intensity have reduced slightly, by 11% and 8% respectively, whereas diesel intensity increased by 74% from 1990 to 2012. Since diesel is principally used to transport ore, this shift may indicate that active mining is occurring at locations farther away from the shaft. Conversely, it is expected that the trend in electricity intensity would follow that of diesel since ventilation systems consuming electricity are used to dilute the emissions produced from diesel use, thus an increase in diesel consumption should result in an increase in electricity consumption. This discrepancy may reflect the positive effect electricity conservation measures such as ventilation on demand, or more efficient motors. However, a comprehensive analysis of the energy intensity is not possible without specific information that would indicate structural shifts and support variables that affect energy use such as the mine depth, ore grade, hauling distances, and climate.

Regardless of the trends and variability of energy use and intensity in the sector, it is clear that despite the prominence of energy issues and energy conservation initiatives there has been no step change improvement with respect to energy consumption in the mining sector in these census periods.

In a macro-economic context for the Canadian mining industry, at least, it appears that the mining sector may be on the verge of a 'perfect storm' of increasing energy input prices, increasing depths of production, and lower ore grades, and this is what has motivated the research conducted and reported in this thesis. In other sectors of industry, the mantra of prioritization of effort with respect to energy is: use less energy (waste less); use what energy one has to more efficiently (increase efficiency); and then utilize energy sources that have much lower marginal costs (renewable).

### 1.3 Objectives

In this work, the opportunities that present in the first two areas are focused upon elimination of wasted energy and implementation of more efficient technologies, both brought about by improved energy management systems. The main objective for this research was to identify whether a robust energy management methodology for mineral production processes (from mine to bullion) could be developed, and to exemplify parts of such a methodology to highlight economic benefit and further potential.

It is presumed that critical review and possible modification of existing methodology to:

- i) manage energy,
- ii) identify priority areas for improvement and,
- iii) assess viability of projects

are necessary in order to render them applicable to any mineral operation; whether a mine, a processing facility or an integrated mining and process operation.

Although a ‘mine to bullion’ energy audit framework was an ambitious undertaking, the scope of this research aimed to set out such a framework upon which further work could build upon, as in a continuous improvement process.

There may be obstacles for the mining industry to overcome to realize the full benefits of energy management, thus this research will examine the evolution of energy management practices adopted by the Canadian mining industry in the past as well as the barriers and drivers that were associated with progress in this sector.

Although the North American Industry Classification System's definition of mining comprises metals, non-metals as well as fuels (Statistics Canada 2012), this thesis focuses on the metals sub-sector. The Canadian mining sector is specifically examined because it is a major contributor on a national as well as a global basis. In 2013, the mining sector provided 3.4% of Canada's Gross Domestic Product (GDP), and has contributed as much as 4.5% of GDP within the last 20 years. On a global scale, Canada is among the top 5 countries for production of 11 minerals and metals, which include among others: potash, uranium, cobalt, tungsten, nickel and diamonds (The Mining Association of Canada ca. 2015).

#### **1.4 Thesis outline**

A critical review of energy management initiatives implemented in the mining industry will be presented in Chapter 2 to determine what progress has been achieved during the past 40 years. Sub-sections examining the barriers and drivers to energy management practices are also included in this chapter so that consideration is given to motivation and obstacles during the development of the energy management framework for the mining sector.

Innovation in any area requires access to reliable data, thus a critical review of mining energy-related data will be presented in Chapter 3. Energy savings from conservation measures can be masked as mines extract ore from deeper levels and thus consume more energy. A case study, presented in Section 3.1.6 develops this key understanding and identifies the need for reporting additional data. Chapter 3 also develops a benchmarking metric for the framework, encompassing the most significant variables that affect energy use in a mine including: mine depth, production, and climate. Mines normalizing against these variables may be able to legitimately compare own performance through time, or compare performance to others with the

use of internal and external benchmarking within the framework. The use of this metric may also be extended to forecasting energy consumption of a mining development either at the design or operational phase.

Chapters 2 and 3 comprise sections that have been published in the Journal of Cleaner Production Special Volume – The sustainability agenda of the minerals and energy supply and demand network: an integrative analysis of ecological, ethical, economic, and technological dimensions (Levesque, Millar et al. 2014).

The first step in energy management corresponds to understanding how and when energy is consumed. As there are different methods for conducting energy audits, there is a need to assess the applicability of these existing methodologies to the mining sector. In Chapter 4, a review of existing energy audit methodologies is included to support the development of a framework for energy management tailored for the mining sector. The work reported in Chapters 2 to 4 formed the basis for the formulation of the key research questions presented in Chapter 5 that were at the heart of the investigations reported in the following chapters.

In Chapter 6 best practice examples for energy management will be critically reviewed; some are specific to the mining sector whereas others are of a general nature. Examples of implemented energy management initiatives in the mining industry were assembled in a database providing i) a standardized reporting framework and ii) opportunity for dissemination of best practice energy conservation measures for the mining sector. The work reported in this chapter was previously published and presented at the 2013 World Mining Congress (Levesque, Millar 2013, Levesque, Millar et al. 2014).



A review of an energy audit conducted for an underground mine ensues in Chapter 7.

Recommendations for an improved audit methodology for mines are provided in this chapter.

Having gathered energy data via an energy audit from an underground mine, the next step should comprise of an analysis stage whereby potential energy conservation measures are identified.

Ventilation corresponds to the largest energy consuming end-use in an underground mine thus Chapter 8 comprises a ventilation study to demonstrate potential energy savings within this sub-system in an underground mine. Techno-economic assessments of hypothetical scenarios were made to determine the viability of energy conservation initiatives and to determine how savings could be enhanced. This chapter also provides recommendations for an improved methodology for conducting ventilation surveys to determine duct friction factors, an important factor used in mine design and for decision making.

Conducting energy audits can be challenging in a mining environment due to the large number of equipment items, especially in mines lacking sub-meters for measurement of energy consumption from various end-uses. This lack of information may hinder identification and approval of energy conservation projects by decision makers. In chapter 9 a novel disaggregation analysis was developed to estimate the electricity consumption by end-uses in an underground mine from the data obtained from the mine's main electricity meter. This draws upon expert knowledge of defining characteristics of the mine's energy use. A case study is presented in Chapter 9 to illustrate the use of this disaggregation methodology to estimate the electricity consumed by a hoist in an underground mine. Further development and adoption of this concept could lead to a simpler and cheaper energy auditing system, thereby reducing the number of sub-meters and associated communication infrastructure and data storage requirements.

Subsequently, a review of a detailed energy audit conducted at a milling facility is presented in Chapter 10. This work highlights the benefits of an energy balance approach to reconcile the bottom-up audit data to establish true understanding of consumption drivers and true conservation of energy and demand. The work presented in Chapter 10 was included in a previous publication (Levesque, Millar 2015b).

Chapter 11 is included for completeness of the 'Mine to Bullion' energy audit and comprises a brief summary of an energy audit conducted for a pyrometallurgical process. The work included in this chapter was previously published as part of a Master's thesis (Levesque 2011).

The findings from the preceding chapters will be synthesized in an extended discussion presented in Chapter 12. Strategies for improved energy audits, enhanced communication, and better data interpretation are discussed within the context of an improved energy management methodology for the mining sector.

The final chapter will present the conclusions of the work and the contributions to the discipline of mine energy management that arose during the execution of this research. The thesis closes by outlining the key actions to further develop this work and to realize even more economic benefit for the minerals industry.

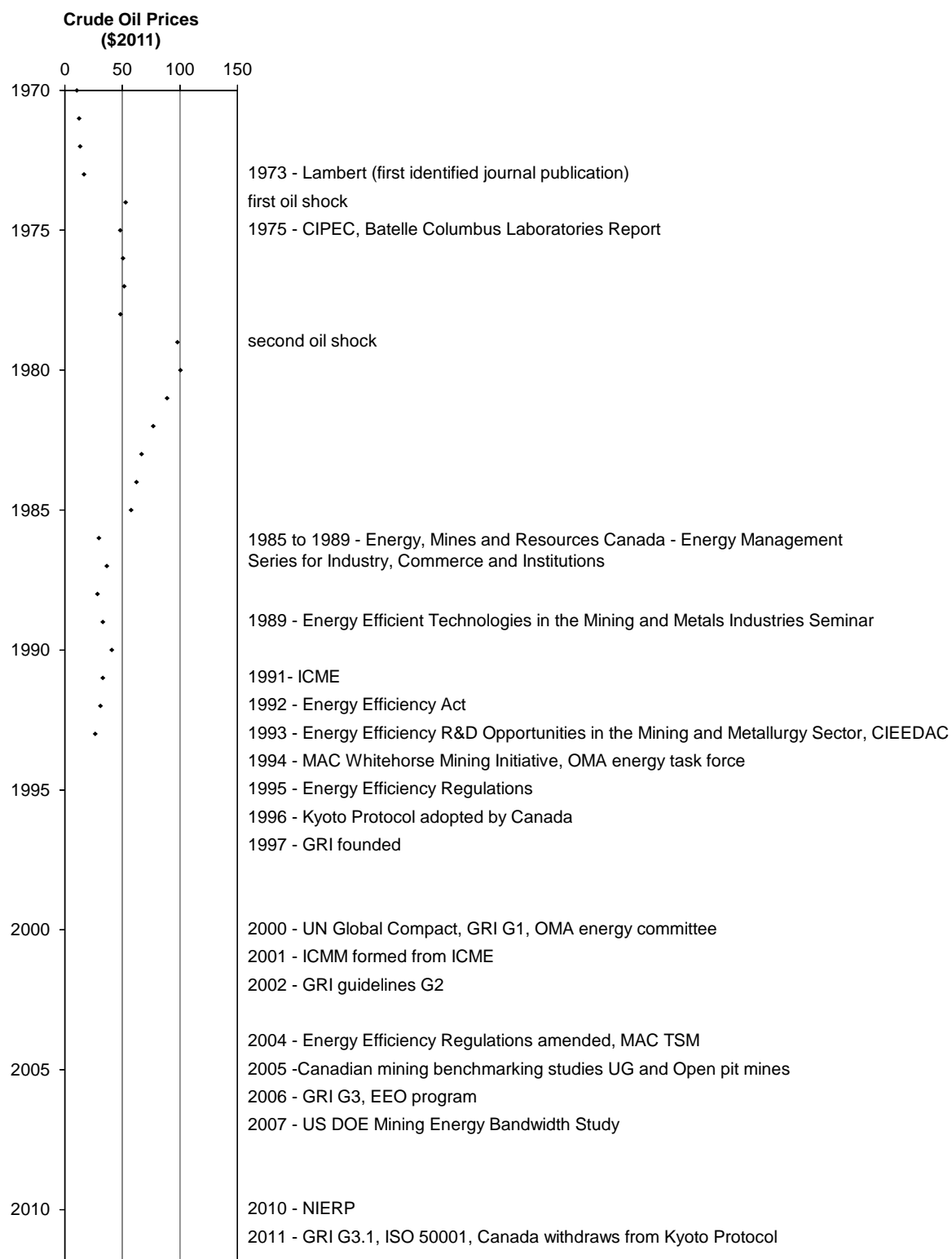
## **2 A critical review of energy management progress in the mining industry**

### **2.1 Energy management timeline**

Over several decades, milestone publications, regulations, committees and guidelines pertaining to energy management and conservation have emerged. These, among others, are illustrated in Figure 7 along with the fluctuation in crude oil prices (BP 2012) .

It can be seen from Figure 7 that the increase in crude oil prices in the 1970's coincided with the first identified journal publication pertaining to energy management in the mining sector in 1973. In 1975, the Canadian Industry Program for Energy and Conservation (CIPEC) was formed (Natural Resources Canada 2011a) and the Battelle Columbus Laboratory, sponsored by the United States Bureau of Mines, published the following studies, "Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing" (Battelle Columbus Laboratories 1975) and "Evaluation of the Theoretical Potential for Energy conservation in Seven Basic Industries" (Hall, Hanna et al. 1975). Subsequently, as crude oil prices decreased, the focus on energy continued with publications describing the energy conservation efforts of various mining companies (Manian 1974, Tittman 1977, Armstrong 1978, James 1978, Doyle 1979, Cullain 1979, Harris, Armstrong 1979). These papers are not included in Figure 7 because they are not considered to be 'milestones' since they were published after Lambert (1973) but they will be discussed in the next section.

From 1985 to 1989 the Department of Energy, Mines and Resources Canada published a series of energy management manuals to assist organizations in identifying energy conservation measures in areas including: lighting, process furnaces and dryers, energy accounting and automatic controls (Energy Mines and Resources Canada various).



**Figure 7: Chronology of crude oil prices and milestones relating to energy management in the mining industry. Source: Figure designed by the authors based on references related to the publications and initiatives cited in text**

In 1989, a seminar entitled “Energy Efficient Technologies in the Mining and Metals Industry” was held, highlighting industry as well as research and development projects which were co-funded by the Ontario Provincial Government through the Ministry of Energy (University of Toronto, Ontario et al. 1989). The papers published in the proceedings included *inter alia*: Heat recovery from mine waste water at LAC Minerals, Development of the Kiruna electric truck at Kidd Mine and Mine energy usage – a mine superintendent’s perspective from Inco Limited (now Vale).

Heat recovery from mine waste water at LAC Minerals described an energy conservation project that was implemented at the Macassa Mine to recover waste heat from mine drainage water and air compressors. The recovered heat was used to heat the mine ventilation air, thus displacing natural gas to prevent freezing in the shaft. An estimated 80% reduction in natural gas cost resulted from the first four months of use of the waste heat recovery system. The study also compared the budget and actual amounts for the various equipment categories. It was shown that the actual spending on the heat recovery system was 13% greater than anticipated due to increased labor costs and additional piping requirements. Conversely, the monitoring and control systems cost 105% more than estimated due to design considerations implemented after completion of the budget and a lack of expertise with application of this equipment in the mining sector. Thus this highlights the importance of the planning stage of an energy conservation project as well as the value of experience and knowledge within the mining industry.

The paper titled ‘Development of the Kiruna electric truck at Kidd Creek Mine, Falconbridge Ltd.’ presented a summary of a feasibility study conducted to investigate the financial viability of using electric trucks as a hauling system for a mine expansion project. Energy savings of 39% were estimated from use of electric haul trucks as opposed to diesel vehicles. These estimated

energy savings were due to the lower power requirements from the electric trucks and thus reducing the ventilation requirements. Although there were no actual results available to confirm these savings, it is suspected that the financial viability of this project electric was favorable since Kiruna trucks were still used at Kidd Creek Mine in 1995 (Paraszczak, Fytas et al. 2014)

The Mine energy usage – a mine superintendent’s perspective paper presented the relative amounts of electricity used by the different mining and mineral processing stages of Inco’s Sudbury operations (now Vale), which compared well with the values from Figure 2. A breakdown of the typical costs incurred by South Mine was also included, which showed that energy (electricity, natural gas and fuel) accounted for only 7% of total expenditures for this mine. Thus energy conservation was not a priority at this site but electric scooptrams were introduced due to the additional benefits from their use. It was stated that “*The main reason for the move to electrics, aside from the environmental benefits, were to improve productivity and reduce maintenance costs. These criteria are essential to justify equipment change.*” It was shown that the electric vehicles consumed less energy per ton, had higher production measured in tons per hour, and lower maintenance costs, than their diesel counterparts. It was also stated that energy costs are largely determined by the mine design thus “*the most effective way to affect efficient energy utilization in a Mine is right at the design stage.*” Another finding in this publication was that energy and maintenance costs were lower, and that production was higher for larger equipment. It was suggested by the superintendent that larger electrically powered equipment may be used as an energy management initiative. However, the higher capital and development costs arising from the use of larger equipment should be balanced against the benefits to determine the economic viability of this measure.

During the 1990's the attention on energy efficiency progressed with the adoption of the Energy Efficiency Act in 1992 which developed into the Energy Efficiency Regulations in 1995 (amended in 2004). The goal of these regulations was to provide minimum energy performance levels for a range of energy-consuming products purchased in Canada, as well as to dictate the inclusion of labels stating the estimated annual energy consumption of some products on the market (Canadian Institute for Energy Training 2006). In 1993, Natural Resources Canada published a study entitled "Energy Efficiency R&D Opportunities in the Mining and Metallurgy Sector" (Sirois 1993), and the Canadian Industrial Energy End-use Data and Analysis Centre was created. The formation of the Ontario Mining Association's (OMA) energy task force in 1994 developed into a standing committee in 2000 (Brownlee 2012). The Mining Association of Canada (MAC) launched the Whitehorse Mining Initiative in 1994 which ultimately evolved into the association's Towards Sustainable Mining initiative in 2004 (Fitzpatrick, Fonseca et al. 2011).

These efforts aimed towards energy efficiency emerged during periods of low oil prices between 1985 and 2000. Thus it is suspected that the guidance was developed as a proactive approach in anticipation of rising energy prices so that industry would be better positioned to face increased operating costs.

Since 2000 there has been a surge in sustainability initiatives with the development of reporting guidelines by several organizations such as the UN Global Compact, the Global Reporting Initiative (GRI) and the International Council on Mining and Metals (ICMM), with the aim of increasing corporate transparency with respect to economic, environmental and social impacts. Natural Resources Canada published two studies in 2005 titled "Benchmarking the energy consumption of Canadian Underground Bulk Mines" and "Benchmarking the energy

consumption of Canadian Open-Pit Mines” (Canadian Industry Program for Energy Conservation 2005b, Canadian Industry Program for Energy Conservation 2005a).

In 2006, the Australian government launched its Energy Efficiency Opportunities Program that requires users annually consuming more than 0.5 PJ (~278 GWh) of energy to conduct an audit to identify measures to improve energy efficiency (Australian Government Department of Resources, Energy and Tourism 2011b). Additionally, the identified initiatives had to be reported and were segregated by industry type. The energy conservation measures for the mining industry are compiled in a database which can be accessed via the internet (Australian Government Department of Resources, Energy and Tourism 2011a). In 2007 the US Department of Energy released a publication titled “Mining industry Energy Bandwidth Study” which estimated potential energy savings of 54% for the U.S mining industry (U.S. Department of Energy 2007). The Northern Industrial Electricity Rate Program (NIERP), created in 2010 and administered by the Ontario Government, promotes energy management by offering rebates on electricity rates to large industrial users in northern Ontario who have prepared an energy management plan (Ministry of Northern Development, Mines and Forestry 2010).

Clearly the topic of energy management has accrued some importance in the past 4 decades, but what has actually been achieved? Have the suggestions from the 1970’s been adopted as best practice? Have any innovative solutions been developed?

## **2.2 1970’s initiatives**

As energy prices were increasing, the industry recognized that energy management was necessary. A review of publications has revealed that the earliest paper found so far pertaining to energy management and conservation in the mining sector dates back to 1973.



Lambert (1973) promoted energy conservation through utilization of waste heat from electric motors, compressors and fossil-fueled electricity generators. He stated that *“The fact that there is no energy crisis today does not mean that there will not be such a situation in the years ahead. In any case, an abundance of energy is still no excuse for not making the best possible use of all energy forms.”*

Manian (1974) presented a paper focusing on energy reductions from process and space heating in a mine and ore processing mill with the following measures:

- Substitution of air stirring with mechanical means
- Substitution of air with oxidizing compounds
- Covering process tanks to reduce heat losses
- Implementation of heat recovery measures
- Insulating tanks
- Improved building insulation
- Use of a heat pump.

In Tittman (1977) the energy conservation efforts at Erie Mining Co. were published. The company established a conservation program in 1973 with a group to assess energy use and an employee training program through which the following measures were identified for energy management:

- Preventative maintenance on power plant steam traps
- Reducing fuel spills
- Fixing compressed air leaks

- Correcting everyday energy waste, such as eliminating vehicle idling
- Education program for employees concerning vehicle idling and turning off lights
- Installation of oxygen analyzers on boilers to control excess air and optimize fuel combustion
- Shutting down heating plant when not required
- Installation of more efficient lighting.

Financial savings generated by energy management result from lowering energy consumption and from reducing the peak demand in any given billing period (Armstrong 1978). Armstrong's paper focused on demand side energy management efforts in the milling stage of a mining operation by utilizing a rod mill as an example, which showed that the reduction of peak demand and energy consumption both result in lower energy costs. Armstrong also illustrated that operation of the rod mill at rated production capacity resulted in lower specific energy consumption in kWh/ton, and reduced unit energy cost.

James (1978) highlighted the following benefits associated with energy efficiency: i) reduced energy consumption will lead to reduced costs, resulting in increased profits and enhanced competitiveness, ii) lower energy demand will extend life of current energy sources and iii) lower energy bills will liberate funds which would have been allocated for energy supply.

Furthermore, James identified three levels of opportunities for improvement. The first level corresponded to 'housekeeping' measures which could typically yield improvements of 10-15% with little or no cost for modifications to operating procedures and equipment maintenance. The second level of opportunities also led to 10-15% savings, but with time or financial investment requirements. The final level involved 'total plant energy flow optimization and equipment and

process design' which could result in improvements beyond the 20-30% savings achieved with the first two levels. James' analysis of Canadian non-metal mines showed that energy consumption as well as unit energy costs in this sector were increasing in the early 1970's. He also examined the share of fuel and electricity costs relative to total production costs and found that this metric was also increasing, as did materials and supplies whereas the percentage associated with production wages was decreasing. James concluded "*Energy savings mean dollar savings. In the late 1970's and beyond, no company or industry can afford to treat energy as a low priority*" (p.103).

According to Wenzl (1978), the Inco Metals Company launched an Electric Power Management Program in 1972 that had the goal of controlling peak power and was successful at improving the power load factor to over 90% in 1976 from 83% in 1973. Load factor corresponds to the ratio of the average demand to the maximum demand for a period (Doty, Turner 2009) and lower values may result in higher billing rates depending on the rate structure of the utility; it can be favorable to redistribute the load in a billing period to increase the load factor. The program included monitoring power consumption to establish a load profile at each plant and mine as well as the installation of power consumption monitors to forecast the demand and assist operators to manage the total power consumption. Subsequently, the program was expanded with the formation of committees at each site which identified potential savings by reducing compressed air and ventilation during periods of low underground activity. The program resulted in electricity demand reductions of 1,400 MW (1.4 GW) and over 280,000 m<sup>3</sup> (10,000 mcf) of natural gas savings per year for one mine (Wenzl 1978). However, such electricity savings are questionable, as this represents roughly 10% of current electricity demand in Ontario, but Wenzl's electricity savings may actually correspond to 1,400 MWh per year.

At Falconbridge Nickel Mines Limited, energy management efforts in 1979 consisted of: identifying major energy consumers, installation of meters and controls, dedication to lowering unit energy consumption, promoting conservation through revised accounting practices and development of an energy management policy at Westfrob Mine in British Columbia (Doyle 1979). The operation realized the importance of load and demand profiles to understand when and how energy was utilized to identify measures for reducing consumption and/or demand, which could also result in cost savings. Subsequently, an energy audit was conducted at the Sudbury operations where energy management initiatives included waste heat recovery from compressors and mine air, and shutting down equipment such as compressors, pumps, fans and heaters when not required, which has resulted in annual savings of 0.9 million dollars, or about 2.7 million dollars (\$2013)<sup>5</sup>. This corresponds to roughly 6% of annual energy expenses, with minimal capital expenditures (Doyle 1979).

A compressed air study was conducted at Inco Metals Company's Levack Mine Complex and according to Cullain (1979) it was determined that an excess of 28% air was generated compared to theoretical requirements and that the excess air consumption occurred during non-production periods. Subsequently, corrective actions were taken which resulted in a 15% compressed air consumption reduction and electrical power savings of \$80,000 per annum, or about \$245,000 (\$2013), which corresponded to roughly 5% of total mine electricity consumption (Cullain 1979). The measures comprised of fixing leaks, reducing compressor usage during off-shift and weekends and increasing employee awareness with respect to compressed air waste and efficient use (Cullain 1979).

---

<sup>5</sup> Bank of Canada, 2013. Dollar values from the 1970's were indexed to \$2013 but values from 2007-2012 were not adjusted since the rate of inflation during that period was quite low.

Harris and Armstrong (1979) published a paper outlining the electrical energy management efforts at Inco Metals Company's Shebandowan Mine, which identified that substantial savings were achieved by “*finding and fixing energy leaks*”, as well as improving maintenance and operating practices. It was stated that “*One of the most difficult, but lucrative, ways to achieve conservation of energy is to identify waste energy. A complete energy profile that accurately describes the individual and total energy input for productive and non-productive functions, for production and down-time periods, for peak and average activity levels, and for principle energy utilization equipment is required. Waste energy during production periods is usually limited to machinery that has high idling energy requirements. Finding waste which is not obvious or occurs in small increments requires a systematic and critical review of every energy connection.*” The paper showed that reducing skip hoist speed, controlling peak load, shutting down equipment during low production periods and the installation of outdoor lighting controls are measures contributed to energy peak and consumption savings of 3% of annual electricity costs, totaling \$25,000 per annum in 1977, or roughly \$76,000 (\$2013) (Harris, Armstrong 1979). Although it was not specified how the reduction in skip hoist speed from 13.72 to 9.14 m/s achieved savings, it can be speculated that they arose due to: i) reduced acceleration rate or period, ii) reduced braking power or period, and iii) reduced air drag on the ore skips. When the hoist is travelling at a constant speed, the force required to keep the unit moving corresponds to the drag, which according to Streeter and Wylie (1983) is characterized by:

$$F_D = C_D A \frac{\rho U^2}{2} \quad (1)$$

where  $C_D$  is the drag coefficient,  $A$  is the area,  $\rho$  is the density and  $U$  is velocity. According to (1), the only factor which affects the drag in this instance is the velocity since all other values are

constant. Therefore it is estimated that a reduction in skip hoist speed from 13.72 to 9.14 m/s would reduce the energy consumption by a factor of at least 2.25. Lowering the acceleration of the skips from or to rest may have also reduced the peak power demand of a hoist cycle. This measure would result in a longer hoisting cycle therefore, prior to implementation an assessment should be conducted to investigate the effect on production.

This section provided examples of energy management efforts of the 1970's at various mines that resulted in financial savings ranging from 3 to 6%, through reducing peak demand, lowering demand charges and through energy consumption savings by eliminating wasted energy. These savings were achieved because operations management understood where and how energy was utilized through energy audits and metered consumption. Although some of the mine sites from these examples are no longer in operation, the companies who owned them still exist and are operating other sites, however, there is conflicting evidence that the energy management efforts from this era are still being practised, sustained or have evolved.

### **2.3 Recent initiatives**

40 years have passed since the publication of the earliest article reviewed with respect to energy management in the mining industry, but what progress has the industry made?

The first observation is that companies have switched from publishing energy conservation efforts in journals to promoting them in corporate sustainability reports and industry newsletters and publications, which are not peer reviewed. Second, most of the papers relating to energy management in the mining industry that have been published in academic journals or conference proceedings pertain to research and development projects as opposed to implemented measures.

A survey of recent energy conservation efforts in the Canadian mining industry dating back to 2007 has revealed several initiatives. These initiatives were compiled from corporate sustainability reports (DeBeers, Xstrata, Teck and Diavik), Sudbury Mining Solutions Journal, a study conducted for the Ontario Mining Association, Heads Up CIPEC newsletter, a media release from Rio Tinto, corporate websites (Diavik and Goldcorp) and proceedings from the International Conference on Renewable Energies and Power Quality.

Mines located in northern Canada have implemented measures to recover heat from diesel generators deployed and operated for the production of electricity and are utilizing this heat to warm buildings. DeBeers's Snap Lake mine has estimated that annual diesel fuel consumption has been reduced by 800,000 to 1 million litres, or approximately 3% of total consumption by increasing the size of their heat exchangers (DeBeers Canada ca. 2011). At Diavik Diamond Mine, the diesel power plant energy utilization is cited as over 80% (Diavik Diamond Mine n.d.) which is a substantial improvement compared to the typical diesel generator efficiency of about 33-40% when electricity is produced alone (Deshpande 1966).

At Xstrata Zinc's Brunswick Mine the heat recovered from the concentrate dryers is used to warm the flotation slurry and in 2007, resulted in annual savings of \$850,000 corresponding to 16% in avoided steam consumption, which was previously required to heat the slurry (Xstrata ca. 2007). Subsequently, the company has implemented measures, such as recirculating water in the thickeners and heat recovery from cooling compressors to double the amount of recovered waste heat, from 30 GJ/h (8.3 MW) in 2007 (Xstrata ca. 2007) to 60 GJ/h (16.6 MW) (Natural Resources Canada 2012b).

When considering waste heat recovery, it is important to consider the grade of the available heat to match the source with an area in the process that can maximize the efficient use of this energy. This can be achieved using Pinch Analysis, which is a widely used Process Integration method. According to Natural Resources Canada (2003), *“It provides tools that allow us to investigate the energy flows within a process, and to identify the most economical ways of maximizing heat recovery and of minimizing the demand for external utilities.”* In essence, these are techniques that match the grade (temperature) of waste heat to parts of a process that require heat of roughly the same grade. The ‘pinch’ refers to the minimum difference between the temperatures of the source (waste) heat and the application. Methodology and additional applications of Pinch Analysis can be found in Linnhoff and Flower (1978), Flower and Linnhoff (1978), Linnhoff and Hindmarsh (1983) as well as Linnhoff (1993).

A second category of initiatives consists of common sense measures to reduce waste energy. Both Teck and Rio Tinto have reported shutting down equipment when it is not required as a means of reducing energy consumption (Teck ca. 2007, Rio Tinto ca. 2010), which at Teck’s Hemlo operations included ventilation.

Diesel fuel reductions for material hauling equipment during idling periods can also lead to substantial savings from anti-idling policies and installation of new heating equipment. At Goldcorp’s Porcupine Gold Mine, heaters were installed to keep the engine and operator cab warm during the winter when vehicles were stationary (Tollinsky 2011). Such an initiative has resulted in estimated annual savings of about \$300,000 or over 3% of total diesel cost, with a payback period corresponding to less than one year including the cost of new equipment.



Another initiative which is gaining attention is Ventilation On Demand (VOD) where the supply of fresh air delivered underground is matched with the demand, which reduces ventilation system use. The simplest implementation of this is by turning auxiliary fans off when they are not required. Another method is the modulation of auxiliary fans through high-half-off settings, requiring relatively inexpensive equipment (Allen 2012) and the most complex and most expensive method is the continuous modulation of auxiliary fans through the use of Variable Frequency Drives (VFD). For example, Xstrata Nickel reported annual energy savings of 10% at its Nickel Rim South Mine (Xstrata Nickel ca. 2010), and Xstrata Zinc's annual savings at Brunswick mine corresponded to \$700,000 (Natural Resources Canada 2012b). At Vale's Creighton Mine the potential energy savings were reported at \$20,000 per fan per annum by reducing the fan speed by 10%, corresponding to a 27% energy savings (Vale ca. 2010).

Comparison and analysis of these initiatives was not possible due to the lack of standardized reporting and incomplete information. For example, total energy use at Brunswick mine was not reported. Therefore, it was not possible to assess the significance of the financial savings relative to the total energy cost. Furthermore, VOD may also lead to reduction in heat requirements, but it was not specified whether the Brunswick mine savings included these or corresponded only to decreased electricity consumption.

Another energy consumption reduction measure in this category consists of fixing compressed air leaks. At Xstrata's Brunswick mine a small team is responsible for monitoring and repairing such leaks (Natural Resources Canada 2012b), which can represent significant losses, if left untreated. For example, in a study prepared for the Ontario Mining Association, da Cunha (2007) conducted a compressed air leak study involving three mines; FNX (now KGHM International) McCreedy West, CVRD Inco (now Vale) South Mine and Barrick's Williams Mine. The study

indicated that most compressed air leaks in mines occur from the effects of blasting or by mobile equipment striking pipes. The common locations of leaks include: couplings, cracked or damaged hoses, tubes and fittings, open condensate traps, pipe disconnects, pipe joints, pressure regulators, shut-off valves and thread sealants. The report concluded that fixing large compressed air leaks at two of these mine sites resulted in approximate annual energy savings of \$100,000. Savings identified by da Cunha were less than 1% of the total electricity consumption from one of the sites, but could represent approximately 50% of the compressed air produced. Although these savings may not seem significant, the situation would be different for mines using more compressed air, which may have been the case with Xstrata's Brunswick mine.

The final initiatives can be grouped into the renewable energy source category, which includes wind, solar and geothermal. These sources of energy are typically used in the minerals industry, when economically feasible, to lower fossil fuel consumption, which in turn reduces greenhouse gas emissions (McLellan, Corder et al. 2012).

Goldcorp's Musselwhite Mine installed a SolarWall® ventilation air heater on the mechanical shop building on the basis of a calculated annual energy savings of 413 MWh and a payback period of less than 4 years (Goldcorp 2010), corresponding to roughly 1% of total propane consumption. While the economics of this project were favorable for this location, an assessment should be conducted prior to implementation to assess the available solar resource, as this type of system may not be financially viable at every site. An assessment of the effectiveness of such an initiative would also be beneficial for industry by comparing the estimated savings versus the actual performance of this energy conservation measure, but no details on the operation of this SolarWall® heater have been published.

Construction of a wind farm at Rio Tinto's Diavik Mine is expected to reduce diesel consumption at this mine site by 10%. The wind farm was commissioned on the 28th September 2012, and the \$33 million investment is expected to be paid back within 5 years (Rio Tinto 2013). The Diavik Mine is located in a remote northern region where there is no available grid electricity supply. As a result, this operation uses diesel generators on site to produce electricity, now integrated with wind power. The diesel supply for the mine must be hauled and stored on site, so any decline in diesel consumption while maintaining production produces a reduction in the fuel transportation and storage requirements. As the mine moves towards a fully underground operation, the electricity demand will increase due to underground water pumping, mobile fleet as well as heating and ventilation requirements (Rio Tinto ca. 2010). When integrating renewable energy sources with conventional fossil fuel generating systems (i.e. running both systems together in parallel) in islanded configurations, the efficiency of the conventional system will be lower when it is running at partial load (Trapani, Millar 2013). The success of such projects needs to be monitored to establish whether there are benefits for the wider mining industry in embracing wind-based, electricity generation technology. Also, Teck and Suncor jointly funded a wind development project in Alberta comprising 55 turbines that will produce 88 MW of peak power, which is enough to supply 35,000 homes in the province (The Globe and Mail 2010). The electricity generated from this wind farm will not be utilized directly by the mining operations, but instead used to offset carbon emissions. Other examples of individual mining operations producing energy from wind include MSPL Ltd in India, Barrick Gold's Veladero mine in Chile and El Toqui in Chile (Paraszczak, Fytas 2012).

Solar energy has also emerged as an option for electricity supply in the mining industry.

Specifically, Chevron Mining's Questa site in New Mexico United States (Latitude:

36°42'15"N), has a 1MW concentrating photovoltaic installation built on the tailings area of the mine, which has now ceased operations. Additional solar projects are planned to supply electricity to Chilean copper mines (Paraszczak, Fytas 2012) and the use of solar thermal energy in copper heap leaching processes has been investigated to increase solution temperatures, which leads to improved metal recovery (Metkemeyer 2012, Piraino, Rimawi et al. 2012). Finally, geothermal energy is being utilized to displace fuel oil for electricity generation at the Lihir Gold Mine in Papua New Guinea and produces 75% of the operation's power (Paraszczak, Fytas 2012).

In summary, the energy management and conservation efforts in the mining industry from the 1970's focused on effective utilization of energy through waste heat recovery and eliminating waste energy and some case studies provided energy consumption data, such as electrical demand profiles and load duration curves. In comparison, recent initiatives report similar energy conservation measures with the added implementation of renewable energy sources, but none provided demand profiles or load duration curves. It appears that the rate of uptake from the 1970's suggestions seems to be low, which could be due to the lower energy prices in the 1980's and 1990's. However, with recent increases in oil price, the industry is now faced with a similar situation as in the 1970's, but the more recent fall in oil price may impede energy progress in the mining industry.

## **2.4 Barriers to implementing best practice**

According to Tittman (1977) at Erie Mining Co., the greatest barrier to implementing energy conservation practice was “...to get 2800 employees to think in the same way about a subject and to act in a uniform, organized manner to conserve when, in today's atmosphere of plenty, they

*can see little need to practice and perform in the most efficient manner.”* This hurdle was overcome with supervision, education and communication to ensure the success of the energy management program. However, the situation at the moment is different – awareness of the finite nature of fossil fuel supply and perception of climate change are greater than before. Therefore, companies wishing to focus on energy efficiency may not need the same level of effort to convince employees of the value of such a program.

A study prepared for the Ontario Mining Association’s Energy Committee in 2008, identified the following barriers to the implementation of energy efficiency measures (Scott 2008):

- Projects require a short payback period – i.e. less than 6 years
- Mining personnel are focused on production as opposed to conservation
- Lack of performance incentives tied to energy conservation key performance indicators for production personnel
- High financial risk of implementing major technological changes
- Competition for capital – minimum acceptable rate of return (ROI) corresponds to 8.5% and
- Mines nearing their end of life do not have sufficient time to recuperate investments from long-term projects.

While some of these barriers are valid, others can be perceived as unfounded; for example, with such a focus on production without consideration of energy consumption, mining operations may not realize their full, profit-maximizing potential. While production is important in generating revenue, why are production costs not always considered? According to cost-benefit principles,

profit-maximizing firms should examine production costs, which include energy, to determine the level of output that would generate the maximum profit (Frank, Bernanke et al. 2012a).

Production costs for the Canadian mining sector, excluding oil and gas extraction industries, were examined for metal ore mines and non-metallic mineral mining and quarrying from 1961 to 2010, using data compiled from the Principal statistics of the mineral industries. The data is available in CANSIM tables 152-0002 and 152-0005 (Statistics Canada 2013), which contain statistics collected by Natural Resources Canada. The Annual Census of Mines (Statistics Canada var.a) and the Canadian Minerals Yearbook (Natural Resources Canada 2011b) provide the same data.

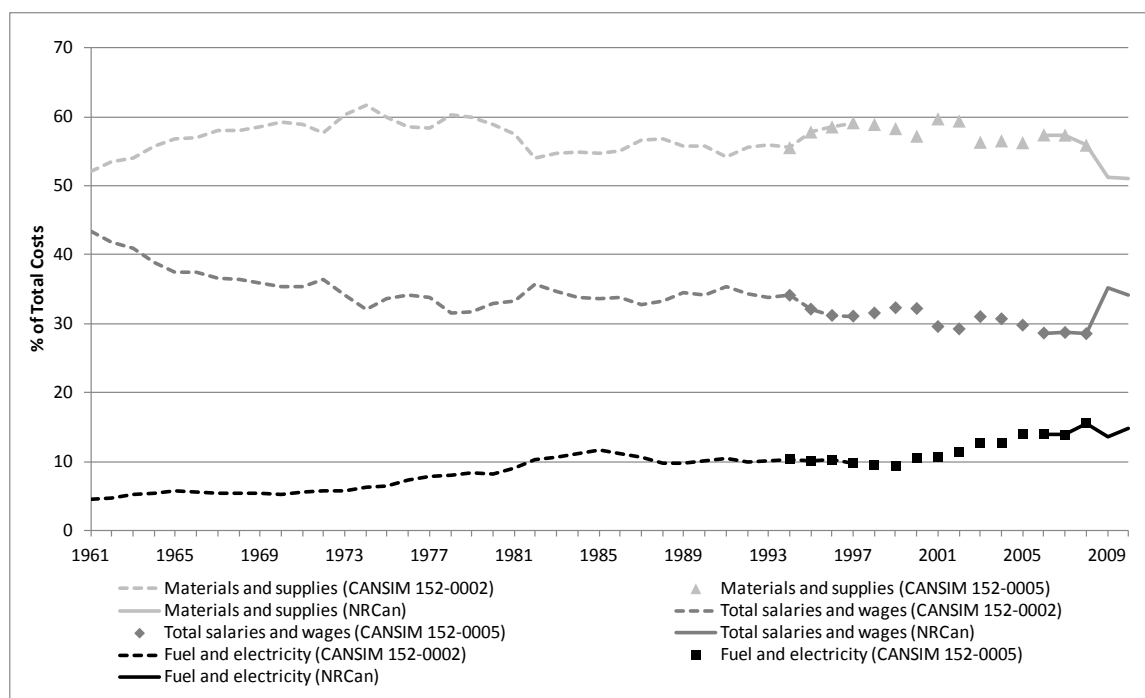
The first CANSIM table contained data from 1961 to 1997, and the second one focused on the period from 1994 to 2008. The 4-year overlap of these tables allowed the data to be combined and established a consistency between the sources, and clarified the varying nomenclature adopted between them. Table 2 shows the corresponding categories between these sources.

**Table 2: Corresponding nomenclature between CANSIM tables for mining sub-sectors**

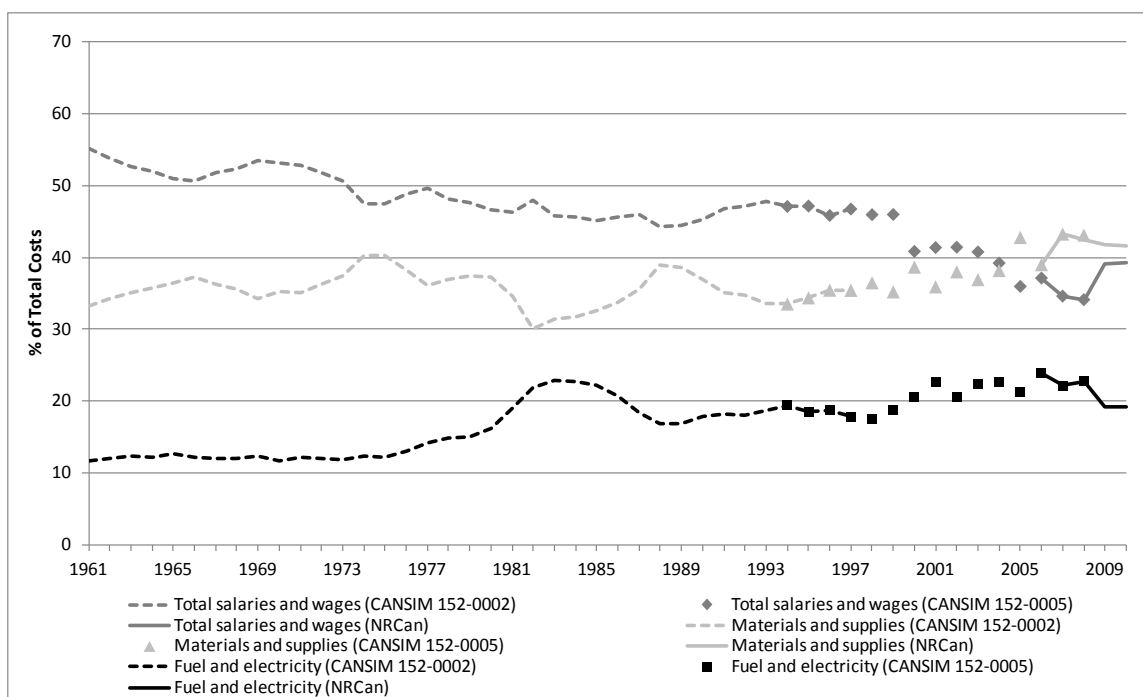
<b>CANSIM table 152-0002</b>	<b>CANSIM table 152-0005</b>
Total metal mines	Metal ore mining
Total industrial minerals (aggregate of Total non-metallic mines, and Total pits and quarries)	Non-metallic mineral mining and quarrying

Statistics Canada discontinued publication of this data after 2008, and the statistical tables in Natural Resources Canada's Canadian Minerals Yearbook were not available online for years beyond 2008. However, figures for 2006 to 2010 were obtained from Natural Resources Canada (2012a) by special request.

The Principal statistics of the mineral industries tables contained annual costs for: i) fuel and electricity, ii) materials and supplies, and iii) total salaries and wages. These were analyzed to determine the relative cost of each component for metal ore mining, as well as non-metallic mineral mining and quarrying. The results are presented in Figure 8 and Figure 9. The dashed lines correspond to the data from CANSIM table 152-0002, the data points comprise data from CANSIM table 152-0005 and the solid lines represent data from Natural Resources Canada.



**Figure 8: Historical annual costs for Canadian Metal Ore Mining (Natural Resources Canada 2012a, Statistics Canada 2013)**



**Figure 9: Historical annual costs for Canadian Non-Metallic Mineral Mining and Quarrying (Natural Resources Canada 2012a, Statistics Canada 2013)**

For both mining sub-sectors, fuel and electricity costs were the lowest of all (Figure 8 and Figure 9), but this is not the case for all mining operations as energy costs vary depending on the location and source. For example, Goldcorp's Porcupine Gold Mine, located in Northern Ontario, claimed that energy costs ranked second in terms of total operating costs (Goldcorp 2011).

The relatively low fraction that energy costs have historically represented of total production costs may explain the low uptake of energy efficiency measures. This suggestion was echoed in the paper titled "Mine energy usage – a mine superintendent's perspective" published in the Energy Efficient Technologies in the Mining and Metals Industries Seminar (University of Toronto, Ontario et al. 1989), which indicated that energy costs corresponded to 7% of total



expenditures, thus a substantial amount of energy savings would result in marginal overall operating cost savings. Furthermore, it was reported that energy consumption is dictated by the mine design, thus a minimum amount of energy is required for production. Although this was perceived as a barrier to energy management, there is no excuse for wasting energy as expressed in Lambert (1973).

The trends in Figure 8 and Figure 9 indicate structural shifts in production costs. In general the share of costs for fuel and electricity has been growing. This trend was valid up to 2008, but in 2009, the share of energy costs relative to other operating costs decreased. This decline can be associated with the economic downturn. For metal mines, spending on fuel and electricity, and materials and supplies decreased in 2009 whereas costs for wages and salaries continued to increase. For non-metal mines, all costs declined in 2009, but the reduced spending on wages and salaries was less severe than the cutbacks on the other costs. This is illustrated by the rising share of costs in 2009 for salaries and wages in Figure 8 and Figure 9. However, in 2010, all costs for both mining sub-sectors increased. Figure 8 and Figure 9 show that the proportion that energy costs comprise total production costs is 15% and 19% for metal and non-metal mines respectively. Such proportions of total operating costs and trends would certainly be classified as material to production decision making in financial accounting terms.

Guerin (2006) provided case studies where energy management initiatives were implemented in the Australian mining industry. In one of these, BHP Billiton utilized waste methane from coal seams to produce 94 MW of electricity which was sold to the electric grid. The economic viability of the project, based on estimates of future electricity prices, was an obstacle to the adoption of this project, however, the additional revenue and reduced greenhouse gas emissions were sufficient to overcome the barriers in this case.

A second case study examined an initiative from Iluka Resources. The company invested in a waste heat recovery plant to capture the energy from the kiln off-gas to produce electricity, which is used at the site to displace electricity consumed from the grid. The main risk identified by the company during this project was the adoption of a new technology that did not correspond to the company's core business. However, the company proceeded with the project since the increased financial return and reduced environmental impact was perceived to outweigh the risk.

Cooremans (2011) echoes the relevance of this factor as a barrier to execution of energy efficiency by stating that several publications identified that the alignment of energy efficiency investments with a company's core business is an important factor when deciding to proceed with a project.

Although Millar *et al* (2012) discuss some remedies to these perceived issues, based around the idea of Energy Service Companies (ESCO) as intermediaries, companies governed by the U.S. Securities and Exchange Commission are bound by the Sarbanes-Oxley Act of 2002 (SOX) (U.S. Government Printing Office 2002). The Act addresses decreased investor confidence, resulting from financial fraud and business failures, through enhanced corporate accountability, internal controls and reporting requirements (Hall, Liedtka 2007). The regulations mandated that corporate managers are responsible for overseeing internal controls, but also that this extends to controls of outsourced services, which includes ESCO provided services. In an outsourcing scheme, it may be deemed to be difficult to meet the SOX internal control requirements, but this can be addressed with a Statement on Auditing Standard no. 70 (SAS 70 Audit). Essentially, this is an auditor-to-auditor report certifying the service company's internal controls (Nickell, Denyer 2007), thus ensuring fulfillment of the SOX requirements. So although such accounting practices

may be perceived to be a barrier to investment in ESCO type initiatives, in practice there are straightforward mechanisms to surmount them.

Barriers can be classified as financial, behavioral, or organizational, but whatever the challenges to implementing energy conservation measures are, it is important for an organization to properly identify them and assess the drivers to determine whether to proceed with an energy efficiency project.

## **2.5 Market drivers for energy management**

Through less wasteful energy consumption, an industry facing increasing prices of energy can better control production costs. Furthermore, lower energy consumption would bring about reduced greenhouse gas (GHG) emissions when fossil fuels are used as a primary energy source. This could contribute to improving the public's view of the mining industry, for which, according to Fitzpatrick et al (2011) and Tuazon et al (2012), there is great pressure to improve sustainability performance throughout the industry. Such improvements could be achieved with energy consumption reductions, since energy consumption is one of the indicators measured by the GRI reporting standard and could be included in the broader guidelines of ICMM and United Nations Global Compact reporting principles. The Mining Association of Canada's Towards Sustainable Mining initiative reports on: the implementation level of energy and GHG management systems, energy use and GHG emission reporting systems, and energy and GHG emission intensity performance targets. Promotion of energy conservation and GHG emission reduction initiatives through sustainability reporting would contribute to improving the public perception of mining companies.

Apart from the obvious financial savings from reduced energy consumption, energy management can provide further economic benefits via carbon pricing mechanisms. In response to climate change, several countries have either adopted or proposed carbon trading schemes and according to Perdan & Azapagic (2011), the carbon market will continue to grow. These schemes provide a financial incentive to reduce emissions through energy management practices for companies operating in these jurisdictions. This type of pricing mechanism may be an effective driver for energy management provided that the cost of carbon exceeds the cost of implementing energy or emission reduction strategies.

Imposition of a carbon tax can also be viewed as a driver for energy management within the mining industry since it would increase production costs. A recent report prepared by the ICMM (2013), assessed the financial impact of carbon pricing on the metals and minerals industry. The report examined various carbon pricing mechanisms from different countries and highlighted that the impact on industry was dependant on the following factors: i) the carbon price ii) the emissions covered, iii) inclusion of indirect emissions from purchased electricity, and iv) compensation measures. It was observed that the economic impact varied significantly between regions, but was greater when electricity was included in the carbon pricing mechanism. Electricity generation sources also affected the impact of a carbon price; in British Columbia and Quebec, impacts were lower due to the low percentage of fossil fuel use for electricity generation in these provinces corresponding to 10% and 1% respectively (Farhat, Ugursal 2010). The financial impact of a carbon pricing scheme may be further reduced by compensation measures consisting of support offered as free allowances or tax reductions to ensure that companies can maintain competitiveness. For example, carbon costs as a percentage of total cash costs for aluminum production were reduced to less than 5% for British Columbia, Quebec, Australia and

South Africa after compensation measures were applied. However, in the EU, the effect of support measures was somewhat lower and the impact from the carbon pricing mechanism corresponded to roughly 6% of total cash costs.

It seems that generally, a corporation's investors are sensitive to energy management issues. According to Jenkins and Yakovleva (2006), *"Investors are increasingly more interested in investigating the social, environmental and ethical dimensions of a company before investing in it. A process of screening out companies that perform badly in these areas is known as Socially Responsible Investing. Disclosing social and environmental information is crucial for the mining industry to shake off a hitherto negative image among such investors."*

According to Wingender and Woodroof (1997), the announcement of an energy management project correlated with a firms' stock price rising an average of 21.33% within 150 days of the declaration. Investors realize the benefits of energy management projects and as such, firms should use this as further motivation to implement energy management initiatives.

Cooremans (2011) reviewed decision making processes and tools and determined that energy efficiency field did not conform to classical economics theory because in some instances financially viable energy efficiency projects were not supported. It was proposed that the strategic character of investments in addition to the financial factors were used to decide on investment of energy efficient measures. Cooremans defined a strategic investment as follows *"An investment is strategic if it contributes to create, maintain, or develop a sustainable competitive advantage."* and suggested that value, cost and risk constitute the dimensions that influence competitive advantage. Thus adoption of energy efficiency projects depends on the strategic goals of a company, and where energy reductions can lower costs, improve value, or

reduce risk, investment in energy efficiency could contribute to a firm's competitive advantage. For example, where a firm's strategic goal consists of achieving the lowest operating cost within the sector, investment in financially viable energy efficiency projects may contribute towards the objective via lower operating costs. For those focusing on increasing value, energy efficiency projects may enhance value via improved public image. Conversely, energy efficiency may contribute to reducing risks from rising energy rates, greater energy consumption from deepening mines, or reduce the risk of energy supply disruptions where grids are nearing capacity.

Consideration of non-energy benefits arising from energy efficiency projects such as reduced maintenance costs, improved worker morale, or reduced risk from rising energy prices among others may provide motivation beyond the economic drivers for investment in energy efficiency measures and these could lead to enhanced competitive advantage. If the drivers align with mining companies corporate strategic goals, increased adoption of energy conservation initiatives in the sector will result, principally to the benefit of those mining companies and their investors.

### **3 A critical review of mining energy-related data reporting**

Mining energy-related data can be found in various sources such as corporate sustainability reports as well as government publications. This chapter will review these publications and their reporting guidelines to assess how the information in these sources could be improved for enhancing energy performance within the mining industry. An example is included to demonstrate how mining companies can enhance communication and demonstrate improvement in energy matters.

#### **3.1 Sustainability reporting guidelines**

Corporate sustainability reports have been published by companies since the 1990's (Perez, Sanchez 2009). According to Jenkins and Yakovleva (2006), sustainable development encompasses "economic development, environmental protection and social cohesion". Energy management initiatives could be communicated in these reports since they relate to environmental protection through energy conservation, which reduces greenhouse gas emissions. This section provides an overview of some of the sustainability reporting guidelines that are available; some are applicable to any industry, while others are specific to the mining sector.

##### **3.1.1 United Nations Global Compact**

The United Nations Global Compact is a voluntary initiative comprising ten principles within four categories; human rights, labour, environment and anti-corruption (United Nations Global Compact 2011). The goal of the organization is to promote sustainable development through alignment with these principles by providing companies with an agenda for developing and communicating sustainability strategies. The principles that companies subscribing to the Global

Compact are encouraged to follow can be vague in nature, which allows companies to be selective regarding which initiatives are reported. For example, energy management initiatives would integrate under the ‘Environment’ heading with Principles 8 and 9, which respectively state that businesses should “undertake initiatives to promote greater environmental responsibility”, and “encourage the development and diffusion of environmentally friendly technologies.” However, companies wishing to keep energy matters confidential, possibly to maintain competitiveness, could disclose environmental initiatives concerning water use only and would be in compliance with these principles. In summary, the Global Compact does not ensure that companies are reporting initiatives in all material areas of business, even though a more comprehensive report would be in the mining industry’s best interest and improve public perceptions.

### **3.1.2 Global Reporting Initiative**

The Global Reporting Initiative (GRI) was established in 1997, backed by two non-profit organizations; the Coalition for Environmentally Responsible Economies (CERES) and the Tellus Institute (Global Reporting Initiative ca. 2013). The initiative provides guidelines for reporting economic, environmental, social, and governance performance indicators. There are three levels of application ranging from A to C, depending on the amount of information provided in the report corresponding to the framework, with C being the lowest level (Global Reporting Initiative 2011). The report level can be self-declared, third-party verified or checked by the GRI, however, if the report is third-party verified the level is accorded a “+”. A more comprehensive revision was released as G3.1 in March 2011. The guidelines are currently in their fourth generation, corresponding to G4, released in May 2013 (Global Reporting Initiative ca. 2013).



As of 2012, the GRI database included 4,813 organizations worldwide, of which 187 were mining companies and 23 were Canadian-owned mining corporations, but not necessarily operating mines in Canada (Global Reporting Initiative ca. 2012). According to Perez and Sanchez (2009), in 2007, over 400 companies published sustainability reports conforming to the G3 guidelines, of which 23 were mining companies. In 2012, over 600 companies had prepared reports following the G3 guidelines and nearly 500 companies followed the G3.1 framework (Global Reporting Initiative ca. 2012). Of these, 44 were mining companies with 29 adopting the G3 standard and 15 implementing the G3.1 guiding principles. These statistics indicate the increased adoption of the GRI framework for preparing sustainability reports in the mining industry.

In 2010, the GRI and UN Global Compact formed a partnership (United Nations Global Compact 2010). The result of this alliance is that in the future, the more detailed GRI guidelines will align with the broad principles of the Global Compact. Additionally, the Global Compact will adopt the GRI framework as the suggested language to communicate advancement in implementing their principles. This union will allow companies to comply with both standards without additional effort.

The GRI has a supplemental guidance document, entitled “Mining and Metals Sector Supplement” (MMSS) tailored to assist the mining companies in reporting sustainability issues specific to the industry (Perez, Sanchez 2009). A surprising omission of the MMSS document (Global Reporting Initiative 2010) was that energy was not one of the sector-specific issues requiring additional commentary or performance indicators. According to the GRI guidelines energy consumption as well as conservation and efficiency improvements are represented under the environmental section (Global Reporting Initiative 2011).

The detailed structure of this reporting framework ensures that companies are transparent with respect to these matters, however, the framework does not set out specific parameters regarding the units used in reporting, which poses comparability issues. The GRI Sustainability Reporting Guidelines version 3.1 states “Issues and information should be selected, compiled, and reported consistently. Reported information should be presented in a manner that enables stakeholders to analyze changes in the organization’s performance over time, and could support analysis relative to other organizations.”(Global Reporting Initiative 2011). The issue regarding the flexibility of reporting units is exemplified when energy sources are reported using volumes or weights. For example, blasting in tonnes, diesel in liters, or natural gas in m<sup>3</sup> requires those interested in assessing energy performance to estimate energy content parameters for these energy source, which may vary depending on the region or the supplier. Thus the calculated energy amounts would not correspond to the actual amounts used.

Furthermore to assess progress or to compare organizations with respect to energy consumption it is imperative that sustainability reports include information regarding the factors that affect these indicators, such as mining depth, ore grade, production volumes and mining method, but this information was omitted from the Mining and Metals Sector Supplement. Furthermore, according to the guidelines companies should aim to report based on individual sites rather than for the entire organization. When organization-wide reports are prepared, an assessment may be difficult if several commodities or various mines are grouped together as averaging energy intensities may mask low performers. Other issues with this framework, outlined in Fonseca et al (2014), were: i) unreliable information was presented and ii) the flexibility of reporting issues allowed companies to be selective with the information they included, so as to enhance their public image.

### 3.1.3 International Council on Mining & Metals

The International Council on Mining & Metals (ICMM) was founded in 2001, from the re-forming of the International Council on Metals and the Environment (ICME), with the aim of enhancing performance with respect to sustainable development within the mining industry (ICMM 2012b). To achieve this goal, the ICMM committed to address the findings from the Mining, Minerals and Sustainable Development's (MMSD) report, titled Breaking New Ground (Walker, Howard 2002). The group developed a framework comprising ten principles benchmarked against other reporting standards including the Global Reporting Initiative and the Global Compact, among others (ICMM 2012a). Members of the ICMM are required to adopt these sustainable development principles as well as measure and report their performance in these areas. In 2012, the group included 22 mining and metal companies and 34 national and regional mining associations, which includes the Mining Association of Canada (ICMM 2012c).

The ICMM worked with the GRI group in 2004 to develop the Mining and Metals Sector Supplement to the GRI guidelines (ICMM 2012d). In 2008, members of the ICMM agreed to publish annual sustainability reports meeting the GRI Level A benchmark (ICMM 2012e).

Although there is not a specific indicator targeting energy management in the ICMM system, this topic could be considered to align with the following three of the ten principles (ICMM 2012a):

- “2. Integrate sustainable development considerations within the corporate decision-making process.
- 4. Implement risk management strategies based on valid data and sound science.
- 6. Seek continual improvement of our environmental performance.”

However, since the ICMM members agreed to adhere to the GRI guidelines, energy consumption and conservation should be reported, since these indicators are included in this framework. The 2010 reports from member companies all achieved this target (ICMM 2015). It should be noted that companies have two years after joining the ICMM to comply with the requirements. Therefore some of these companies were exempt, however in 2010, of the six companies that were exempt, four achieved the target level A reporting standard. In 2011 and 2012 two companies did not achieve this target and in 2013, only 15 of the 21 companies reached the target reporting level because the remaining 6 followed the new G4 guidelines. Table 3 shows a summary of member companies' performance and it can be observed that sustainability reporting has improved since 2008.

**Table 3: ICMM member companies' sustainability reporting performance (ICMM 2015)**

Report year	Total companies	GRI A level	Below target	Exempt
2008	19	10	6	3
2009	18	15	0	3
2010	21	15	0	6
2011	22	20	2	3
2012 <sup>6</sup>	21	18	2	0
2013 <sup>7</sup>	21	15	0	2

<sup>6</sup> Sum of individual columns does not match total because one member company did not submit a report due to a merger

<sup>7</sup> Sum of individual columns does not match total because 6 member companies adopted the G4 reporting guidelines

### **3.1.4 Mining Association of Canada's Towards Sustainable Mining**

Towards Sustainable Mining (TSM) was launched in 2004 by the Mining Association of Canada (MAC) (2011c, 2011b) to enhance the Canadian mining industry's performance and reputation by providing principles and performance indicators in six key areas: crisis management, energy and GHG emissions management, tailings management, biodiversity conservation management, safety and health, and aboriginal relations & community outreach. Annual performance assessment of each of these subjects is mandatory for MAC members. The current rating system consists of five performance levels ranging from C, where no systems are in place, to AAA which corresponds to excellence and leadership. Performance with respect to each of the indicators is self-assessed but members are required to obtain external verification of their assessment every three years (Mining Association of Canada 2012a).

The association membership includes 34 mining companies and 48 associate members, either directly or indirectly linked to mining and mineral processing (Mining Association of Canada 2011a).

In 2009, the Mining Association of Canada endorsed the ICMM climate change policy, recognizing that energy and carbon management are critical to mitigating the anthropogenic effects of climate change (Mining Association of Canada 2012b). The TSM program recognized that energy and carbon management were material issues relating to the mining industry and has identified indicators within these areas, which should be reported on. Specifically, the TSM protocol requires assessment of the following:

1. Energy use and greenhouse gas emissions management systems
2. Energy use and greenhouse gas emissions reporting systems
3. Energy use and greenhouse gas emissions performance targets.

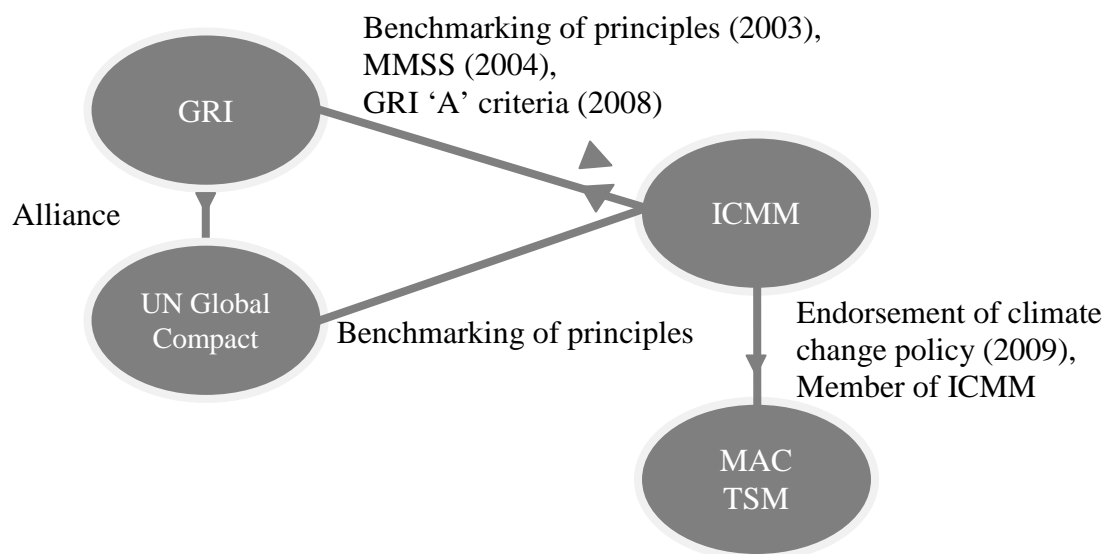
MAC members plan to attain at least Level A performance with respect to energy use and GHG emissions management indicators (this does not correspond to level A reporting of the GRI).

According to the 2011 TSM Progress Report, which compared the 2006 and 2010 performance indicators for Tailings Management, Energy use and GHG emissions management, External outreach as well as Crisis management planning, there was improvement within each category from 2006 to 2010 (Mining Association of Canada 2011d). The report presented the percentage of facilities that realized self-assessed Level A performance for both years and the category with the lowest values corresponded to Energy use and GHG emissions management, indicating a need for improvement and focus in this area.

Towards Sustainable Mining provides companies with a self-assessment framework for key sustainability issues that present a snapshot of strengths and weaknesses, allowing companies to identify areas for improvement where performance levels are low. Another positive aspect of this program is that it encourages energy use and GHG assessments to be performed at the facility level, which allows companies to benchmark sites within an organization and recognize those that perform at a high level, and identify those sites where performance is inferior. However, the program could improve the transparency of the industry by requiring the reporting of quantitative results as opposed to simply reporting performance levels, which would assist mining companies to maintain their social licence to operate.

### 3.1.5 Issues with current reporting guidelines

The review of the sustainability guidelines discussed revealed that there are links between the various groups' developing frameworks. Figure 10 illustrates these interactions.



**Figure 10: Sustainability framework web**

Despite the large number of reporting standards and guidelines for the mining industry the Federal, Provincial and Territorial Social Licence Task Group (2010) stated, “...*there is no recognized standard reporting mechanism for sustainability indicators in Canada. This absence has a direct impact on the ability to gather quantifiable data to measure performance improvements and raises credibility issues for the industry. This is also compounded by the fact that not all companies participate in these initiatives.*” In addition, a director of a mining company asserted the following: “*There are so many frameworks out there governing issues related to sustainable development in the mining industry. It takes a lot of time to understand where they overlap, do not overlap, and all that needs to be done to comply with the ones we are committed to.*” (Fitzpatrick, Fonseca et al. 2011).

These statements emphasize the need to adopt one standard for reporting sustainability-related performance indicators in the mining industry. This would make it easier for companies to report, and allow assessment from stakeholders to be more straightforward. Since the goal of the organisations promoting sustainability is to ensure transparency and accountability in the industry, having one accepted standard covering material issues pertaining to the mining industry would improve these objectives. The UN Global Compact and the ICMM have provided broad principles to address for sustainability reporting, and the GRI and Mining Association of Canada's TSM have identified specific indicators within these principles. The evolution of a single framework that combines these principles and indicators would result in less confusion and increased transparency.

Nobody likes to report waste in corporate sustainability reports after it has been identified, unless it has been saved. Such issues can lead to delays in the dissemination of best practice. As the amount of waste is potentially so great, when good practice is implemented at mines, the savings can be substantial. Ensuring that reporting of energy conservation measures is mandatory may accelerate adoption of best practice from enhanced transparency. Furthermore, reporting of performance of energy conservation measures may alleviate some of the risks by reducing the amount of unknown information associated with energy projects. Although release of this information may enhance the energy performance of the mining sector, it may reduce individual companies' competitive advantage.

In addition to reporting energy savings, it would also be beneficial for both external and internal stakeholders, if sustainability frameworks mandated companies to report energy targets specifically. This would facilitate performance assessment by measuring actual accomplishments



against goals. Furthermore, this could foster a continuous improvement environment within companies striving to achieve or surpass their targets.

Corporate sustainability reports have become a valuable resource for researchers focusing on the mining sector. Mudd (2007, 2010) used these types of reports for energy and carbon emission figures to construct datasets to assess environmental impacts on an industry-wide basis for both the nickel and gold mining sectors. Thus standardized reporting guidelines to ensure consistency between the organizations preparing these reports, and to make sure that useful information, such as factors of influence are provided would be beneficial. The following section will illustrate how stakeholders could use energy and support variables to assess an underground mine's performance with respect to energy efficiency.

### **3.1.6 Demonstration of a need for reporting appropriate metrics – Musselwhite Mine case study**

Goldcorp's Musselwhite Mine, located in northern Ontario, Canada, has been producing gold since 1997 (Goldcorp ca. 2011). This operation makes for an interesting case study due to the availability of public domain information with respect to energy, and its factors of influence. This section provides an analysis of the energy consumption trend over time for this mining operation.

Energy consumption data provided in the Musselwhite Mine Sustainability Report 2008-2009 (Goldcorp ca. 2010) were converted to coherent units of MWh using energy content parameters for each primary source to compare the consumption of each source. Using production data from various sources (Mason, White et al. 2002, Mason, White et al. 2003, Smyk, White et al. 2004, Smyk, White et al. 2005, Smyk, White et al. 2006, Smyk, White et al. 2007, Smyk, White et al.

2008, Smyk, White et al. 2009, Smyk, White 2010) the specific energy consumption in kWh/t ore and kWh/ oz of gold (Au) was calculated from 2001 to 2009, illustrated in Figure 11.

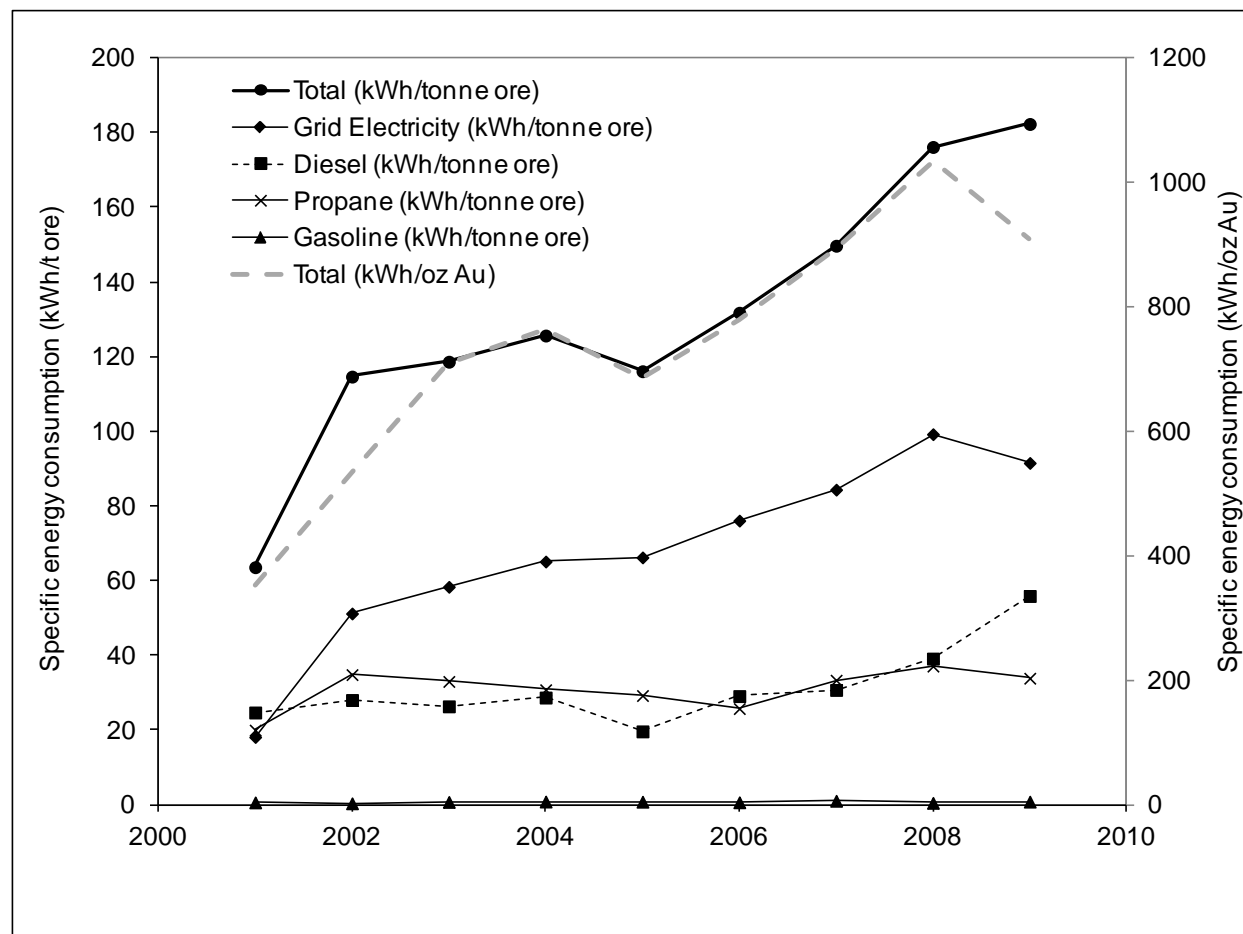


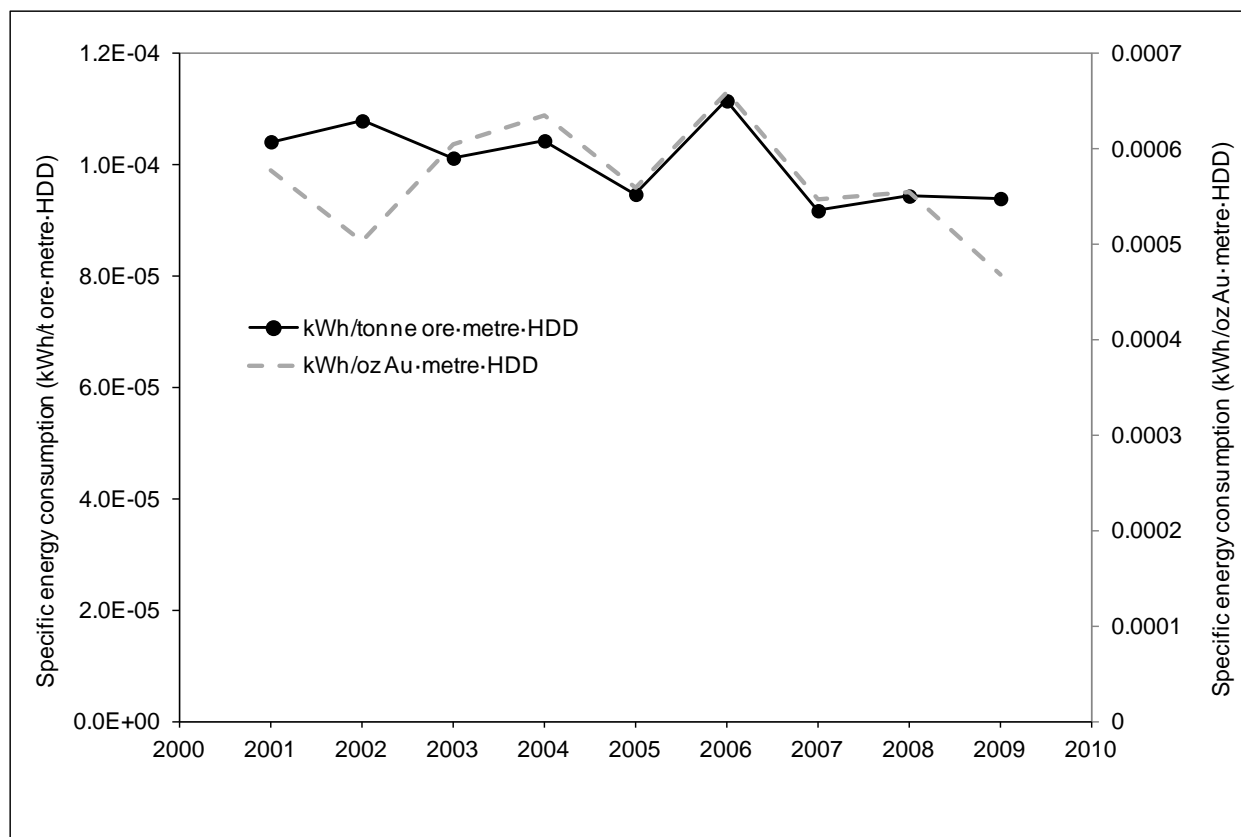
Figure 11: Specific energy consumption, expressed as kWh/tonne ore and kWh/oz of gold, for Musselwhite Mine

Figure 11 shows that the specific energy consumption at Musselwhite Mine, expressed in units of kWh/t ore, trends upward from 2001 to 2009. The amounts of energy represented in Figure 11 correspond to the amounts purchased by the operation. Gasoline use is the lowest of all sources followed by propane, diesel and grid-supplied electricity. The amounts of gasoline and propane used were relatively stable, but diesel use after 2004 increased. Also, grid-supplied electricity experienced an upward trend in use, except for 2009. Over the 2001-2009 period, the mine has

been mining progressively deeper from 275 m to 820 m (Goldcorp ca. 2005, Scales 2007). With increasing depth, electricity requirements also rise for ventilation, which is required to maintain safe production (Goldcorp ca. 2010). Around 2008, electricity demand at the mine exceeded the capacity of their electrical grid connection. As a result, diesel generators had to be installed. This explains the rise in diesel consumption during the end of the observed period in Figure 11.

For completeness, specific energy consumption expressed as kWh/oz of gold (Au) was included in Figure 11. It can be observed that the trend is similar to the specific energy consumption in kWh/tonne of ore. This is due to the relatively stable ore grade at Musselwhite Mine, with the exception of 2002 and 2009, where the ore grade was slightly higher than the other years. This information may be valuable in certain situations, but in energy efficiency studies, changes in ore grade could make changes in energy intensity difficult to identify.

Subsequently, a multi-variable regression analysis was conducted using RETScreen Plus (Natural Resources Canada ca. 2013b). The dependant variable consisted of total energy and the independent variables corresponded to tonnes of ore milled, mining depth in metres, and climate represented as heating degree days (HDD). The reference temperature used for calculating HDD was 2°C, which was the optimal value determined by the RETScreen Plus software. This reference temperature varies from the traditional value of 18°C, which is used for comfort heat in buildings. However, heat in mines is used to prevent the shaft from freezing, so 2°C is a reasonable value. It was found that 97% of the proportion of variance in total energy consumed at Musselwhite Mine could be explained with these three variables: tonnes of ore produced, mining depth, and HDD. The results of this analysis are presented in Figure 12, where the energy consumed at Musselwhite Mine has been normalized to better assess annual changes in specific energy consumption.



**Figure 12: Specific energy consumption, expressed as kWh/(tonne ore•metre•HDD) and kWh/(oz Au•metre•HDD), for Musselwhite Mine**

Figure 12 shows that the specific energy consumption, expressed in terms of kWh/(tonne ore•metre•HDD), improved from 2001 to 2009, with the exception of 2006. According to the analysis, Musselwhite mine consumed 10% more energy in 2006 than was predicted by the model. A cursory examination revealed that electricity and diesel usage contributed to that year's rise in specific energy consumption, but further investigation is required to determine the root cause. The same trend can be observed with energy consumption normalized by the amount of gold produced, mining depth and climate, expressed as kWh/(oz Au•metre•HDD). The exceptions in 2002 and 2009 correspond to the years where the ore grade was higher.

Figure 12 indicates that the mine continually improved its energy efficiency, despite the installation of diesel generators to meet the mine's growing electrical needs. Although in sustainability, energy or cost efficiency terms this is an achievement, the prime motivating factor could have been to sustain production in the face of finite transmission capacity. However, increases in electricity and fuel prices prompted energy conservation measures (Goldcorp ca. 2010), which contributed to the decline in specific energy consumption, expressed in kWh/(t ore•metre•HDD) and kWh/(oz Au•metre•HDD). The initiatives contributing to this reduction included: installation of automatic fan controls, replacement of lights with more efficient units, and the establishment of a vehicle anti-idling policy that dictated the allowable time for idling, based on outdoor temperature (Goldcorp ca. 2010).

This example has shown how the use of appropriate support variables can be applied to better measure the energy efficiency performance of a mine. Inclusion of these variables in corporate sustainability reports would help stakeholders assess and compare performance, which is a criteria set out by the GRI guidelines.

### **3.2 CIPEC Canadian benchmarking studies**

The Canadian Underground Bulk Mines (Canadian Industry Program for Energy Conservation 2005b) study is cited so frequently in journal and conference papers as well as government and industry reports that it is dealt with in detail. The benchmarking study prepared by CIPEC comprises a total of five sections which include:

- Introduction
- Methodology
- Energy costs: competing countries

- Results: benchmarking participating mines and
- Potential savings: achieving benchmark standards.

The introduction and methodology sections outline the report content as well as the calculations used to determine the figures found in the following sections.

In the third section, “Energy costs: competing countries”, Canadian mining energy costs were compared to those of other countries. The figures presented included costs per tonne of ore hoisted, costs per tonne of ore milled and costs per unit of metal produced. The concluding segment of this chapter compared the energy costs of mining in Canada to those of the lowest cost countries included in the study and highlighted that Canadian costs per unit of metal were reported to be greater than the benchmark country. For example, energy costs in the Canadian underground gold mining sector surpassed those from the U.S. gold mines by 84%. Underground copper mining costs in Canada were reported to be 35% greater than those in Chile, and costs for underground lead and zinc mines in Canada were reported to be 213% higher than in Peru.

Detailed examination of the basis for these statements uncovered a diversity of treatment across these sectors. For gold, data from the top four producing countries were used, however, for copper, lead and zinc some of the top producers were not included. For example, the energy costs of mining copper in Canada were compared only to those of Chile and Australia. Energy costs for American and Indonesian mines were excluded although these mines respectively represent 15% and 7% of world copper production (Canadian Industry Program for Energy Conservation 2005b). Additionally, the analysis of lead and zinc omitted operations in the largest single producing country of these metals, specifically China, which represents 23% and 17% of world production of lead and zinc, respectively. The inclusion of these data would have

permitted a more complete analysis and the outcome of the international comparison may have been quite different. The analysis also failed to examine several factors that affect mining energy costs, such as: i) the quantity of energy consumed, which is influenced by mining depth, geology of deposit, and mining method, ii) the price of energy, which varies between different countries, iii) the energy sources used, which may explain the different costs between countries and/or commodities and iv) whether the energy is purchased or produced on-site.

In the CIPEC study, the benchmarking section provides and compares total energy costs, consumption and unit energy cost for eleven operations. In addition, disaggregated figures for separate processes are also available for ten mining operations. The data for these are compared for underground processes, however, for the surface mineral processing plants, the five gold producing facilities were examined separately from the five base metal mines. Examination of the benchmarking data in this section revealed that there is great variability in the values. On average, the variance between the highest and lowest energy consumption for each production stage examined was 1,799%, 755% and 1,087% for underground processes, base metal concentration and gold concentration, respectively. For example, the energy cost of transporting the ore to the mill varies from \$0.01 to \$0.64 per tonne of ore hoisted which translates to a 6,400% variation. In addition, the energy consumption for the same process varies from 0.13 to 14.34 kWh<sub>e</sub> per tonne of ore hoisted, or 11,031%. However the study does not specify the method of transportation (ramp or shaft) or the distance travelled (vertical, at grade), all of which would influence these parameters. An important deficiency of this report is that it simply highlights variability from one site to another without explaining the variance. Only with the latter is it possible to identify appropriate remedial actions. Furthermore, disaggregation of

energy by type may also have been useful to gain a better understanding of energy use in the mining sector.

Data in the CIPEC study indicate that some processes in a portion of the mines obtain their energy at a unit cost of 0.0000 \$/kWhe. One can only assume that the provided data was either erroneous, missing for that specific mine, or that the energy was a co-product with a zero allocated cost. It is possible that the mines concerned are utilizing energy which is produced on site, possibly from a hydroelectric station, however, there is still a cost associated with this. Consequently, this data should perhaps be omitted from consideration, or the figures be recalculated to reflect appropriate circumstances, to avoid misrepresentation of the results.

The final section of the CIPEC report identifies potential savings that could be achieved assuming that each mine reduces its energy costs to match the mine with the lowest cost in each respective group. This simplified method of identifying potential savings failed to consider the major factors that influence the energy consumption in the mining industry. These include: mining depth, mining method, ore grade and hardness, vehicle fleet, processing route, and the mine location, which influences the choice of energy and electricity sources.

The CIPEC study surveyed eleven Canadian underground mining operations, of which ten had surface mineral processing facilities; five were base metal concentrators and the other five were gold recovery operations. In 2011, there was a total of 64 underground base metal and gold operations with 30 base metal concentrators and 30 gold concentrators in Canada (Minerals and Metals Sector of Natural Resources Canada and the National Energy Board 2012). Therefore, one has to question whether the sample mines chosen for the study were truly representative of the Canadian industry. However the study did not mention how the sample mines were selected.



It became apparent that studies of this type are not common. Sourcing the supporting data can be challenging, because the information may be commercially sensitive. This could explain why several other publications are derived from, or reference, this study. While not an exhaustive list, these include: (U.S. Department of Energy 2007, Scott 2008, LCG Management Group 2009, Canada Mining Innovation Council (CMIC) 2010, Eckelman 2010, Norgate, Haque 2010, Sterling 2010, Paraszcak, Fytas 2012).

In summary, the data in the report can be used as a rough estimate of energy consumption in mining, however, additional information is required to render the data useful for energy management practices. For example, if an operation wanted to compare its energy costs or consumption with those in the study to determine its level of performance, it would be problematic. This is due to the omission of the basic details of support variables that characterise operations such as the mining method, mining depth, mineral process route and type of energy source.

While the open-pit study (Canadian Industry Program for Energy Conservation 2005a) has not been reviewed extensively, it does suffer from similar deficiencies found in the underground report. The study did not include an international comparison of surface mining, but focused on different Canadian operations. The sample included two oil sands, four gold and three iron ore mines, which again raises the question of representativeness. One also has to question whether these diverse types of mining operations can really be compared. There was also a large difference between the energy costs and consumption for each of these operations, and yet the potential energy savings were estimated using the same methodology as the underground study. In open-pit mines, energy consumption is influenced by the stripping ratio, as was mentioned in the study, but these values were not provided. Despite the shortcomings of the open-pit study, it

did present some information that was not present in the underground report. For some processes, data illustrating the economies of scale with respect to energy consumption were presented, but further information regarding the type of ore or process should also have been provided to support the data. These types of benchmarking studies are critical to assess the energy consumption of mining operations but the inclusion of important supporting information, as mentioned earlier would make these studies far more useful.

### **3.3 US DOE study**

The U.S Department of Energy Mining Industry Energy Bandwidth Study (2007) examined the energy consumption of mines and estimates of possible energy savings for coal, metal and mineral mining. The energy savings opportunities were categorized as “Best Practice” corresponding to widespread adoption of available high-efficiency technologies or “R&D” for additional efficiencies, which could be attained with research and development. For example, it was reported that the most efficient pumps available (best practice) had an efficiency of 83%, whereas with R&D pumps could achieve 88% efficiency.

The energy consumption and best practice savings opportunities may have been overestimated, since the analysis included transmission and distribution losses in these figures. In the study, these losses corresponded to 2.17 units for every unit of electricity consumed, translating to losses of 217%, however, transmission and distribution losses in the U.S. average roughly 7% according to the U.S. Energy Information Administration (2011). This study stated that most mining equipment is powered by electricity, therefore, the estimated current consumption and best practice savings, which include higher than actual transmission and distribution losses, may be exaggerated.

The energy consumption data for the U.S. study (2007) were derived from a model using mining parameters that described the ore body characteristics as inputs, rather than using data from existing operations. The model then listed the equipment requirements, the number of units of each piece of equipment, and the estimated daily operating time for each unit of equipment for a hypothetical mining operation. Using this information with an assumed production rate for the hypothetical mine, it was possible to calculate the specific energy consumption per short ton of material handled. This approach was repeated for different mining methods as well as for different commodities to generate a set of data samples. However, the model did not incorporate beneficiation and processing, therefore, the projected energy consumption figures for these production stages were provided by industry experts. Subsequently, the weighted average specific energy consumption was calculated for all U.S. mines for each commodity group, by using knowledge of their mining methods and production rates. Finally, the annual energy consumption for each commodity group was estimated by using the annual production of each commodity group across the U.S. While this approach provides a useful estimate of energy consumption in the U.S. mining industry, there is a definite need to validate these figures with actual data from operating mines, to reduce the uncertainties associated with this analysis. In addition, benchmarking several operations would be necessary, as multiple factors that significantly influence energy consumption were omitted, such as mining depth, mining method and geology.

### **3.4 Statistics Canada**

Canadian energy consumption data is collected by Statistics Canada via various surveys and censuses which are made available in reports and CANSIM tables. Caution should be exercised

when consulting the published reports since data may be revised post-production. Therefore it is advised to consult the CANSIM tables to obtain the most recent data.

Relevant reports, published on an annual basis from the Canadian mining sector include (Statistics Canada var.a, Statistics Canada var.c): i) Report on Energy Supply and Demand in Canada (RES-D), and ii) General Review of the Mineral Industries (or Annual Census of Mines). The corresponding annualized data from these reports is available in the following CANSIM tables (Statistics Canada 2013): 128-0016 Supply and demand of primary and secondary energy in terajoules, 153-0032 Energy use by sector in terajoules, and 128-0006 Energy fuel consumption of manufacturing industries in gigajoules.

CANSIM table 128-0016 gives the total Canadian energy use by source from 1995 to 2011, as well as by sector and sub-sector. Unfortunately, the level of disaggregation is not sufficient to conduct an in-depth analysis. For example, energy use for the mining sector is identified by “Total mining and oil and gas extraction” and no further disaggregation of data is available. This data may be useful in some instances, but if trends in energy efficiency are to be examined, it would be difficult to do because of the number of sub-sectors included in this group. It was indicated that this table replaced CANSIM table 128-0009, which contained data from 2002 to 2009, but a note specified that comparison of these tables should be undertaken with caution. Furthermore, for mining sector data it was also revealed that some sub-sectors were excluded from the dataset prior to 2004, therefore a historical analysis would also be difficult to complete.

Annual energy use by sector from 1990 to 2008 is provided in Table 153-0032, where data pertaining to the mineral industry, disaggregated according to the North American Industry Classification System (NAICS), is available for i) oil and gas extraction, ii) coal mining, iii)

metal ore mining, and iv) non-metallic mineral mining and quarrying, as well as v) miscellaneous non-metallic mineral product manufacturing, and vi) primary metal manufacturing. This level of disaggregation is better than that of Table 128-0016, but is only useful when corresponding data that could be used to explain variation in energy use are available. This includes: production, ore grade, mining depth and stripping ratio. Disaggregated data by energy type (i.e. electricity, fuel, gas, etc.) could also be useful.

Mining production data from 1996 to 2006 can be accessed in the Annual Census of Mines (ACM), published by Statistics Canada, under the direction of Natural Resources Canada (Statistics Canada var.a). The reports provide provincial mineral production data for metallic and non-metallic minerals, as well as national energy use by source for mineral industries excluding fuels. Used together, the energy and production data from this report can be used for an industry-wide energy analysis to examine energy use per tonne of product, however it may not be possible to assess efficiency trends because these values would be affected by: i) changes in ore grade over time, and ii) structural shifts within the industry. An analysis based on the various commodities or sub-sectors could not be completed, because the energy data was aggregated to the sector level only. The reports also provided production costs such as wages and salaries, materials and supplies, as well as fuel and electricity for the minerals industry and selected manufacturing industries. This information could be used to assess the relative costs of production within the mining sector.

Disaggregated information pertaining to the smelting and refining sector was collected via Statistics Canada's Annual Survey of Manufacturers. Annual data was available in CANSIM table 128-0006 Energy fuel consumption of manufacturing industries in gigajoules, by NAICS (Statistics Canada 2013) from 1995 to 2011, and was disaggregated by sub-sector. This level of

detail could be useful for comparing and assessing energy consumption from these sub-sectors, however, an efficiency analysis would require more data, such as production or throughput.

Statistics Canada is a valuable resource for energy use and production data from the mineral sector. However, for an energy efficiency analysis, significant effort would be required to construct a useful dataset, with consistent boundary definitions between sub-sectors for each metric (i.e. energy use, production, etc.). Furthermore, an analysis at the sub-sector level would be the most granular that could be achieved, since energy data are not published by commodity.

### **3.5 Natural Resources Canada**

#### **3.5.1 Canadian Minerals Yearbook**

Natural Resources Canada compiles information, focused on the non-fuel mineral industry, from surveys and Statistics Canada data in an annual report entitled, Canadian Minerals Yearbook (CMY) (Natural Resources Canada 2011b). Reports, available online, have been published for census years from 1944 to 2011 and include production, price, export and import data for various minerals. Earlier Canadian mineral production data is also available, dating as far back as 1858 for gold (Canada Department of Trade and Commerce 1945, Canada Department of Trade and Commerce 1939), however, the corresponding energy consumption data is absent, which is required for a historical energy efficiency analysis.

The content of the Canadian Minerals Yearbook reports has changed over time, therefore, not all information is available for each year. For example, since 1956 energy consumption data was included in the reports, which consisted of electricity consumption in kWh and other fuels in dollar values, disaggregated by sub-sector for metal mining, industrial minerals and fuels. This

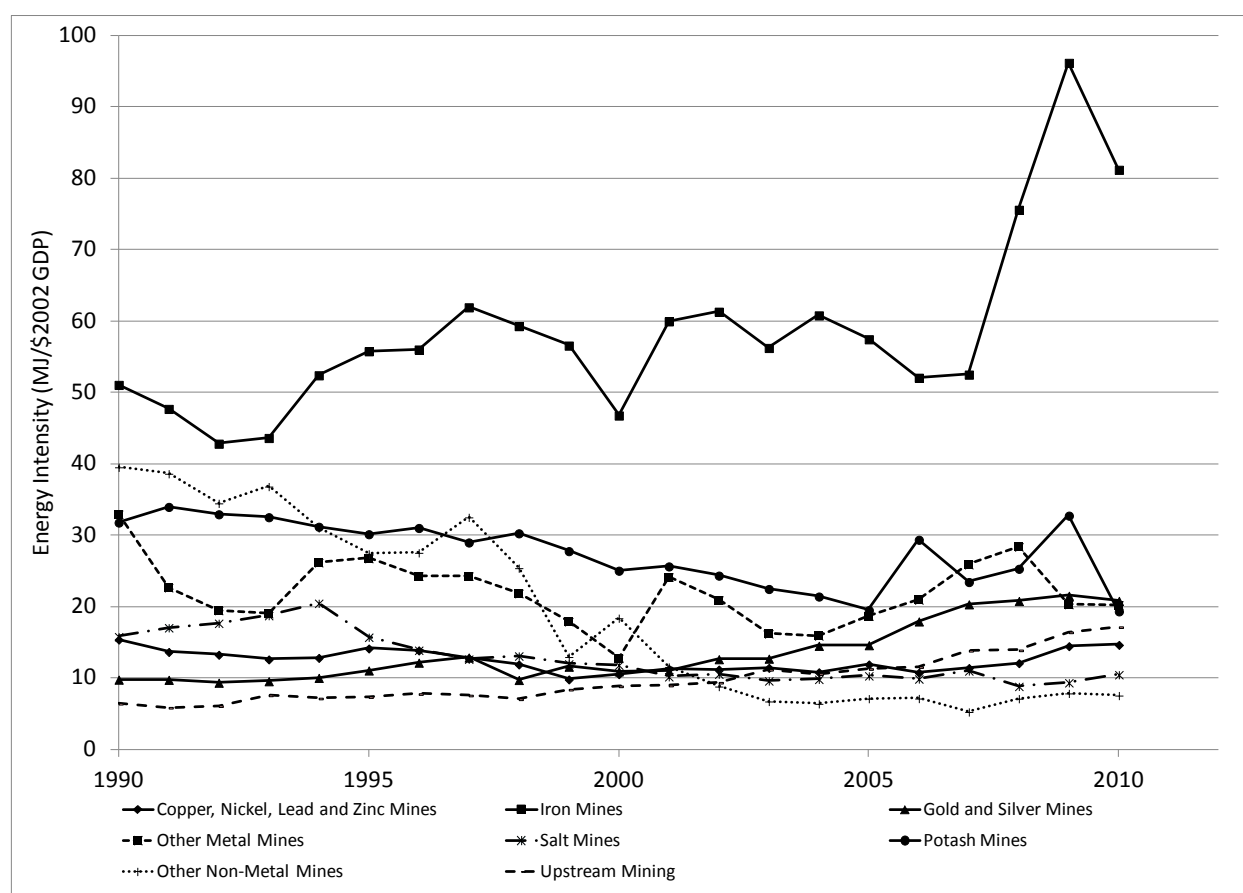
information only allowed an energy efficiency analysis to be done for electricity, since there was no way to convert the aggregated other fuels to energy units. In 1957, the reports began listing disaggregated energy consumption data by source for metals, smelting and refining, industrial minerals and mineral fuels. However, later on the reports excluded smelting and refining as well as fuel minerals data. The same data was also included in the Annual Census of Mines. An energy efficiency analysis using the data from the CMY can provide an industry perspective but assessment at the commodity level is not possible when only aggregated energy data is available.

### **3.5.2 Energy Use Data Handbook Tables 1990-2010**

Natural Resources Canada's Office of Energy Efficiency publishes the Energy Use Data Handbook Tables, which contain data showing annual energy use, greenhouse gas emissions and energy prices (Natural Resources Canada ca. 2013a). These tables, which can be downloaded in spreadsheet format, contain: residential, commercial / institutional, industrial, transportation, and total end-use data as well as information on electricity generation. Mining industry data is found in the industrial section of the publication and was obtained from Statistics Canada and the Canadian Industrial Energy End-use data and Analysis Centre (CIEEDAC). These tables provide the annual energy consumption of the Canadian mining industry, however, without production data this information cannot provide any insight into energy efficiency. The tables do provide the annual energy intensity for industries. Unfortunately, since the units are not consistent, comparing the various mining sub-sectors is not straightforward. For example, there are eight commodities which are included in the mining sector, of which six report energy intensity in MJ/tonne, one sector uses MJ/\$2002- GO (Gross Output) and the last one uses MJ/ \$2002 GDP (Gross Domestic Product). However, since energy consumption and GDP are provided for each

of the commodities, it was possible to calculate all of the mining sub-sector energy intensities in MJ/ \$2002 GDP, which are shown in Figure 13.

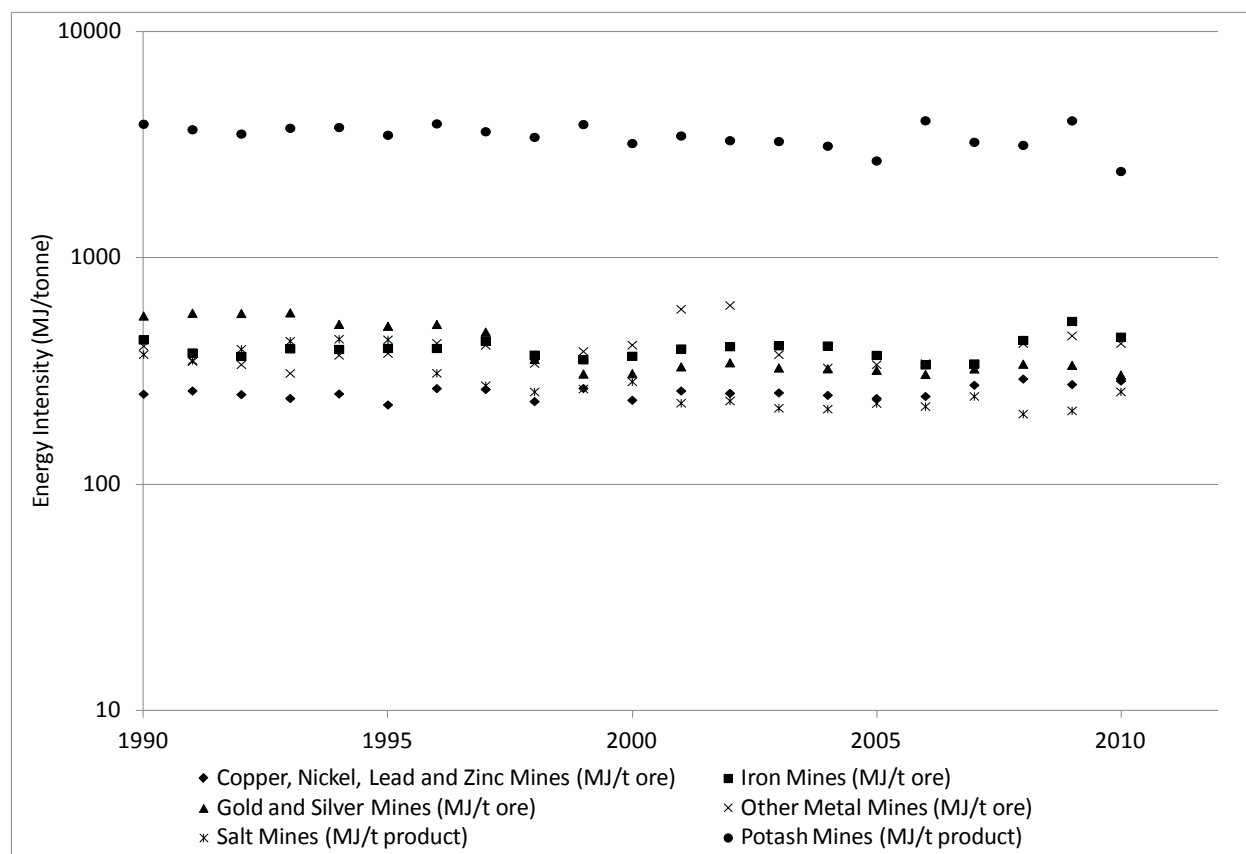
Since the GDP incorporates commodity prices, the energy intensities provided (Natural Resources Canada ca. 2013a) cannot be used to identify energy efficiency trends in the mining industry. For example, if we consider two years where production and energy consumption remain stable, a rise in the price of a commodity for one year would increase the GDP, but the resulting energy intensity would be lower when utilizing MJ/GDP units.



**Figure 13: Energy intensity, expressed as MJ/\$2002 GDP for selected Canadian mining sectors (Natural Resources Canada ca. 2013a)**

However, the tables do include energy intensity per unit of output for six mining sub-sectors, which are illustrated in Figure 14.





**Figure 14: Energy intensity in MJ/tonne ore (metals) and MJ/tonne product (non-metals) for selected Canadian mining sectors (Natural Resources Canada ca. 2013a)**

It can be observed from Figure 14 that the energy intensity of potash mining is approximately one order of magnitude higher than the other types of mining included in the analysis. Further investigation revealed that the units for the commodities are not consistent. For example, salt and potash production is based on the amount of final product, whereas the other commodities include the amount of ore milled. The comparison is biased because the energy intensity of the metals is calculated using the amount of final product and waste. However, for the non-metals sector, only the final product amount is used to calculate the energy intensity. It appears that the potash mines are more energy intensive, but this data does not provide sufficient information to properly assess the energy efficiency between metal and non-metal production. A proper

comparison between commodities, normalized by consistent units, would help identify where energy management efforts should be focused within the mining sector.

### **3.5.3 Comprehensive Energy Use Database Tables**

Natural Resources Canada publishes energy consumption data, disaggregated by type for the following sub-sectors within the Canadian mining sector (Natural Resources Canada nd):

- copper, nickel, lead and zinc mines
- iron mines
- gold and silver mines
- other metal mines
- salt mines
- potash mines
- other non-metal mines
- upstream mining.

The tables also include energy intensity for these sub-sectors but suffer from the same issue as the Energy Use Data Handbook Tables; the units used to measure production are not consistent between commodities. Tonnes of ore milled were provided for the metal mines, tonnes of product were given for salt and potash whereas GDP was presented for other non-metal mines and upstream mining.

The value from these tables was the breakdown of energy use by type (electricity, natural gas, diesel...) which could permit an assessment of historical trends within a sub-sector, or a

comparison between different sub-sectors. However, insufficient information is available for a comprehensive assessment. For example, energy intensity for the copper, nickel, lead and zinc mines increased by 7% from 1990 to 2012, but electricity use per tonne of ore milled decreased by 11% whereas an increase of 74% was observed for diesel intensity, as was shown in Figure 6. This may be explained by structural shifts within the sub-sector such as new mines employing open-pit mining methods thus using more diesel but not requiring ventilation. Alternatively, this could also be explained by the use of larger hauling equipment and improvements or energy conservation efforts adopted in underground ventilation systems. Thus further disaggregation by mine type (underground vs open-pit) may provide a better understanding of the energy trends within the sub-sectors.

### **3.6 Canadian Industrial Energy End-use Data and Analysis Center (CIEEDAC)**

CIEEDAC, a research group at Simon Fraser University in British Columbia analyzed and published reports focussing on Canadian industrial energy use for various sectors (Canadian Industrial Energy End-use Analysis Center (CIEEDAC) var.). Reports specific to the Canadian mining industry were prepared and included annual energy use and indicators for metal mines, non-metal mines as well as the smelting and refining sub-sector, with data gathered from various Statistics Canada and Natural Resources Canada sources. In addition, the group maintains a database that contains energy by source and production data, disaggregated by NAICS (Canadian Industrial Energy End-use Analysis Center (CIEEDAC) 2013).

Composite intensity indicators were used in CIEEDAC reports to aggregate specific energy consumption values (i.e. energy per tonne milled) for the mining sector. These indicators were designed to remove the influence of structural shifts within an industry by weighting the energy

use of a sub-sector, normalized against its share of the total sector energy consumption. Although structural shifts within a sector could be misinterpreted as a change in energy efficiency, the use of the composite indicator failed to include other factors that could influence energy consumption in the mining sector. For example, mines extracting ore from deeper levels consume greater amounts of energy, which can mask any improvements achieved by energy conservation efforts, as demonstrated by Goldcorp's Musselwhite mine example in Section 3.1.6. Therefore the inclusion of such factors needs to be considered to quantify energy efficiency trends. Admittedly, some data, such as mining depth, are typically not available.

### **3.7 Other sources**

Statistics Canada has also published Historical Statistics of Canada, of which mining is a separate section (Statistics Canada 1999). The data contained in this report includes the same type of information listed in the CMY and the ACM but dates back to 1923.

Two other reports pertaining to the mining sector were published by Statistics Canada; the Metal Ore Mining Report covers 1996 to 2005 and the Non-metal Mines Report only covers 1996 and 1997 (Statistics Canada var.b, Statistics Canada var). These publications include the same type of data as was in the CMY and ACM. The data is more disaggregated in some cases, but contains several confidential values that were excluded from the tables. Although the data in these reports is disaggregated, a complete analysis cannot be completed, because of the exclusion of confidential data. Furthermore, the short publication periods also limit the scope of analysis of these data and prohibit any analysis of recent trends.

### **3.8 Issues with Canadian mining data**

Comparison of the data from CANSIM tables 128-0006 and 153-0032 revealed that the values were slightly different. For example, energy consumption from Primary metal manufacturing in 2008 corresponded to 503,793,887 GJ in Table 128-0006 and 512,104 TJ in Table 153-0032. Presumably, the difference may be due to different boundary definitions of the sector or by varying data collection or conversion methods employed by the respective surveys, but the final reason for this is unclear.

Over the years, sector and sub-sector definitions have been revised with the introduction of the NAICS. Even after the NAICS was defined, some reports excluded certain sub-sectors from their reports and data tables. For example, energy consumption from the mining industry presented in RESD excluded two sub-sectors and part of another prior to 2004. Although the changes may be considered marginal, this could introduce a level of uncertainty when conducting a historical analysis.

Energy consumption by type was available in the Canadian Minerals Yearbook (for metals, non-metals and total industry) as well as in the Annual Census of Mines (for mineral industries excluding fuels). Although the data in these publications are comparable, the ACM indicates that smelting and refining is included whereas the CMY does not provide a clear indication of its boundary definitions, which introduces uncertainty when using this information in an analysis.

CIEEDAC defines the mining industry by using the NAICS but excludes quarries, sand, gravel, clay and ceramic minerals as well as oil, gas and coal. This may make the assessment of data difficult during comparisons with other mining sector publications which may have included all sub-sectors from the mining industry, as defined by the NAICS. Therefore, it is imperative when

comparing or combining information from various sources to fully understand their boundary definitions.

The references examined seemed to be circular. Data was collected by Statistics Canada and from Natural Resources Canada surveys, and published in reports and CANSIM tables. Mining related energy and production data from these sources were then assembled by CIEEDAC into reports and a database. Subsequently, the CIEEDAC reports were referenced in Natural Resources Canada's Energy Handbook Tables, which also sourced information from Statistics Canada's RESD. However, the 'same' data listed in these sources are not always identical. Table 4 shows examples of these discrepancies.

**Table 4: Comparison of reported energy consumption from various sources**

Sector	Year	NRCan Handbook tables	CIEEDAC	RESD	CANSIM 128-0016
Iron mines	1990	39.75 PJ	42,352 TJ	N/A	N/A
Iron mines	2010	45.41 PJ	41,314 TJ	N/A	N/A
Total industrial	2008	3,283 PJ	2,565 PJ	2,280,195 TJ	2,392,115 TJ

Although some of the differences between the values in Table 4 could be considered minor, these differences undermine confidence in either source as being definitive. A cursory investigation revealed that these discrepancies were caused by the different aggregation methods used to generate the reports.

The construction of a complete dataset for an energy efficiency analysis of the minerals industry was not possible by only using information from a single source. However, CIEEDAC compiled and presented the most comprehensive set of statistics, from an energy efficiency analysis perspective. Furthermore, the data presented by CIEEDAC was disaggregated according to the NAICS, and included energy consumption by type as well as production. This level of disaggregation was found to be the most useful, but the data could not be independently verified, because even though the data are still being collected by Statistics Canada, they are not being published.

Due to the varying levels of disaggregation, different sector definitions, different date ranges and discontinued surveys from available resources, conducting an in-depth analysis of energy efficiency in the mining industry is not as straightforward as it should be. A proposed solution would be to: i) ensure the use of the NAICS in all reports and tables to clearly define the boundaries of the presented data, and ii) provide energy by source and production data, disaggregated to 6-digit NAICS format, as is the case with CIEEDAC. This data is suitable for an analysis at the sub-sector level, but to assess the performance of individual mines, publication of additional support variables is needed. This was illustrated with the Musselwhite Mine case study in Section 3.1.6.

### **3.9 Proposed solution for improving reported energy- related data from the mining sector**

The review of data relating to energy use in the mining sector has revealed deficiencies. As this information may be used to inform policy makers and to provide guidance for industry priorities it is imperative that these shortcomings are addressed. The following recommendations are

proposed for moving forward for gaining a better understanding of energy use and trends within the mining sector.

Adoption of one standard for publication of sustainability reports would reduce confusion and effort requirements to comply with multiple frameworks. As the UN Global Compact, the ICMM and TSM are all linked either directly or indirectly to the GRI it appears that the GRI standard may be the one of choice. Furthermore, this framework includes a comprehensive list of indicators and separate guidance for the mining industry with the Mining and Metals Sector Supplement (MMSS). However, it is suggested that this guidance document be revised to include reporting of energy use from individual sites, disaggregated by energy type. The addition of reporting support variables such as mine depth (for underground mines) and hauling distances (for open-pit mines), production (amount of material processed), proportion of ore mined from underground and open-pit mining, as well as heating and cooling requirements (reported as heating degree days and cooling degree days) would benefit those consulting these documents as well as good performers within the mining industry. Disaggregation of data on a quarterly basis is recommended to permit assessment of seasonal variability and inclusion of historical data would permit an assessment of performance from individual mine sites. It is also suggested that reporting of energy conservation measures are included in such reports to enhance or accelerate dissemination of best practice.

Alignment of the reporting criteria for sustainability reports and government publications to limit any additional effort required by industry is suggested. The data could be aggregated to the sub-sector level, which could allow comparison between commodities. Inclusion of the same support variables as those proposed for sustainability reports is suggested however, composite indicators that use weighting factors as those developed by CIEEDAC would be required for use at the sub-



sector level. However, reporting production as total material processed for all sub-sectors is suggested so that a fair comparison can be made between the various commodities extracted in Canada. Table 5 summarizes the proposed recommendations for sustainability and government reporting. It should be noted that the shaded cells correspond to currently reported criteria.

**Table 5: Recommendations for improved reporting**

	Sustainability reports	Government reports
Disaggregation level	individual sites	sub-sector
Energy use	by type	by type
Support variables	mine depth / hauling distance production proportion of ore mined underground vs open-pit HDD, CDD <sup>8</sup>	mine depth / hauling distance production proportion of ore mined underground vs open-pit HDD, CDD
Presentation of data	quarterly	quarterly
Historical data	5 years	20 years
Other	energy conservation projects	

It can be observed from Table 5 that some of the recommendations are currently implemented in government reports. Although some companies choose to report energy use and/or production in sustainability reports these indicators are not required for compliance with reporting standards.

<sup>8</sup> HDD: heating degree days, CDD: cooling degree days

Inclusion of the proposed additional information may clarify energy performance and provide insight on focus areas for future improvements.

#### **4 A review of existing energy audit methodologies and guidelines**

Energy audits are an underpinning element in energy management; they provide the information to understand how, and when energy is used, which is subsequently relied upon to identify potential savings. This section aims to describe different methodologies employed to conduct energy audits, as well as their advantages and disadvantages.

The amount of detail and energy conservation measures identified in an energy audit depends on the audit level; a higher level would include a more detailed analysis. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) define three energy audit levels:

- Level 1: Also known as a walk-through audit, where energy conservation measures are recognized with minimal or no measurements. This type of audit can serve to identify priority focus areas for the next energy audit level.
- Level 2: Consists of an energy survey and analysis stage where metering is carried out to gather sufficient information to assess the economic viability of any proposed energy conservation measures.
- Level 3: Large investments are usually included in this type of audit, which can involve energy modeling for a more in depth analysis (Rosenqvist, Thollander et al. 2012, The Association of Energy Engineers nd, Thumann, Mehta 2008).

Three additional audit types were defined by the Association of Energy Engineers as follows:

- Benchmarking audit: This type employs an energy use index (EUI) or energy cost index (ECI) to compare the energy performance of separate facilities. The EPA Energy Star

Portfolio Manager was designed to benchmark energy, water, and carbon emissions for buildings (The Association of Energy Engineers nd, United States Environmental Protection Agency 2015). This platform has also been adopted by the Canadian Government to benchmark commercial and institutional buildings (United States Environmental Protection Agency 2015, Natural Resources Canada 2014).

- Investment grade audit: With this type, a risk weighting is incorporated into the economic assessments used in Level 2 and Level 3 audits (The Association of Energy Engineers nd).
- Master audit: This type of audit would be used for construction and future operation of a system, and would consider codes and standards, maintenance schedules and equipment inventory (The Association of Energy Engineers nd).

Energy audits can be conducted in three phases, illustrated in Figure 15.

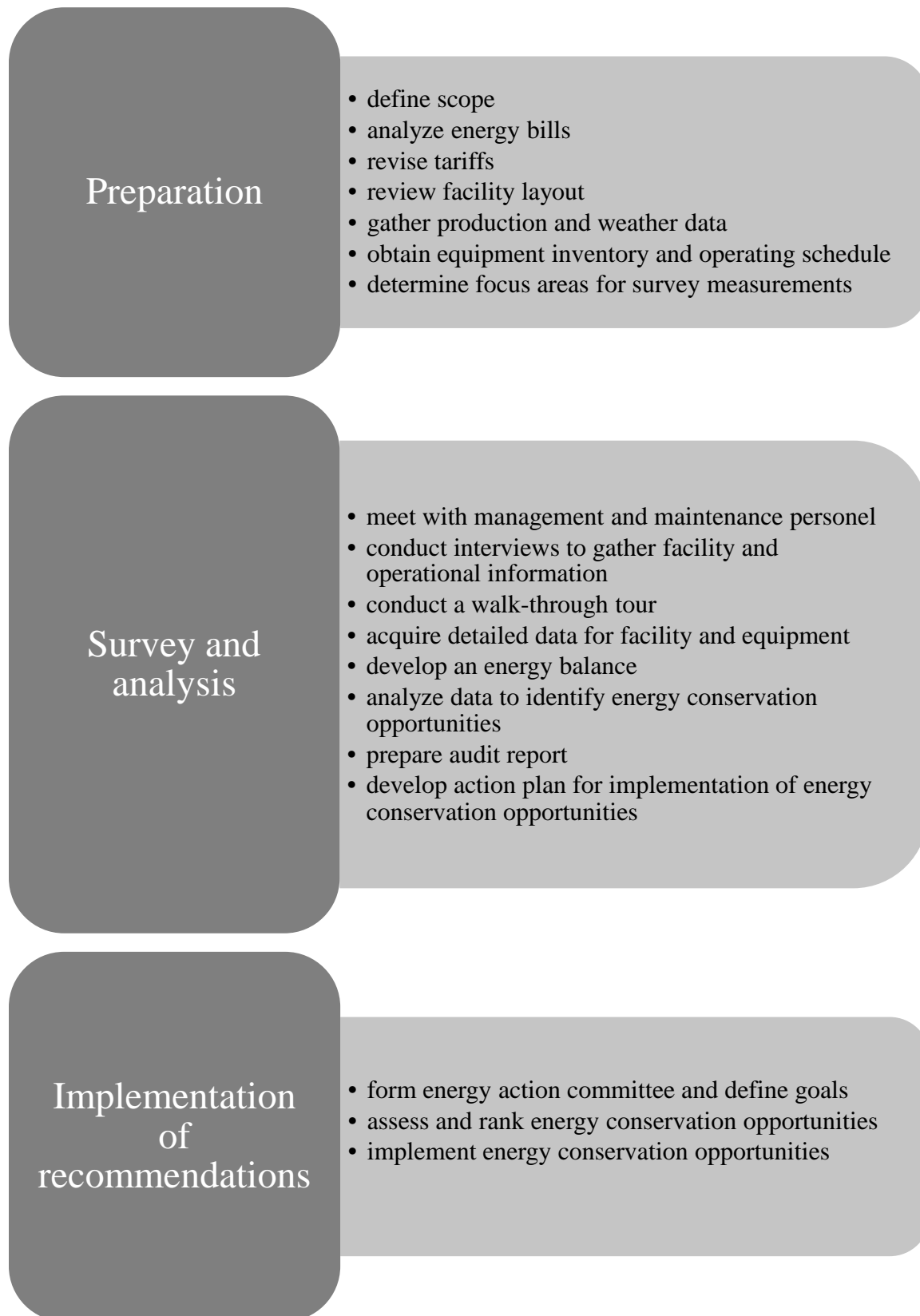


Figure 15: Energy audit phases (Capehart, Turner et al. 2012, Doty, Turner 2009)

The type of measurements that should be conducted during the survey phase of the energy audit corresponded to: voltage, amperage, power factor, flowrate, temperature, light intensity, leakage, and combustion efficiency. These measurements can then be used in the analysis stage to estimate: the energy consumption of equipment, energy waste, and energy associated with material flows.

Energy audits can be performed using a bottom up, or a top down methodology, or a combination of these approaches. In a bottom up audit, data for individual items are gathered and aggregated to determine the total consumption of a facility. Conversely, in the top down energy audit, data is gathered at the highest echelon within the defined energy audit boundary to identify priority focus areas then the assessment proceeds to the next level of granularity. Each auditing methodology will be considered in greater detail in the following sections.

#### **4.1.1 Top down energy audit**

Rosenqvist *et al* (2012) presented an energy audit methodology for industrial facilities combining a top down technique with an iterative process. The proposed methodology, developed at Linköping University, in Sweden has been used to carry out roughly 500 energy audits that comprised a survey, an analysis, and an energy conservation stage.

The method was referred to a top down process since the audit began with a wide scope that aimed to highlight focus areas where additional data and analysis may ensue. The iteration step corresponded to returning to the survey stage of the process with the identification of information gaps during the analysis phase, which continued until sufficient information was gathered to identify potential energy conservation initiatives. Figure 16 shows an overview of the top down energy audit process described in Rosenqvist (2012).

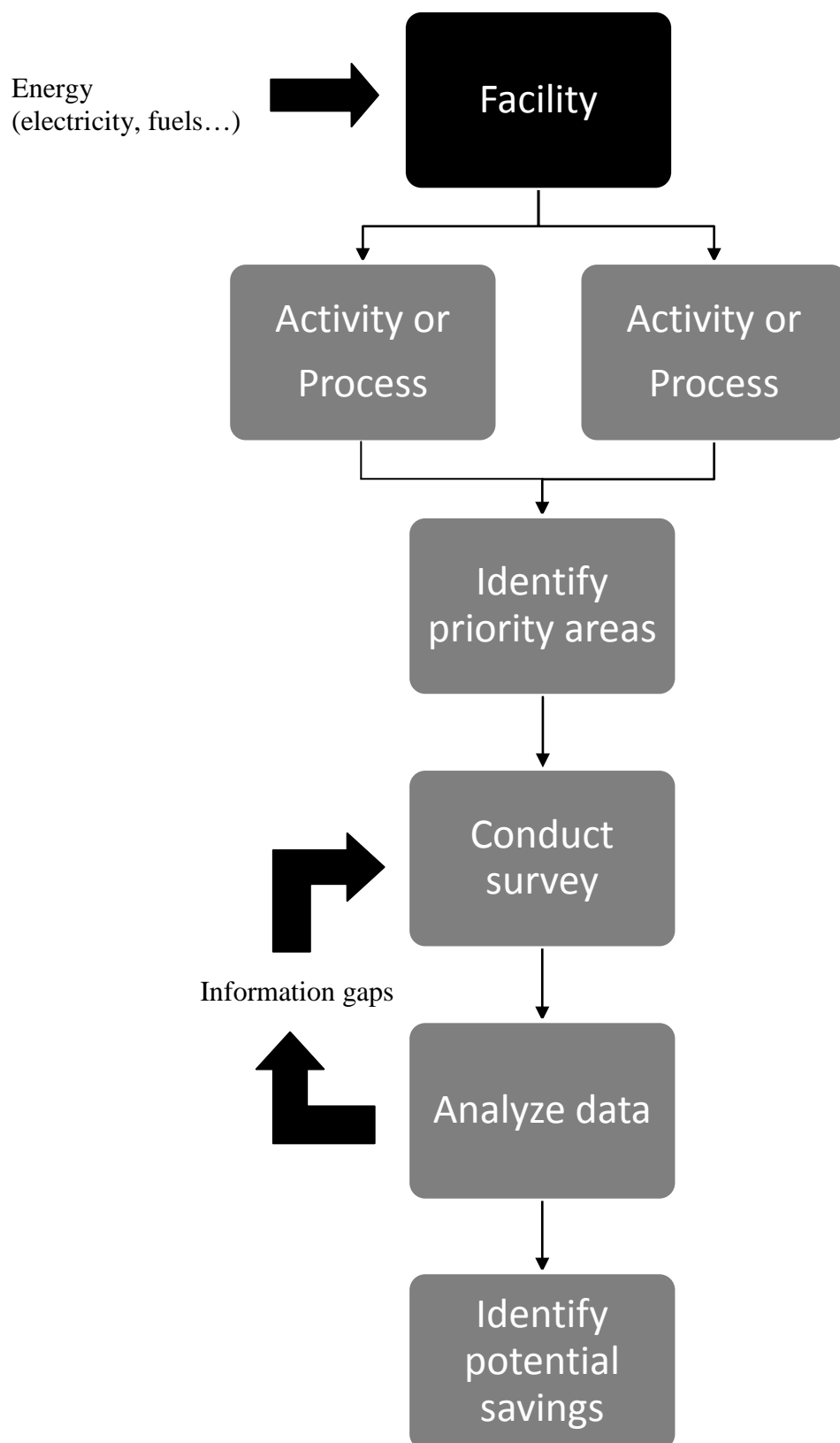


Figure 16: Overview of top down energy audit (adapted from (Rosenqvist et al., 2012))

The top down energy audit methodology proposed the use of six steps (Rosenqvist, Thollander et al. 2012):

1. Gather information by activity or process: this included a review of energy bills, facility drawings, and production schedules, among others. This stage also led to the identification of focus areas for the next steps.
2. Conduct the survey by visiting the facility during production periods: this step was used to collect data via installation of meters and data loggers or other measuring devices. During this step it was also suggested to discuss with personnel to gain a better understanding of the facility and the processes.
3. Gather additional survey data by visiting the facility during non-production hours: this step would permit the identification of potential sources of energy waste, such as idling equipment.
4. Analyze the data to allocate energy consumption and create a balance: this step corresponded to using the data gathered from the previous steps to determine the energy use from different processes which were identified as priority focus areas. The energy balance ensured that all energy use within the defined boundaries was allocated.
5. Identify potential energy savings and create new energy balance: this step was used to illustrate the potential impact from the various energy conservation measures identified during the audit.
6. Meet with industry representatives: the purpose of this step was to communicate the survey findings and discuss a potential path forward for implementation of energy conservation measures.



Use of the top-down energy audit presents the disadvantage that with focus in specific areas of the facility or process, detailed energy consumption from all end-uses is not quantified.

However, this may also represent an advantage of this method since the examination of priority areas may correspond to those with the greatest potential for energy savings.

#### **4.1.2 Bottom up energy audit**

In a bottom up audit, extensive metering, modeling or estimation is undertaken to determine the energy consumption of the individual end-uses within the boundaries of the energy audit.

Although there is no substitute for metered data, metering all of the equipment may not be financially feasible. An alternative may be to monitor major energy consuming items and energy consumption for non-metered equipment could be projected from estimates of hours of operation and equipment loading (Vogt 2003) or modeling. However, this approach would introduce uncertainty with the audit values and results. The bottom up method requires substantial investment and commitment for purchasing and installing the meters, or for modeling and estimating energy use, and for analyzing the collected data.

An alternative method called the energy balance was developed to simulate the bottom up energy audit (Pawlik, Capehart et al. 2001). An overview of the steps involved in the energy balance methodology is illustrated in Figure 17.

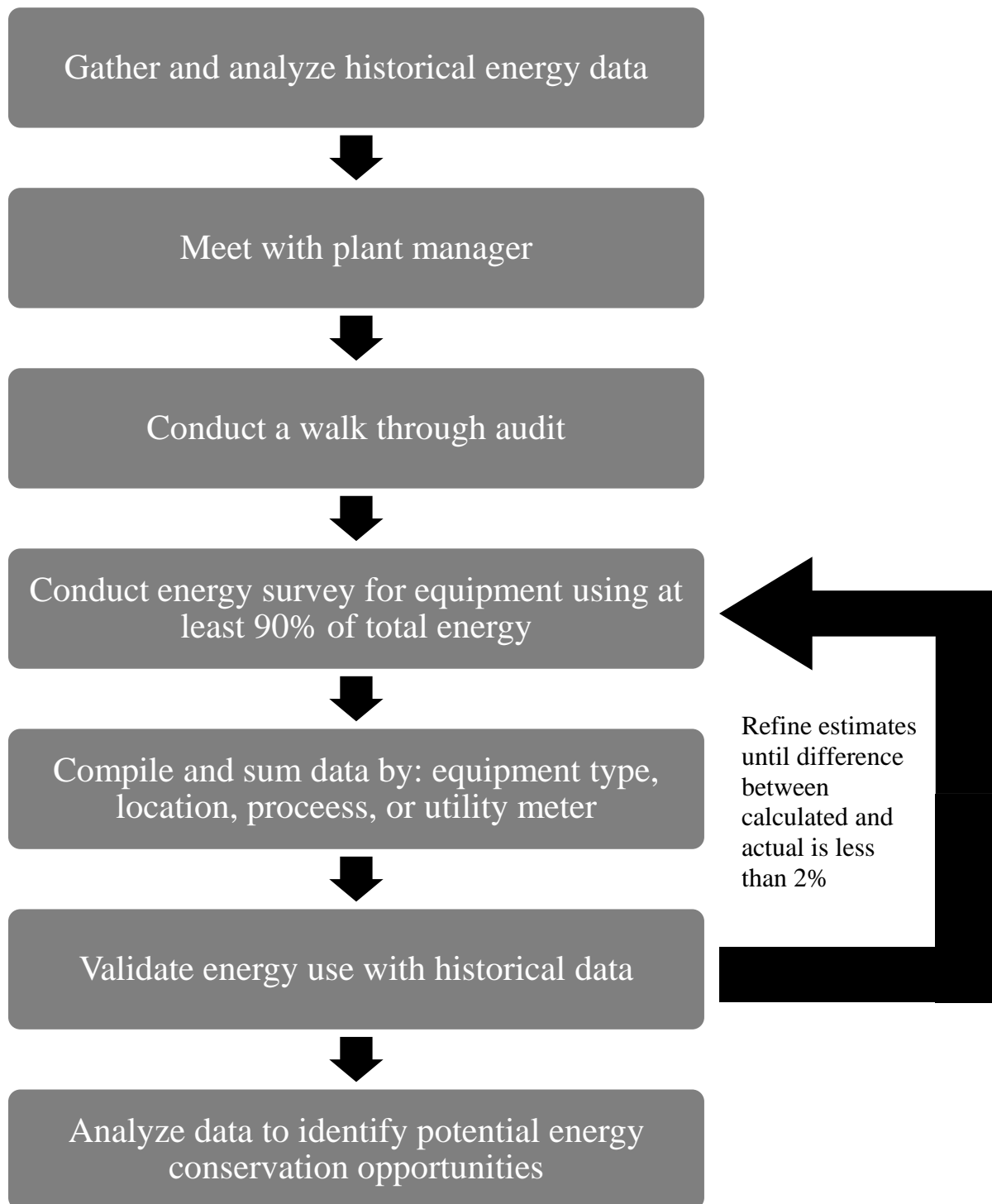


Figure 17: Energy balance audit methodology (Pawlik, Capehart et al. 2001)

The principle behind the energy balance is to improve the accuracy of the estimated data during a bottom up energy audit by ensuring that the sum of the individual end-uses corresponded to the total consumption at the facility. In the absence of extensive continuous metering, as could be involved in a bottom up energy audit, the energy balance methodology allows the auditor to estimate the energy use from individual equipment that would account for a minimum of 90% of total facility energy use. This includes either data or estimates of the following (Pawlik, Capehart et al. 2001):

- annual operating hours for the facility
- utilization factor for the equipment (fraction of total annual operating hours for which a specific piece of equipment was in operation)
- rated power of equipment
- equipment efficiency
- motor load factor (fraction of rated power at which a piece of equipment was operated)
- diversity factor (probability of equipment running during the facility's peak demand).

Subsequently, the data from the individual equipment is used to calculate the annual energy consumption, as well as the minimum and maximum demand for the entire facility. These figures are then compared to historical billing information to validate the assumptions or estimates used in the audit. If the calculated and actual values differ by more than a few percentage points, it is suggested to review the equipment inventory to ensure that it was complete. Further actions to reconcile the data consist of understanding of the equipment and its use, as well as understanding the utility invoices. It was also recommended to adjust the load factor, the utilization factor, or

the diversity factor depending on the situations exemplified in Table 6, to ensure that the calculated and actual energy and demand values were within 2% of each other.

**Table 6: Recommended adjustments for reconciling energy audit data (Pawlik, Capehart et al. 2001)**

Demand	Energy	Adjustments
calculated < actual	calculated < actual	Increase load factor for some motors
calculated > actual	calculated > actual	Decrease load factor for some motors
calculated = actual	calculated < actual	Increase utilization factor for some equipment
calculated = actual	calculated > actual	Decrease utilization factor for some equipment
calculated < actual	calculated = actual	Increase diversity factor for some equipment
calculated > actual	calculated = actual	Decrease diversity factor for some equipment
calculated > actual	calculated < actual	Decrease diversity factor and increase utilization factor for some equipment
calculated < actual	calculated > actual	Increase diversity factor and decrease utilization factor for some equipment

The final step in the energy balance methodology consists of data analysis to identify potential energy conservation measures.

### 4.1.3 Hybrid top down / bottom up energy audit

A hybrid method combining the top down and bottom up methodology was used by Bennett and Newborough (2001) to conduct a city-wide energy audit. The task began using the top down approach to separate the city into sectors and sub-sectors, illustrated in Figure 18.

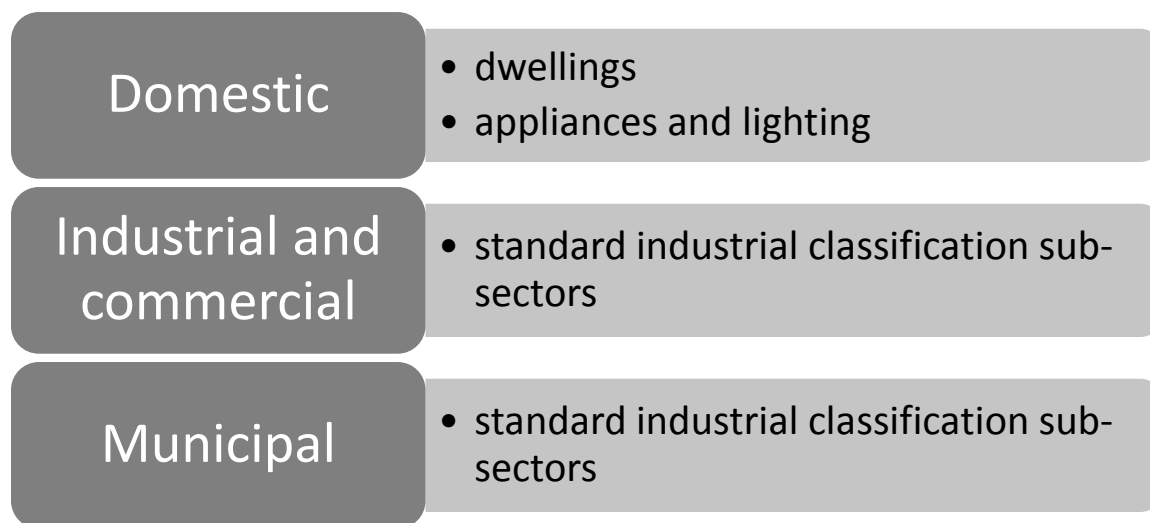


Figure 18: Sector and sub-sector classification from top-down method (Bennett, Newborough 2001)

Subsequently, the energy consumption of the components within each sub-sector was estimated with the use of metered data, using inventory or census information with energy intensity factors, or by employing mathematical models. These values were summed to determine the energy use allocated to each sub-sector, which corresponded to the bottom up portion of the method. The sub-sector data was then aggregated to estimate the corresponding sector energy use, which was summed to approximate the city-wide energy consumption. Bennett and Newborough (2001) suggested the implementation of a checking procedure to minimize discrepancies identified during the aggregation process by refining assumptions. This checking procedure could entail an

energy balance whereby comparison of sector or sub-sector estimates with actual energy use is employed.

The level of detail from this hybrid method does not compare with that of the bottom up energy audit where all end-use consumption is metered but it does provide an indication for priority focus areas for energy conservation measures. However, it was indicated by the authors that setting energy conservation targets was not straightforward since some of the values determined during the audit were estimated from average or typical energy use and the penetration rate of energy efficiency measures was not known. Thus proposing appliances or equipment replacement with more efficient units may not yield the anticipated energy savings if most of the actual components in use were already classified as high efficiency.

The energy audit methods presented in this section were included to illustrate different approaches that can be undertaken to conduct energy audits. Although there is not a standardized methodology, there were some common items between the reviewed procedures that could be considered good practice. For example, all methods included a balancing step to ensure that the sum of energy use at the bottom level corresponded to the energy from the top level. The reviewed methodologies also proposed an iterative step to refine the energy balance between the top and bottom energy use. Furthermore, all proposed a historical energy audit for at least a 12 month period to assess the seasonal variability of energy consumption.

The main benefit of the top down method and the hybrid method is that it permits identification of areas for conducting a more detailed investigation. This would entail less time and effort, thus less cost than an exhaustive bottom up audit but there may be some missed opportunities for energy conservation in areas that were ignored. Conversely, while the bottom up method does

provide a detailed understanding of energy use at a granular level, a larger investment is required regardless if the end-use consumption is metered or estimated. Continuous monitoring of all end-uses would require purchase, installation and maintenance of meters, as well as data storage capacity and a system for monitoring and analyzing the data. Although the installation of meters was not a requirement in any of the methods reviewed in this section, the use of metered data would reduce the level of uncertainty in an energy audit.

The bottom up method yields a great amount of detail regarding individual end-use energy consumption but the amount of data may be overwhelming for facilities with a large amount of equipment, which could consequently hinder the data analysis and identification of energy conservation measures. Although the energy balance method lacks the accuracy of continuous metering, it does provide the same level of detail as the bottom up method and may be used to identify loads that should be monitored. The energy balance methodology presented practical guidelines that could be used for balancing the calculated energy use with the actual value, which the other methods suggested as an essential step but did not provide guidance.

Selection of an appropriate method is not straightforward but should be based on the scope and goals of the audit and could comprise a combination of the reviewed methodologies.

## **4.2 Industrial energy audit guidelines**

The top-down and bottom-up methods illustrate general approaches for conducting energy audits that could be applicable to different sectors including: residential, commercial or industrial.

Government agencies have developed resources for assisting with energy audits considering specific applications to industrial facilities. Some examples were chosen and a brief overview of each is presented in the following.

#### **4.2.1 Energy Savings Toolbox**

The Energy Savings Toolbox was developed by the Canadian Industry Program for Energy Conservation (CIPEC) and provides detailed guidelines for conducting an energy audit in industrial facilities (Natural Resources Canada 2009). Inclusion of checklists and Microsoft Excel tools facilitate the energy management process.

The guidance adopted a process flow based on the energy audit phases outlined in Figure 15, but suggested that a condition survey, which corresponded to the walk through step, be undertaken as the first step in the audit. The purpose of this step was to help guide the definition of the scope and boundaries by identification of focus areas.

The proposed condition survey employed a checklist that used a rating system to identify and rank priority focus areas for energy management. Checklist examples were provided for common utilities and types of areas common to industrial sites (e.g. walls, doors, compressors, boilers, etc.) but custom checklists would have to be prepared for site specific uses. For example, in an underground mine, checklists for pumps, hoists, ventilation systems, or mobile equipment would have to be developed. A checklist was also included to assist with the development of the audit mandate and scope.

The Energy Savings Toolbox included a guidance section and a spreadsheet aimed to assist with understanding energy use and billing tariffs. Conversion of all energy sources to common units was suggested to facilitate comparison. Use of the tool provided may be of limited use for mines since it failed to include transportation fuel, which could correspond to a significant proportion of total energy especially for open-pit mines.



A comparative analysis was suggested to benchmark and assess energy performance against internal and external facilities. Regression analysis was used to determine a facility's baseline energy consumption from the relationship between energy use and one driver but the tool only has the capability of including one factor of influence. Furthermore, a cumulative sum of differences (CUSUM) analysis was included to examine the difference between the baseline and the actual energy use, which is illustrated in Figure 19 where 'Variance Energy' values indicated in brackets correspond to periods of better than expected energy performance, which are illustrated by the negative values on the plot.

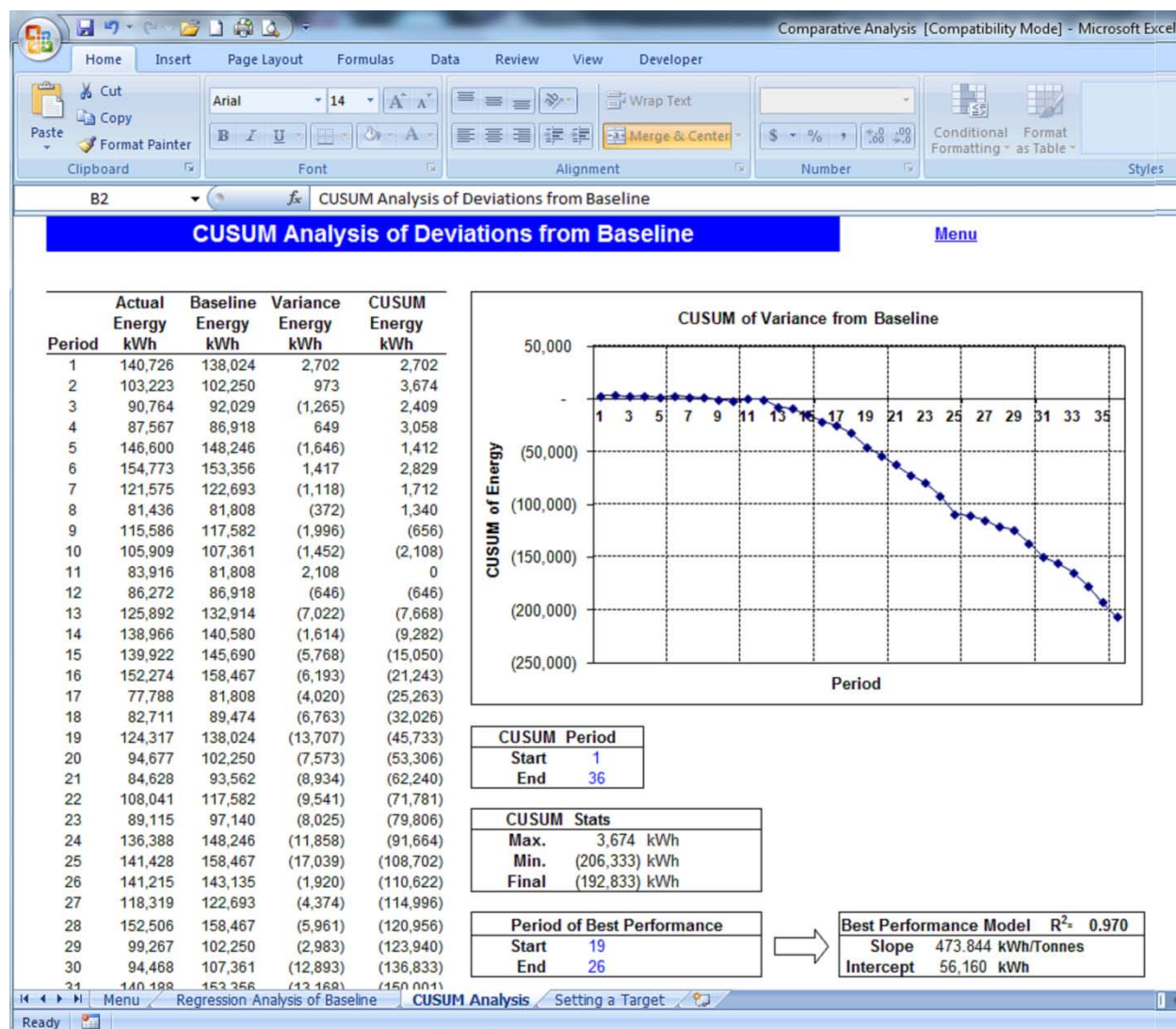


Figure 19: Screenshot of CUSUM analysis tool from Energy Savings Toolbox (Natural Resources Canada 2009)

The spreadsheet also contains a tab that allows the user to define the period of best performance, which can assist in setting an energy conservation target. Alternatively, a target can also be defined by the baseline energy use established from all data. For example, a target of 5% overall energy reduction could be set but the target should not exceed the facility's best performance because this may not be attainable. Figures are automatically produced for visual interpretation of the data.

A section in the guidance document and a spreadsheet were also included in the Toolbox to assist with the interpretation of demand profiles. A correlation between demand and operating schedules was suggested to determine the equipment or activities that are contributing to the facility load. This section also explained how to analyze demand profiles to identify savings arising from load shifting, load shedding, or shutting down idling equipment during non-production periods. Figure 20 shows the Demand Profile Analysis tool.



Figure 20: Screenshot of Demand Profile Analysis tool from the Energy Savings Toolbox (Natural Resources Canada 2009)

A tool and guidelines were provided to determine the electrical load inventory consisting of a breakdown of energy and demand from different categories. This was achieved using equipment rating, operating hours, and a diversity factor. Suggestions for energy conservation opportunities that may arise from analysis of the load inventory were included. This section of the guidelines also described how to map thermal energy flows and promoted the use of a Sankey diagram to illustrate these and to ensure that there is an energy balance between inflows and outflows.

A three step procedure was proposed in the guidelines to identify energy conservation opportunities as follows:

1. ensure that energy usage was matched to the requirements,
2. maximize energy efficiency, and
3. optimize the energy supply via heat recovery, heat pumps, cogeneration, renewable energy systems, fuel switching, or purchase optimization.

Evaluation of the economic viability of the proposed energy conservation measures was suggested using a discounted cash flow model, which was included in the toolbox. The model provided an estimate of the net present value, internal rate of return, simple payback and GHG reduction for the proposed energy savings.

The final section of the guidance document provided a template that could be used to prepare an energy audit report.

The Energy Savings Toolbox comprised comprehensive, systematic guidance and the tools to conduct an energy audit and perform an analysis to identify energy conservation opportunities.

#### **4.2.2 Industrial Energy Audit Guidebook – Guidelines for Conducting and Energy Audit in Industrial Facilities**

The Industrial Energy Audit Guidebook, sponsored by the U.S. Department of Energy, was developed based on the framework outlined in the CIPEC Energy Savings Toolbox and the Energy Efficiency Planning and Management Guide publications (Hasanbeigi, Price 2010). Microsoft Excel spreadsheets were also provided for assessment of demand profiles, and specific energy use for electricity and four types of fuel that are defined by the user. Inputs were included to convert energy use of the various types of fuel to megajoules (MJ), allowing determination of MJ/ton of product for fuel specific energy use. However, specific energy use for electricity was assessed using kWh/ton, thus the conversion of fuel energy use to kWh rather than MJ would allow comparison of the specific energy use of electricity and fuel. Furthermore, this would also allow calculation of total specific energy consumption. The supplied tool also derived an energy use model using regression analysis but it is not as sophisticated as the CIPEC tool because it lacked the capability of target setting. Variability of energy and production can be assessed with a scatter diagram, automatically produced from the input data. A discounted cash model was provided to assess the economic viability of the proposed energy conservation projects and guidelines were included for audit report preparation and post-audit activities for implementation of energy conservation measures.

The guidance document provided suggestions for cross-cutting energy conservation opportunities for motors, compressed air systems, pumping systems, fan systems, lighting systems, steam systems, and process heating systems and also provided estimates for potential savings.

Industry-specific resources listed in the guidebook were published by the following: US EPA, Lawrence Berkeley National Laboratory, European Integrated Pollution Prevention and Control (IPPC), CIPEC, and U.S. Department of Energy's Industrial Technologies Program (ITP).

Mining sector-specific resources were included in the CIPEC (Canadian Industry Program for Energy Conservation 2005a, Canadian Industry Program for Energy Conservation 2005b) and ITP (U.S. Department of Energy 2007).

Additionally, the manual promoted the use of energy assessment guidebooks prepared by the American Society of Mechanical Engineers (ASME), available for the following systems: compressed air, process heating, pumping, and steam (American Society of Mechanical Engineers (ASME) 2015).

#### **4.2.3 Energy Efficiency Opportunities Energy Mass Balance: Mining**

The Australian Government Department of Resources Energy and Tourism produced a guidance document for development of an energy-mass balance (EMB) for the mining sector, a requirement for compliance in the Energy Efficiency Opportunities Regulations 2006 (Australian Government Department of Resources, Energy and Tourism 2010). The regulations stated that the EMB should comprise at least 80% of a site's total energy use with an accuracy of  $\pm 5\%$ .

An EMB may lead to the identification of potential energy conservation measures via mapping all mass and energy flows within a site to gain an understanding of these as well as the factors that influence them. Mapping all energy and mass flows, including energy conversions, permits identification of energy losses and waste which may not be easily recognized by examination of energy inputs alone. Although it was stated that energy consumption in the mining sector could

be influenced by mine depth and ore grade, among other variables, the EMB guidance document did not specifically indicate how these influence variables could be used during the process.

The EMB essentially followed an iterative top down energy audit methodology by first mapping the energy and mass flows at a mine site and listing the factors that would affect these. An example was provided but explosives were categorized as a mass flow rather than an energy flow. The proportion of total mass attributed to explosives corresponded to 0.0088% whereas this item corresponded to 2.13% of total energy flow. Furthermore, it has been shown that changes in blasting procedures can influence the energy consumption in the milling stage of the process (Napier-Munn 2015), which was also included as an energy conservation opportunity recommended in the EMB guidance document. As such, explosives should have been included with the energy flows. Mapping the whole site energy consumption permitted identification of the systems or processes that would constitute at least 80% of the total site energy use.

Subsequently, a high level analysis ensues on the selected systems to gather available mass and energy data as well as identify additional data acquisition requirements. Establishment of key performance indicators (KPI) was also suggested to benchmark system performance during this step. The final step consisted of an in-depth analysis of the processes and equipment included in the selected systems for the EMB. The iterative part of the process occurred between the data collection and analysis stages to satisfy the accuracy requirements of the regulations.

The document provided key considerations in the development of an energy mass balance, and identification of potential energy conservation opportunities for the following four mining-specific systems: i) comminution, ii) resource extraction, excavation and haulage systems, iii)

compressed air systems, and iv) ventilation systems. Methods for modeling the energy use from these systems were also included, which may assist in benchmarking and target development.

The EMB guidance document provided an overview of a methodology that could be used to assess energy use and identify potential conservation measures applicable to the mining industry. However, further benefit might have been realized with the inclusion of specific details regarding the application of influence factors and energy use for mine sites, such as in the Musselwhite Mine case study presented in section 3.1.6. Furthermore, interpretation of the energy mass balance may have been enhanced with the use of Sankey diagrams, which were promoted in the CIPEC Energy Savings Toolbox (Natural Resources Canada 2009).



## **5 Key research questions arising in the context of ‘Mine to Bullion’ energy management**

The information presented in this work has shown that the proportion of total costs spent on energy within the mining sector is increasing. This may be due to rising energy rates or increased energy usage.

Energy consumption in the Canadian mining sector has risen, mostly from the contribution of the petroleum sub-sector. Although energy use and intensity has fluctuated within sub-sectors of the mining industry, possibly influenced by market drivers such as energy rates and commodity prices, it is inevitable that as mines extract ore from increasing depths the energy use will also rise. Further energy increases may also arise from extracting lower grade ore in order to meet mineral demands.

Although there has been an increased attention on energy and sustainability since 1990 as was demonstrated by the development of various guidelines and reporting frameworks, progress with respect to energy management in the sector has been slow. So what has gone wrong?

Is it due to a lack of communication on energy matters? Is there a lack of energy data? Is there a lack of data interpretation? Is there too much focus on production? Or is it a combination of these issues?

Although it may not be possible to specifically determine the reason for the current energy situation in the mining sector, the following chapters will investigate several of these aspects and provide recommendations for improved communication and interpretation.

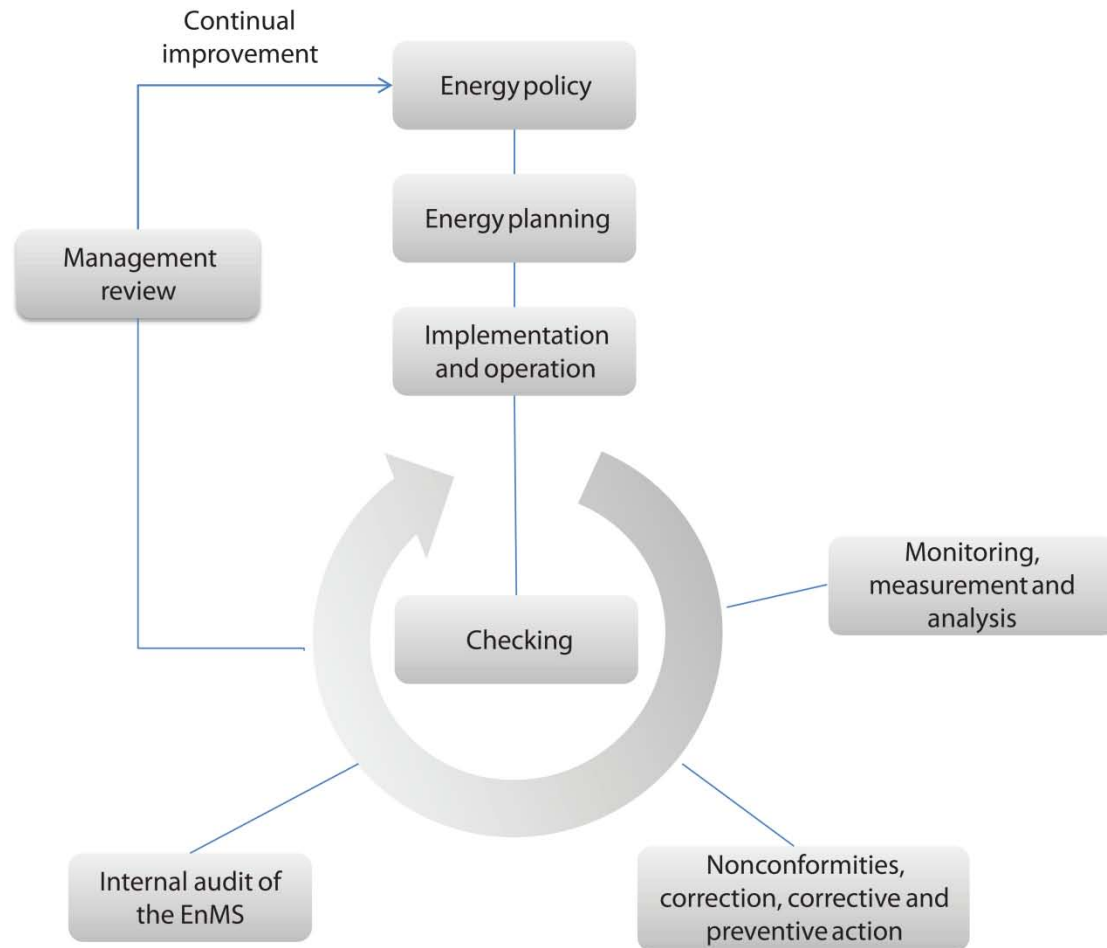
## **6 Improved communication of best practice energy management**

Improved energy use can be achieved by assessment of internal performance as well as learning from others. This chapter will provide an overview of an energy management standard that can be used as a continuous improvement model for energy performance. A critical review of a database developed to highlight energy conservation projects identified by Australian mining companies will ensue, then an improved database for enhanced dissemination of best practice will be proposed.

### **6.1 Continuous improvement and ISO 50001 compliance**

The International Organization for Standardization (ISO) is a global organization responsible for drafting and approving standards for various disciplines, such as quality management, energy management and risk management. It also aims to provide consistency in product specification, services and systems across a global investment market (International Organization for Standardization 2011a).

ISO 50001 is the standard that addresses energy management. Published in June 2011, the ISO 50001 document includes definitions, responsibilities and roles within an organization for energy management as well as the measurement, documentation and reporting requirements (International Organization for Standardization 2011b). ISO 50001 does not impose any firm thresholds on energy or power consumption. Instead, certification is fundamentally dependent on a commitment to the continual improvement of energy management. It also advocates the adoption of a Plan – Do – Check – Act (PDCA) approach to demonstrate ongoing improvement, which is illustrated in Figure 21.



**Figure 21: Continuous approach model from ISO 50001 standard (International Organization for Standardization 2011b)**  
 Permission to use extracts from ISO 50001:2011 was provided by Standards Council of Canada. No further reproduction is permitted without prior written approval from Standards Council of Canada.

In 2013, the New Afton mine located in British Columbia Canada, became the first North American mine to obtain ISO 50001 certification (Baldwin 2014). The process involved conducting an energy review followed by the establishment of energy baselines to which actual consumption could be compared to. Subsequently, targets and objectives were set and an action plan was devised to meet these goals. After implementation of the plan it was necessary to verify the performance to measure the success of the strategy (Clean Energy Ministerial 2014).

The company decided to adopt the ISO 50001 standard to integrate an energy management culture within the organization's systems and processes. For whatever reason it is motivated, implementation of an energy management system at a mining operation can achieve reductions in energy consumption that result in lower operating costs, increased profits and enhanced competitiveness as well as an improved public image and greater investor confidence. But at New Afton mine it was stated by the site's energy specialist that *"All of the projects we've done so far have had an operational benefit, environmental benefits and safety benefits. So even though we're improving efficiency, we're actually improving the process at the same time. It's a great match: everything you do helps to contribute towards improved performance of the facility."* (Baldwin 2014), thus, echoing Cooremans (2011) observations that energy conservation measures can provide competitive advantage by decreasing costs, increasing value, or decreasing risk.

The energy target for 2014 was to reduce energy by 3% of 2012 consumption. The company identified projects for reducing energy use in the mine ventilation system, from the compressors and the flotation equipment in the mill (Baldwin 2014). However, production at this mine only began in June 2012 and energy use was lower (Clean Energy Ministerial 2014). Although it appears that the 2014 target may not be ambitious, it is still better than not taking any action to control energy.

The keys to successful implementation of energy management at New Afton mine were identified as follows (Clean Energy Ministerial 2014):

- use of an energy management information system to assist with target setting and performance assessment,

- availability of good energy data,
- use of a sound information management infrastructure, and
- an energy planning process that involved senior management and staff.

It was also stated that enlisting the assistance of energy management professionals that have industrial experience was a valuable contribution to the project. Another lesson that was shared by the company consisted of consideration specifications for metering equipment; meters installed at a facility that operates 365 days per year cannot be removed for calibration thus this needs to be considered at the time of purchase. Sharing of observations that could be useful for other mines wishing to adopt an energy management system, illustrates how organizations can collaborate to improve the energy performance of the sector.

## **6.2 Dissemination of best practice**

### **6.2.1 Overview of existing frameworks**

Two energy management databases will be discussed in this section. The first database highlights measures to improve energy efficiency in various industrial systems, while the second focuses on initiatives identified in the mining industry.

The Institute for Industrial Productivity, consisting of groups operating in China, India, United States and Europe, focuses on promoting energy efficiency to energy-intensive industrial sectors. One of their efforts involved the development of the A2A Toolkit for ammonia companies, which contains resources for energy management and best practices designed to assist companies reduce energy consumption (Institute for Industrial Productivity 2012). This toolkit contains a

generic library of energy management measures that can be applied to a wide range of industries, including mining.

The structure of the A2A Generic Library consisted of an index which provides a snapshot of initiatives in the register. The database entries summarized in the index can be filtered by implementation level (plant, area, system, end use or other), cost, difficulty, and energy savings by source (natural gas, electricity, refined petroleum products, coal or other), which facilitates the task of finding the best energy management initiatives for a specific operator site. Detailed information for each measure is provided in separate tabs.

Energy conservation measures are provided for equipment used in various industrial systems which include: steam boilers, dryers, kilns, chillers, pumps, fans, motors, and compressors among others. Although the database provided good examples of energy conservation measures that could be applicable to the mining sector, there may be other relevant measures. For example, mobile equipment consuming diesel is used at mines, thus inclusion of diesel conservation examples would be useful for the mining sector. Although this database is well structured and contains good energy conservation examples, there is a need to develop a mining-specific tool to enhance dissemination of best practice within the industry.

The Australian Government's Energy Efficiency Opportunities (EEO) program launched in 2006 obliges companies that use more than 0.5 PJ (petajoule) or roughly 139 GWh (gigawatt hour) per year to conduct an energy assessment in order to identify measures to improve energy efficiency (Australian Government Department of Resources, Energy and Tourism 2011b). The opportunities identified by the mining sector were assembled in the Mining Significant Opportunities Register (Australian Government Department of Resources, Energy and Tourism

2011a) that permitted companies not yet embracing and adopting an energy management program to see what those who are, were doing and how much energy was saved. The objective of the register is to help disseminate best practice.

A review of the Mining Significant Opportunities Register has revealed several exemplar entries however the structure of the database could be improved by isolating the included information into separate fields. Currently, users must manually look through the entries in order to find relevant information; energy savings, type of energy saved (electricity, diesel...), and description of the conservation measures are all encompassed into one field. Figure 22 illustrates the structure of this register; the column located in the center corresponds to “Opportunity Description” which includes information that would be deemed important and should thus be easy to identify.

Company Name	Public Report Year	Opportunity Description	Opportunity Category	Equipment type
Anglo American Australia Ltd	2010	<b>Coal Loss and Recovery Project</b> Coal loss reduction projects are delivering significantly increased value for the business. AAMC has reduced coal loss by: - Introducing new blasting methods that protect the coal roof and improve fragmentation of the overburden. - Implementing standardised coal recovery operating procedures. The coal loss improvement project draws on existing best practice, encourages collaboration through replication across sites and utilised innovation through the application of new 'baby-deck' blasting technology. Coal reconciliation in late 2009 highlighted that coal losses up to 25% was occurring at Dawson due to poor mining methods and blasting operations. Based on experience from other AAMC sites, it was clear that standardised operating procedures needed to be developed that incorporated visual control standards - specifying what the machine operator should physically see when removing overburden, and how to operate machinery when close to the top of the coal seam to avoid damaging the coal. A drill and blast project for Dawson was formally endorsed and commenced in November 2008. Dawson Mine has steep breakdowns and increase overall reliability of key equipment. Using this process, the Calide maintenance team have improved availability of the EH4500 truck fleet from 63% to 85%. At Calide, 8750 dragline productivity was identified as a key opportunity for further value creation. Following benchmarking and a configuration review, the dragline swing time and bucket capacity were identified as potential areas for improvement. The dragline swing motors were upgraded and a higher capacity bucket was installed, delivering a significant improvement in production rate. Additionally, an operator benchmarking system was established by the operations teams and has also delivered further improvement. The EX5000 excavator fleet at Drayton are the benchmark in their class within Anglo Coal. Not satisfied with this, they have continued to further increase their production rates through a range of initiatives across pit design, overburden inventory management, inter-crew and intra-crew operator benchmarking and planned delay alignment. Increasing production rates results in electrical efficiency outcomes.	Improvement in process control	Mining, earth moving and other off-road materials handling equipment
Anglo American Australia Ltd	2009	<b>Equipment Efficiencies - Opencut Operations</b> - The Calide maintenance team have a structured defect elimination program to eliminate breakdowns and increase overall reliability of key equipment. Using this process, the Calide maintenance team have improved availability of the EH4500 truck fleet from 63% to 85%. At Calide, 8750 dragline productivity was identified as a key opportunity for further value creation. Following benchmarking and a configuration review, the dragline swing time and bucket capacity were identified as potential areas for improvement. The dragline swing motors were upgraded and a higher capacity bucket was installed, delivering a significant improvement in production rate. Additionally, an operator benchmarking system was established by the operations teams and has also delivered further improvement. The EX5000 excavator fleet at Drayton are the benchmark in their class within Anglo Coal. Not satisfied with this, they have continued to further increase their production rates through a range of initiatives across pit design, overburden inventory management, inter-crew and intra-crew operator benchmarking and planned delay alignment. Increasing production rates results in electrical efficiency outcomes.	Changes in maintenance practices	Mining, earth moving and other off-road materials handling equipment
Anglo American Australia Ltd	2009	<b>Equipment Efficiencies - Underground Operations</b> The Grassie Longwall at the Capcoal Underground Operation is delivering significantly improved performance. The recent change to operating regime has resulted in an increase in both process reliability and utilisation. The changes in operating regime focus on getting the basics right such as communication, focussing on a maximum of 3 longwall issues at a time, improving conveyor performance and improving bonus schemes. Recent advancements at Grassie mine in the automation program have also reduced operational delays and delivered increased cut rates, further increasing production output. Moranbah is currently trialling automated bi-directional shearing. Bi-directional shearing is where a full face of coal is cut in a single pass instead of the current process of uni-directional shearing which cuts the face in two passes. This has the potential to improve cut rate by up to 15% with minimal increase in the sites power consumption. Other improvements also under consideration are automated uni-directional shearing, improved cut out distance	Investment in the same but more efficient technologies	Mining, earth moving and other off-road materials handling equipment

Figure 22: Screenshot of The Energy Efficiency Opportunities Mining Register (Australian Government Department of Resources, Energy and Tourism 2011a)

Inclusion of separate fields for these items would render the identification process more efficient with the use of searchable filters. Having completed a detailed review, an improved best practice energy management database for the mining industry that overcomes many of the problems of the EEO system has been developed. This section aims to explain the analysis methodology and the design of the new opportunities register to encourage its adoption by the minerals industry.

### **6.2.2 Methodology used to develop improved best practice database**

The intent of this research was to enhance transparency and facilitate dissemination of best practices with respect to energy matters in the mining industry. The methodology followed to achieve this goal consisted of the following steps. A literature review was conducted to examine existing frameworks for reporting energy efficiency measures. Peer-reviewed journals, corporate sustainability reports, industry publications and websites were consulted and it was determined that there was a need for a standardized reporting mechanism in order to facilitate the assessment of the reported initiatives. It was decided that a database with filtering capabilities would suit this purpose.

Next, a review of energy efficiency databases ensued in order to identify a suitable framework to promote energy efficiency initiatives. The Energy Efficiency Opportunities Mining Register (Australian Government Department of Resources, Energy and Tourism 2011a) and the Institute for Industrial Productivity's (2012) Generic Library which is included in the Assessment to Action (A2A) Toolkit were reviewed.

A review of over 90 case studies of energy efficiency initiatives in the mining industry followed to identify what information is typically presented. Subsequently, the Mining Energy Efficiency Best Practice database was created by starting with the A2A Generic Library structure and



adding the relevant fields for mining energy efficiency measures. The reviewed case studies were entered into the register to test the ease of use and ensure that the appropriate fields were included.

### **6.2.3 Critical review of energy efficiency opportunities mining register**

The opportunities identified by the Australian mining sector through the Energy Efficiency Opportunities (EEO) program were compiled in the Mining Significant Opportunities Register (Australian Government Department of Resources, Energy and Tourism 2011a) that permitted a mechanism through which best practice could be disseminated. The structure of the database includes fields for company name, public report year, opportunity description, opportunity category and equipment type. The Microsoft Excel based register allows users to apply filtering capabilities to the data where the information can be organized by these fields. A critical review of the EEO register was conducted to assess the strengths and weaknesses of the structure in order to improve the next iteration.

The register comprises a total of 259 energy efficiency opportunity entries from 39 companies dating from 2008 to 2010. The opportunities listed are assigned to one of fourteen categories where the group with the most entries corresponded to “Improvements in process control” with 32% of total records. Thus it appears that most of the identified energy conservation measures may lead to an improved process in addition to realizing energy savings.

The database includes a field for identification of equipment to which the energy efficiency opportunity is applicable. In the register there are a total of 33 types of equipment, of which “Mining, earth moving and other off-road materials handling equipment” comprised the largest number of entries corresponding to 30% of the total examples. Since most energy conservation

measures pertained to mobile equipment, this indicates that the A2A database did not include a complete set of initiatives for use in the mining sector.

### **6.2.3.1 Key fields omitted in register**

The creation of a central repository of energy efficiency initiatives is valuable but the existing database could be improved. For example, fields identifying the energy and carbon emission savings associated with a given initiative are a surprising omission of this database, as it does not permit the relative effectiveness of different measures for energy and carbon reduction to be readily assessed. In order to determine the energy savings from each of the opportunities it is necessary to read the descriptions provided for each measure. However, Gold Fields Australia Pty Ltd. recognized the need for identification of these fields and included separate lines in the description of their opportunities for Energy Saving, Emission Saving and Cost Saving. This allows users to quickly retrieve key data from the reported measure. Another company felt compelled to add fields within the opportunity description to provide a higher level of detail; BHP Billiton Limited specified the status of the project as well as the area where the measure was applicable. Inclusion of these as separate fields would provide users with improved filtering capabilities resulting in more efficient identification of relevant information.

Other fields which may be of use to the industry would be the inclusion of; energy source, payback period, status of a project (identified opportunity or implemented measure), status of savings (estimated or confirmed) as well as relative cost and difficulty level of implementation. There may also be measures applicable only to a specific commodity therefore inclusion of such a field in the database with the aforementioned fields would encourage its increased consultation.

### **6.2.3.2 Lack of standardized reporting**

Most of the savings were reported with GJ as the units whereas some were reported as percent savings, diesel volume, dollars, MWh or kWh while others did not provide any indication of reduction levels. Adoption of standard reporting units would allow users to easily compare the energy conservation initiatives included in the register.

### **6.2.3.3 Entries improperly classified**

The inclusion of opportunity category and equipment type fields permits identification of initiatives applicable to specific circumstances or equipment however these are not always appropriately allocated. For example, one entry from Big Ben Holdings Pty Limited in 2008 identified the opportunity to reduce energy consumption by 433 GJ per year with the installation of a wind turbine to displace a diesel generator which was utilized to charge a battery which powers a communication repeater tower. The opportunity category associated to this entry corresponded to “Investment in new technologies or new configurations of technologies not used before” but it is suggested that an opportunity category labeled Renewables would have been a more appropriate selection. Inclusion of such an option would allow users to quickly identify renewable energy projects which are applicable to or already implemented in the mining industry. Another example consisted of the “installation of timers to reduce the operating time of air conditioners” listed under the “Investment in new technologies or new configurations of technologies not used before” opportunity category which is erroneous since the use of timers has been employed in the past. Other measures within this category that do not belong included: use of variable speed drive to control underground primary ventilation fans, reducing hauling distances, automatic lighting controls, and a power monitoring project among others. This

category description leads users to believe that these companies are implementing revolutionary technologies when this category heading was likely interpreted as new to the company versus new to industry.

Examination of the equipment type included in the register revealed that “Heat losses” and “Transmission losses” were listed, but clearly they do not belong with the other items in this category which included among others: dryer, electric motors and furnace. Furthermore, “Own use” is another entry which is listed under the equipment type field but it is unclear what should be included under this label. Investigation of the opportunity descriptions linked to these 25 entries showed that these were attributed to a variety of items. For example there were measures pertaining to mills, blasting, energy monitoring systems, buildings, flotation circuit and training among others. It is suggested that additional fields, better describing these measures be added to the register for more effective identification.

#### **6.2.3.4 How is energy saved?**

Some of the descriptions did not provide any indication of how energy savings would be realized. The following entry from Idemitsu Australia Resources Pty Ltd. illustrated this observation *“TANDEM DRAGLINE "PULLBACK" OPERATION This method of dragline operation involves the use of electric draglines to remove a larger portion on the overburden which covers the coal, prior to Coal Mining. This initiative is expected to have a low cost of implementation because it involves changes to mining processes and systems rather than capital investment to replace diesel powered overburden removal with electric dragline overburden removal.”* Replacement of a technology that utilized diesel with an electric one should not have

constituted an energy efficiency opportunity since it is assumed without further explanation that the same amount of energy will be consumed.

#### **6.2.3.5 How significant is a “Significant Opportunity”?**

According to the Australian Government Department of Resources, Energy and Tourism (2011c), a significant opportunity is defined as: *“Any potential change or modification to a system, an activity or equipment that the corporation reasonably considers could result in a material reduction in a site, fleet or process’s energy use, a material improvement in energy efficiency of a site, fleet or process, or generate materially significant financial savings for a site or business, and that was identified as part of an Energy Efficiency Opportunities assessment.”*

However it is doubtful that some of the entries in the Significant Opportunities Register were significant. For example, Newmont Australia Limited reported the following *“Thermal Oil Burner Fuel Switching (Newmont Jundee Operations): LPG is currently used at the process plant to provide heating to the thermal oil burner, gold smelting furnace and the carbon regeneration kiln, which are all operated 2-3 times per week. A fuel switching opportunity has been identified to convert all three items of equipment from LPG to natural gas. Natural gas is a suitable alternative fuel, is already supplied to the main electricity plant and is a cheaper fuel with a slightly lower greenhouse gas emission intensity. This opportunity is budgeted to be implemented in 2010 and will reduce costs and a small amount of carbon dioxide emissions.”*

There was no evidence that this initiative would result in reduced energy use. Furthermore, this initiative was categorized as an improvement in process control, which clearly should have been labeled as fuel switching if it was indeed considered significant.

A second example where significance was questioned corresponded to one example provided by Kagara Ltd. which is expected to reduce energy use by 1,200 GJ per annum. However, since participants in the Energy Efficiency Opportunities program consumed at least 0.5 PJ, this amount corresponded to a maximum of 0.2%. Although this measure could result in energy savings, it should not have been considered significant according to the Australian Government's definition.

#### **6.2.3.6 Multiple initiatives included in single entry**

Review of the opportunities also revealed that some companies included more than one initiative per description. For example, Unimin Asia Pacific Pty Limited could have separated the replacement of a motor with a high efficiency unit coupled with variable speed drive from the feed pre-heating using kiln exhaust, which were reported as one measure. Aggregation of opportunities may prevent users from identifying relevant initiatives when filtering data, thus guidance may be required to ensure that separate entries are used for each example.

#### **6.2.3.7 Some of the entries have an obfuscating lack of detail or obvious errors**

The level of detail provided in some of the descriptions was found to be lacking. For example, one company claimed that up to 5% savings could be achieved with one opportunity but failed to specify if these savings represented percent of total site energy or percent of energy use from this cost center. This type of information can be confusing or misleading to users trying to find applicable initiatives through the use of the register.

The entries in the register were not thoroughly reviewed for errors as one initiative from Xstrata Holdings Pty Limited (Copper) reported that switching from diesel to natural gas in the smelter

would provide cost savings of \$1.5/annum. Clearly, if this is correct it should not have been considered for inclusion in the significant opportunities register.

#### **6.2.3.8 Some excellent examples of reporting are present with the Australian database**

There were some exemplar entries in the Australian Government's register. Several opportunity descriptions included relevant information presented in a clear and concise manner. For example, Centennial Coal Company Limited presented the following submission: *“Clarence Colliery – relocating pump - The water management system at Clarence Colliery included pumping from the main dam to a header tank. By relocating the pumping to another dam the head has been reduced by 40 metres thus decreasing the pump power requirements from 200kW to 75kW , this load reduction equates to an annual saving of 1,095MWh (3,942GJ) also reducing electricity costs by \$66,000.00 and emissions of 1,079 tonnes of CO<sub>2</sub>e per year. These savings were achieved at a cost of \$70,000 and a payback of less than 13 months.”* It can be observed that this description included the key data; a brief summary of how the energy reduction was achieved, the energy, financial and carbon emission savings as well as capital investment and payback period.

Another good example consisted of the opportunity described by Barrick (PD) Australia Ltd by revisiting a previously identified measure for its Mill Reconfiguration to report the actual savings, which in this case exceeded the estimated energy reduction; *“This opportunity was reported in the last public report but savings were higher than anticipated. In 2007 there was a reduction in Mill throughput that resulted in an investigation in to ways that electricity consumption could be reduced. The investigation lead to reconfiguration of the mill processing*

*plant and the retiring of major plant equipment including the ball mill, secondary crushing circuit and leach tank agitators. Variable speed drives were installed on the SAG Mill discharge motors. In the last public report the energy savings were estimated at 119,000 GJ. This opportunity was implemented in March 2008. The March to December 2008 energy saving was 328,724 GJ.”*

#### **6.2.3.9 Data disaggregation would be useful**

First Opportunities in Depth: The Mining Industry (Australian Government Department of Resources, Energy and Tourism, 2010) is a report published with the goal of providing a better understanding of energy use and saving potential in the Australian mining industry. The data in this report was aggregated by sub-sector within the mining industry; comprising of coal mining, oil and gas extraction, metal ore mining and other mining and services. Analysis of energy and greenhouse gas emission savings as well as financial benefits and payback period for these mining sectors is presented in this report, which indicates that disaggregated data for these fields was reported. If this was the case, then why was this data not presented in separate fields in the Significant Opportunities Register? This would have rendered the database a more useful tool by providing a more effective data filtering method to obtain relevant information.

Inclusion of separate fields highlighting key data pertaining to energy management initiatives in the mining industry may be useful for dissemination of best practices. Creation of a database with the appropriate structure could provide a powerful tool for mining industry energy managers, allowing them to quickly and easily identify relevant initiatives to improve on energy matters.



#### **6.2.4 Structure of proposed improved mining industry energy management database**

A review of energy management efforts implemented in the mining industry, published in peer reviewed journals, corporate sustainability reports or industry publications during the last 40 years has revealed many examples of best practice. However, the lack of a standardized reporting framework in any of these sources has made it difficult to assess the effectiveness and compare the adopted energy management measures – just as is the case with the Australian register.

In an attempt to address this issue, an improved database structure has been created for energy management measures from the mining industry which identifies energy and financial savings arising from energy management initiatives, classifies applications to specific processes or equipment, and recognizes leaders in the mining industry with respect to energy management. The structure of the register includes the key data relevant to energy management in mining that is absent in the Australian version. The framework used to develop this database was based on the Institute for Industrial Productivity's (2012) Generic Library which is included in the Assessment to Action (A2A) Toolkit. The data entry template of the Mining Energy Efficiency Best Practice database is illustrated in Figure 23 and an online version of this template is also available for users wishing to submit case studies for inclusion in the register (Levesque 2013).

Energy Savings Measure Profile			Template	
Reference Year:		Company:		
Mine:		Country:		
Mine Type:		Commodity (primary):		
Profile Type		Relative Implementation Cost		
Measure Profile Title:		Relative Implementation Difficulty		
Level 1 - Plant Region:		Payback period (years):		
Level 2 - Plant Area:		CO <sub>2</sub> eq annual reduction (tonnes)		
Level 3 - Equipment:		Results status		
Level 3 - Other:		Installation type		
Group:		Project Status		
Applicable industry sector		Renewable energy		
<b>Annual Savings</b>				
Energy Type	Power (MW)	% Savings	Energy (MWh)	Cost (\$)
Electricity				
Natural Gas				
Diesel				
Propane				
Coal				
Fuel Oil				
Steam				
Other (specify in description)				
Total	0	0%	0	\$ -
<b>Description</b>				
<b>Other Notes:</b>				
<b>Links</b>				
<b>Reference Sources</b>				

Figure 23: Energy Savings Measure Profile data entry template

The information to be compiled in the template can be broken down into 5 sub-sections: background company information, energy efficiency initiative key data, annual savings, description, and references.

#### **6.2.4.1 Background company information**

The background company information section includes fields for year of project implementation, company name, mine, country, mine type and commodity. These details provide information which could be useful for performing an analysis of the data to: i) identify energy efficiency leaders in the mining industry, ii) construct a timeline of energy efficiency initiatives pertaining to the mining sector and iii) examine where measures were implemented – underground vs. surface operations, gold vs. coal mines, etc.

#### **6.2.4.2 Energy efficiency initiative key data**

Next, the profile section allows input of key data which will assist users to quickly identify applicable measures when filtering the information. The data entered in most of these fields is selected from a drop-down list which allows for the information to be categorized.

The selections for the profile type field include: technology, operating, and maintenance. The technology type is defined as implementation of new or more efficient equipment, whereas modifications with respect to operation of equipment or management would be included in the operating type. The last option, consisting of maintenance concerns change implemented to maintenance practices.

The fields for Level 1 - Plant Region, Level 2 - Plant Area and Level 3 - Equipment were included to recognize where the initiatives were implemented at the mine; the various levels

allow one to narrow the area down from a high level towards the equipment. This allows distinguishing between initiatives pertaining to underground versus surface operations as well as processing, transport or support systems. A measure implemented in comminution, smelting, refining or leaching for example would be classified as processing whereas the transport heading would include initiatives relating to mobile equipment and the support category consists of systems involving heating, cooling, lighting, energy supply, building envelope, compressed air and steam. An option to select “Other” for the equipment is available if the list does not possess the specific component but in this case, the user can specify the equipment in question in a separate field labeled “Level 3 – Other”.

The Group field includes categories which may be assigned to initiatives as follows: Automation, Conservation, Fuel Switching, Heat Recovery, Improved measurement and monitoring, Internal policy, Maintenance change, Optimization, Process change, Process control, R&D / new technology, Renewable energy and Training. Inclusion of this field provides a greater level of detail with respect to the nature of the energy efficiency initiative.

Relative Implementation Cost and Difficulty were included in the data entry template in order to provide users with an understanding of the financial commitments and level of expertise required for implementation of energy efficiency measures. These levels were defined in the Assessment to Action (A2A) Toolkit’s (Institute for Industrial Productivity 2012) Generic Library. Table 7 provides definitions for each level.

**Table 7: Relative cost and difficulty level definitions (Institute for Industrial Productivity 2012)**

Item	Level	Definition
Cost	High	Implementation cost is very high, and a detailed economic feasibility analysis (based on a detailed process design) is required to justify and estimate the cost.
	Medium	Cost is relatively average, and usually requires a first-order economic feasibility analysis to justify and estimate the cost.
	Low	Limited to no cost involved to implement the opportunity. Generally referred to as "low hanging fruit."
Difficulty	High	Replacement of existing, large equipment / process units, or complex modification to the process, which requires external expertise to design and implement. Requires a detailed technical and economic feasibility assessment and detailed process design prior to implementation.
	Medium	Replacement of existing, small/medium size equipment / process units, or relative minor modification to the process, which can often be design and implemented by in-house expertise. Retrofit of equipment that require a moderate effort to implement. Generally requires only a first order technical and economic feasibility assessment and minor process design prior to implementation.
	Low	Process modifications, equipment replacements and retrofits that are relatively easy to implement. Most often can be integrated with maintenance activities and include operational and behavioural changes. A high level economic and technical feasibility analysis may be required in some instances.

Subsequently, fields were included for specification of payback period as well as carbon emission reductions. The Results status options allows one to distinguish between estimated and confirmed savings whereas the Installation type explains whether the project consisted of setting up new equipment, retrofitting existing equipment, replacement of existing equipment or no installation at all. Whether a project is proposed, in progress or has already been implemented, may be specified in the Project Status line. The template also allows users to specify which sector within the mining industry a measure would be applicable to; the options for this field are the same as those from the Level 1 – Plant Region, which include: underground, open-pit, process, transport, and support. In instances where renewable energy projects are concerned, the source can be identified in the Renewable energy field which enables companies to highlight these types of projects.

#### **6.2.4.3 Annual Savings**

The Annual Savings section provides information regarding power (MW), percent, energy (MWh) and financial savings achieved via the implementation of energy efficiency measures. The savings are also categorized by the type of energy that is reduced; users can specify electricity, natural gas, diesel, propane, coal, fuel oil, steam or other source of energy which was saved by the initiative. In a case where a measure results in lowering multiple energy sources, savings are entered for each energy type and the sum of these would be shown in the total savings field.

#### **6.2.4.4 Description of energy efficiency initiative**

In the next section, an area is provided to supply a description of the energy efficiency measure, which may include details regarding how energy is saved. A separate field labeled ‘Other Notes’ is included to provide users an opportunity to highlight any other pertinent information which may have been omitted in the pre-defined fields.

#### **6.2.4.5 References and links for additional information of energy efficiency measure**

The last section provides space for users to include hyperlinks to websites as well as reference sources which could be used to direct other users who wish to obtain additional information to available resources.

#### **6.2.4.6 Navigation buttons**

The buttons on the right-hand side of the template are used to navigate between screens as well as update information in the register. The “Update Database” button’s function is to append the newly entered information to the existing data and adds the initiative to the index. A user wishing to enter a new measure would click on the “Enter New Measure” button which opens a blank template. “Back to Index” and “Back to Menu” buttons allow users to navigate to the index and menu screens respectively whereas the “Delete Measure” button will permanently remove a record from the database.

#### **6.2.4.7 Best practice database Index for quick reference**

The Mining Energy Efficiency Best Practice database comprises an index which provides a snapshot of the initiatives included in the register; each row is allocated for individual measures and the key data is indicated in separate columns.

From the index screen, users can filter the data from any of the key fields in order to find relevant energy efficiency measures. For example, the data can be categorized by company in order to identify energy efficiency leaders in the mining industry or by payback period to distinguish initiatives with the quickest return on investment. Alternatively, users may narrow down the applicable initiatives which may be of relevance to a specific circumstance by application of a filter to the Equipment or the Applicable industry sector field. In order to gain perspective with respect to energy and financial savings achieved, figures for each initiative were included in the index for each energy type. This also provides functionality to isolate projects which could reduce energy consumption from a specific source. For example, a mine energy manager wishing to identify measures to reduce diesel consumption could filter the data from the register to highlight applicable projects to this energy source.

Additional information for any of the initiatives can be obtained from the index by clicking on the “Tab Number” link in the first column, which will open the Energy Saving Measure Profile for that specific project. The supplementary data available from this screen includes mine type, carbon emission savings, renewable energy source, energy efficiency measure description, links to websites and reference sources.

#### **6.2.4.8 Quality assurance**

Dissemination of energy conservation projects can be via journal publications, magazine articles, corporate sustainability reports, or company websites and newsletters, however these may not all undergo a peer-review process. Thus, to ensure that the entries in the improved database are complete and accurate, a checking procedure is used prior to uploading case studies to the register.



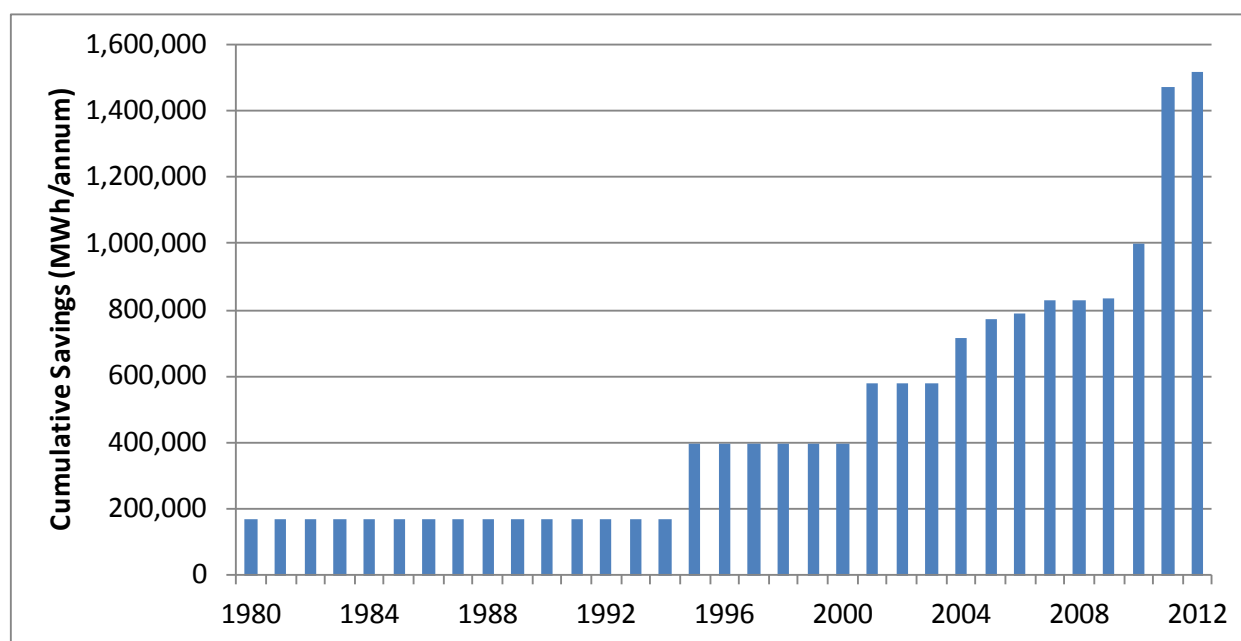
The quality checking procedure entails comparing the estimated or reported energy savings against an estimate of energy use from that demand center to verify that the savings are realistic. A secondary verification of the energy savings is done by comparison with similar entries. Currently this procedure is undertaken by an individual that is familiar with energy use in the mining sector but a future version of the database may include a self-checking procedure. This may entail that users are required to upload additional information such as the total amount of energy used annually, but may not necessarily be published due to the sensitive nature of the data required for checking purposes.

#### **6.2.4.9 Lessons from the database**

The goal behind the creation of the Mining Energy Efficiency Best Practice database was to facilitate dissemination of best practices with respect to energy matters in the mining industry. To achieve this target, it is essential to populate the register with case studies. The mining industry energy management database has been made available in the public domain where mining companies can examine the best practice examples. Mining energy champions may also contribute to the register by providing case studies; a standardized entry template affords a quality assurance dimension that is absent in other reporting initiatives.

As the information in the register grows, an analysis may be performed to create a timeline of energy efficiency initiatives in the mining industry which may reveal trends with respect to focus areas throughout the years. Alternatively, the Profile Type and Group fields may be utilized to determine the nature of the implemented measures and assess the mining industry's behaviour in energy matters.

To date, 107 case studies have been recorded in the Mining Energy Efficiency Best Practice database, of which annual energy savings for 54 projects have been reported or estimated, totaling roughly 1.5 million MWh. The entries were from numerous mining companies, operating in various countries and mining several commodities. The examples dated from 1980 until 2012 and the annual energy savings resulting from initiatives in the mining industry during these 32 years are illustrated on Figure 24.



**Figure 24: Example to illustrate the form of cumulative energy savings curve in mining sector from 1980 to 2012**

Although it may appear from Figure 24 that most of the energy savings have been realized during the most recent years, this may not be accurate since there are gaps in the dataset; the database contained only one case study from 1980 with the next entries corresponding to 1995 then 2001, but there were entries for every year between 2004 and 2012. Furthermore, the case studies entered in the database represent a partial account of all energy management initiatives implemented in the mining industry since the data entry stage is in progress.

Further investigation revealed that, of the 1.5 million MWh energy savings in the mining sector, most of the savings were realized from technology type initiatives (56%), followed by operating measures (43%) and very little from maintenance examples (0.2%).

A more detailed analysis of the data was undertaken by examining the annual energy savings achieved by the various groups of measures. The top 3 groups consisted of heat recovery examples which provided the most energy savings followed by renewable energy projects then internal policies. Although renewable energy projects may not result in energy savings, this category was included in the database since they result in reducing carbon emissions. Figure 25 illustrates the results.

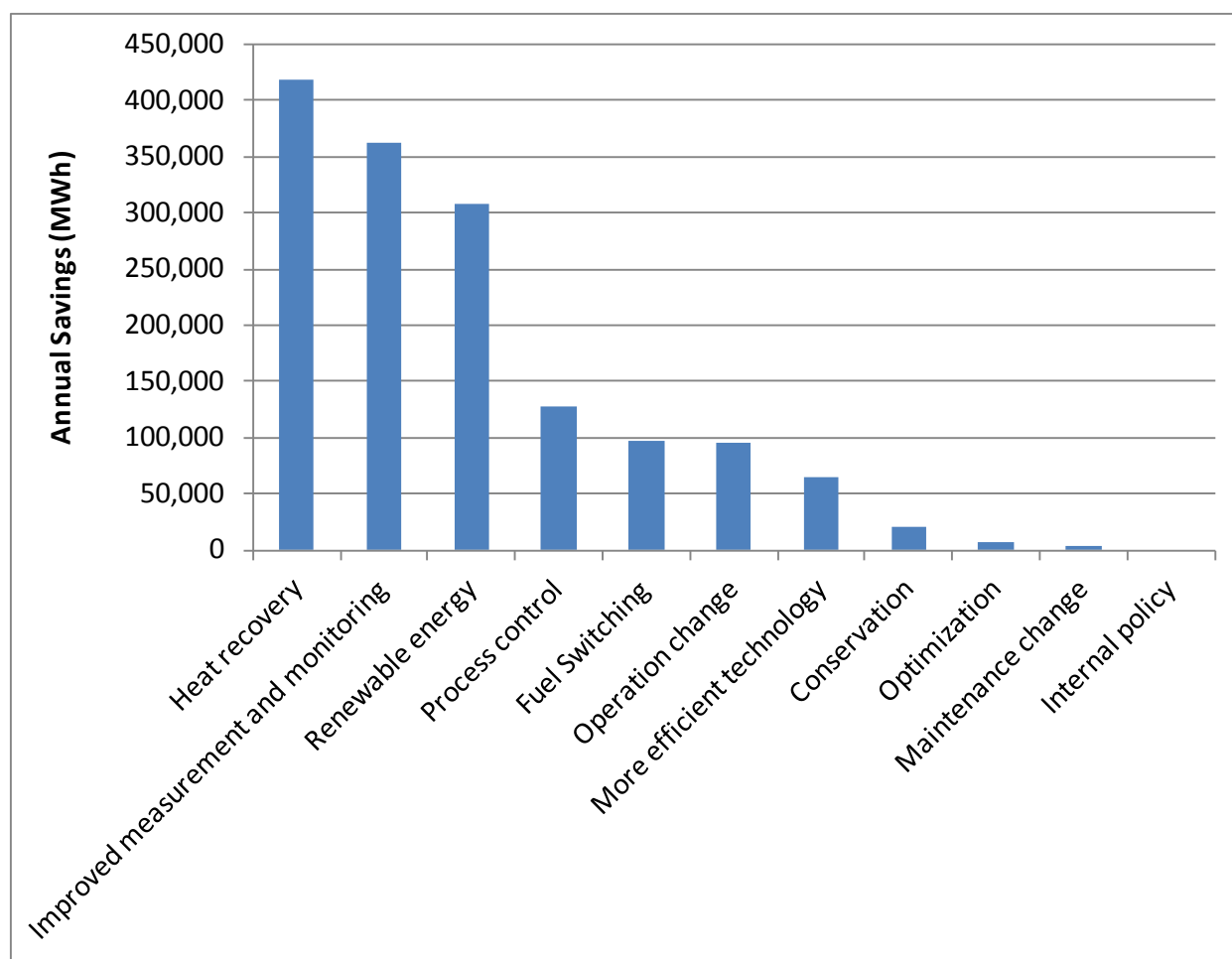


Figure 25: Energy savings by group

Additional analysis may ensue as the database matures to examine the energy savings by commodity, by country, by energy source or by company; depending on the objective of the investigation any of the fields could be analyzed.

### 6.2.5 Adopting the improved database

Adoption of the Mining Energy Efficiency Best Practice database with its standardized reporting mechanism will enhance transparency of the mining industry in energy matters and may help it maintain its social license to operate.

Multiple frameworks are currently available to mining companies for promotion of sustainability initiatives however there seems to be a lack of consistency in these reports which would allow effective assessment, benchmarking and comparison of energy efficiency measures. The use of a database to facilitate dissemination of best practices can be effective but the appropriate structure needs to be implemented so that users can quickly and easily identify applicable measures. The Australian Government's Energy Efficiency Significant Opportunities Register comprises mining industry efforts aimed towards improving energy use. Although this was a good attempt at improving transparency and dissemination of best practice, an improved database structure was developed in order to provide a more effective means of identification of relevant opportunities.

Currently, more than 40 users have downloaded the Mining Energy Efficiency Best Practice database. Some of these individuals are mining company employees, consultants in the mining sector, or academics. Increased adoption of the tool may be achieved by targeting its promotion to these groups. Further enhancements could also be implemented in subsequent versions of the database to address the needs of various stakeholders which may be achieved through increased collaboration between users.

## **7 Improved auditing for mines – an example from Garson Mine**

An energy audit was conducted at Garson Mine in 2014 as part of a Master's level project within the Natural Resources Engineering program at Laurentian University (Mallett 2014). The audit consisted of gathering data and information that would allow estimating the annual energy consumption of the various end-uses at the mine.

### **7.1 Background**

Garson Mine is an underground mine located in Sudbury Ontario and is owned and operated by Vale. Ore is extracted from three orebodies which are accessed either via the Garson Ramp or a shaft developed to 1,288 meters (Mallett 2014).

A total of 68 pieces of underground equipment including drills, bolters, scissor lifts, and personnel transportation vehicles, which consume diesel and/or electricity, are used to support production. Scoop trams and haul trucks transport and dump ore and rock to an ore pass or a rock pass where the materials are fed to the rail tramming system. These 24 pieces of equipment make up the underground mobile equipment fleet, all of which consume diesel fuel as an energy source. The ore is then crushed underground then hoisted to surface via the skip hoist, consuming electricity for these processes. Personnel and supplies are transported in the cage hoist from surface to the underground workings, also using electricity. Ventilation fans, powered by electricity are necessary to supply fresh air to the underground workings. The main ventilation system at Garson Mine comprises 16 main and booster fans, whereas 54 fans make up the auxiliary system. The ventilation system also consumes natural gas to heat the mine air supply during the winter months. Electricity is also consumed by 5 compressors which are used at the mine to supply compressed air to one of the backfill plants and to pneumatic powered

equipment used underground. Process water and inflow water from precipitation is evacuated from the underground workings with the use of 7 electrically powered pumps located at different levels underground. The mine also consumes electricity in 2 backfill plants which are used to fill areas underground where mining activities are complete. Although there are only 10 distinct end-uses consuming energy at the mine, the number of individual equipment within these categories can be substantial, thus a detailed energy audit at an underground mine may be challenging. Furthermore, a mine is a dynamic environment which may pose obstacles to installation of infrastructure for continuously monitoring the energy use from all equipment.

## **7.2 Conducting the energy audit**

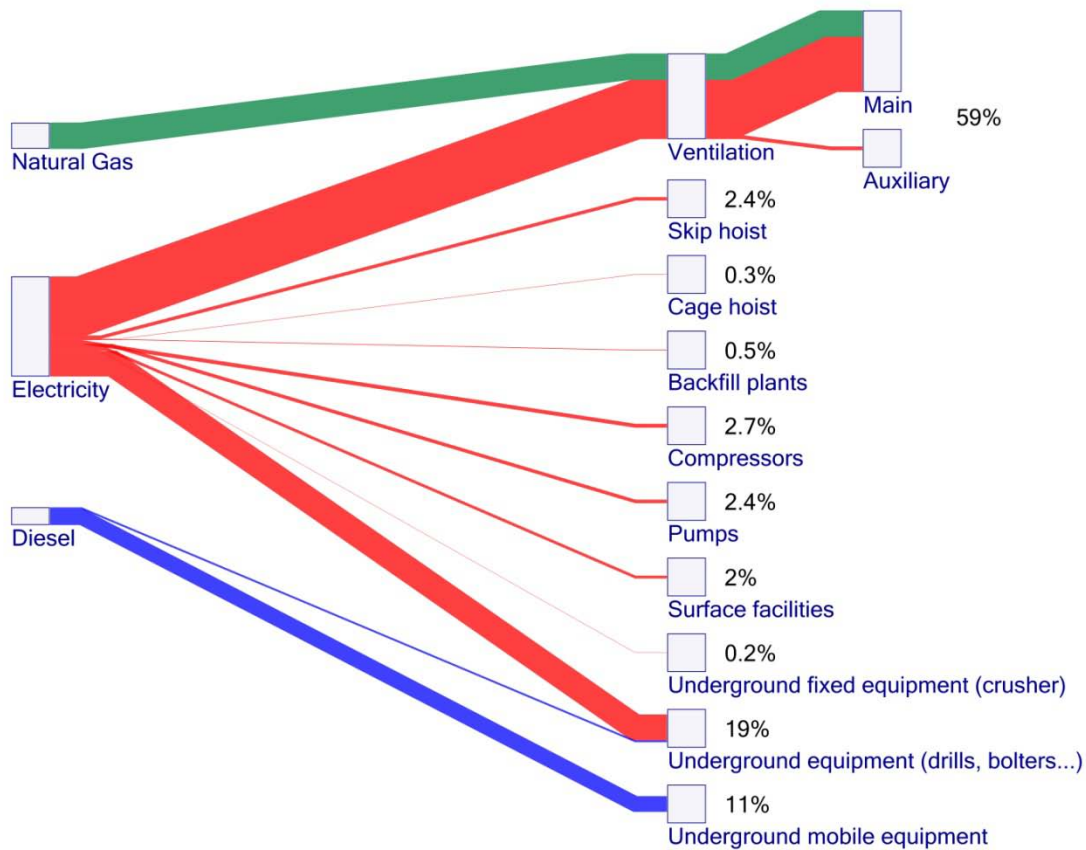
The first step in the energy survey consisted of gathering invoices and metered data to determine the total annual consumption from each type of energy; these consisted of electricity, natural gas and diesel. Subsequently, the energy consumption from the various end-uses was measured or estimated. Table 8 describes the methodology used for estimation of energy consumption for each end-use.

**Table 8: Method used to obtain energy consumption from various end-uses at Garson Mine**

<b>End-use</b>	<b>Data gathering methodology</b>
Ventilation	Natural gas consumption was metered.  Electricity use was estimated from each individual fan's rated power and an estimate of the annual operating hours.
Skip hoist	Obtained root mean square (RMS) power per cycle from hoist logger and average cycle time to determine the energy use per cycle. Then the number of cycles per month required to hoist the amount of ore produced was calculated and used to estimate the monthly energy consumption.
Cage hoist	Obtained root mean square (RMS) power per cycle from hoist logger and average cycle time to determine the energy use per cycle. Then the number of cycles was determined from the cage hoist schedule to estimate the monthly energy use.
Backfill plants	Estimated the number of operating hours based on plant capacity and actual fill produced. Then the energy use was estimated with the rated power of the motors in the plants and the estimated operating hours.
Compressors	Data obtained from logged meter values
Pumps	Data obtained from logged meter values
Surface facilities	Estimated 2% of total energy use at the mine
Underground fixed equipment (crusher)	Estimated number of operating hours per year from actual ore production data and tramming capacity. It was assumed that the crusher operating hours corresponded to the tramming time. Annual energy consumed was estimated from the number of operating hours and the crusher's rated power.
Underground equipment (drills, bolters)	Estimated from the difference between the total electricity use at the mine and the sum of all other end-uses.
Underground mobile equipment	<p>Fuel consumption of each piece of equipment was calculated by the following formula (Hays 1990) as cited by Mallett (2014) :</p> $FC = \frac{CSF \times P \times LF}{FD}$ <p>where <math>FC</math> is fuel consumption (L/hr), <math>CSF</math> is specific fuel consumption at full power (kg/ kW per hr), <math>P</math> is power (kW), <math>LF</math> is load factor (%), and <math>FD</math> is fuel density (kg/L).</p> <p>The energy consumption for each machine was estimated with the calculated hourly fuel consumption and an estimate of the operating hours.</p>



Figure 26 presents a Sankey diagram prepared from the audit data to illustrate the energy consumption allocated to the various end-uses.



**Figure 26: Energy flows at Garson Mine**

Figure 26 shows that ventilation, and underground equipment were the main electricity consuming activities. However, the electricity consumption from the auxiliary mine ventilation system seemed low whereas the use from drills and bolters appeared high.

### 7.3 Reconciling the data

A review of the equipment inventory, power rating and load factors for these demand centers revealed that the electricity use from underground equipment may have been overestimated whereas the auxiliary ventilation consumption was underestimated. For example the weighted average rated power from all auxiliary fans in the inventory corresponded to roughly 50 kW and it is assumed that these had a 97.5% load factor, which corresponded to the load factor attributed to the main fans in the study. Conversely, the average rated power of the hydraulic power pack for the underground equipment (bolters and drills) was 75 kW but the average load factor for electricity consuming activities for these units corresponds to roughly 25% (Hauta 2015).

Although the average rated power for the drills and bolters was higher than that of the auxiliary fans, the load factor and the number of equipment was lower. There were more than 50 auxiliary fans in the inventory whereas there was a total of 15 drills and bolters. Thus it is anticipated that the electricity consumption from the auxiliary ventilation fans would be greater than that of the drills and bolters. As such, the electricity consumption of the drills and bolters was estimated from the rated power and the average load factor values. It should be noted that the rated power of the hydraulic power packs for the drills and bolters was obtained from manufacturer's technical specification sheets and catalogues (Boart Longyear 2014, Cubex Ltd. 2010a, Cubex Ltd. 2010b, Cubex Ltd. nd., Sandvik Mining and Construction 2007, Tamrock 1995, Tamrock 2000). In some instances, model numbers were not included in the inventory thus the rated power value used in the estimate corresponded to the maximum value listed for the equipment series. Further, the value for the drills and bolters from the original audit was 242% greater than that from an estimate with a load factor of 100%.

A review of the auxiliary fan inventory revealed that 42 of the 54 auxiliary fans were excluded from the original audit, thus this supported the hypothesis that the consumption from this demand center may have been underestimated. The other remaining unknown value from the audit corresponded to the electricity consumption of the surface facilities, which was allocated an arbitrary value of 2% of total energy consumption in the original audit. As such an attempt was made to balance the electricity use at the mine. The electricity consumption of the auxiliary mine ventilation system was estimated using the rated power and a 97.5% load factor for all the units from the fan inventory, which left 6% of total electricity for the surface facilities. This value seemed high and since there were some fans from the inventory with unknown locations it was decided to keep the electricity use from the surface facilities at 2% of total and allocate the balance to the auxiliary mine ventilation system to account for fans with unknown locations. Installation of electricity meters to quantify the surface electricity consumption as well as updating the fan inventory would either confirm these revised values or provide more accurate estimates. Subsequently a revised Sankey diagram was prepared from the revised energy consumption values for Garson Mine which is presented in Figure 27.

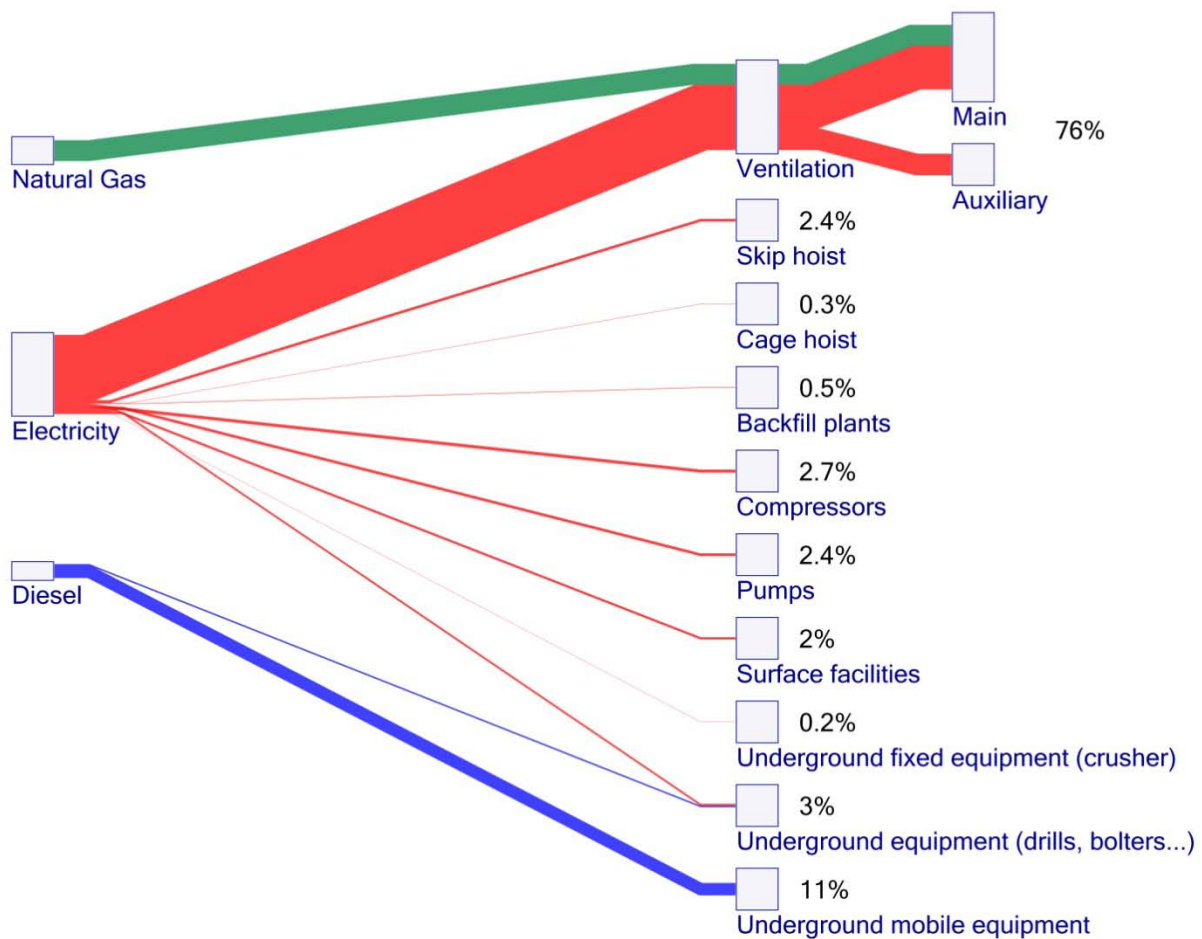


Figure 27: Revised Sankey diagram for energy flows at Garson Mine

It can be seen from Figure 27 that the end-uses consuming the most energy, thus those that future work should focus on were: ventilation, and underground mobile equipment.

The Garson Mine energy audit illustrated a snapshot of energy use at this site with many estimated values, but provides a basis for further refinement. Table 8 shows that the natural gas consumption and the electricity use from the pumps and compressors were the only values obtained from metered data comprising 23% of energy use thus estimates were used to allocate

77% of total energy used at his mine. The preliminary audit permitted the identification of information gaps as presented in the Top-down energy audit method (Rosenqvist, Thollander et al. 2012). Thus re-iteration of the Garson Mine energy audit with adoption of an improved methodology may enhance confidence in the audit values.

#### **7.4 An improved energy audit methodology for Garson Mine**

The following recommendations are suggested and it is anticipated that adoption of these measures could lead to an improved energy management methodology for Garson Mine.

- Install meters on main ventilation fans (16 meters required)
- Install meters to obtain electricity use from skip and cage hoists (2 meters required)
- Install meters at the plant level for backfill plants (2 meters required)
- Install meter to gather electricity use from underground fixed equipment (crusher) (1 meter required)
- Install meters for surface facilities (4 meters required)
- Include blasting as an additional end-use
- Obtain diesel consumption for underground mobile equipment and underground equipment (drills, bolters...) from engine management systems
- Obtain ventilation survey data and accurate fan inventory from ventilation group to estimate electricity use from auxiliary ventilation system.
- Gather and analyze data for a 12 month period.
- Collect data for factors that influence energy consumption as presented in Table 9

Table 9 also indicates the expected diurnal and seasonal variability as well as potential demand side management (DSM) measures to reduce energy use for each demand center.

**Table 9: Variables that influence energy consumption in an underground mine**

<b>End-use</b>	<b>Energy type</b>	<b>Influence variables</b>	<b>Diurnal variability</b>	<b>Seasonal variability</b>	<b>Potential DSM opportunities</b>
Ventilation	electricity, natural gas	production, mine depth, mine layout, outdoor temperature, mine air heaters setpoint	Increased use of natural gas may occur at night during heating season	Increased natural gas consumption in winter	Ventilation on demand, use of electric vehicles
Hoisting	electricity	production, mine depth, hoist speed	May have increased use during lower electricity rate periods	N/A	Maximize use during low electricity rate periods, investigate slower travel speed
Backfill plants	electricity	production	N/A	N/A	Investigate maximizing use during low rate periods, ensure use of premium efficiency motors
Compressors	electricity	production	N/A	N/A	Investigate use of waste heat, fix leaks
Pumps	electricity	production, precipitation, depth of pump locations	N/A	Higher consumption with increased inflow from precipitation	Maximize pumping during low electricity rate periods
Underground equipment (drills, bolters)	electricity	production	N/A	N/A	Adopt anti-idling policy

Surface facilities	electricity, natural gas	outdoor temperature, heating system setpoint	Increased use of natural gas may occur at night during heating season	Increased natural gas consumption in winter	Assess building envelope and lighting opportunities
Underground fixed equipment (crusher)	electricity	production, ore hardness, feed size, product size	N/A	N/A	Investigate increased use of explosives
Underground mobile equipment	diesel	production, distance travelled, road grade	N/A	N/A	Use of electric vehicles, adoption of anti-idling policy
Blasting	explosives	production, ore hardness, fragmentation size	N/A	N/A	Investigate increased use of explosives <sup>9</sup>

<sup>9</sup> Although increasing the use of explosives would result in higher energy use from blasting, the potential for lower energy consumption during the comminution stage may offset this additional energy.



The installation of 25 additional electricity meters at Garson Mine, to monitor the electricity use from fixed equipment, would reduce the uncertainty of electricity use within 6 of the studied end-uses. Thus if all the electricity consumed by fixed equipment is metered and ventilation survey data is used to estimate the auxiliary ventilation consumption, the remaining balance can be allocated to the mobile equipment. Furthermore, use of vehicle engine management systems to determine diesel consumption from the underground mobile equipment and production support equipment would provide further confidence in the audit values. Thus with these proposed refinements to the Garson Mine audit, the proportion of metered data would increase from 23% to 78% of total energy at the mine based on the allocated energy values from the preliminary audit.

Ideally, all equipment should be metered to assess energy use but in an underground mine this may not be practical. An underground mine is a dynamic environment with development occurring in several areas, where installation of meters on auxiliary fans for example would have to be relocated with the fans as areas are developed. Thus, it was suggested to estimate the energy consumed from this end-use from ventilation survey data. In Ontario testing is required on a weekly basis to determine the air volume flowrate where diesel equipment is used as per Regulation 854 Section 183.2 (Workplace Safety North 2011). Therefore combining knowledge of the fan model and blade setting with the measured flowrate values can be used to determine the fan operating pressure from the manufacturer's fan curves. This information can also be used to determine the fan efficiency, all of which could be used to calculate the fan electricity consumption as shown in (2) (McPherson 1993).

$$W = \frac{P \times Q}{\eta_{fan} \times \eta_{motor}} \quad (2)$$

where  $W$  is the power (kW),  $P$  is the fan pressure (kPa),  $Q$  is the airflow rate (m<sup>3</sup>/s),  $\eta_{fan}$  is the fan efficiency, and  $\eta_{motor}$  is the motor efficiency. An estimate of the motor efficiency and fan operating hours would be required to determine the energy use from each fan. Although this would only provide the energy use corresponding to the period where the ventilation survey was conducted, it would be better than using the rated power with an assumed fan efficiency.

Furthermore, the location of some of the auxiliary fans listed in the inventory was labeled as “unknown” during the preliminary audit thus it is possible that the electricity consumption allocated to the ventilation system may be incorrect. Therefore coordination with the ventilation team to gather an updated fan inventory list would eliminate some of the uncertainty.

Implementation of the aforementioned recommendations for improving the Garson Mine audit would leave only the electricity consumed by the underground equipment (drills, bolters...) as fully estimated values. In the preliminary audit the energy use from these was allocated based on the difference between the sum of all other electricity and the total consumed at the mine. A value of 2% was allocated to the surface facilities and the remaining balance to the underground equipment. Monitoring the electricity use from equipment within the underground equipment category was not suggested as an improvement to the audit since it may be challenging because these are mobile units. Some of the 68 pieces of equipment consume both diesel and electricity; diesel is used for mobility whereas the electricity is used for powering the equipment’s specific application. For example, electricity can be used to power the drilling mechanism on a drill. Thus installation of electricity meters on mobile units may not be practical. All of the 68 pieces of equipment in the underground equipment category use diesel for mobility regardless if these

consume electricity for additional purposes. Thus diesel consumption may be obtained from engine management systems, and the electricity use would be the only estimated energy use from this category.

Gathering data for the variables listed in Table 9 could permit an assessment of diurnal or seasonal variability in energy use, as well as establishment of benchmarks from the individual end-uses. This may facilitate the analysis stage of the audit and the identification of potential energy conservation measures. Subsequently, these variables could be used in a Level 3 energy audit, whereby potential savings from energy conservation measures may be quantified with the use of models.

The preliminary Garson Mine energy audit consisted of a bottom-up / energy balance audit method, and corresponded to a level between Level 1 and Level 2 as defined by ASHRAE standards. The Garson study was more in-depth than a walk through audit since data was gathered and energy use was allocated to the various end-uses. However it lacked a thorough analysis step to identify potential energy conservation measures that would be included in a Level 2 audit.

Review of the Garson Mine audit provided a starting point for assessing energy use in an underground mine and provided the basis for development of an improved energy audit methodology which may be adopted at other mine sites. The proposed method can be generalized as follows:

Conduct a Level 1 or a walk-through audit consisting of reviewing historical energy billing data for all energy types to provide an overview of the amount of energy consumed at a site. Then a

site visit ensues to identify obvious energy conservation measures. For an underground mine these could include identification of:

- leaks (for example from compressed air, ventilation, or pumping systems)
- idling equipment (such as conveyors running empty, or idling vehicles)
- sources and sinks for waste heat
- low equipment utilization (such as equipment running but not fully loaded).

Subsequently, conduct a preliminary audit by gathering all available metered data and estimating energy consumption for the remaining end-uses. The purpose of this audit is to identify information gaps which may be addressed with future iterations of the audit, providing a basis for continuous improvement. It is suggested to install meters to monitor energy use from all fixed equipment and whenever possible on mobile equipment; the greater proportion of energy that is metered improves the confidence in the audit.

Subsequently, a level 2 energy audit may be conducted with sufficient confidence to identify potential energy conservation measures. If installation of meters is not feasible due to physical or budgetary constraints, it is recommended to use the energy balance audit method as described in Pawlik et al (2002). Inclusion of a utilization factor, equipment efficiency, motor load factor, and a diversity factor in addition to the equipment rated power and an estimate of the annual operating hours may result in a more accurate estimate of energy use. Furthermore, this method provided guidance to adjust estimated values when the sum of individual equipment and the total consumption at a site did not balance.

Use of the CIPEC Energy Savings Toolbox (Natural Resources Canada 2009) is recommended for the data analysis step of the audit. The key to identification of potential energy savings

measures begins with an understanding of how, when and why energy is used at a facility. The guidance and tools included could be adapted to suit the mining industry which may provide a systematic method for data analysis and identification of energy conservation measures, which was employed by New Afton Mine during implementation of ISO 50001 (Clean Energy Ministerial 2014).

Where reduced uncertainty in the energy savings from the proposed measures is required, a Level 3 audit may ensue to model the specific system or equipment. However, these models should also consider the impact of the proposed measures on downstream processes. For example, reducing the energy used in blasting may increase the energy used in the comminution stage of the process, thus an integrated approach is recommended to ensure that the overall energy use at the site is minimized. Figure 28 illustrates an overview of the proposed energy management methodology with a continuous improvement approach.

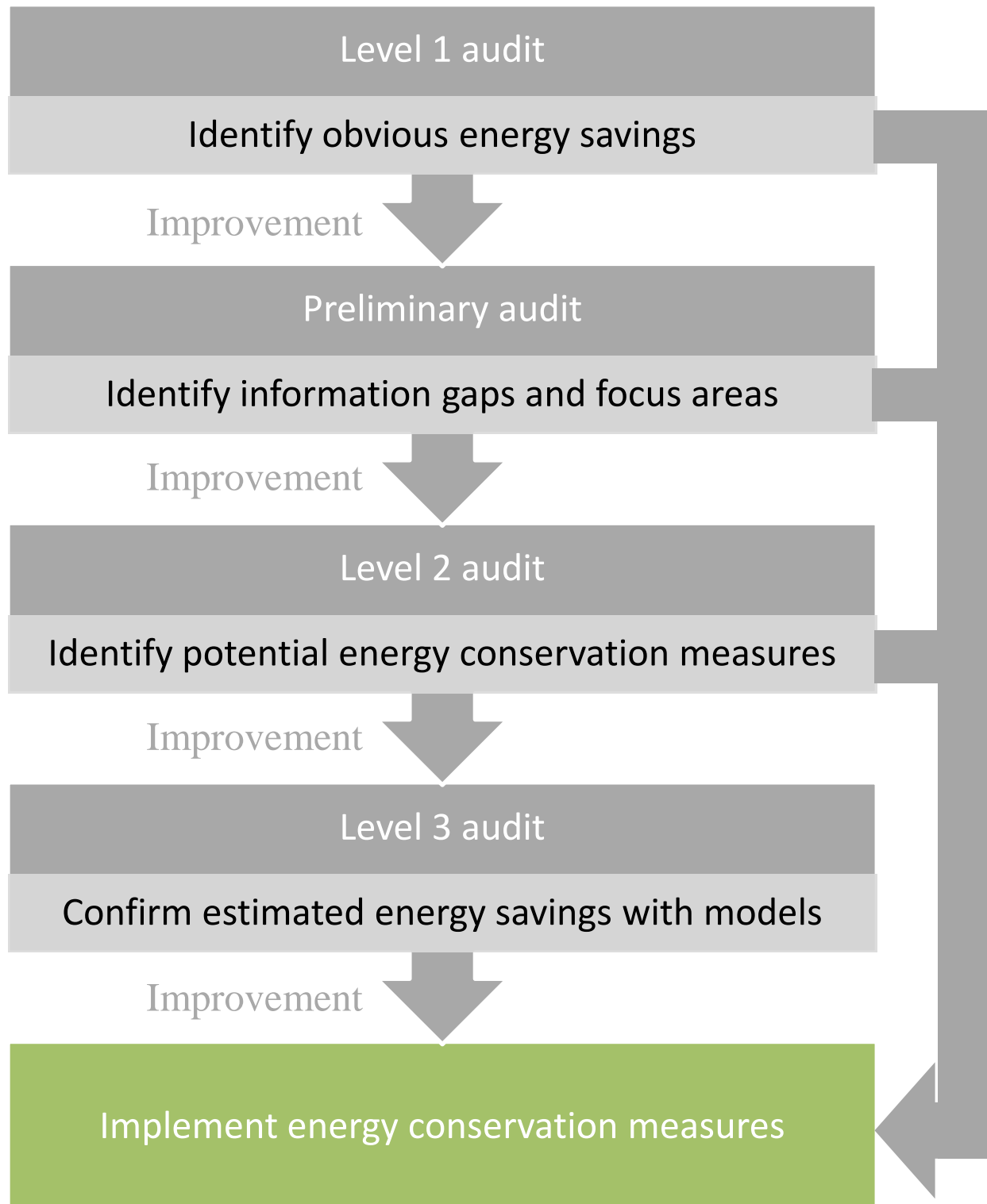


Figure 28: Proposed energy management methodology with continuous improvement approach

## **8 Improved interpretation of energy consumption data - Energy management pertaining to auxiliary mine ventilation systems**

### **8.1 Introduction**

As can be appreciated from the previous Chapter, ventilation can account for a significant portion of the electricity consumption in underground mines. As such, any gains that can be made to improve energy use for ventilation of the sub-surface can have an impact on the facility's overall energy costs.

Research and/or experience has identified that savings could be obtained in ventilation systems from measures including, but not limited to, ventilation on demand (VOD) (Bartsch, Laine et al. 2010) or fan drive frequency control (Wang, Chen et al. 2010). Potential savings for VOD implementation estimated by Bartsch *et al.* corresponded to 52.8% and 36.5% for electricity and propane respectively. Alternatively, innovative materials with lower friction factors could also have the potential to provide energy savings, ranging from 56% to 71% depending on the materials compared, as exemplified in Tardiff *et al.* (2010) however their overall economic value needs further assessment and has been examined within this Chapter.

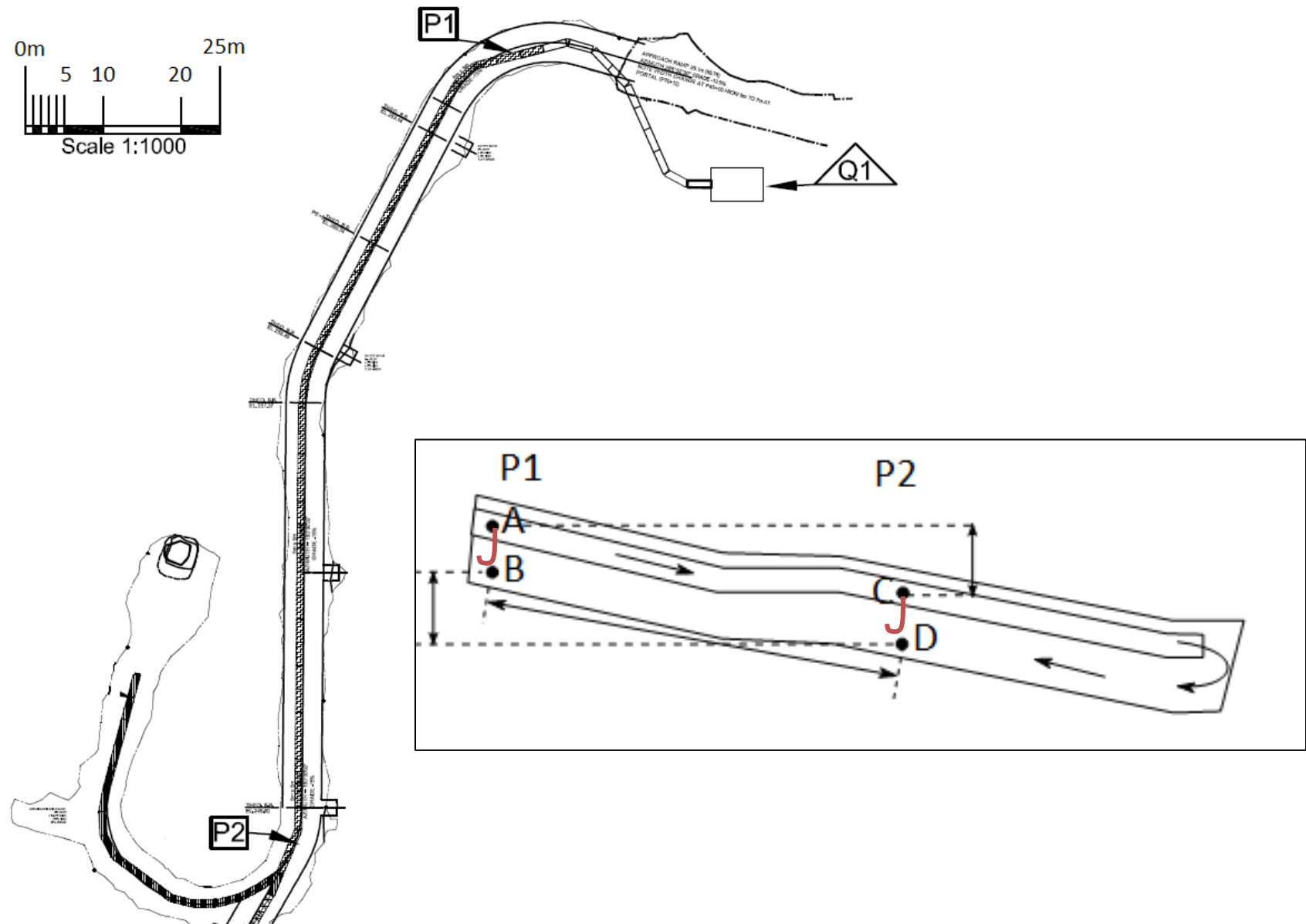
A series of ventilation surveys were conducted at Mining Technologies International Inc. (MTI)'s underground research and demonstration site, located in Lively, Sudbury, Ontario, Canada, to: i) quantify the Atkinson friction factor of the polyethylene auxiliary ventilation duct, and ii) quantify the possible energy savings from use of this material, compared to some of the more conventional products used in the mining sector, such as steel and layflat ducts.

An auxiliary mine ventilation model was developed to assess energy and life cycle costs and hypothetical case studies were examined to compare the economics of various systems.

## **8.2 Ventilation survey methodology**

The survey was conducted by measuring the static pressure, at various fan speeds, at two duct stations, separated by a distance of 125 meters. Figure 29 shows the layout of the facility and the locations where measurements were taken. Q1 corresponds to the surface fan location where air velocity measurements were taken, whereas P1 and P2 are the static pressure reading locations for the plastic duct. The inset in the figure shows a schematic of the elevation view between the pressure measurement stations.





The use of two barometers and two manometers allowed for simultaneous pressure observations at both locations. Measurements using the barometers followed the 'leapfrog' procedure (McPherson 1993) except that since there were only two measurement locations the barometers remained at the same locations.

Static pressure observations were also recorded simultaneously at both locations with the use of two manometers with the high port connected to a plastic tube inserted in the side of the duct and the other gauge port open to atmosphere inside the drift. Two trials were conducted for each of the 5 fan speeds tested, with each trial consisting of an average of 5 pressure values.

The elevation difference between the measurement locations needed to be considered for determination of the pressure drop when using the barometer values, whereas the elevation difference was cancelled when using the manometer readings, illustrated by the inset in Figure 29. Points A and B indicated the location of the pressure differential between the duct and the drift measured by the manometer at station P1 whereas C and D represented the corresponding measurement points at P2. The elevation difference between points A and C in the duct was the same as the elevation difference between B and D in the drift, therefore the difference between the simultaneous manometer readings at P1 and P2 would be equivalent to those taken on a horizontal level, providing that the drift resistance is negligible compared to the duct resistance which is often the case according to Duckworth and Lowndes (2003).

For each fan speed, the duct air velocity was measured with the use of a hot wire anemometer. Measuring positions were determined for an 8 point traverse following the log-linear traverse method for a circular duct (McPherson 1993). Three measurement values, all within 5% of one another were recorded and averaged for each measuring position inside the duct. However, the

hot wire anemometer could only reach up to the center of the duct thus it was not possible to obtain values at all of the measuring points. Therefore only half of the duct velocity profile could be measured and it was assumed that both halves were symmetrical. The four velocity values were then averaged to determine the air velocity inside the duct at each fan speed. Table 10 shows the measuring positions of the traverse from the side of the 1.2 m diameter duct but only the first four points were measured.

**Table 10: Velocity measurement positions**

Point	Fraction of diameter (McPherson 1993)	Distance from side of duct (m)
1	0.021	0.026
2	0.117	0.143
3	0.184	0.224
4	0.345	0.421
5	0.655	0.798
6	0.816	0.995
7	0.883	1.076
8	0.978	1.192

Subsequently air velocity measurements were taken for a complete 8 point log-linear traverse as per the locations in Table 10 which revealed that the velocity profile was not symmetric as is illustrated in Figure 30, thus the original values were discarded and the survey was repeated. It should be noted that the values recorded during the first survey with only 4 points corresponded

to those from ~0.8 to 1.2 m across the duct, thus the average air velocity values from these trials was overestimated.

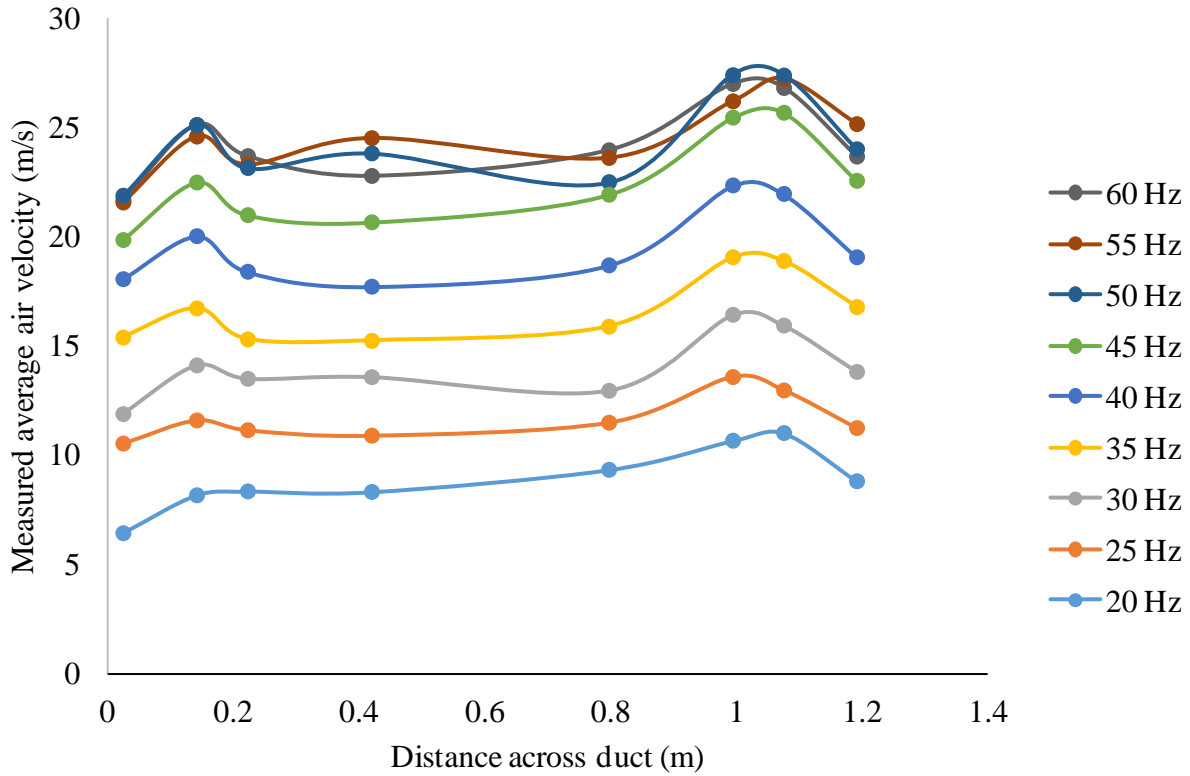


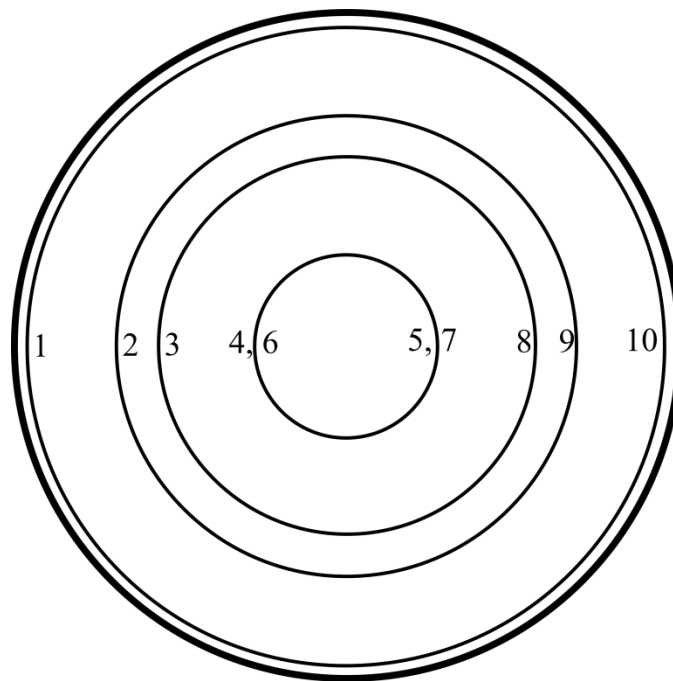
Figure 30: Air velocity values for 8 point log-linear traverse at various fan speeds

It was suspected that the silencer located prior to the measurement location was the cause of the asymmetry in the velocity profile, thus a new air velocity measurement location was chosen.

Furthermore, one of the duct segments at the beginning of the system was damaged between the time of the original and revised surveys therefore a new location was also selected for the P1 pressure measurement location from Figure 29. This new location, which also corresponded to the new air velocity measurement station, was chosen to be at least 10 duct diameters past the

first bend in the system. A distance of 107 m separated the pressure measurement locations for this survey.

An 8 point log-linear duct traverse methodology was used in the new survey however, since measurements were taken from both sides of the duct, both values in the center were recorded from each side of the duct for verification purposes. The duplicate values were averaged and treated as one value with the other data to calculate the average air velocity in the duct. Figure 31 illustrates the measurement locations inside the duct with the numbers corresponding to the sequence of the measurement whereas Figure 32 shows the velocity profile of the new survey.



**Figure 31: Measurement location and sequence of 8 point log-linear traverse along the duct**

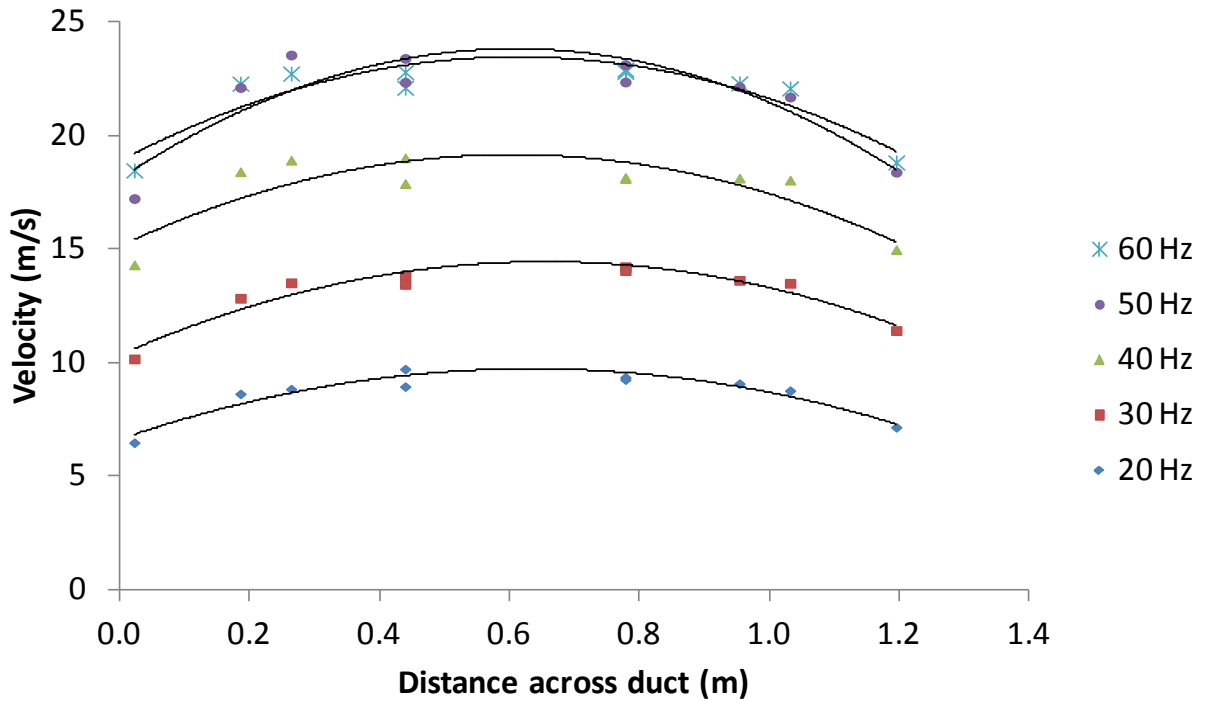


Figure 32: 8 point velocity profile for new survey

Use of the duct diameter to calculate the cross-sectional area allowed determination of the volumetric flowrates from the velocity values. Psychrometric measurements (dry bulb and wet bulb temperatures) were also taken with a whirling hygrometer to determine the air density in the drift between the pressure measurement points during the survey.

### 8.3 Determination of friction factor

#### 8.3.1 Friction factor calculations

The first step consisted of determination of the frictional pressure drop between both pressure measurement locations (P1 and P2) for each fan speed. This was achieved by determining the difference between both manometer readings because the use of these eliminated the need to

correct for the difference in elevation between the measurement stations. The difference between the barometer values with correction for the elevation difference was used to verify the manometer readings.

Air density is a variable that was used in several formulas for determining the Atkinson friction factor. Measurements of the atmospheric pressure, the dry bulb and wet bulb temperatures were used to calculate the value of the air density, using equations 14.6, 14.10, 14.4, 14.32 and 14.14 from McPherson (1993). Then the general gas law was used to calculate the specific volume of the air/vapor mixture and the reciprocal of this value provided the air/vapor mixture density.

The following step consisted of calculation of the flowrate ( $Q$ ) from velocity measurements ( $u$ ) and the dimension of the duct area ( $A$ ) using:

$$Q = uA \quad (3)$$

The next step consisted of calculation of the total resistance ( $R$ ) in the system between the two measurement locations. This was achieved with (4), where  $P$  corresponded to the pressure difference from the manometer readings between measurement locations and  $Q$  was the flowrate.

$$R = \frac{P}{Q^2} \quad (4)$$

The total resistance ( $R$ ) between P1 and P2 comprised i) frictional resistance in the duct, ii) frictional resistance in the drift, iii) equivalent Atkinson resistance from shock losses in the duct, and iv) equivalent Atkinson resistance from shock losses in the drift, all of which are in series:

$$R = R_{fr.duct} + R_{fr.drift} + R_{shock duct} + R_{shock drift} \quad (5)$$

Calculation of the shock losses due to the bends in the duct and the drift were carried out as follows:

1. The shock loss factor ( $X_{90}$ ) for a right angled bend of circular cross section corresponding to 0.13 was determined from Figure 5.A.1 in McPherson (1993).
2. A correction factor ( $k$ ) for bends of angles other than  $90^\circ$  corresponding to 0.40 for the  $28^\circ$  bend was determined from Figure 5.A.3 in McPherson (1993).
3. The shock loss factor ( $X_\theta$ ) for each bend at angle  $\theta$  was determined using:

$$X_\theta = X_{90} * k \quad (6)$$

4. The equivalent Atkinson resistance ( $R_{shock}$ ) was determined from (7), where  $\rho$  was the air density and  $A$  referred to the cross-sectional area of the airway.

$$R_{shock} = \frac{\rho X_\theta}{2A^2} \quad (7)$$

5. Steps 1-4 were repeated for all bends in the duct as well as the drift. The total equivalent Atkinson shock resistances for the duct and the drift were determined by summing the respective values.

The frictional resistance in the drift ( $R_{fr.drift}$ ) was calculated with the dimensions of the airway, and the friction factor ( $k$ ) for an ‘unlined, typical conditions, no major irregularities’ airway value corresponding to  $0.012 \text{ kg/m}^3$ , determined from McPherson (1993), and applied to (8), where  $L$  was the length between measurement locations,  $per$  was the perimeter length of the drift, and  $A$  was the cross-sectional area of the drift.

$$R_{fr.drift} = \frac{k * L * per}{A^3} \quad (8)$$

Then, rearranging (5) allowed determination of the frictional resistance in the duct ( $R_{fr.duct}$ ).

Table 11 shows the average resistance values from all of the trials and the proportion of total resistance from each of the components.



**Table 11: Resistance of ventilation system components**

	Resistance (Ns <sup>2</sup> /m <sup>8</sup> )	% of total resistance
$R$	0.5435	
$R_{fr.drift}$	0.0012	0.23
$R_{shock\ drift}$	0.00004	0.01
$R_{shock\ duct}$	0.0229	4.22
$R_{fr.duct}$	0.5193	95.54

Subsequently, the Atkinson friction factor ( $k$ ) for the duct could be determined from (9), where  $L$  was the length between measurement locations,  $per$  was the perimeter of the duct, and  $A$  was the cross-sectional area of the duct.

$$k = \frac{R_{fr.duct} * A^3}{L * per} \quad (9)$$

The friction factor values determined using the experimental data were then corrected to standard air density using (10), thus allowing comparison to published values, where  $k$  corresponded to the experimental friction factor, and  $\rho$  corresponded to the air density observed during the trials.

$$k_{1.2} = k \left( \frac{1.2}{\rho} \right) \quad (10)$$

### 8.3.2 Error analysis

To assess the uncertainty or error associated with each of the calculated friction factor values, a Monte Carlo simulation following the methodology outlined in Xiao and Vien (2003) and Sonnemann *et al* (2003) was used with the omission of the sensitivity analysis. However, the

former study conducted the Monte Carlo simulation with 1,500 trials and the latter reference indicated that at least 10,000 trials were required to establish sufficient confidence, but this may not always be the case as the number of simulations is dependent on the number of variables in the model according to (11) (Harr 1987)

$$N = \left( \frac{h_{\alpha/2}^2}{4\varepsilon^2} \right)^m \quad (11)$$

where  $h_{\alpha/2}$  corresponded to the confidence coefficient for a normal distribution,  $\varepsilon$  corresponded to the maximum allowable estimate error, and  $m$  corresponded to the number of variables.

The probability density function was determined for each variable. It was assumed that all variables followed a normal distribution, but a Beta distribution resembling the normal distribution was used to limit the range of possible values which prevented the occurrence of unrealistic extreme values in the model.

A Monte Carlo simulation was then run to determine the uncertainty associated with the calculated friction factor values by varying: both manometer pressure values, the air velocity, the dry bulb and wet bulb temperatures and the barometric pressure values. The Monte Carlo simulation was carried out for each of the 10 sets of data, from which the mean friction factor and standard deviation were calculated within 10% of the value at a 95.45% confidence level.

Table 12 provides a summary of the results.

**Table 12: Summary of friction factor simulation results**

Fan frequency (Hz)	Pressure drop (Pa)	Flowrate (m <sup>3</sup> /s)	Friction factor $k_{1,2}$ (kg/m <sup>3</sup> )	Standard deviation	Lower limit	Upper limit
					95.45% confidence	
20	56.2	9.86	0.0022	7.6E-5	0.0019	0.0024
20	69.0	9.86	0.0027	8.6E-5	0.0024	0.0030
30	127.5	15.01	0.0021	6.5E-5	0.0019	0.0023
30	121.8	15.01	0.0020	6.3E-5	0.0018	0.0022
40	181.1	20.33	0.0016	5.1E-5	0.0014	0.0018
40	213.7	20.33	0.0019	5.8E-5	0.0017	0.0021
50	318.7	24.91	0.0019	5.7E-5	0.0017	0.0021
50	336.0	24.91	0.0020	5.9E-5	0.0018	0.0022
60	316.9	25.09	0.0019	5.6E-5	0.0017	0.0020
60	332.6	25.09	0.0020	5.8E-5	0.0018	0.0021
Average			0.0020	6.3E-5	0.0018	0.0022

### 8.3.3 Other quoted friction factor values for low friction ducts

The friction factor value determined during the ventilation survey at MTI's Test Mine was subsequently compared to other values reported for plastic ducts presented in Table 13.

**Table 13: Atkison friction factors reported for plastic ducts**

Friction factor (kg/m <sup>3</sup> )	Duct diameter (m)	Reference
0.0004	1.05	(Tardif, Paquet et al. 2010)
0.0006	N/A	(G+ Industrial Plastics Inc. 2014)
0.0009	N/A	(G+ Industrial Plastics Inc. nd.)
0.0009	N/A	(Mecanica nd.)
0.0021	1.2	(Ventilation engineer 2015) <sup>10</sup>
0.0023	1.2	(Ventilation engineer 2015)
0.0028	0.7	(Ventilation engineer 2015)
0.0025	0.5	(Ventilation engineer 2015)

The lowest friction factor value presented in Table 13 was sourced from a publication which was co-authored by a representative of one of the plastic duct manufacturers. The reported friction factor value was evaluated from an auxiliary ventilation system installed at the Casa Berardi Mine, located in Quebec, Canada. The next highest values ranging from 0.0006 to 0.0009 were from plastic duct manufacturers' sources whereas the higher values were from ventilation surveys conducted in actual auxiliary mine ventilation systems. It is interesting to note that these higher values correspond well with the value obtained from the MTI ventilation survey.

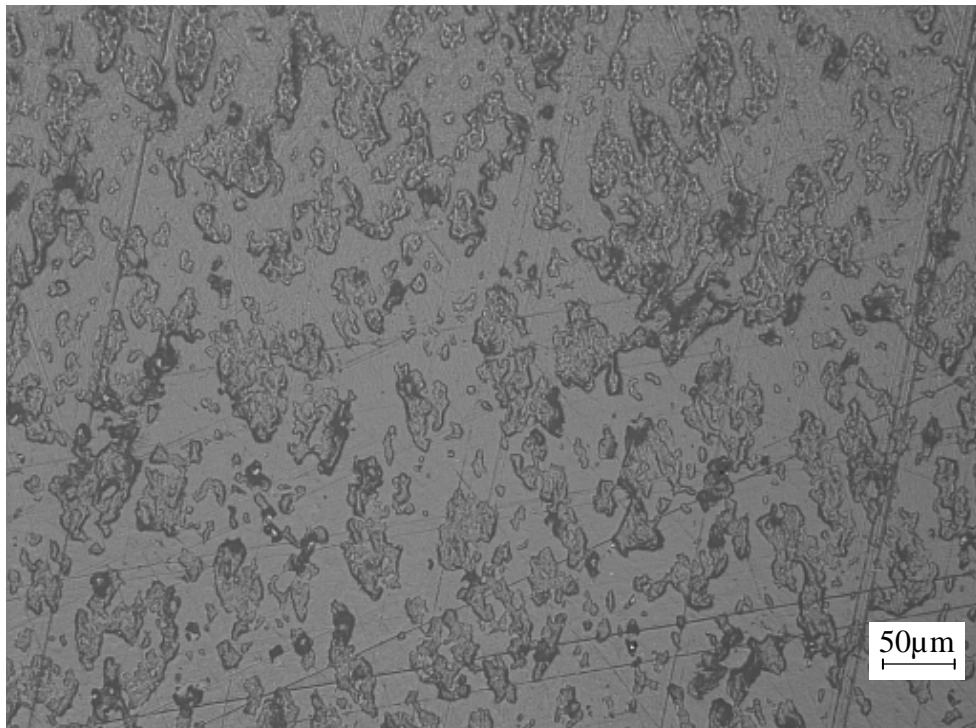
#### **8.3.4 Surface roughness**

Subsequently, a sample of the material used to fabricate the plastic ducts tested at MTI's Test Mine was obtained from the manufacturer. The purpose of this was to determine the asperity

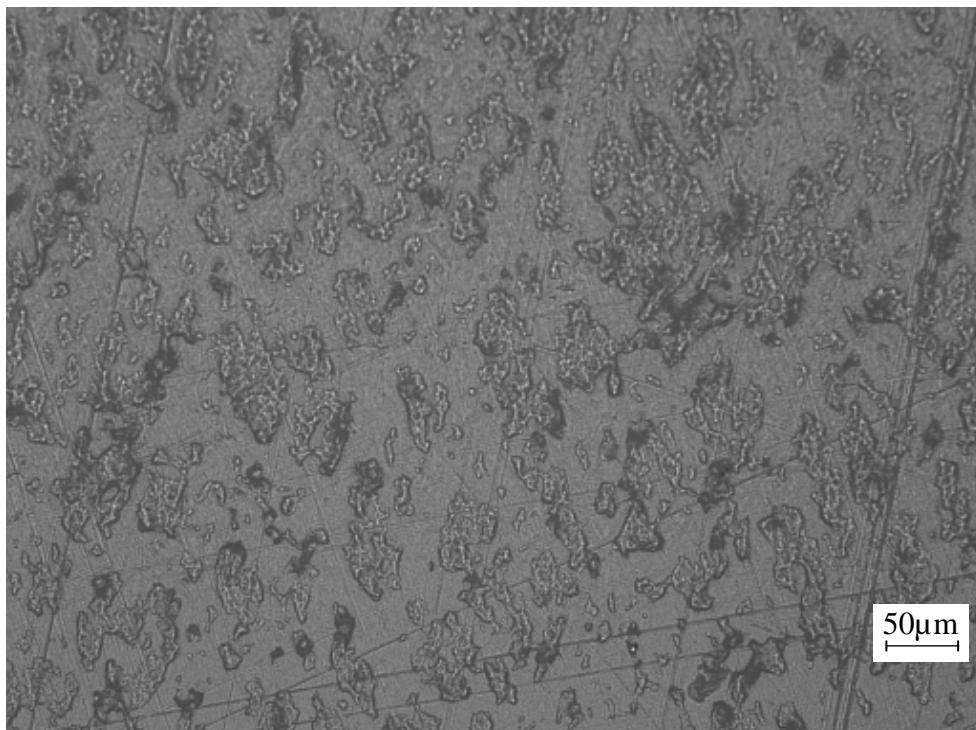
<sup>10</sup> These data were obtained via personal communication with the Principal Engineer – Ventilation at a mine but due to confidentiality reasons the name of this source cannot be disclosed.

height, which would provide an alternative method to calculate the material friction factor and assess the validity of the ventilation survey results as well as the other reported values.

The sample was examined using a reflected light microscope equipped with a QImaging MicroPublisher™ 5.0 camera. The asperity height was determined by focusing the microscope on the duct material surface, then focus on the asperity peaks was achieved by adjustment along the optical axis, whereby the difference between these positions, measured with a micrometer, corresponded to a height of  $5\mu\text{m} \pm 3\mu\text{m}$ . The error range was determined by taking several measurements of the distance between the material surface and the asperity peak planes. Figure 33 and Figure 34 show samples of the images focused on the material surface and the asperity peaks respectively.



**Figure 33: Sample image with microscope focus on the material surface plane**



**Figure 34: Sample image with microscope focus on asperity peaks plane**

It can be observed from Figure 33 and Figure 34 that there were scratches in the duct material sample as well as a texture, which was assumed to be attributed to a coating applied to the surface. It was also determined that the major factor contributing to the roughness was the coating since the sample observed in Figure 33 did not show any roughness on the material surface.

Determination of the friction factor from the surface roughness, measured as asperity height, consisted of calculation of the Reynolds number to determine the flow regime from the testing conducted at the MTI test mine. The values ranged from 7.1E+5 to 1.8E+6 with the average corresponding to 1.4E+6, therefore it was determined that the flow was turbulent.

Subsequently, the relationship between the Atkinson friction factor and the asperity height for turbulent flow was examined using the Von Kármán equation (Duckworth, Loomis et al. 2012, McPherson 1993):

$$f = \frac{2k}{\rho} = \frac{1}{4[2 \log_{10}(\frac{d}{e}) + 1.14]^2} \quad (12)$$

where:  $f$  was the Chezy-Darcy coefficient of friction

$k$  was the Atkinson friction factor ( $\text{kg/m}^3$ )

$\rho$  was the air density ( $\text{kg/m}^3$ )

$d$  was the hydraulic mean diameter (mm)

$e$  was the asperity height (mm)

Using the range of asperity height of  $5\mu\text{m} \pm 3\mu\text{m}$ , determined from the microscopic material surface observations, the Atkinson friction factor for a 1.2 m diameter duct and an air density of  $1.2 \text{ kg/m}^3$  was calculated. The results are presented in Table 14.

**Table 14: Atkinson friction factor values calculated from asperity height measurements**

Asperity height ( $\mu\text{m}$ )	Atkinson friction factor ( $\text{kg/m}^3$ )
2	0.0009
5	0.0011
8	0.0011

It can be seen from Table 14 that the Atkinson friction factor values that were calculated from the asperity height measurements were lower than those obtained during the ventilation survey in Table 12 as well as those from the ventilation surveys in Table 13, but were close to those reported from the manufacturer's sources.

### 8.3.5 Friction factor of hydraulically smooth pipes

The discrepancies between the reported Atkinson friction factor values for plastic ducts as well as those obtained from the microscopic analysis prompted an investigation to determine a value that could be used to characterize a plastic duct. The Atkinson friction factor values for a smooth tube were determined for various Reynolds numbers. Figure 35 shows a Moody chart where the dashed lines labeled 1 and 6 correspond to the limits that determine turbulent flow, the dashed lines labeled 2 and 3 correspond to the range of Reynolds number values from the ventilation survey at MTI, and the dashed lines labeled 4 and 5 represent the values corresponding to a 4 m/s air velocity in a 5x5m drift supplied by a 1.2 m and 0.6 m diameter duct respectively. This corresponds to the recommended maximum air velocity value in a working face as reported in McPherson (1993). The smooth tube line examined corresponded to that having an  $\frac{\varepsilon}{D}$  value of 0.000001 on Figure 35.



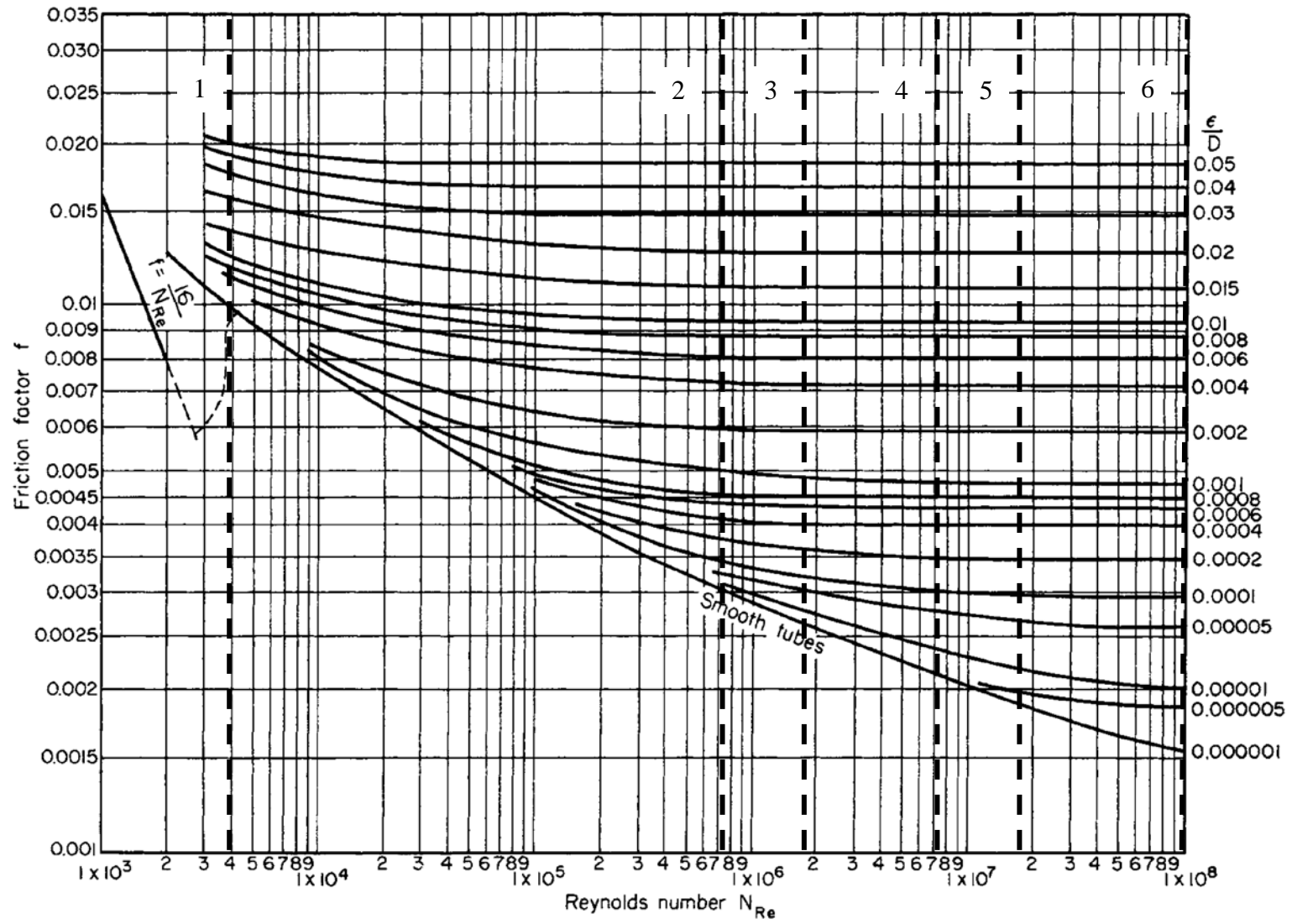


Figure 35: Moody chart (Perry, Green et al. 1997)

The Atkinson friction factor values at each Reynolds number ( $N_{Re}$ ) were calculated by using the corresponding friction factors read from Figure 35, a value of  $1.2 \text{ kg/m}^3$  for air density, and (12), the Von Kármán equation (Duckworth, Loomis et al. 2012, McPherson 1993).

**Table 15: Friction factors for a smooth pipe at various Reynolds numbers**

Defined point on Moody chart	$N_{Re}$	$f$	$k \text{ (kg/m}^3\text{)}$
Minimum $N_{Re}$ for turbulent flow	4.0E+3	0.0095	0.0057
Minimum $N_{Re}$ from MTI survey	7.1E+5	0.003	0.0018
Maximum $N_{Re}$ from MTI survey	1.8E+6	0.0026	0.0016
$N_{Re}$ in a 1.2 m duct supplying a 5x5m drift with maximum velocity of 4 m/s at working face	7.2E+6	0.0021	0.0013
$N_{Re}$ in a 0.6 m duct supplying a 5x5m drift with maximum velocity of 4 m/s at working face	1.4E+7	0.0018	0.0011
Maximum $N_{Re}$ on Moody chart	1.0E+8	0.0015	0.0009

The values from Table 15 show that the Atkinson friction factor for a smooth pipe ranges from 0.0009 to  $0.0057 \text{ kg/m}^3$  depending on the flow as described by the Reynolds number. Thus the Atkinson friction factor values presented herein are within the accepted range for a smooth pipe with the exception of two of the values presented in Table 13 which indicated that these were smoother than a smooth pipe and so must be disregarded.

#### **8.4 Techno-economic assessment of ventilation systems with various duct friction factors**

The interactions between the variables in an auxiliary mine ventilation system can be complex; changing one value can alter multiple parameters. An interaction matrix, illustrated in Figure 36, was established to illustrate the dependencies between the variables in a mine ventilation system. The shaded boxes represent the variables and the links between them are in the boxes located at the intersection of the variables. For example, the effect of the fan on the flowrate is located in the upper right hand corner; changing the fan or the speed leads to a new operating point and hence a new pressure and flowrate. The effect of flowrate on money can be found in the third box from the left in the bottom row, which indicates that a change in flowrate leads to a change in power that is translated to a change in energy cost.

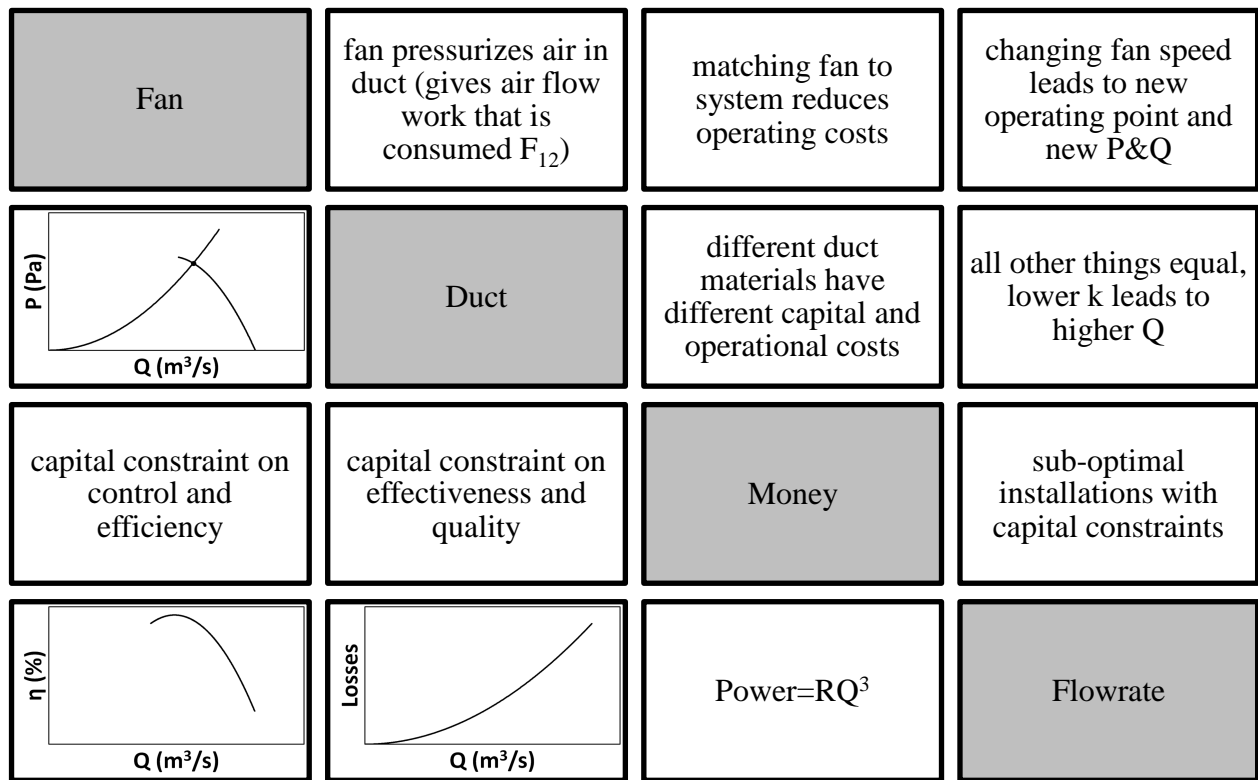


Figure 36: Interaction matrix of mine ventilation system variables

Although a lower friction factor could result in lower energy consumption it is equally important to consider the capital costs for a given system to assess the financial viability of a project. A model was derived to conduct a techno-economic assessment and examine the effects of changing different variables in an auxiliary mine ventilation system. Ducts with a range of Atkinson friction factor values ranging from low ( $0.0011 \text{ kg/m}^3$ ) to high ( $0.0037 \text{ kg/m}^3$ ) were compared. The methodology employed and the results are presented in the following sub-sections.

#### **8.4.1 Capital costs of various duct materials**

The first step consisted of determining the unit cost per meter for the various ventilation duct materials. Information with respect to material costs was provided by vendors and was used to establish the unit costs for the respective duct materials. The material costs included expenses for purchasing the ventilation ducts as well as all accessories used for joining the individual duct sections (steel rings, ratchet straps, drawbands) and supporting these in a mine installation (chains, messenger cables, anchors). For simplicity, the costing analysis assumed a straight ventilation duct, between 90 and 320 meters with no elbows or bends, then the total costs were normalized by the respective total lengths quoted to provide an estimate of the cost per meter for each material. Table 16 shows a summary of these costs.

**Table 16: Unit costs for various duct materials (1.2 m diameter)**

		Duct A	Duct B	Duct C
Total length (m)		320	91	305
Material cost	Duct section length (m)	2.67	3.05	7.62
	Number of duct sections	120	30	40
	Duct (\$)	84,974	9,240	5,880
	Joining accessories (\$)	12,442	2,700	n/a
	Supports (\$)	6,000	1,500	1,418
	Total material cost (\$)	103,416	13,440	7,298
<b>Material unit cost (\$/m)</b>		<b>323</b>	<b>147</b>	<b>24</b>

For increased accuracy, the costs for transporting the materials to underground and for installation could have been included however, as these vary from one site to another they were ignored in this assessment. Furthermore, it was assumed that the capital costs of the ducts were much larger than the transport to underground and installation costs, thus any effect from inclusion of the latter costs would be minor.

#### **8.4.2 Development of ventilation system model**

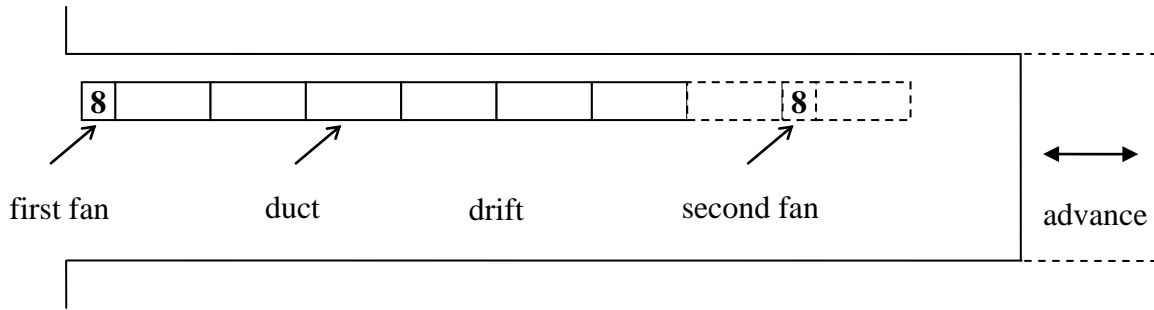
To assess and compare various scenarios, a ventilation model was developed which comprised an advance rate to simulate a drift development where the duct length increased over time; the duct length was increased by adding duct segments as the drift was extended. This provided a more accurate estimate of the energy consumption compared to using a fixed duct length for the project life because this illustrated the change in operating point along the fan curve and the

number of fans needed as the system resistance increased with increasing duct length. The duct length was extended until the maximum length input value from the model was achieved.

Subsequently, it was assumed that the length remained constant but the fan continued to supply air through the duct until the total time corresponded to the project life.

The model was not limited to the use of a single fan for the duct being considered. Once the system resistance exceeded the fan capacity, additional fans were installed in series. The supplementary fans were located at the point in the duct corresponding to the maximum length for the specified fan, as opposed to installing the fans at the beginning, which would increase any leakage in the system due to the higher pressure developed by the fans. However, it is important to note that leakage was not considered in this analysis; it was considered more important to understand the relative performance of the three types of ducting under common operating conditions. In reality, each duct type could have a different leakage resistance, a variable number of leakage locations and specific leakage at any location would be a function of the number of fans, their pressure development and placement. How leakage could be considered has been explored by several authors (Gillies, Wu 1999, Vutukuri 1993, Onder, Sarac et al. 2006, Duckworth, Lowndes 2003) that have led to the development of specific software utilities.

Figure 37 is a graphic representation of a fan and duct system within a drift development.



**Figure 37: Ventilation system of drift development with extending duct**

Input parameters for the model used here comprised: project life, discount rate, duct characteristics (material, diameter, length, friction factor, cost), advance rate, fan parameters (fan curve and efficiency curve values, speed, blade setting, and capital and maintenance costs), motor efficiency, annual operating hours, electricity rate, air density, and shock loss coefficients. It should be noted that the duct length used can correspond to an equivalent length combining the physical length with losses from bends or splits in the system.

The fan characteristic and efficiency curves were used in calculations to determine the fan operating point and energy consumption. It was assumed that the fan characteristic curve could be defined by a second order polynomial equation as illustrated in (13). Values for pressure and corresponding flowrate for the fan characteristic curve were entered and the coefficients (a, b, and c) were determined using least squares regression.

$$P = aQ^2 + bQ + c \quad (13)$$

Subsequently, the same procedure was employed to determine the coefficients (A, B, and C) of the second order polynomial fan efficiency curve:

$$\eta_{fan} = AQ^2 + BQ + C \quad (14)$$



The auxiliary ventilation system resistance corresponded to the sum of the duct resistance ( $R_{duct}$ ), and the equivalent Atkinson resistance from exit and entry shock losses ( $R_{shock}$ ), calculated using (15) and (16) respectively. For the purpose of this assessment, the drift resistance was assumed to be negligible compared to the duct resistance (Duckworth, Lowndes 2003) which was shown by the results from the MTI testing in Table 11, and thus was omitted.

$$R_{duct} = \frac{k \cdot L \cdot \rho}{A^3} \quad (15)$$

$$R_{shock} = \frac{X \cdot \rho}{2A^2} \quad (16)$$

where:  $X$  was the sum of shock loss coefficients for entry and exit losses

$\rho$  was the air density ( $\text{kg/m}^3$ )

$A$  was the duct area ( $\text{m}^2$ ).

The number of fans required was determined based on the length of the duct, equivalent Atkinson resistance from exit and entry shock losses, and the maximum length of duct that the selected fan could handle before entering a stall condition. Equations (16) and (17) were used to determine the maximum duct length per fan and the number of fans respectively.

$$\text{Max } L / \text{fan} = \frac{(R_{max} - R_{shock}) \times A^3}{k \times \rho} \quad (17)$$

$$\text{No. fans} = \frac{L_{duct}}{\text{Max } L / \text{fan}} \quad (18)$$

The operating point of a fan was determined by calculating the flowrate corresponding to the intercept of the fan curve (13) and the system resistance curve (19), in other words the point where the pressure from both equations was the same.

$$P = RQ^2 \quad (19)$$

$$(a - R)Q^2 + bQ + c = 0 \quad (20)$$

where:  $P$  is the pressure (Pa)

$R$  is the total system resistance ( $\text{Ns}^2/\text{m}^8$ )

$Q$  is the flowrate ( $\text{m}^3/\text{s}$ )

$a, b, c$  are the fan characteristic curve coefficients.

Then solving the quadratic formula in (20) yielded the operating point flowrate. Subsequently, the operating point pressure could be calculated by substituting this flowrate into (19). Once the operating point flowrate was calculated it was also possible to calculate the fan efficiency by substitution of this flowrate into (14).

When multiple fans were installed in series, the flowrate was determined by the intercept of the system resistance curve and the combined fan curve. This fan curve was constructed by multiplying the pressure for each flowrate value by the number of fans from the single fan characteristic curve. Then the pressure and efficiency for the individual fans were determined from the single composite fan curve. In this treatment it was assumed that the performance of the additional fans was not affected by its predecessors. Figure 38 shows the system resistance curve of a duct length exceeding the limit of a single fan by 1 meter. The combined and single fan curves, and the fan efficiency curve are also plotted.

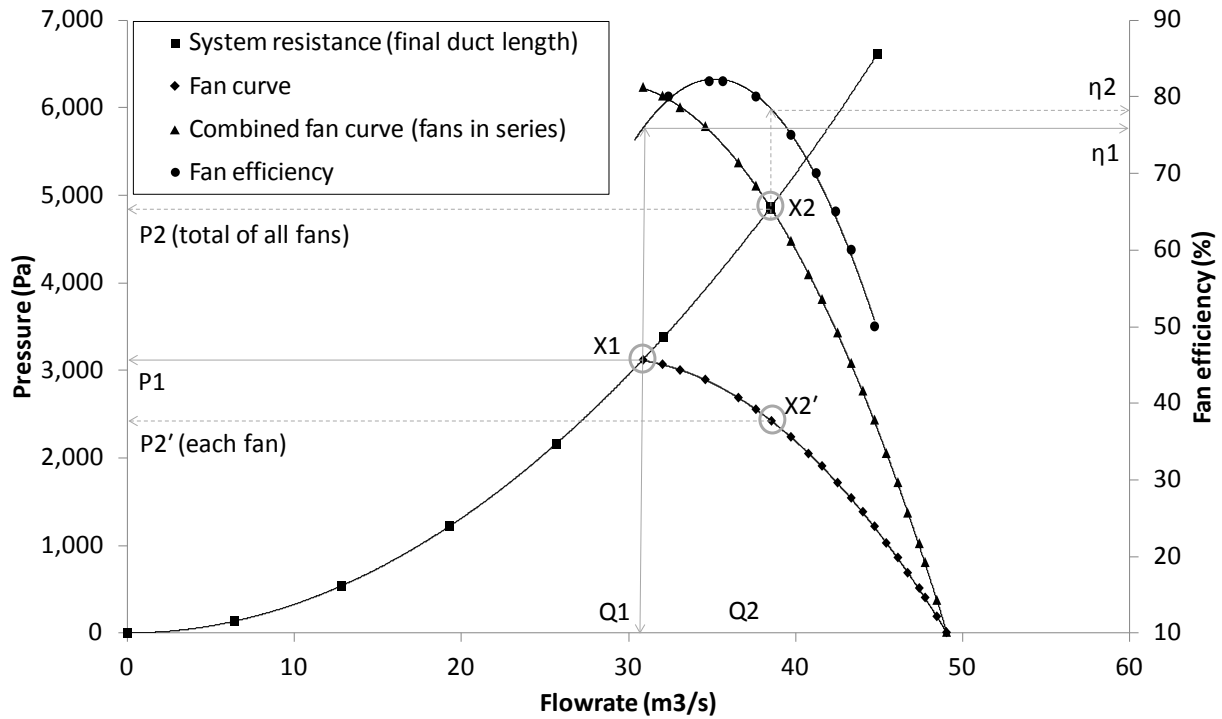


Figure 38: Operation points of single fan and combined fans in series

It can be observed from Figure 38 that for a given system operating at the stall point (X1) the corresponding pressure, flowrate and efficiency are represented by P1, Q1 and  $\eta_1$  respectively. However, when the system resistance was increased to 1 meter beyond the limit of the fan, an additional fan was added to the system. The operating point of this system (X2) was determined by the intercept of the system resistance curve and the combined fan curve, but the operating point for the individual fans (X2') showed that the flowrate (Q2) and the efficiency ( $\eta_2$ ) were higher than that of the single fan operating at the stall point, but the pressure (P2') was lower.

The auxiliary ventilation model was also designed to consider a system equipped with variable speed fans, thus the required airflow then becomes an input value. Using the fan laws, the fan

speed required to deliver the desired airflow was calculated based on the operating point of the system at the fan's maximum speed, illustrated in (21).

$$n_2 = n_1 \left( \frac{Q_2}{Q_1} \right) \quad (21)$$

where:  $n_2$  is the fan speed required to deliver the requested airflow (rpm)

$n_1$  is the maximum fan speed (rpm)

$Q_2$  is the airflow at maximum speed, calculated as the intercept of the system resistance and fan curves ( $\text{m}^3/\text{s}$ )

$Q_1$  is the desired airflow ( $\text{m}^3/\text{s}$ ).

Since the input value for the advance rate was in meters per day, the ventilation analysis was conducted on a daily basis. Capital costs for purchasing the fan and the duct were annuitized to a daily basis following the equivalent annual cost method from McPherson (1993). Then these were added to the daily operational cost, which corresponded to the electricity cost incurred for delivering air through the duct and included the fan and motor efficiencies, also described in McPherson (1993).

The calculations in this section were repeated on a daily basis until the duct length had reached the desired value then the total costs were aggregated annually until the project life was expired. Subsequently, the following output values were computed: annual energy consumption, annual costs (energy, fan, duct, and total), unit costs (\$/m), number of fans required in the system, minimum, maximum, and average flowrate, average pressure and fan efficiency. The average flowrate, pressure and efficiency values corresponded to the life cycle weighted average values

determined for the duration of the project. Specific cost (\$/year)/(m<sup>3</sup>/s) was also computed to compare scenarios and determine the best option for a given situation.

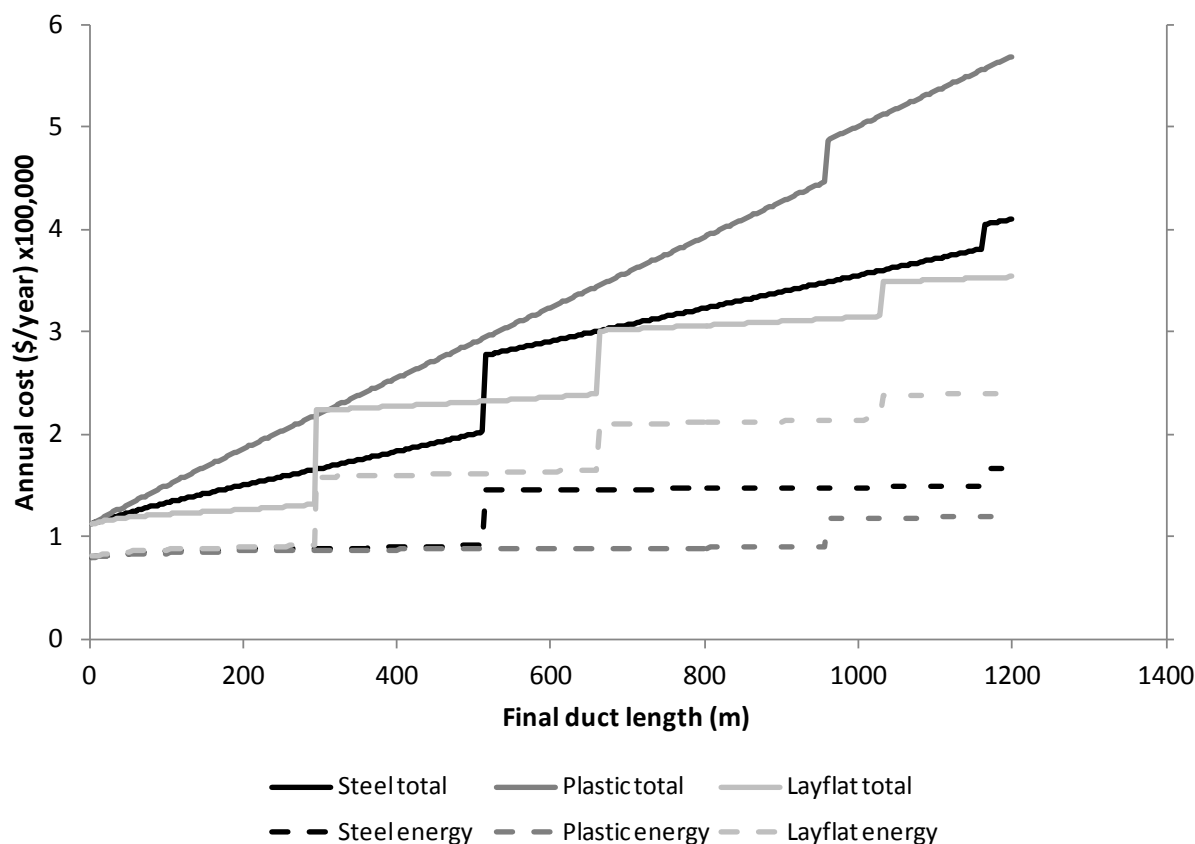
## **8.5 Hypothetical case studies using the ventilation model**

### **8.5.1 Examination of scenarios with fixed-speed, fixed-custom speed, and variable-speed fans, for duct lengths up to 1200m**

Several case studies were examined with the use of the model presented in the previous section. The duct materials compared in the assessments were layflat PVC, plastic, and steel, with duct lengths up to 1200 m. Capital costs for the ventilation systems were computed using the relevant total duct unit costs (\$/m) presented in section 8.4.1, and an estimate of the fan cost obtained from a supplier. Operational costs included an estimate for fan maintenance, and the calculated energy costs derived from the model. The layflat PVC and steel friction factors were obtained from McPherson (1993), whereas the plastic friction factor was the value determined for that of a smooth pipe with a diameter of 0.6m supplying air to the working face in a 25m<sup>2</sup> drift at a maximum air velocity of 4 m/s. Although this value is lower than that determined with the ventilation survey results, the purpose of this study was to illustrate the methodology for assessing ventilation systems with different costs and different duct friction factors. The analysis was completed for a project life of 1, 3 and 5 years to examine the economics of short-, medium-, and long-term projects.

The first set of case studies was conducted using a fan running at 1800 rpm. This could entail the use of a fan from an existing inventory, that has been retired from use in an area where mining was complete. In these scenarios, it was assumed that the ventilation engineer determined that the airflow supplied by the fan at these settings (blade pitch, and fan speed) would meet or

exceed the ventilation requirements. However, there were no attempts to minimize the excess airflow and thus surplus energy consumption from this system. Figure 39 illustrates a summary of the results for a 1 year project using a fixed fan speed of 1800 rpm.



**Figure 39: Summary of annual cost versus final duct length for different duct types**

Figure 39 was derived from 3 scenarios (one for each duct type), all having the same input parameters, and each scenario presented the results of individual case studies for duct lengths ranging from 4 m to 1200 m.

Then another series of scenarios was analyzed, where the minimum flowrate supplied during the project for all duct types and lengths corresponded to 31 m<sup>3</sup>/s, the lowest value from the fixed-

speed fan scenarios at 1800 rpm. This was achieved by setting the fan speed to a custom value for each duct type and length. Although the fan speed was adjusted for each case study it should be noted that it remained constant throughout each project and that at certain points the delivered amount of air exceeded the minimum requirement. An alternative to adjusting the fan speed could have been to adjust the fan blade pitch, which would have also shifted the fan characteristic curve, however to be practical this would require an external method of varying the pitch which would be more costly. These scenarios were used to mimic a situation where a ventilation engineer would make use of a fan from an existing inventory, as in the previous scenarios, but in these cases a one-time adjustment to the fan settings were considered to minimize energy consumption while meeting airflow requirements.

A third analysis was conducted using a variable-speed fan to maintain a constant flowrate as the duct was extended. The input parameters were the same as those for the fixed-speed scenarios however, the fan capital cost was adjusted to include a variable frequency drive (VFD), and the fan speed input was replaced with a flowrate input. The flowrate selected for this analysis also corresponded to  $31 \text{ m}^3/\text{s}$ . Table 17 shows the input parameters used in the case studies, the values for duct diameter through to fan maintenance cost were considered common throughout all cases.

**Table 17: Input parameters for ventilation system analysis**

	Fixed-speed (1800 rpm)	Fixed-speed (custom rpm)	Variable-speed
Duct diameter (m)		1.22	
Advance rate (m/day)		4	
Layflat PVC friction factor (kg/m <sup>3</sup> )		0.0037	
Steel friction factor (kg/m <sup>3</sup> )		0.0021	
Plastic friction factor (kg/m <sup>3</sup> )		0.0011	
$X$ (exit and entry shock loss coefficient) <sup>11</sup>		1.5	
Electricity rate (\$/kWh)		0.08	
Operating hours (hrs/year)		8760	
Motor efficiency (%)		95	
Discount rate (%)		10	
Average air density (kg/m <sup>3</sup> )		1.22	
Fan model	Alphair 4800-VAX-2700		
Fan maintenance cost (\$/year)		360	
Fan capital cost (\$)	30,000	30,000	45,000
Fan speed (rpm)	1800	custom	N/A
Flowrate (m <sup>3</sup> /s)	N/A	31 minimum	31 constant

<sup>11</sup> where  $X$  for exit losses corresponded to 1 and for sharp-edged entry losses was 0.5

(McPherson 1993)



Figure 40 summarizes the results for ventilation systems equipped with a fixed-speed, a fixed-custom speed, or a variable-speed fan, for a project life of 1, 3, and 5 years. The results include total annual costs (capital and operational) illustrated by the solid lines, and annual energy costs shown by the dashed lines for all duct types considered in the case studies. It should be noted that although the analysis was conducted using an advance rate, the results represent the average annual cost corresponding to projects with various final duct lengths ranging from 4 m to 1200 m. This should not be confused with the life-cycle cost of a duct extended from 4 m to 1200 m.

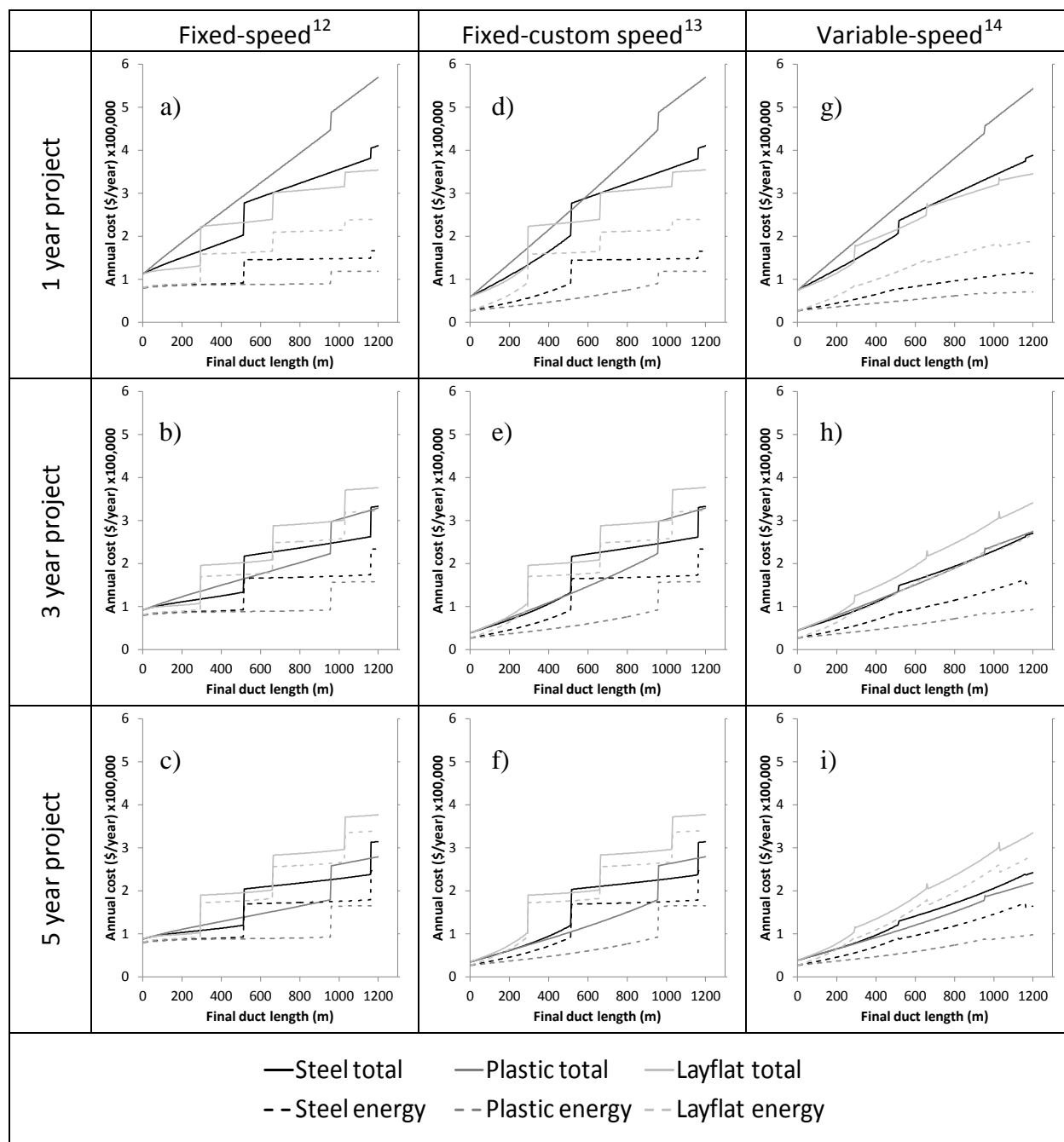


Figure 40: Total and energy costs for ventilation systems of various duct materials and lengths

<sup>12</sup> Use of a fan from an existing inventory, such as one that is retired from use in an area where mining is complete, without consideration of the fan settings.

<sup>13</sup> Use of the same fan as with the fixed-speed, 1800 rpm scenarios, but fan speed is set such that the minimum air supply meets requirements, but the speed is constant throughout the project.

<sup>14</sup> Use of the same fan as other case studies but a variable frequency drive is added to control the fan speed and maintain a constant airflow throughout the project.

Throughout Figure 40 it can be seen that the plastic duct system consumed the least amount of energy for all scenarios, regardless of the project duration or fan settings. The steel duct was the second lowest energy user and the layflat was the highest energy consumer. This is to be expected as it is directly related to the friction factor. The relative differences were small on the shorter duct lengths where the entry and exit losses common to each were more dominant. The relative spacing between the energy use profiles also varied as a function of length, reflecting the differences in the number of fans employed. Also, as might be expected, as the project duration increased, the proportion of total costs attributed to energy costs increased for each duct type at corresponding duct lengths.

From the simulation results shown in Figure 40a, it can be seen that the most costly option overall corresponded to the plastic system for all duct lengths, despite its energy cost being the lowest. However which was cheapest depended on the final duct length. Up to 292 m, the option with the lowest total cost was the layflat PVC duct, but at a duct length of 292 m through to 515 m where the layflat PVC needed a second fan the steel system became the cheapest. At this distance the steel system required an additional fan and the layflat PVC again became the lowest cost option. Despite the addition of fans to both systems at longer lengths, the layflat PVC duct remained the cheapest to 1200 m.

Throughout panels a to f of Figure 40, it can be seen that whether a certain duct has the lowest combined operating and capital cost, is the most expensive or is comparable is very dependent on the step changes, corresponding to the requirement of supplementary fans in the ventilation system. These figure panels (a to f) also show that the step change becomes less significant for longer duct lengths as the operating cost (energy) becomes more dominant. The cause of these notable step changes in panels a to f is two-fold: the obvious increase in capital cost for

purchasing the additional fan, and then an increase in operational cost as a result of the system supplying higher flowrates than required when the fans are combined in series, as exemplified previously in Figure 38. At the change over point, the increased flowrate increased the power. Although the pressure was lower and the efficiency was higher than that of the single fan at the stall point, these differences were not sufficient to overcome the effect of the increased flowrate when a second or third fan was added, due to the cubic relation between the power and the flowrate.

Comparing panels a to c of Figure 40 highlights the time factor and that energy becomes more dominant in the long-term. It can be observed from Figure 40b that all options had similar costs up to 50 m and that the steel and layflat options were comparable up to 80 m but the lowest cost option was the layflat PVC duct up to a length of 292 m. At this point where an additional fan was added to the layflat PVC system, the steel option was the lowest cost up to a duct length of 515 m. Then when an additional fan was added to the steel system, the plastic duct still operating with one fan became the most economical solution until it needed a second fan. The lowest total cost system for these scenarios alternated between the steel and plastic ducts with the addition of supplementary fans in each system. The steel was cheaper where both systems employed the same number of fans, while the plastic was cheaper as long as it needed less fans.

Figure 40c shows that the economics for a 5 year project with a fixed-speed fan at 1800 rpm were similar to those of the 3 year project. For short systems employing one fan the difference between the various types of duct are even less significant. The layflat PVC is the lowest cost system up to 292 m then the steel option becomes the cheaper system while the layflat PVC required an additional fan. Beyond 515 m the lowest cost option would be plastic ducting as long as it required less fans than the other systems.

In Figure 40d through f where the fan has been set to a customized fixed duty, it can be observed that the lowest total cost options for the shorter duct length and project life scenarios alternated between the layflat PVC and steel ducts depending on the number of fans required in the systems. However as for the fixed speed fan, steel and plastic would be the preferred choice for longer length and life systems. The plastic duct increasingly becomes the low cost option with the longer project life and longer length when it required less fans. As shown in Figure 40f, the plastic duct was the most economical up to 956 m and beyond 1160 m.

Figure 40g through i show the benefits of systems with a fixed delivery provided by variable speed fans. Throughout, the step changes incurred on introducing additional fans are less significant. This indicates that the capital cost of the fan is less of a factor compared to the additional flow provided in the previous two fixed duty scenarios. These figures also show that the cost benefit of one type of duct over another can be less distinct with volume control.

Figure 40g shows that the plastic system was the most expensive option at all duct lengths for a 1 year installation life. A similar low cost alternating pattern was observed between the layflat PVC duct and the steel duct depending on the number of fans in the systems up to 515 m beyond which the layflat PVC system remained the lowest cost option regardless of when fans were added to this system. This figure also shows that the energy cost did not rise as abruptly as in the fixed-speed fan scenarios due to maintaining a constant flowrate, and thus controlling the power. The energy step function can also be reversed, through Figure 40 g to i, it can be seen that the addition of an extra fan can reduce the overall annual operating cost (energy) compared to operating a fan or fans near their stall condition at low efficiency.

As the life of the installation lengthens from 1 to 3 and then 5 years, the layflat PVC clearly becomes the least attractive. For the 3 year case study, the most economical solution alternates between the steel and plastic options. For the 5 year project, when the energy costs start to dominate, the plastic system was the lowest cost option for all duct lengths beyond 200 m.

Overall these figures show that the choice of ducting type should be reasonably straightforward for a long term project where a constant flow is maintained, especially for long installations. However, where less concern is given to providing the appropriate flow, the optimum selection becomes more orientated to the system using the lowest number of fans.

### **8.5.2 Flow variability**

The hypothetical case studies with a fixed-speed fan (either at 1800 rpm or at a custom speed selected to deliver the minimum flowrate) supplied varying flowrates for each duct type at a specific length because of the different resistances of the materials. This is illustrated in Figure 41 which shows the system resistance curves for a 200 m layflat PVC, steel and plastic duct. Each resistance curve intersects the fan curve at a different point with a different associated efficiency.

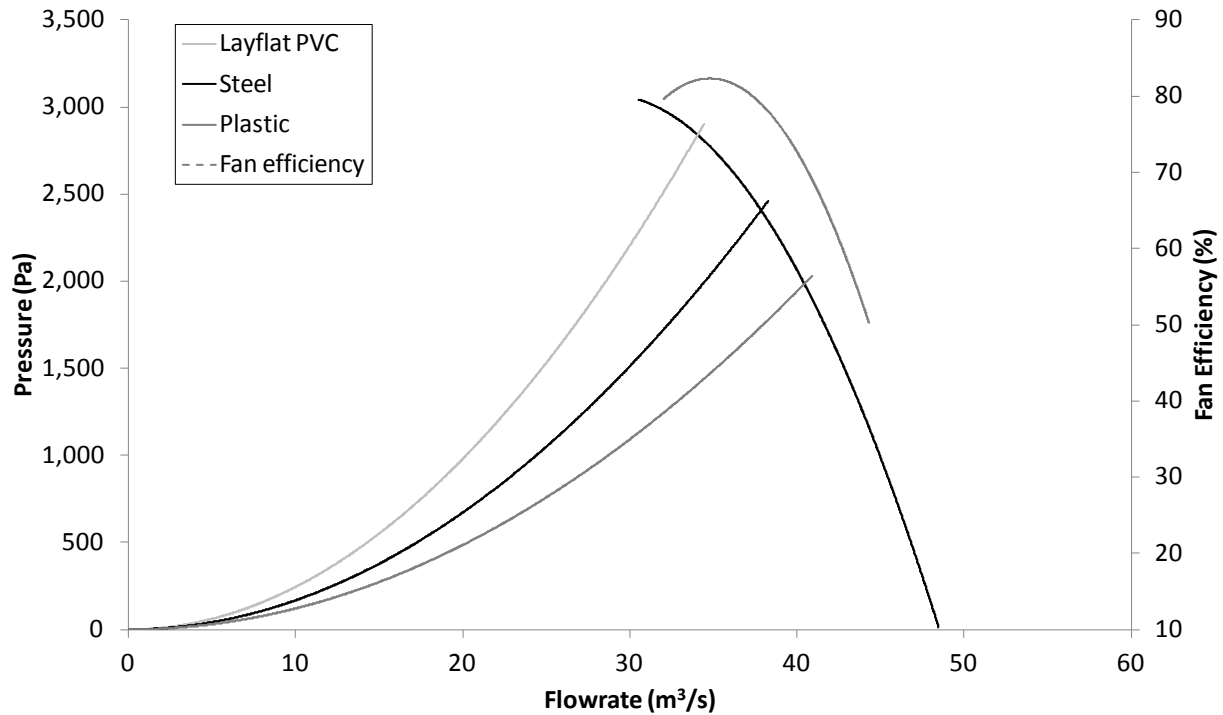


Figure 41: System resistance curves for a 200 m duct length of layflat PVC, steel and plastic duct

Figure 41 shows that the layflat PVC duct delivered the least amount of air at the highest efficiency whereas the plastic duct delivered the most air at the lowest efficiency.

However, as and when additional fans are added with increasing duct length the relative delivery of each system will change, which was also illustrated in Toraño Álvarez *et al.* (2002). For example, Figure 42 shows the flowrate supplied at the end of the duct for each of the systems at various duct lengths corresponding to the case studies with the fan speed set at 1800 rpm.

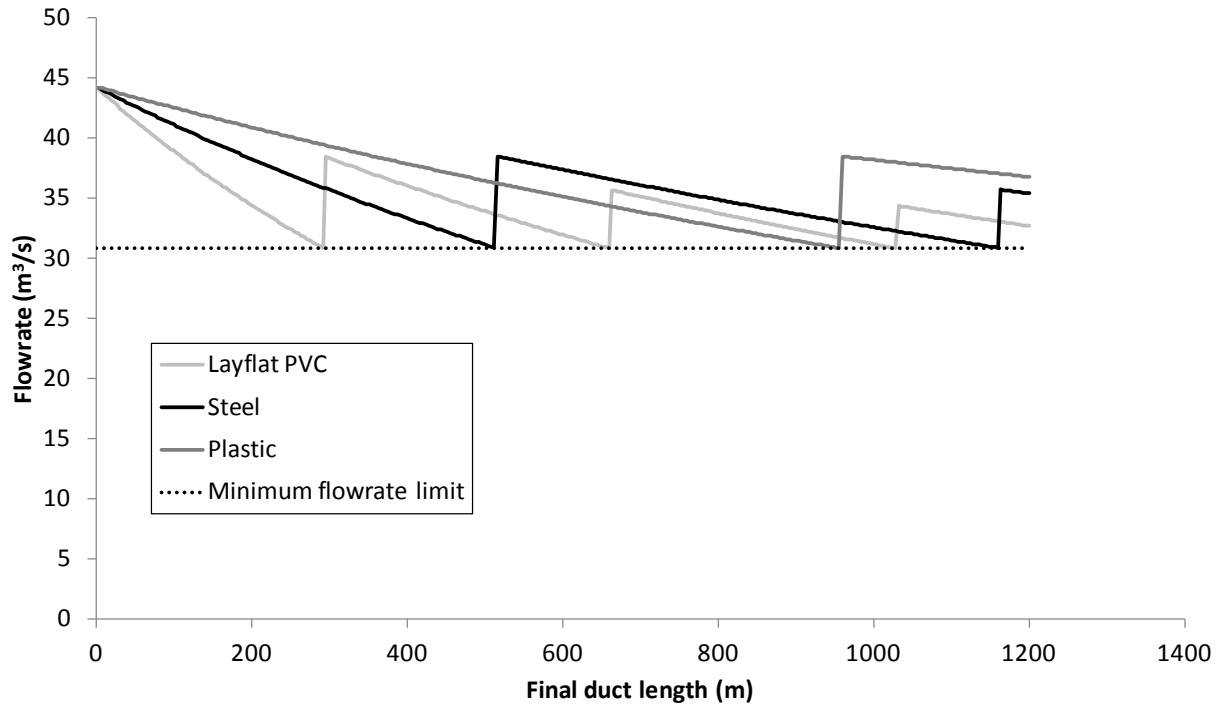


Figure 42: Supplied flowrate versus final duct length for fixed speed fan at 1800 rpm

This figure shows that substitution of one type of duct for another for a given fan could lead to varying degrees of over-supply of air for a given duct length. With consideration given to specific fan settings, the oversupply of the steel and plastic ducts would be less than that of the layflat as long as these systems are operating with a single fan. With a variable speed ventilation system the minimum flow would be maintained throughout.

Consequently, fixed-custom speed and variable speed systems should consume less energy than the fixed-speed 1800 rpm scenarios at corresponding duct lengths and project durations. This illustrates the important fact that the selection of the lowest energy consuming duct based on a lower friction factor despite maximizing energy savings may not give the most cost effective solution. Thus when a fan is taken from an existing inventory, it is imperative that the fan



characteristics are examined to determine: i) whether the fan is suited for this situation, and ii) whether the fan settings are optimal to minimize operational costs.

### 8.5.3 Potential energy savings

Energy savings in auxiliary ventilation systems can be achieved by controlling the air flow or by substitution of a duct with one having a lower friction factor. Figure 43 and Figure 44 shows the potential energy savings of the fixed-custom speed fan and the variable-speed case studies compared to their fixed-speed 1800 rpm counterparts throughout their advance and while at maximum extension for the duration of the project.

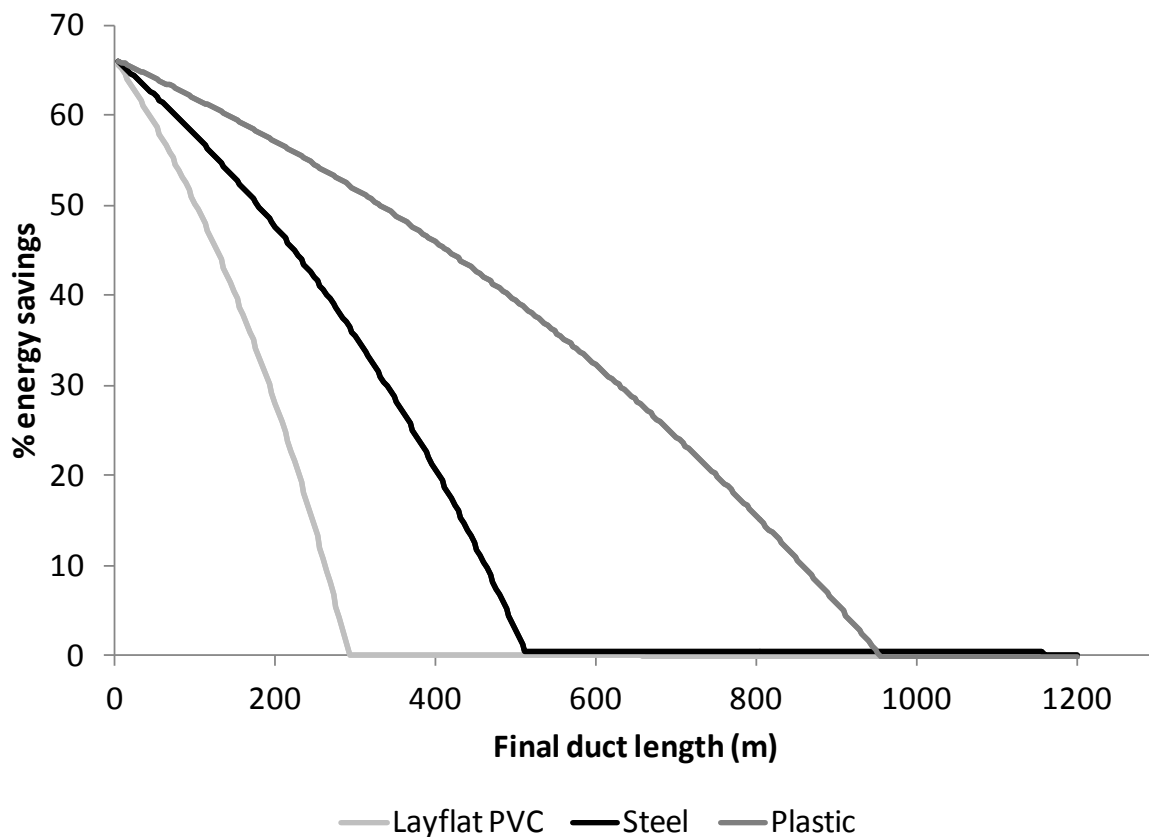
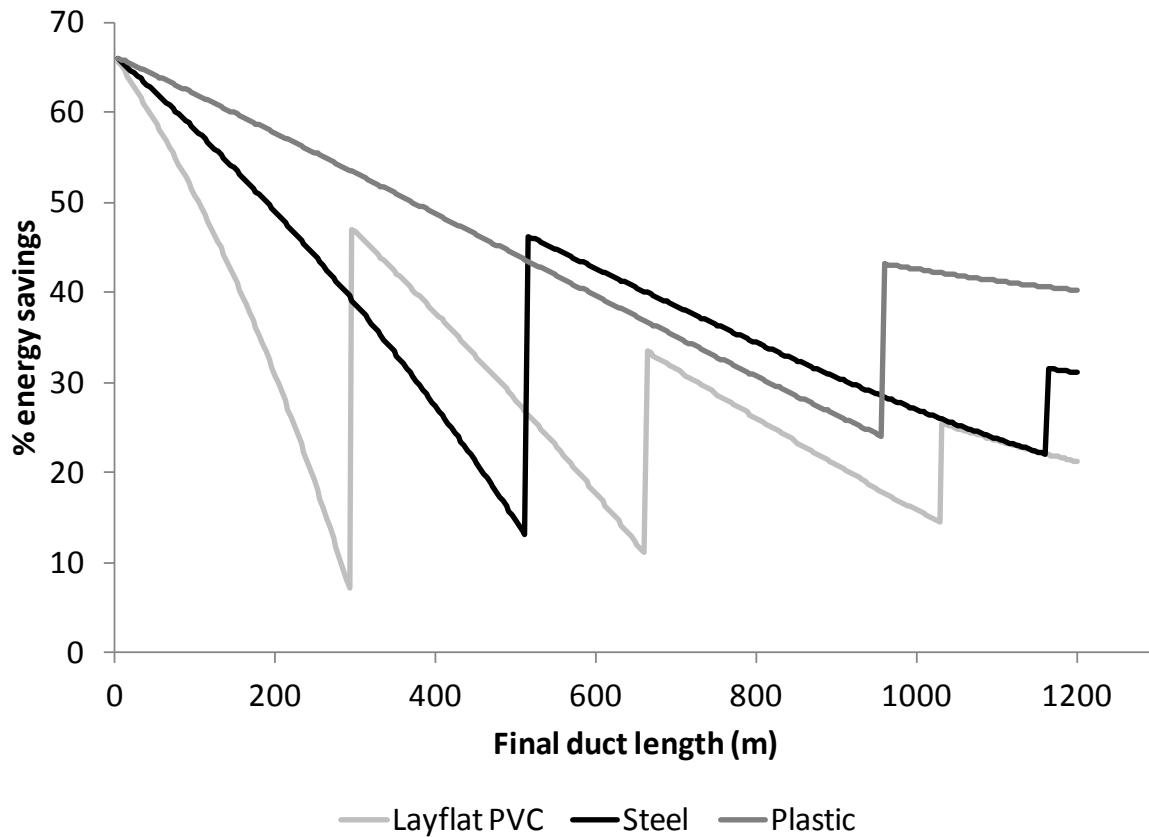


Figure 43: Energy savings for fixed custom speed fan compared to fixed speed stock fan for 1 year project



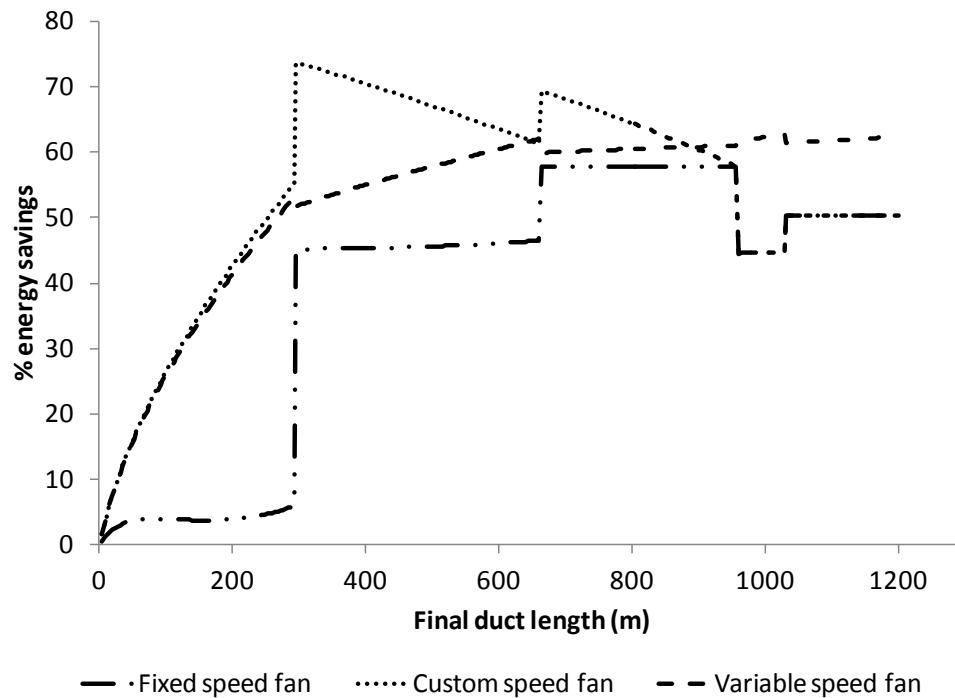
**Figure 44: Energy savings for variable speed fan compared to fixed speed stock fan for 1 year project**

The lowest energy savings for both the fixed-custom speed and variable-speed fans occurred at duct lengths where a second fan was added to each of the systems. There were no savings for the fixed-speed system compared to the one with the fan at 1800 rpm when a second fan was added because at a certain design length both systems would have fans operating at 1800 rpm and delivering the same amount of air, thus the operating points of these systems were the same throughout the duration of the project.

The maximum savings occurred at the shortest length, because the largest fan speed reduction compared to the fixed-speed fan at 1800 rpm occurred at the shortest length, and correspondingly the larger reduction in airflow between systems.

Figure 43 and Figure 44 also illustrates that proper speed selection for a fixed-speed fan can deliver similar energy savings than with the use of a variable-speed fan compared to the fixed-speed stock fan option. At the shortest duct lengths, the energy savings between these systems were comparable for a given duct type, however the savings between these systems increased with duct length. For example, the energy savings for a 100 m plastic duct was 62% for both the fixed-custom speed and variable-speed fan systems compared to the fixed-speed stock fan. For a 500 m plastic duct the energy savings corresponded to 39% with the use of a fixed-custom speed fan, and 44% with the variable-speed fan, thus the additional savings for the variable-speed system was 5%. However, the energy savings for a 800 m plastic duct were 16% and 31%, thus the variable-speed option provided an additional 15% energy savings. The energy savings increased with duct length for two reasons. First, at a short duct length, the range of fan speed for a variable-speed fan to maintain a constant airflow was less than for a longer duct, thus the savings were minimal. Second, although the fixed-custom speed fan systems delivered more air than that required at the start of the projects, once the final duct length was reached they operated at the same operating point as the variable-speed systems. For short ducts, this point was reached quicker therefore the energy consumption was mainly influenced by the final operating point, which was the same for these systems.

Another option to reduce energy consumption would be through the use of a lower friction duct while keeping the same fan. Figure 45 illustrates the potential energy savings of substituting the layflat PVC duct with plastic for a 1 year project.



**Figure 45: Energy savings from substitution of a layflat duct for a plastic duct for 1 year project**

For plastic substitution with a fixed custom speed fan the savings increase when additional fans are introduced in the layflat system because of the increased flowrate when a fan is added. The savings were reduced when a second fan was added to the plastic duct system for the same reason. The maximum savings from substitution of the layflat duct with a plastic one with a fixed-speed fan corresponded to 58%.

In the custom-speed scenarios, the maximum savings from duct substitution corresponded to 74% and occurred at the duct length where a second fan was added to the layflat system, the reason again being the increased flowrate. At duct lengths greater than 956 m, both the layflat

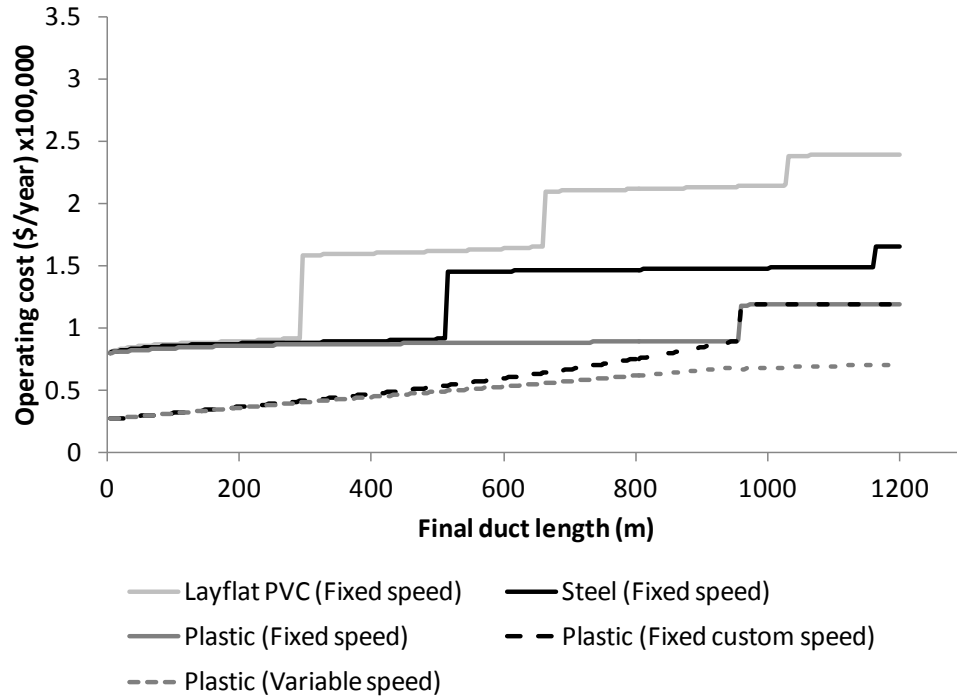
and the plastic systems have fans operating at 1800 rpm to supply the design flowrate, thus the savings for these lengths are the same as for the fixed-speed fan scenarios.

In the variable-speed scenarios the savings increased with duct length, where small reductions in savings were observed when additional fans were introduced in the layflat system because of the higher fan efficiency. The maximum energy savings corresponded to 63% and occurred at the longest duct length examined in the scenarios.

The energy savings in the fixed-speed fan scenarios were greater than those with the variable-speed fan when more than one fan was used in the layflat system because the excess flowrate, resulting from introduction of additional fans, was controlled in the variable-speed option.

Although duct substitution and flowrate control provide measures for energy savings, the use of both strategies would maximize energy conservation in auxiliary mine ventilation systems.

Figure 46 shows the annual operating costs, corresponding to electricity costs for the various duct types examined in the case study using a fixed speed fan compared to the plastic option where the flowrate was controlled for a 1 year project.



**Figure 46: Energy costs from duct substitution and flowrate control for 1 year project**

Figure 46 shows that although the plastic duct consumed less energy than the other duct types with a fixed speed fan, the energy use was lessened when the flow rate was controlled. For short duct lengths the energy consumption between the fixed custom speed and variable speed options were similar. As the duct length increased, the energy savings from the variable speed system increased because the fixed custom speed fan delivers excess air until the final duct length is reached, which occurs later for longer ducts.

Project duration also influenced the annual operating costs as illustrated in Figure 47 and Figure 48.

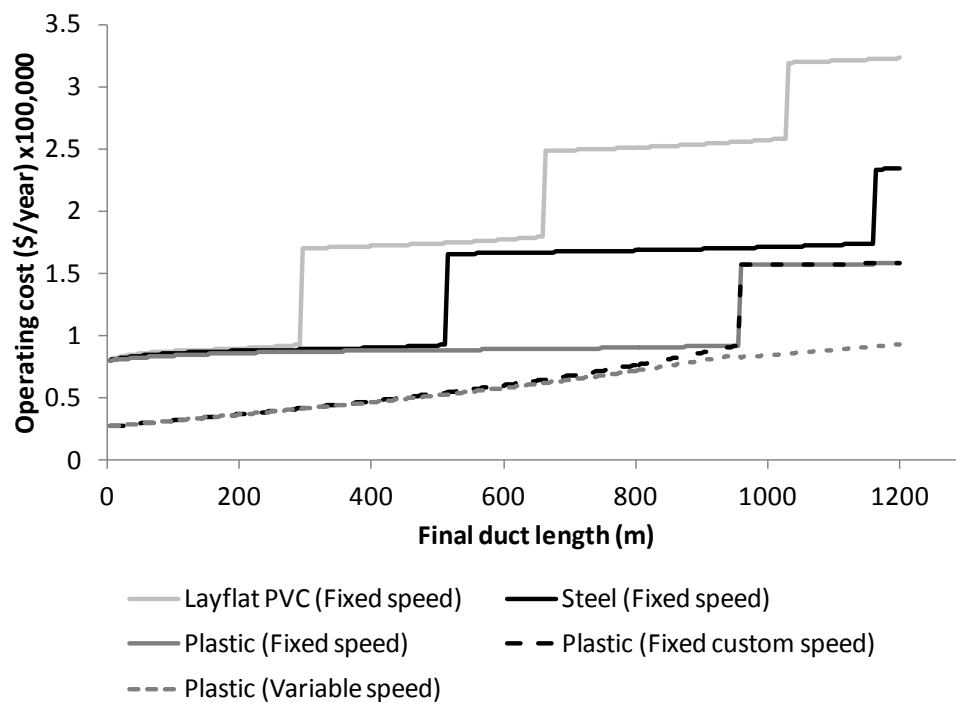


Figure 47: Energy costs from duct substitution and flowrate control for 3 year project

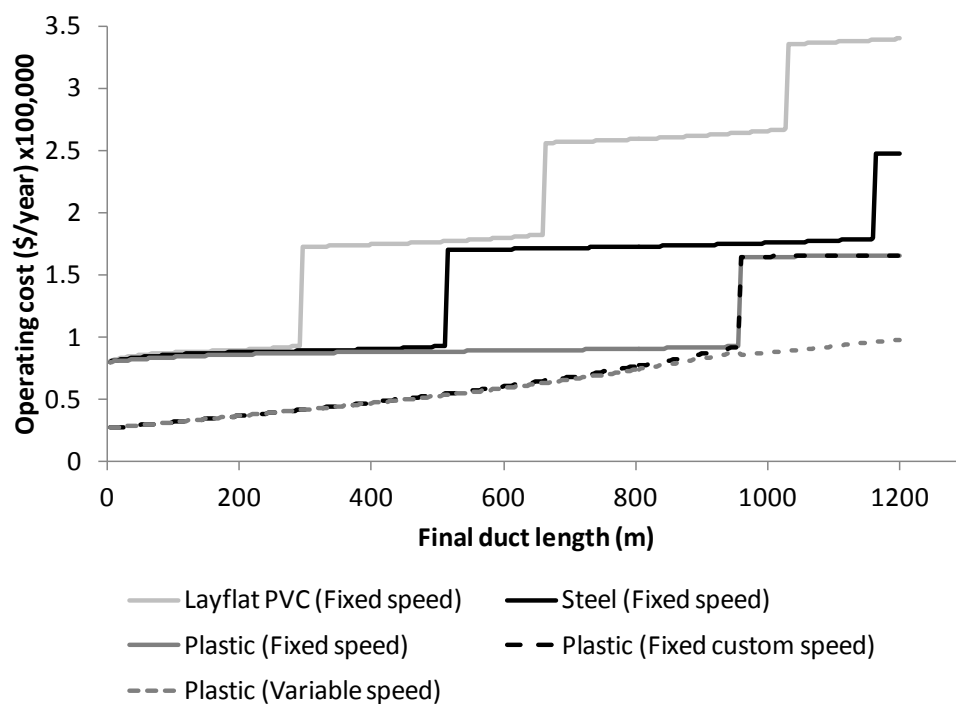
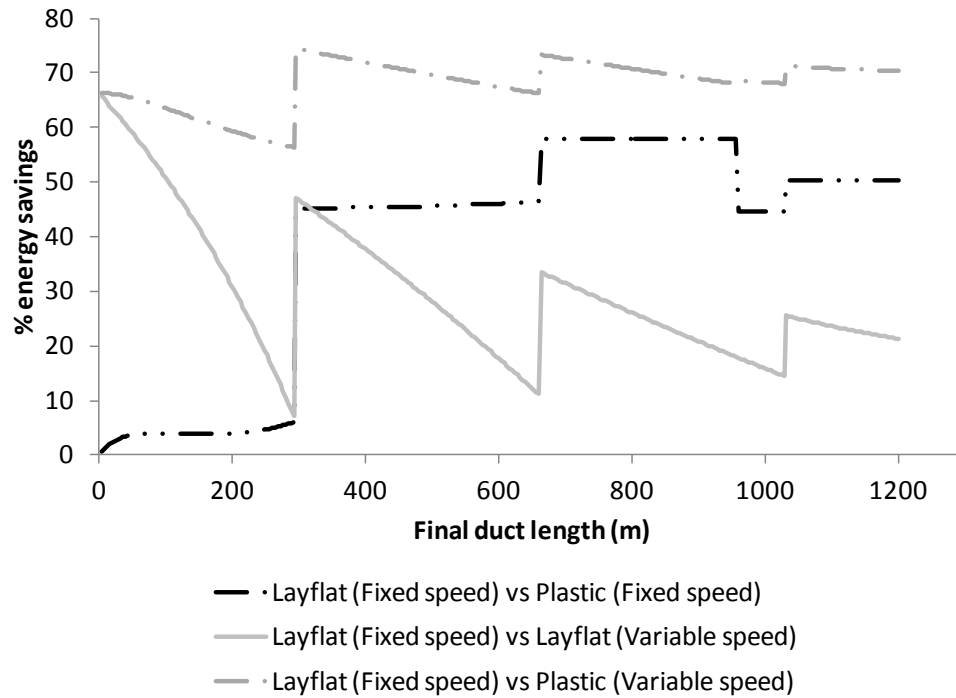


Figure 48: Energy costs from duct substitution and flowrate control for 5 year project

It can be observed from Figure 47 and Figure 48 that the lower friction plastic duct with flowrate control options consumed the least amount of energy. However, the difference between the fixed custom speed and variable speed fan systems with one fan was reduced because both systems were at the same operating point for longer durations. The variable speed fan provided energy savings via flowrate control as the duct was being extended but once the final duct length was reached both systems operated at the same speed. As the project life lengthened the proportion of time corresponding to the installation period where the duct length was extended was smaller; thus the energy savings were reduced. The advantage of the variable speed system occurred in systems with more than one fan by minimizing the discontinuity introduced by the excess flowrate when additional fans were added to the fixed custom speed system.

Energy savings can be obtained in auxiliary mine ventilation systems by substitution of the duct with one with a lower friction factor, or by controlling the excess flowrate in a given system but energy savings could be maximized with the use of both measures. Figure 49 compares the potential energy savings of the individual and combined measures.





**Figure 49: Potential energy savings from duct substitution and flowrate control**

In Figure 49, the “Layflat (Fixed speed) vs Plastic (Fixed speed)” series demonstrated that the potential energy savings from duct substitution varied from 1% to 58% depending on the final duct length. The “Layflat (Fixed speed) vs Layflat (Variable speed)” series illustrated the potential energy savings from flowrate control, ranging from 7% to 66%. It can be observed that the potential for energy savings, ranging from 56% to 74% was greater when both energy conservation measures were combined, shown by the “Layflat (Fixed speed) vs Plastic (Variable speed)” series.

#### 8.5.4 Capital cost versus energy savings

Although the steel and plastic installations consumed less energy, the higher capital costs for these systems in certain scenarios presented an obstacle to ranking these materials as the lowest

cost option. Regardless of the type of system (fixed-speed or variable-speed fan), for short-term projects, the energy savings were not sufficient to recover the higher capital cost of the plastic duct. For medium and long-term projects, the economic viability of the lower energy cost systems was improved, and for some duct lengths the plastic system was the lowest cost option.

The variable-speed ventilation systems investigated within the case studies that had lower energy costs than their fixed-speed counterparts were due to the flowrate control which lowered the energy consumption. However, for short duct lengths, the fixed-custom speed scenarios had lower total costs for all projects for two reasons. First, the capital cost increased because an additional \$15,000 was incurred for the purchase of the VFD, corresponding to a fan capital cost increase of 50%. Second, the range of flowrate values, between the start of the duct and the final design length as supplied from fixed-custom speed systems, was small for short ducts. Thus where the excess flowrate was small, the energy savings directly related to flow were similarly small.

For fixed-speed systems, the addition of supplementary fans leads to an increased flowrate, resulting in higher energy cost. In some instances, this increase was sufficient to alter the ranking of options based on total cost.

Thus when capital costs are included, the lowest energy system may not be the cheapest option; energy use, capital costs and project duration are variables that influence the economic viability of the various systems.

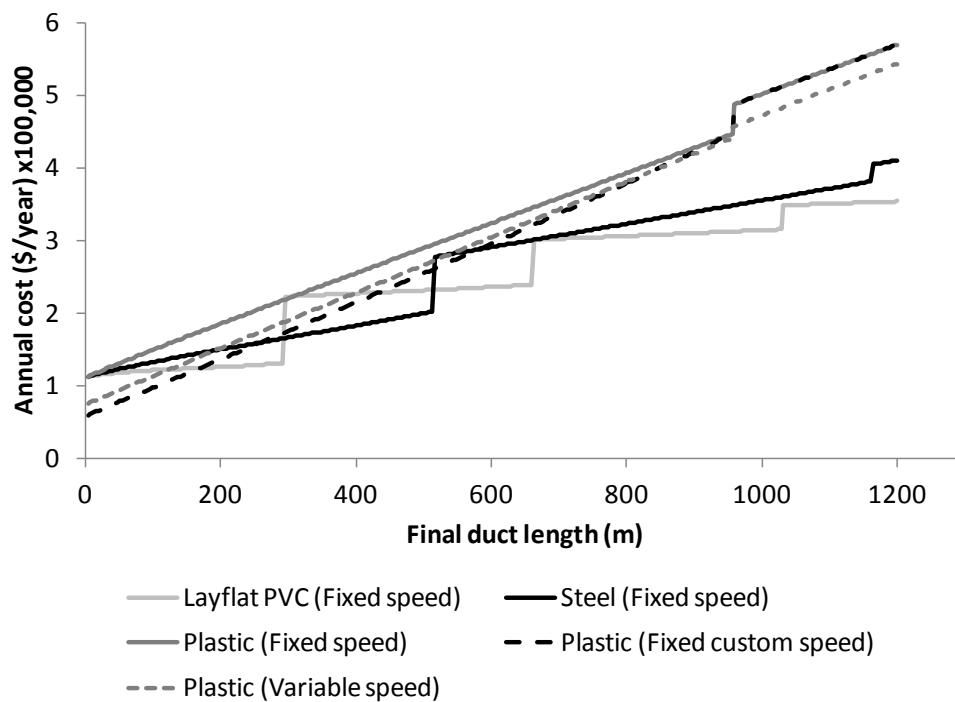


Figure 50: Annual costs from duct substitution and flowrate control for 1 year project

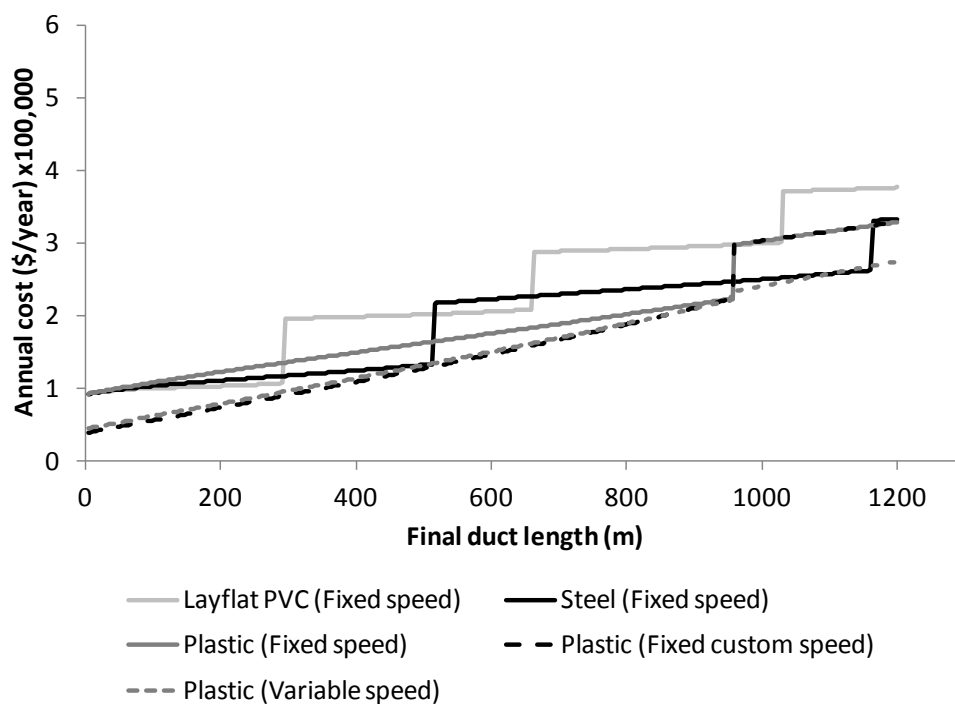
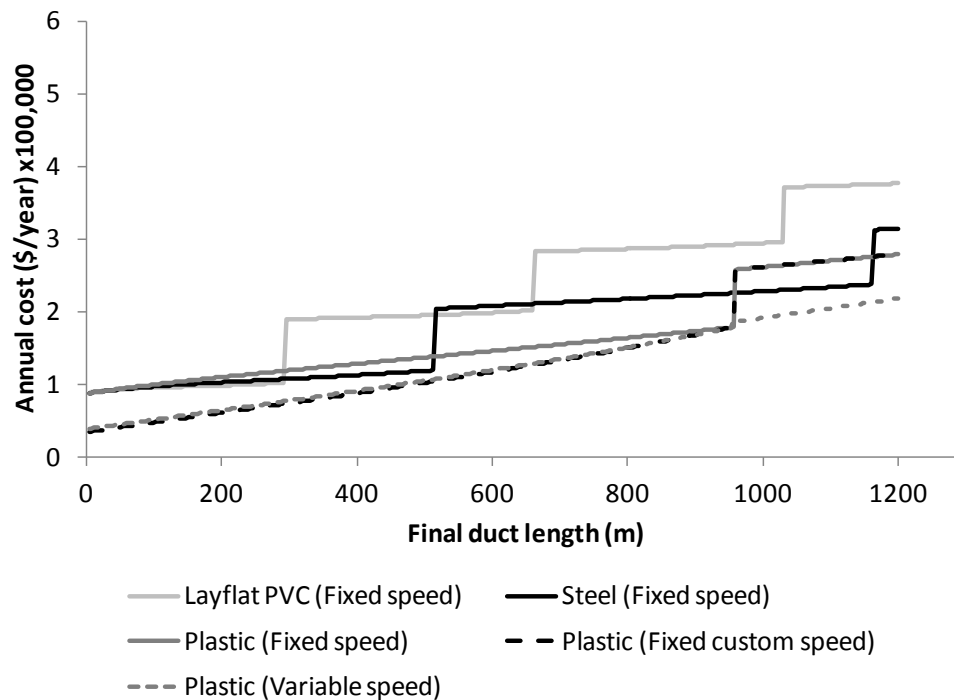


Figure 51: Annual costs from duct substitution and flowrate control for 3 year project



**Figure 52: Annual costs from duct substitution and flowrate control for 5 year project**

From Figure 50 it can be observed that for a 1 year project, although the energy use was minimized with use of the plastic duct and flowrate control, these systems were the lowest cost options for short duct lengths only. However from Figure 40 it was shown that the steel and layflat PVC systems were cheaper than the plastic option with flowrate control. Thus regardless of whether the energy savings were maximized via flowrate control, the economics did not favor the plastic system.

For the 3 year project options illustrated in Figure 51 it can be seen that the cheapest option corresponded to the plastic system with flowrate control. For systems with one fan, the cost of the variable speed and fixed custom speed fan options were comparable, but the variable speed

fan system was the cheaper option with two fans. However, from Figure 40 it was observed that for fixed custom speed systems the cost of the steel and plastic systems were comparable when both options had only one fan. Conversely, the costs of the steel and plastic systems with variable speed fans were comparable for all duct lengths. Thus the lowest cost system in these scenarios corresponded to the steel or plastic duct with either a fixed custom speed or a variable speed fan with one fan installed in the steel system. When a second fan is introduced in the steel system the fixed custom speed option cost rose above the other system costs and left the plastic duct with a fixed custom speed fan and the steel and plastic ducts with variable speed fans competing for the lowest cost. Subsequently, the addition of a second fan in the plastic system eliminated the fixed custom speed scenario from the lowest cost options, thus only the steel and plastic systems with a variable speed fan remained for longer duct lengths.

In Figure 52 it can be observed that for a 5 year project the lowest cost options corresponded to the use of a plastic duct with either a fixed custom or variable speed fan when the system only required one fan. When a second fan was added, the cost of the plastic system with a variable speed fan was the lowest. But from Figure 40 it was observed that the costs of the steel duct with a fixed custom speed or a variable speed fan were comparable to that of the corresponding plastic systems for short duct lengths. Thus the lowest cost option corresponded to either of these four systems. For duct lengths greater than 200 meters the cost of the plastic system operating with only one fixed custom speed fan was lower than its steel counterpart. When a second fixed custom speed fan was added to the plastic system, the steel option was cheaper however the cost of the plastic duct with a variable speed fan system was even lower.

As there are a large number of possible scenarios that can exist, it was not possible to examine every plausible situation; therefore the model used in this study has been made available for

individual users to explore custom scenarios and to assist in determining the optimal solution for a given mine ventilation system, whether the objective is to choose the lowest cost or lowest energy consumption option (Levesque, Millar 2015a).

## **8.6 Examination of leakage effects on ventilation survey results**

A subsequent model was developed to investigate the effect of leakage in auxiliary mine ventilation systems. The leakage model retained the feature to model a duct as a drift is extended from the original leak-free model but to determine the operating point of the fan, an equivalent system resistance is calculated using a series-parallel methodology based on that presented in Vutukuri (1983).

### **8.6.1 Series-parallel theory and resistances**

The resistance of the various components in an auxiliary ventilation system can be connected in series or in parallel. Figure 53 illustrates a ventilation system with the following components: an inlet bell (blue), a fan (green), and four duct segments (yellow) which are installed in a drift. In this simple system, the leakage at the joints between the components may be considered to be connected in parallel between the duct and the drift. The jagged lines in the diagram represent the resistance of the various components;  $R_{d1}$  is for the inlet bell,  $R_{d2}$  is for the fan,  $R_{d3}$  to  $R_{d5}$  are for the duct segments,  $R_{sh} = R_7$  is for the exit shock loss,  $R_{b1}$  to  $R_{b5}$  is for the drift, and  $R_{j1}$  to  $R_{j5}$  are for the leaks.

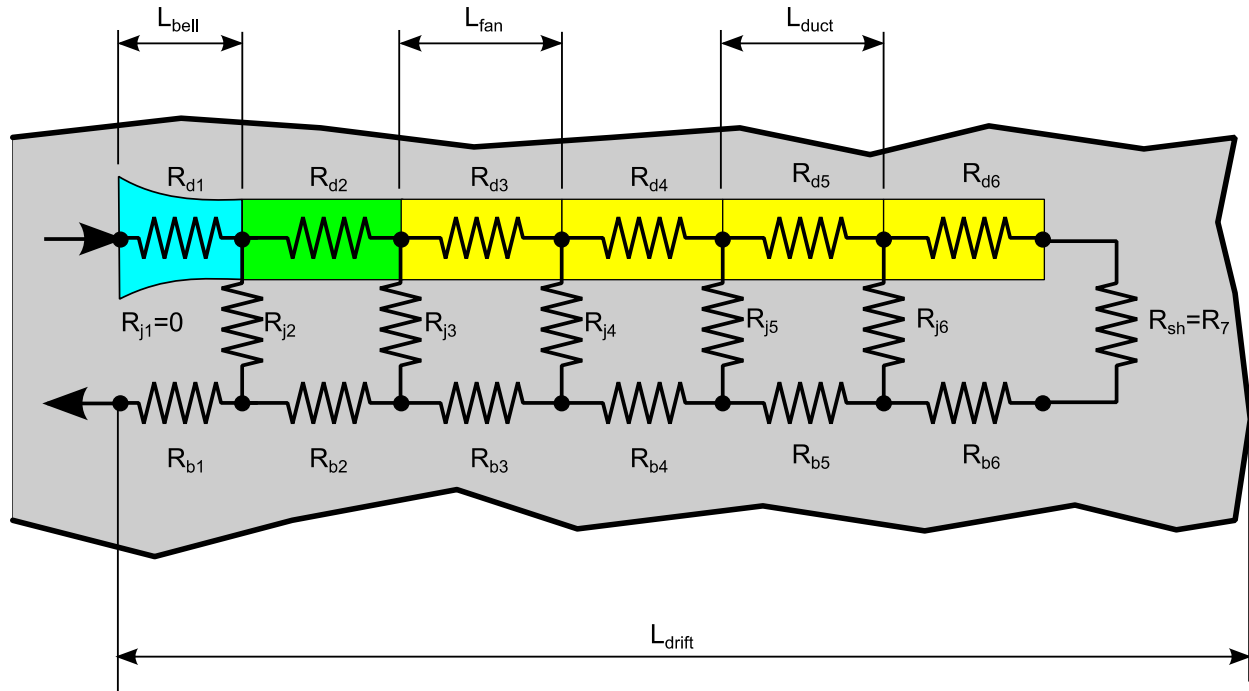


Figure 53: Schematic of series-parallel theory in an auxiliary ventilation system

The resistance for each drift and duct segment is calculated using (8) and (15) respectively (McPherson 1993). The exit shock loss is calculated as (16) where  $X$  corresponded to a value of 1 and the inlet bell resistance was also calculated by (16) but the value of  $X$  was 0.03 (McPherson 1993). A resistance value for the leakage paths is entered as an input to the model where the resistance for all leakage paths is assigned this value. However, any of the individual leakage resistance values can be overwritten to simulate a poor joint or a very good seal at any location in the system. All resistance values have the units of  $\text{Ns}^2/\text{m}^8$ .

Calculation of the resistance for a system with components in series corresponds to the mathematical sum of the individual resistances. However, for parallel resistances, the system resistance is calculated using (22) from McPherson (1993).

$$\frac{1}{\sqrt{R_{par}}} = \sum \frac{1}{\sqrt{R}} \quad (22)$$

Calculation of the system resistance for the simple ventilation system in Figure 53 which comprised resistances in series and in parallel proceeded as follows, and is illustrated in Figure 54.

1. Calculations begin by calculation of the last branch, represented by  $R_6$  at the end of the duct.
2. The resistances of the last duct segment ( $R_{d6}$ ), the exit shock loss ( $R_{sh}=R_7$ ), and that of the drift segment ( $R_{b6}$ ) are summed since these are joined in series.
3. Then  $R_{j6}$  is added to the calculations but this resistance is in parallel with those from step 2, thus  $\frac{1}{\sqrt{R_6}} = \frac{1}{\sqrt{R_{j6}}} + \frac{1}{\sqrt{R_{d6}+R_{sh}+R_{b6}}}$  where  $R_6$  is considered the equivalent resistance of the last branch.
4.  $R_6$ ,  $R_{d5}$  and  $R_{b5}$  are connected in series and thus are summed, but the sum of these is in parallel with  $R_{j5}$ , thus the equivalent resistance of the last two branches in the system is calculated using  $\frac{1}{\sqrt{R_5}} = \frac{1}{\sqrt{R_{j5}}} + \frac{1}{\sqrt{R_{d5}+R_{b5}+R_6}}$
5. The procedure continues until the resistance of all of the branches has been characterized by one equivalent resistance value represented by  $R_1$  in the bottom frame of Figure 54.



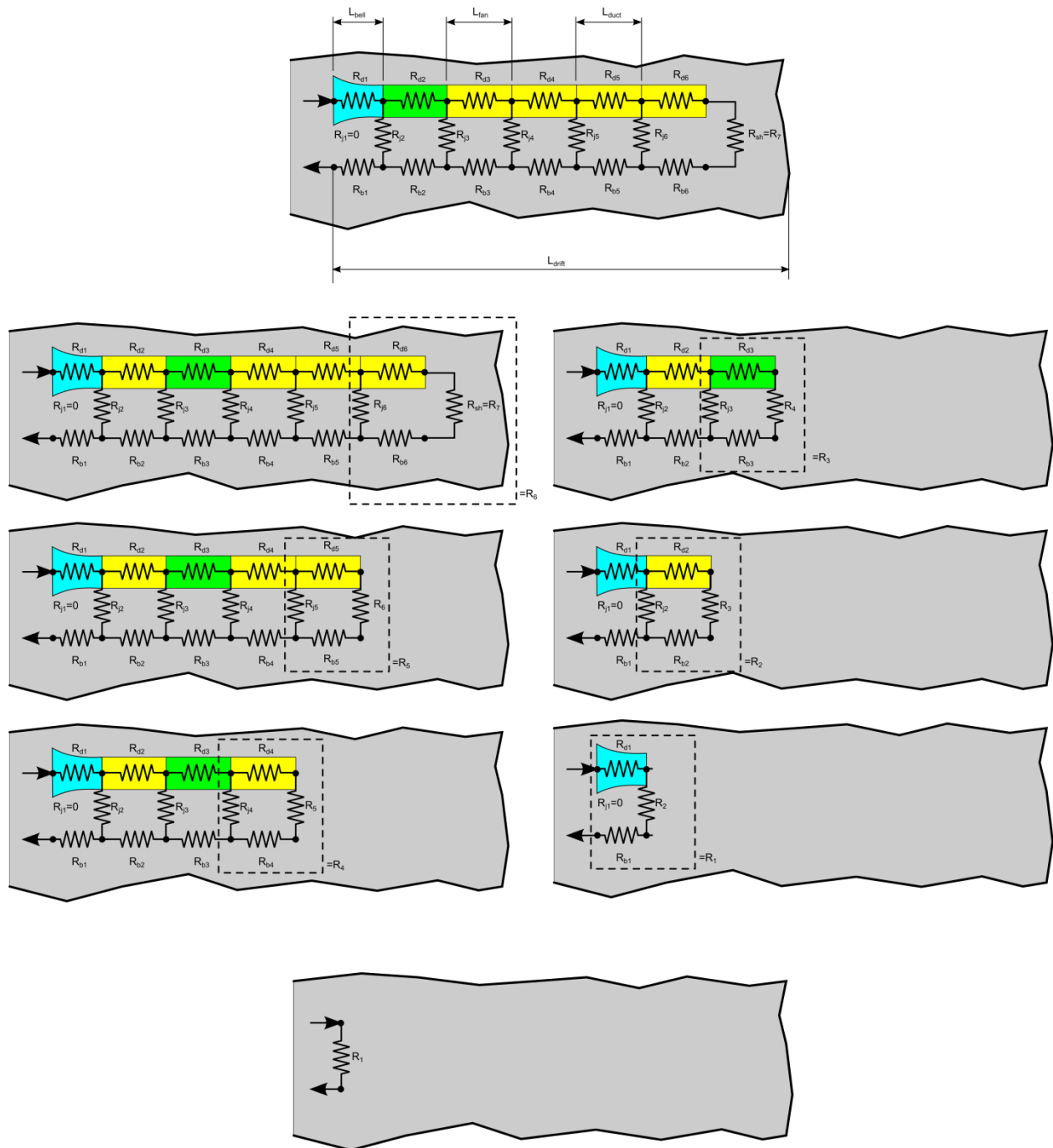


Figure 54: Schematic illustrating the steps to calculate the equivalent resistance of a series-parallel ventilation system

The fan operating point can then be determined by the intercept of the fan curve and the system equivalent resistance curve. Pressure and flowrate values are also calculated for each segment within the ventilation system.

### 8.6.2 Case studies of auxiliary ventilation systems with leaky joints

The leakage model was subsequently used to compare different auxiliary ventilation systems with low, medium, and high friction factor ducting with different degrees of leakage; the leakage in the case studies was assumed to be uniform throughout the system. Use of the model allowed simulation of values that would be obtained during a ventilation survey which could be used to determine a duct friction factor— as was done at MTI’s Test Mine. Table 18 shows the input parameters used for all the simulated ventilation systems compared using this leakage model.

**Table 18: Common input parameters for all simulated ventilation systems with leakage**

Variable	Parameter
Fan	Alphair 4800-VAX-2700
Drift length (m)	210
Duct diameter (m)	1.2
Duct length (m)	200
Distance from the start of the system for first measurement location (m)	26
Distance from the start of the system for second measurement location (m)	170

A total of six ventilation systems were simulated with the model with various combinations of duct friction factors and joint resistance ( $R_j$ ) values.

The input value used to characterize leakage in auxiliary ventilation models corresponds to the resistance of leakage paths ( $R_L$ ) (Vutukuri 1984, Mine Ventilation Services 2003). This quantity can be determined from pressure and flowrate values obtained during ventilation surveys or from a ‘leakage coefficient’ ( $L_c$ ) value determined from a nomogram for metal ducts (Le Roux 1979) but this method also requires knowledge of flowrates and pressures in a given ventilation system. The leakage coefficient according to Vutukuri (1983) corresponds to the amount of air in  $\text{m}^3/\text{s}$  that would leak from a 100 m duct under a uniform pressure of 1kPa and the relationship between  $L_c$  and  $R_L$  is shown in (23).

$$R_L = \frac{1000}{L_c^2} \quad (23)$$

Conversely, the definition of  $L_c$  presented in LeRoux (1979) was the amount of air in  $\text{m}^3/\text{s}$  that would leak from 1000 m of ducting at 100 Pa. Although these definitions of  $L_c$  differ they both define the leakage at a given pressure for a given length but the amount of air that leaks from a duct is influenced by the difference in pressure between the inside and outside of the duct among other factors such as the number of joints (Wu, Gillies 2014). But the number of joints in a given duct length will vary depending on the duct segment length and since the number of joints in each of these definitions was unknown it was not considered prudent to use these characterizations in the model developed herein.

Thus the values chosen for  $R_L$  were determined by calibrating the model against expected leakage amounts from mine ventilation systems as reported by DeSouza (2004); it was stated that approximately  $0.09 \text{ m}^3/\text{s}$  is expected to leak per joint and that leakage should not exceed 10% of

the initial air volume but leakage values exceeding 50% of the initial flow have been observed. Consequently it was decided to use a leakage value of 10% to define a low leakage system and a value of 50% for a high leakage system in the model.

A value of  $300,000 \text{ N s}^2 \text{ m}^8$  for  $R_j$  which was considered for the low leakage systems, resulted in an average flow volume loss of 11% of the initial flow at the fan all duct systems examined in the model, and average leakage of  $0.07 \text{ m}^3/\text{s}$  per joint. For the high leakage systems a value of  $4000 \text{ N s}^2 \text{ m}^8$  for  $R_j$  resulted in average leakage of 55% for all duct systems examined in the model. The results for the low and high leakage systems are presented in Table 19 and Table 20 respectively. Pressure and flowrate values at the same 2 locations within the system were obtained from the simulations for all cases examined, illustrated by P1 and P2 in Figure 55. These were then used to calculate a duct friction factor value simulating the methodology described in 7.3.1 employed at the MTI Test Mine. Three friction factor values were calculated, varying in the method and location of flowrate determination as follows:

- $k_{Q1}$  used the flowrate measured at the first location (Method A),
- $k_{Q2}$  used the value at the second location (Method B), and
- $k_{Qavg}$  used the average of the flowrate values observed at both measurement locations (Method C).

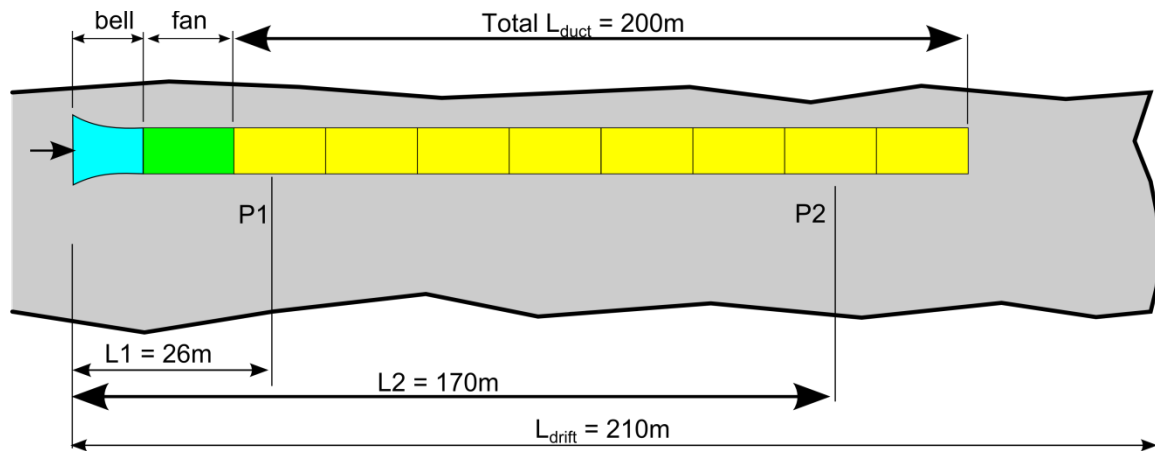


Figure 55: Diagram illustrating measurement locations for simulated ventilation survey<sup>15</sup>

<sup>15</sup> Note that drawing is for illustrative purpose and not to scale

**Table 19: Leakage model results for low leakage systems**

	Low friction	Medium friction	High friction
$R_j$ ( $\text{Ns}^2/\text{m}^8$ )	300,000 (low leakage)		
k duct ( $\text{kg}/\text{m}^3$ ) - specified	0.0011	0.0021	0.0037
$R_{eq}$ ( $\text{Ns}^2/\text{m}^8$ )	0.9089	1.3412	2.0105
Fan pressure (Pa)	1,639	2,129	2,639
Fan flowrate ( $\text{m}^3/\text{s}$ )	42	40	36
Face flowrate ( $\text{m}^3/\text{s}$ )	38	35	31
Flowrate loss (%)	9.5	10.9	12.7
Airpower (kW)	69	84	95
P1 (Pa)	1,492	1,915	2,351
P2 (Pa)	824	814	786
Q1 ( $\text{m}^3/\text{s}$ )	42	39	35
Q2 ( $\text{m}^3/\text{s}$ )	39	36	32
Back calculated values of k			
k_Q1 ( $\text{kg}/\text{m}^3$ )	0.0010	0.0019	0.0033
k_Q2 ( $\text{kg}/\text{m}^3$ )	0.0012	0.0023	0.0041
k_avg ( $\text{kg}/\text{m}^3$ )	0.0011	0.0021	0.0037

Comparison of the known duct friction factor (2<sup>nd</sup> row in Table 19) with those back calculated using the simulated observations show that use of Method A will result in underestimation of the duct friction factor, whereas use of Method B leads to overestimates of the duct friction factor.

**Table 20: Leakage model results for high leakage systems**

	Low friction	Medium friction	High friction
$R_j$ ( $\text{Ns}^2/\text{m}^8$ )	4,000 (high leakage)		
k duct ( $\text{kg}/\text{m}^3$ ) - specified	0.0011	0.0021	0.0037
$R_{eq}$ ( $\text{Ns}^2/\text{m}^8$ )	0.4293	0.6234	0.8916
Fan pressure (Pa)	1,004	1,340	1,732
Fan flowrate ( $\text{m}^3/\text{s}$ )	45	44	42
Face flowrate ( $\text{m}^3/\text{s}$ )	22	20	17
Flowrate loss (%)	50.1	54.9	60.3
Airpower (kW)	45	58	72
P1 (Pa)	743	987	1,262
P2 (Pa)	290	259	227
Q1 ( $\text{m}^3/\text{s}$ )	41	39	37
Q2 ( $\text{m}^3/\text{s}$ )	25	22	19
Back calculated values of k			
k_Q1 ( $\text{kg}/\text{m}^3$ )	0.0007	0.0012	0.0020
k_Q2 ( $\text{kg}/\text{m}^3$ )	0.0019	0.0040	0.0079
k_avg ( $\text{kg}/\text{m}^3$ )	0.0011	0.0021	0.0036

For ventilation systems with high leakage, estimation of the duct friction factor from either Method A or Method B resulted in a larger error than those from the low leakage systems but the estimate using the average flowrate (Method C) still provided a good estimate.

Comparison of the equivalent resistance values ( $R_{sys}$ ) of the low leakage systems with those from the corresponding high leakage ducts reveals that increased leakage results in lower system

resistance values. The fan operating point is determined by  $R_{sys}$  which comprises resistance of the drift, the duct, leakage and shock losses, thus it is important to quantify the leakage in a system when using survey results for more accurate determination of a duct friction factor unless flowrate determinations are done at both ends. For example, if one measured 2 pressure values and 1 flowrate in a leaky system but assumed that the installation was leak free, the calculated duct friction factor may be over or underestimated depending on the location of the flowrate measurement. Thus these simulations and the different methods used to calculate the duct friction factor may explain the appreciable variability of reported k factors, which should be an intrinsic material property, for plastic ducting presented in Table 13.

Wu and Gillies (2014) stated that canvas or fabric materials used for fabrication of ventilation ducts leak due to the porous nature of these materials, thus it was suggested that the use of lower leakage materials in ventilation systems will lower fan operating costs compared to higher leakage materials.

The data from the leakage models presented in Table 19 and Table 20 support this notion but it only applies when considering equal flowrate amounts at the face for each case. For example, if we consider a low leakage system with a low friction factor it can be seen that the airpower required corresponded to 69 kW which supplied 42 m<sup>3</sup>/s through the fan but only 38 m<sup>3</sup>/s at the face. Conversely, the high leakage system with a high friction factor required 72 kW to supply 42 m<sup>3</sup>/s through the fan but only delivered 17 m<sup>3</sup>/s at the face. Although the amount of air delivered at the face varied substantially between these systems, the amount supplied by the fan was the same. Thus in drifts with activities requiring fresh air only at the face it is possible that the amount of air reaching the working area in the high leakage duct may not be sufficient and would require more power to increase the air supply. However, in situations where activities



requiring fresh air are occurring at various areas along a development drift, it may be acceptable that the high leakage duct distributes the fresh air where it is required. Both of these systems may be adequate to meet the demand requirements for fresh air, and would require similar power, but the meaning of 'adequacy' alters between the cases.

## **8.7 Discussion of auxiliary ventilation systems and friction factors**

An Atkinson friction factor for the plastic ventilation duct was calculated using two methods. The ventilation survey resulted in a value of  $0.0020 \text{ kg/m}^3$  but although these values were repeatable, which provided an indication of the precision, it was unknown whether the values obtained were accurate. Calculation of the Atkinson friction factor from material roughness yielded a value of  $0.0011 \text{ kg/m}^3$ , thus this introduced uncertainty with the values obtained during the survey.

The microscopic images of the duct material samples revealed that the roughness or asperity height of the plastic material was primarily influenced by the coating applied to the surface. Therefore, any inconsistencies with the application of this substance could alter the roughness and thus the friction factor. Alternatively, different application methods could be investigated to ensure consistent surface coverage, which if smoother than the current application technique could lead to a lower Atkinson friction factor.

Although the method employed for the determination of the asperity height in this study may not have been the most accurate since it was subject to subjective identification of focus points, it did provide an estimate of the order of magnitude for the roughness. The material samples could have been examined by scanning electron microscope for a more accurate assessment but it was not deemed necessary for the purpose of this study. Even if the maximum asperity height value

was tripled from 8  $\mu\text{m}$  to 24  $\mu\text{m}$ , the Atkinson friction factor would only increase to 0.0013  $\text{kg}/\text{m}^3$ , which is still lower than that of other duct materials such as steel or layflat, as well as that determined from the ventilation survey at MTI.

Examination of a Moody chart revealed that the roughness of the plastic ventilation duct as determined by the surface roughness examined with the microscope approached that of a hydraulically smooth pipe, thus the possibility for ventilation ducts with even lower friction may be non-existent. It should be noted that although the flow measured during the MTI survey reached the requirement to be turbulent, according to the Moody chart it was not fully turbulent, consequently the friction factor can also be dependent on the Reynolds number, which may provide an explanation for the discrepancy between the values determined with the asperity height and those from the ventilation survey. It was shown in Table 15 that the Atkinson friction factor values for a smooth pipe corresponded to 0.0016 to 0.0018  $\text{kg}/\text{m}^3$  for the range of Reynolds number values corresponding to those calculated from the ventilation survey data. Thus the value of 0.0020  $\text{kg}/\text{m}^3$  also indicates that the friction factor value as determined during the survey approached that of a smooth pipe.

It was also shown that the minimum friction factor value for a smooth pipe corresponded to 0.0009  $\text{kg}/\text{m}^3$ , but some values reported for plastic ducting were lower than this minimum. The examples presented in 7.6 from the leakage model may be used to explain this discrepancy; it was shown that use of the average flowrate value between 2 measurement locations would provide a good estimate of the duct friction factor, however use of the flowrate value as measured at the first location would result in underestimation, which was greater in leaky systems.

The analysis presented demonstrated that although the installation of ducts with lower friction factors can lead to reduced energy consumption it is also important to consider the fan and duct as a system to maximize these energy savings, and overall costs. For example, all else being equal in a given fixed-speed fan ventilation system, the substitution of a lower friction factor duct can result in an increased flowrate. Although the resulting energy consumption can be lower, the energy savings would be maximized if the fan speed was reduced to supply the required amount of air only. This would allow a faster recovery of the higher capital cost for the plastic duct and render it a financially viable project given sufficient time. Therefore, to maximize the energy savings from duct material substitutions, either the fan speed, the blade setting or the fan itself needs to be changed to a lower duty while still ensuring that the minimum flowrate requirements are met.

For fixed-speed fans, changing their blade setting could adjust the operating point of the ventilation system, however there is a possibility that the blade setting may not be changed sufficiently to regulate the airflow to the desired quantity. Therefore some consideration needs to be given to replacing the fan to maximize energy savings, especially when the proportion of total cost associated with energy becomes greater than that for capital costs. In these instances, the energy savings may be sufficient to warrant the purchase of a new fan to match the ventilation requirements. Alternatively, in a situation where a fan from the existing mine inventory, possibly repurposed from another area, is intended to be used in another location, it is imperative that the fan characteristics match the resistance of the new application. This would be similar to providing an accurate duty specification to ensure proper selection of a new fan as indicated in De la Harpe *et al* (2014).

Although energy savings from installation of ducts with lower friction factors can be realized in terms of investment payback, it is also important to consider the life of the duct. As was shown in the case studies, with various project life values ranging from 1 to 5 years, in some scenarios, although the plastic duct consumed the least amount of energy, the project life was not sufficient to recover the investment in this relatively more expensive duct material. Thus the lowest annual cost option was the steel or layflat PVC duct installations. However, it should be noted that the resiliency of the duct types and likelihood of needing repair or replacement has not been reflected in these assessments and these could make a more expensive durable product attractive earlier.

The friction factor values used in the assessment for the steel and layflat were those reported in McPherson (1993), however there is evidence in the literature of different types of steel ducting having different friction factor values, ranging from 0.00252 to 0.00409 kg/m<sup>3</sup> (Meyer 1990). Ambrosio (2012) also conducted testing and determined that the average friction factor of the Videx Mining Products galvanized steel spiral ventilation ducting corresponded to 0.00305 kg/m<sup>3</sup>. Therefore the value of 0.0021 kg/m<sup>3</sup> used in this study may not be applicable to all types of steel ducting and thus this would change the economics of the scenarios examined and render the plastic duct more attractive when compared to steel ducts with higher friction factors. Furthermore, it was not indicated whether leakage was considered for determination of the reported steel friction factor values. If not, it is possible that these values are incorrect.

Despite the plastic duct being more expensive and not normally justifiable, there may be situations where its use for a short period may be a financially viable option due to other limitations. For example, in a case where a mine site has energy supply constraints, it may be

more economical to use the higher cost duct to meet the required airflow than to upgrade the electrical supply.

The case studies also highlighted that the friction factor and the maximum length of duct for a given fan were inversely related. Thus for the same fan, the maximum duct length for the steel system was increased by 76% compared to the layflat PVC, whereas for the plastic duct it was increased by 227%, all consuming the same amount of energy and delivering the same amount of air. Although this appears to provide an advantage to the plastic system, the capital costs of this duct were such that it was not an economically viable solution for short-term projects where only one fan is required.

A case study using an alternative polymer ventilation duct in a Quebec mine presented benefits in addition to lower energy consumption of using this type of system compared to other traditional materials (Tardif, Paquet et al. 2010). These included reduced installation time, as well as lower transportation costs on surface and to deliver the ventilation ducts underground. It should also be noted that in the case study presented, the booster fans were adjusted to reduce the flowrate, thus by considering the fan settings the energy savings were increased, as was illustrated by the hypothetical examples of the current study.

The polymer duct friction factor reported in Tardif *et al.* (2010) corresponded to a value of  $0.0009 \text{ kg/m}^3$  which was initially used as an estimate for design however testing after the product was installed resulted in a revised value of  $0.0004 \text{ kg/m}^3$ . Although it is not possible to confirm these friction factors with the information provided in the study, it can be hypothesized that the lower value is erroneous since it infers that the material was smoother than a hydraulically smooth pipe. Thus it can be postulated that the error may be due to either ignoring

leakage in the calculations from survey results, use of a higher flowrate value than the average flow in the duct, or ignoring the effect of elevation differences when determining the pressure loss in the duct. This demonstrates the importance of obtaining accurate flowrate and pressure values during ventilation survey, as well as considering leakage for the purpose of determination of a duct friction factor. Conversely, an assessment of the quality of installation can be made from ventilation survey results by calculation of the leakage resistance if the duct friction factor is definitely known.

It can also be observed from the case studies in Figure 40 that the total annual costs for short duct lengths were similar for all duct types. For example, in the 1 year project with a fixed-speed fan and a final duct length of 40 m, the total cost for the steel, plastic and layflat systems corresponded to \$92,811, \$93,288 and \$93,154 respectively; the difference between the highest and lowest total cost option for this case study was \$477 per annum. Furthermore, at certain duct length ranges in the variable-speed case studies, there were numerous instances of two duct types having comparable costs. For example, the steel and layflat options had similar costs in the 1 year project, whereas the steel and plastic systems had comparable costs in the 3 year project, thus the best option was not obvious. In these instances further analysis would be required to determine the best system by investigation of other cost affecting factors such as, but not limited to, installation cost, transportation cost or availability.

The original ventilation model developed during this study was designed for quick and simple analysis of auxiliary mine ventilation scenarios to aid the selection of duct type and did not account for every possible situation. The model did not consider system leaks at this time since accurate leakage values derived under common conditions for all the ducting types are not known. There were other restrictions, for example, the model was limited to allocation of capital

costs for duct and fan purchases at the beginning of the project and cannot be accurately used for purchases made at other periods during the project. Also, when multiple fans are used in a branch, it was assumed that these were installed in series and that all the fans in the same branch were of the same model and had the same operating settings. Furthermore, it was assumed that the fans were separated by duct sections corresponding to the maximum duct length for the specified fan and duct type. This arrangement minimized the total pressure in the duct compared to placement of the fans at the beginning of the duct therefore leading to lower leaks (Workplace Safety North 2011). Also it was unknown if the duct included in the scenario would be capable of handling the pressure developed by multiple fans installed close together.

Although other ventilation models have been developed for various purposes (Li, Kocsis et al. 2011, Duckworth, Lowndes 2003, Fytas, Perreault et al. 2000), the advantage of those produced as part of this study were their capability of modeling a dynamic auxiliary system with the inclusion of an advance rate, which more closely resembles an actual mine setting. Furthermore, the leak free model has the means to consider capital and operational costs to help determine the most economical option for a given scenario, and facilitate comparison of fixed and variable speed systems.

For simplicity, the ventilation model developed during this study was limited to a single branch analysis and did not consider the overall effect on the other branches in the ventilation network. This effect would be negligible if the auxiliary system was a stand-alone system responsible for taking the air from a specific location to a delivery point and the air being freely allowed to return to its pick-up point. Where the auxiliary system is responsible for drawing or delivering air through a bulkhead that has a pressure differential generated by the mine's overall ventilation

system, additional consideration would be required to consider the interaction of the auxiliary with other primary or secondary fans.

It can be observed that generalized recommendations for duct material selection cannot be made for mine ventilation systems. Several factors such as project life, drift length, duct material, and fan settings influenced the total cost of the various systems, and the outcomes may have been altered with the use of a different fan. Electricity rates and duct costs may also differ for different mines, thus changing the economics of the various options. For mine sites with higher electricity rates, such as those in remote locations not connected to the electricity grid, may render the plastic duct as the lowest cost option for shorter duct lengths or project durations, which would have to be assessed based on the specific circumstances of the mine.

## **8.8 Conclusions of ventilation system analysis**

The friction factor for the plastic duct material was determined to be  $0.0011 \text{ kg/m}^3$  via surface roughness values and  $0.0020 \text{ kg/m}^3$  from a ventilation survey, with the discrepancy possibly attributed to the dependency on the Reynolds number. Thus for smooth ducts the use of a single friction factor value may not be accurate.

Comparison of the friction factor determined from the survey at MTI to friction factors such as those reported in design tables for other duct types may not be fair because the method used to derive these other values is unknown. For example, the data provided in the design table from McPherson (1993) was derived from several ventilation surveys but it was shown herein that when leakage is not quantified, or that elevation differences between measurement locations are not considered the resulting duct friction factor value may not be accurate.



Thus there is a need for development of a standardized methodology for determination of duct friction factor values in auxiliary ventilation systems. Such a methodology should include the use of simultaneous manometer reading to eliminate the effect of different elevation levels between the measurement stations, but it is imperative that the distance between the manometer and the duct is equal at both stations. Recording flowrate quantities at both pressure measurement locations may allow quantifying the amount of leakage in a given system, and by means of averaging the flowrates, provide a more reliable estimate of the duct friction factor. Furthermore, the use of asperity height measurements, as well as a Moody chart are suggested to provide independent checks to assess the friction factor values determined from ventilation survey data.

Development of a standard methodology for friction factor determination, as indicated herein, will enhance the information used for decision making. For example, anticipated cost savings may be lost when using artificially low friction factor values that were derived from ventilation surveys that did not quantify leakage or used an incorrect flowrate value in the calculation.

Low friction factor and low leaks are generally desirable characteristics for auxiliary ventilation systems, but leaky systems have lower system resistance and may supply the same amount of air through the fan as a low leakage system. Thus should leakage in a ventilation system be an accepted method of distributing the fresh air throughout the drift rather than supply it all to the face, a high leakage system may be acceptable. This would require an assessment to determine the amount of air necessary to meet the requirements set out by regulations, as well as examination of locations where fresh air is required and how it is distributed with a deliberately leaking system.

Although a ventilation system using a lower friction factor duct would return lower energy consumption for the same flowrate, it could equally result in a higher flowrate for a given fixed-speed fan due to the different intersection of the system resistance and fan characteristic pressure-quantity curves. Unless this increased airflow was required for production, adjustment of the fan settings or replacement of the fan control to limit the excess airflow would be required to maximize the energy savings.

One of the attributes identified from the use of the plastic ventilation duct was that for a given fan, the lower friction offered by this material allowed a maximum length that was 76% and 227% greater than for the steel and layflat options respectively. This ability for a single fan to deliver air further with the plastic duct has a major influence on the economics when it allows fewer fans to be used. However it was also shown that the plastic type of ducting did not provide an economic advantage for short-term projects.

Examination of the use of specifically adjusted speed/blade setting or variable-speed fan compared to a fixed setting stock fan showed that they could reduce oversupply and maximize energy savings. However, even with this refinement to the costlier product in certain situations, the energy savings from these systems were not sufficient to recover any capital investment i.e. the VFD control. For short-term projects with short duct lengths it was shown that the economic viability of the use of a fixed-custom speed fan was better than that of a variable-speed system. However, in situations where the airflow requirements change frequently, the use of a variable-speed system to match these requirements could result in a financially viable solution for short-term, short duct length projects.

In the case studies examined, the maximum potential energy savings from substitution of a layflat PVC duct with a plastic duct corresponded to 58% for fixed-speed (1800 rpm) installations, 74% for fixed-custom speed systems, and 63% for variable-speed systems. The corresponding energy savings for plastic ducts compared to steel ducts were 39%, 62%, and 39%. These can represent significant energy savings for a mine since the auxiliary ventilation system energy consumption can correspond to a large portion of the total mine electricity use, shown in Chapter 7.3. But even when the energy savings were maximized by controlling the excess airflow through the plastic ducts, in certain situations the higher capital costs for this duct type resulted in a higher annuitized ventilation system cost. These costs, which considered capital and operational expenditures, were strongly influenced by the number of fans required. Therefore this may limit the use of lower friction, higher cost materials for auxiliary ventilation ducts and thus prevent the mining sector from lowering this aspect of its energy consumption.

Regardless, this analysis has shown that there are several ways to lower the energy consumption from auxiliary ventilation systems, these include: the use of a lower friction ducting, adjustment of stock fans to better match the minimum airflow requirements of each installation so limiting the degree of excess supply when it occurs, and the use of VFDs to adjust a fan's speed and thereby supply an airflow much nearer, or at, minimum requirements. While this work has not fully met the objective of determining which type of ducting was the most economical, it has shown that the selection is complex. Depending on the specifics of the installation, layflat PVC, steel and plastic can be optimal depending on their unique combination of capital and operating expenses.

## **9 A novel demand-side estimation of consumption**

Disaggregation of energy consumption from the various types of activities or equipment in a facility is an important step in energy management; it provides an understanding of how energy is used, how much and when, so that energy management activities can identify energy and cost reduction measures. Analysis of energy use with a finer granularity in examination of end-uses at the bottom of the energy hierarchy can assist in development of energy and demand management initiatives.

Metering all end-use energy consumption may not be practical or economical at facilities with a large amount of equipment. Nonetheless, some facilities such as Clarabelle Mill which will be the focus of Chapter 10 have implemented extensive metering. This would require a large capital investment for purchase and installation of meters, communication infrastructure, and data storage. Operational expenses for data analysis as well as calibration and maintenance of these meters would also be incurred. This chapter presents the development of a novel top down methodology for disaggregating a single, main meter electricity consumption signal to its various end-uses, as well as an example illustrating its application to electricity demand data for an entire underground mine.

### **9.1 Existing disaggregation methods**

A review of existing methods used to disaggregate electricity consumption revealed that publications in this research field mostly pertained to residential and commercial building

applications (Wang, Yan et al. 2012, Akbari, Konopacki 1998, Birt, Newsham et al. 2012, Firth, Lomas et al. 2008).

Energy quantification methods for buildings were summarized in three categories: calculation, measurement, and hybrid methods (Wang, Yan et al. 2012). The calculation methods consisted of modeling the energy use of buildings from input values such as weather, occupant behavior, and building characteristics. For the measurement methods, energy bills were disaggregated using either a bottom up or a top down method from estimated or measured end-use consumption data (Wang, Yan et al. 2012). Although both the calculation and measurement methods may employ modeling energy of end-uses, the main difference between these was that the calculation method is used for new buildings where no energy data is available whereas estimates can be reconciled with top-level meter data or energy bills when the measurement method is used for existing buildings. The hybrid method comprised the use of bottom-level measurements either of input variables or energy use to validate the calculated electricity consumption adopting a model (Wang, Yan et al. 2012).

An end-use disaggregation algorithm using computer simulations and statistical analyses was developed for use in commercial buildings (Akbari, Konopacki 1998). The statistical analysis comprised developing a relationship between the hourly whole building electricity load and the outdoor temperature to distinguish the temperature-dependent load which was used to define the energy use from air conditioners (Akbari, Konopacki 1998). Then the balance of energy consumption was allocated to the remaining end-uses (ventilation, cooking, miscellaneous, refrigeration, exterior lighting, interior lighting, process loads, and street lighting ) with building simulation models. Hourly electricity data was used as a constraint in the simulations to reconcile the sum of end-use consumption with the total load. The model was validated using

metered data from an office where the average error was less than 5%. However, the model overestimated the electricity loads from HVAC (heating ventilation and cooling) equipment and lighting by 12 and 27% respectively, and miscellaneous electricity loads were underestimated by 35% (Akbari 1995). Thus the use of these simulated electricity consumption values may not provide accurate estimates for energy management decision making.

Others disaggregated residential electricity consumption into various categories using alternative approaches. Birt *et al* (2012) studied the relationship between whole-house hourly electricity use and outdoor temperatures and identified that electricity consumption increased at temperatures below 10°C and above 18°C which was suspected to correspond to heating and cooling loads respectively. Subsequently, Birt *et al* (2012) used electricity data collected at 1 minute intervals for 13 months from 12 houses which included sub-meters on HVAC equipment to determine the electricity use from furnaces and air conditioning units, which confirmed the aforementioned assumption. A model was fitted to the median values, as well as the 10<sup>th</sup> and 90<sup>th</sup> percentile data from the group of households which were plotted against outdoor temperature. These were then used to determine the baseload and activity based consumption which corresponded to the minimum value on the 10<sup>th</sup> percentile line and the 90<sup>th</sup> percentile line respectively.

Firth *et al* (2008) estimated electricity consumption of continuous and standby appliances, cold appliances (fridges, freezers), and active appliances from whole house 5-minutely metered data for 72 households. Electricity use from each category was estimated based on time of consumption and patterns. For example, minimum consumption during the early hours of the day were allocated to continuous and standby appliances, whereas energy use from cold appliances was estimated from a cyclic pattern observed, and the active consumption was estimated from step changes and peaks in electricity consumption.

Several publications describe the use of algorithms to disaggregate electricity consumption using load signatures and pattern recognition (Berges, Goldman et al. 2011, Liang, Ng et al. 2010a, Kim, Marwah et al. 2011, Marceau, Zmeureanu 2000, Liang, Ng et al. 2010b, Farinaccio, Zmeureanu 1999, Egarter, Sobe et al. 2013, Zoha, Gluhak et al. 2012, Chang, Yang et al. 2008). The load signatures in these studies were determined from sub-metering, interrogating an existing database, or pattern recognition of electrical demand changes over time, then algorithms identified periods where the various appliances were in use to estimate their electricity consumption.

It was reported that some loads in industrial facilities have transient features during equipment start up which differ from their steady state signature; thus the use of both signatures could improve the use of algorithms for load recognition (Chang, Yang et al. 2008). Wavelet transforms and a Neural Network were used to detect the operating state of equipment, where the current and voltage were monitored. Testing was conducted in an experimental setup that included loads representative of an industrial facility and it was determined that the accuracy of the signature detection using transient and steady state features was 95%.

Application of the existing techniques may be difficult for underground mines for several reasons. Use of the bottom up calculation method would require a large amount of input variables, likely greater than 300 assuming a small mine with 100 pieces of equipment and 3 parameters for each (rated power, operating hours, and efficiency). Thus a significant time investment would also be required for gathering this data and any other information used to validate the estimates from the calculation method. Furthermore, it is possible that some of the required input variables are not measured at the same time interval as the electricity use. For example, ore production could be used to estimate the energy use of a hoist cycle which occurs

over several minutes depending on the loading pocket depth and the hoist speed. But if ore production data is recorded on an hourly basis this may not match the total electricity consumption intervals measured in seconds at some mines. Thus estimates or average values of the inputs, ore production in this example, to match the sampling interval of the electricity data would be used and this may introduce uncertainty in the analysis. Alternatively, electricity use could be determined for longer intervals, based on the longest sampling interval of all input variables, but these periods may not provide sufficient information for application of energy management initiatives. In this example the hourly average electricity consumption of the hoist may be estimated but this information would not be sufficient for energy management purposes in jurisdictions with demand charges based on 15 minute peaks because one would not be able to identify the time and duration of these peaks.

Some disaggregation methods relied on assumed schedules for electricity allocation whereas others used load signature pattern recognition. For example, in Firth *et al* (2008) the electricity consumption from continuous and standby appliances was allocated to the minimum electricity used during the nighttime, when it was assumed that the household occupants were sleeping, whereas the cold appliance (fridges and freezers) electricity use was determined by the cyclic pattern observed during the night, and consumption from active appliances was determined by the increased electrical load during the day. The large amount of equipment and associated diversity of loads operating in a mine could make application of such methods challenging. Application of the pattern recognition method in an underground mine would require a large database of load signatures (likely over 100), of which there may be several types of equipment with similar characteristics, making it difficult to discern consumption between the equipment. Coincident start up and shut down of different pieces of equipment may hinder detection of



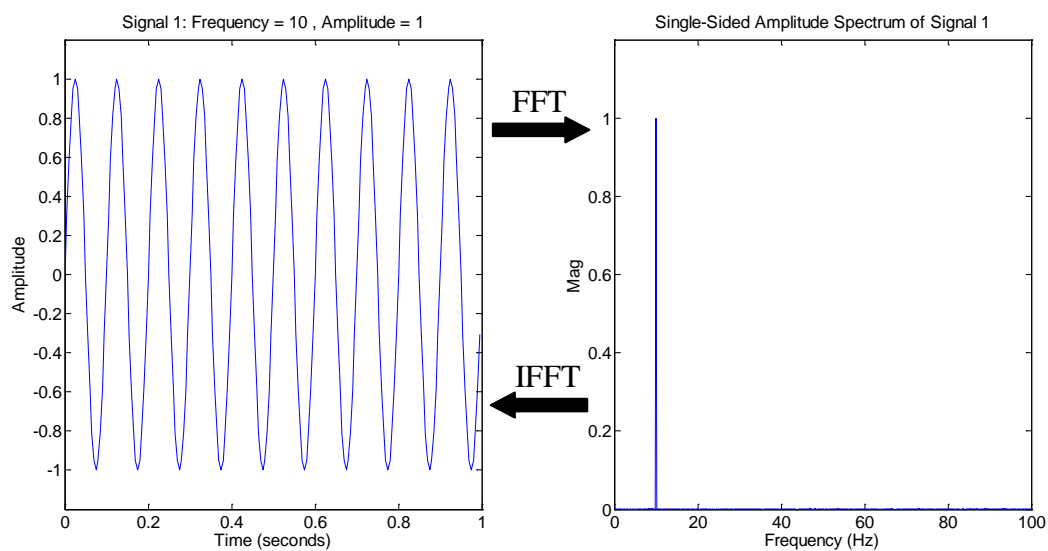
energy use from individual equipment items. But a method, combining aspects of the reviewed disaggregation algorithms could potentially be used. This precipitated the development of a robust top down disaggregation method for allocating the electricity consumption of an underground mine to its various end-uses, that is set out in this Chapter.

## **9.2 Proposed top down electricity disaggregation method using time and frequency domain information**

The existing electricity disaggregation methods reviewed were performed by load signature or pattern recognition in either the time or frequency domains (Zoha, Gluhak et al. 2012, Marceau, Zmeureanu 2000, Berges, Goldman et al. 2011, Liang, Ng et al. 2010a, Liang, Ng et al. 2010b, Kim, Marwah et al. 2011, Chang, Yang et al. 2008, Farinaccio, Zmeureanu 1999) to detect periods of specific appliance energy use. Others used knowledge of operating schedules (Firth, Lomas et al. 2008) or modeling techniques (Akbari, Konopacki 1998, Akbari 1995, Birt, Newsham et al. 2012, Yan, Wang et al. 2012) for estimating electricity use. A novel method that combines some of these methods, with other signal processing techniques, is proposed in this chapter to disaggregate the electrical signal of an underground mine. The methodology proposed herein uses load signature recognition combined with knowledge of the operating schedule to identify electricity consumption allocated to a specific end-use. Subsequently, the electricity consumption pattern of a specific end-use is modeled; the model is based on the load signature of the equipment and includes parameters that allow for variability of individual cycles. Fourier analysis is used to produce the spectra associated with the load signature of the end-use activity; this information is used to develop a ‘smart’ filter to separate the electricity use of the specific end-use from the aggregate electricity signal. The filter is said to be ‘smart’ because it is applied to an aggregate electricity signal only when the specific end-use is operational.

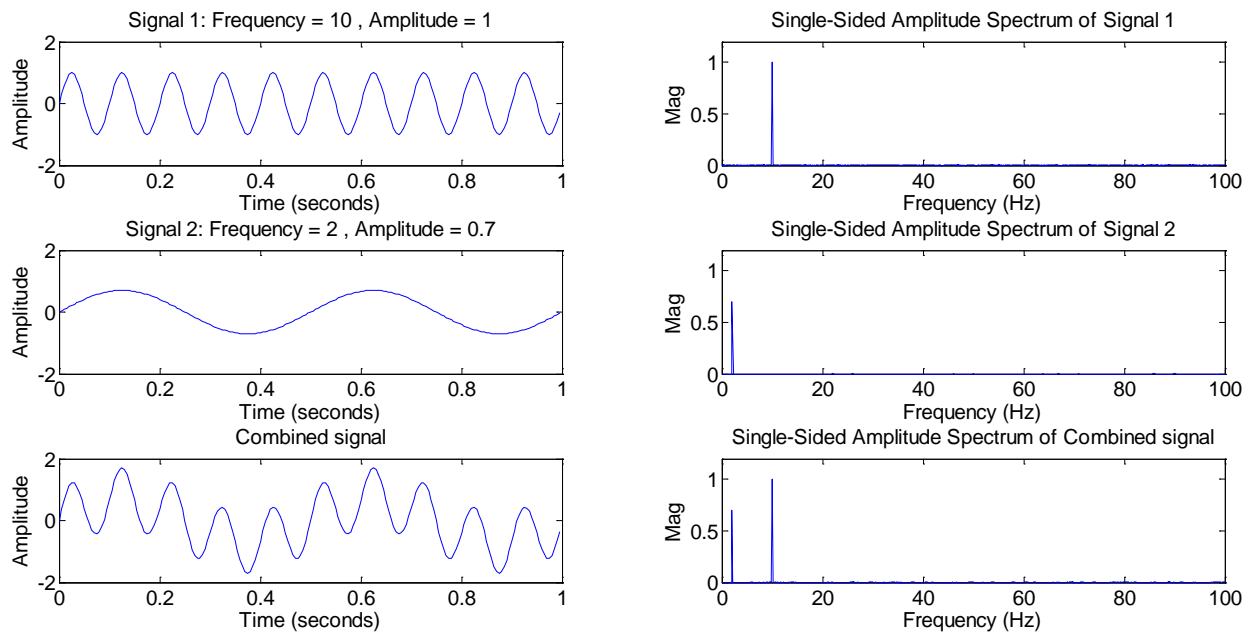
### 9.2.1 Signal processing background

Time varying information, as in contained within a signal, can be represented in various support variable domains such as: the time domain and the frequency domain. This flexibility can provide alternative perspectives, opening up options for adoption of signal processing and analysis techniques (Ramirez 1985) that otherwise would not be used. In 1822, Fourier showed that all time domain signals can be considered composed of sinusoids of various frequencies, amplitudes and phases (Lynn 1989). Signals recorded in the time domain can be transformed to the frequency domain using Fourier Transform, a mathematical technique derived by Jean Baptists Fourier. Conversely the inverse Fourier Transform (IFFT) can be used to establish a time domain signal from the frequency domain. Figure 55 shows an example of a sinusoid with an amplitude of 1 and a frequency of 10 Hz; the left figure shows the time domain signal and the right shows the corresponding frequency domain spectrum. It should be noted that both of these contain the same information but it is presented from a different perspective.



**Figure 56: Time and frequency domains**

When multiple signals are combined the resulting aggregate signal may be more complex but the same concepts are applicable. Figure 56 shows an example where two sinusoids (signal 1 with amplitude of 1 and frequency of 10 Hz, and signal 2 with amplitude of 0.7 and frequency of 2) are added together to form the combined signal at the bottom left of the figure. The corresponding frequency spectrum for each signal is shown on the right; the spectrum of the individual signals show one peak corresponding to the signal's amplitude and frequency whereas the combined signal shows the peaks from both sinusoids.



**Figure 57: Time signals and frequency spectra of combined signals**

Thus decomposition of a time domain signal to identify these parameters may provide additional information or insights that are not directly apparent in examination of the time domain electricity consumption. For this reason, in the foregoing, we subject a time series electricity

consumption signal to transformation to the frequency domain which may provide useful information for disaggregation purpose.

A limitation of the Fourier analysis relates to the sampling theorem, also referred to as the Shannon or Nyquist sampling theorem as discussed by Smith (1997). The theorem states that the highest frequency that can be determined corresponds to half the sampling rate, this being termed the Nyquist frequency. For example, in a signal sampled at 100 Hz, only frequencies lower than 50 Hz can be correctly represented, whereas those higher than 50 Hz would *alias* lower frequencies. Thus the Nyquist sampling theorem was an important consideration for the proposed disaggregation method because it limits the phenomena that can be reconstructed from the signal.

There are four classes of signals, each with a corresponding Fourier transform algorithm (Smith 1997), outlined in Table 21.

**Table 21: Fourier transform categories**

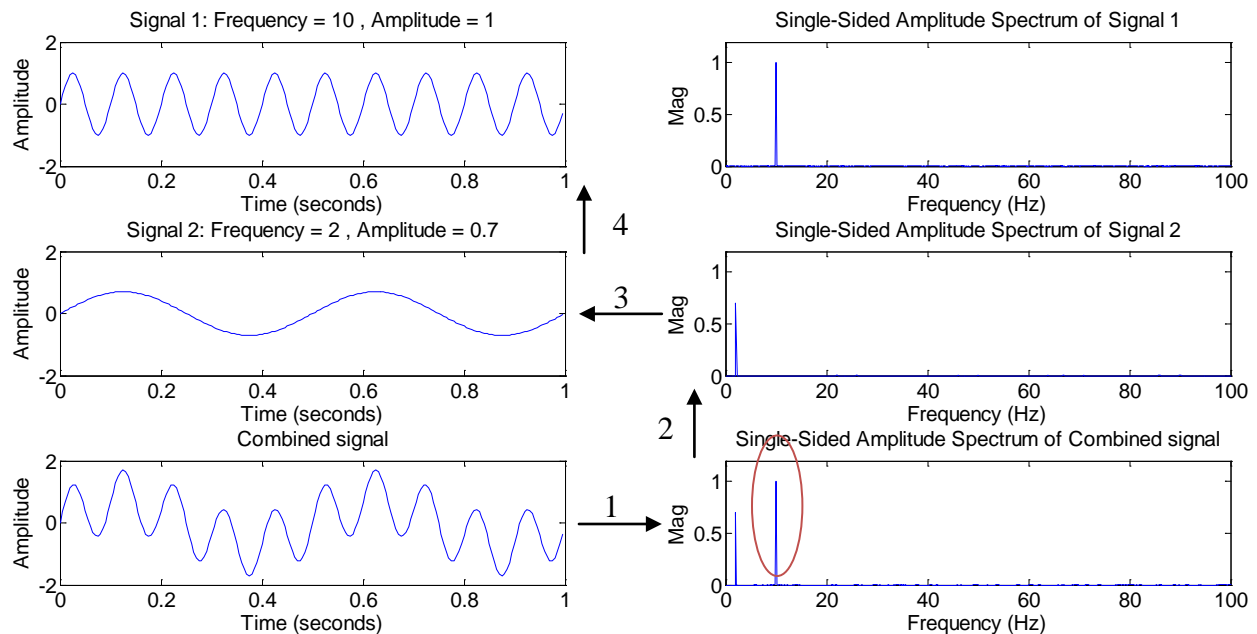
Signal	Fourier transform category
Aperiodic, continuous	Fourier Transform
Periodic, continuous	Fourier Series
Aperiodic, discrete	Discrete Time Fourier Transform
Periodic, discrete	Discrete Fourier Transform

Signals representing electricity consumption correspond to discrete signals because they are sampled at specific intervals; therefore the Discrete Time Fourier Transform and the Discrete Fourier Transform algorithms could be applied. All of the aforementioned algorithms work with signals that extend from negative to positive infinity in time but electricity consumption signals exist over finite, positive periods of time. Thus there are two options open to render electricity consumption signals compatible with these procedures: the finite signal could be i) padded with zeros on both sides, or ii) repeated as an infinite periodic signal. For this work the latter option was determined to be the best because synthesis of the first signal would require an infinite number of sinusoids (Smith 1997) because of the lines at zero on both sides of the signal and the sharp discontinuity between the actual signal and the zeros used for padding. The algorithm used in signal processing corresponds to the Discrete Fourier Transform (DFT), implemented with the Fast Fourier Transform (FFT) algorithm (Smith 1997). The process used in the FFT entails a reduced number of calculations therefore it is considered more efficient and is incorporated in various software programs such as Microsoft Excel and MATLAB.

Filters have been used in various signal processing applications for separation of combined signals, or restoration of distorted signals (Smith 1997). For example, the quality of an audio signal recorded in a noisy environment can be improved with the use of filters to remove or reduce the noise in a recording.

Separating signals can be done in the frequency domain as will be exemplified with the combined signal containing 2 sinusoids in Figure 57. The first step in this example corresponds to transforming the combined signal to the frequency domain. Next, a filter is designed to remove the high frequency signal with an amplitude value of 1 and frequency of 10 Hz. This provides the spectrum of signal 2, which is then transformed to the time domain. Subsequently

the time domain signal of signal 1, which was filtered, is obtained by subtraction of signal 2 from the combined signal.



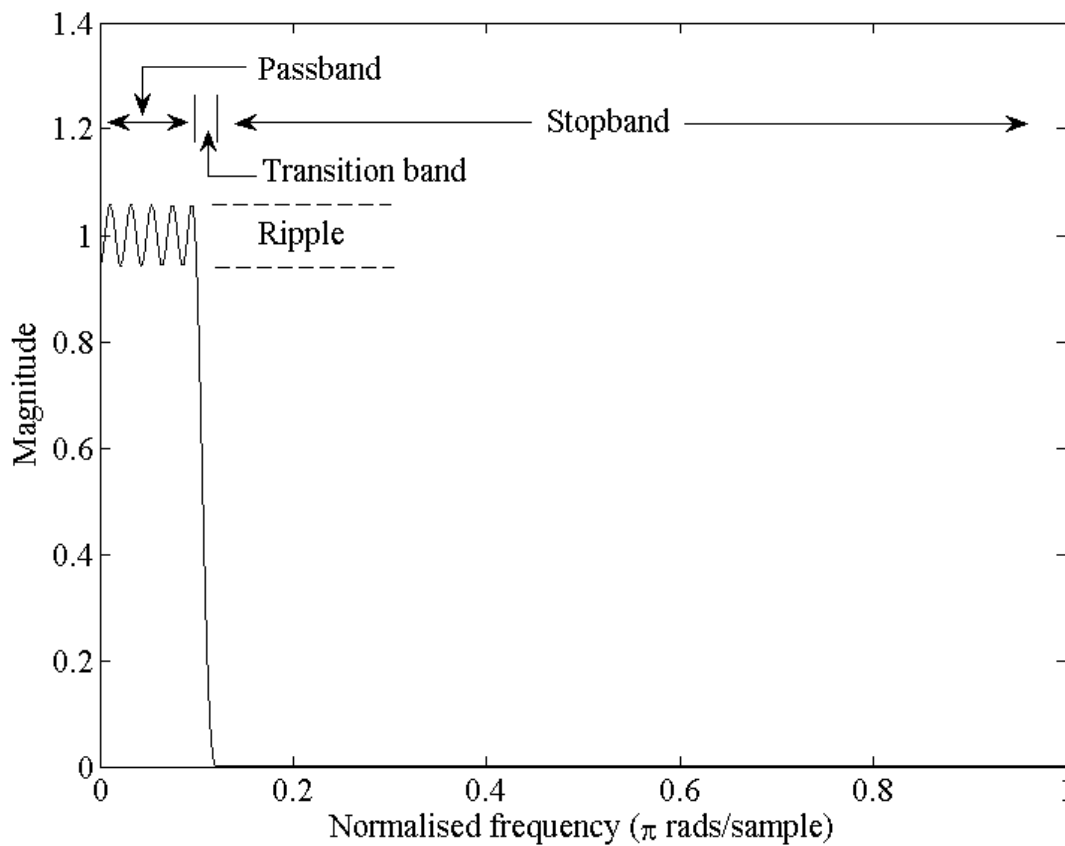
**Figure 58: Simplified method for signal disaggregation**

Various types of filters have been designed and can be categorized as Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) depending on the implementation method (Smith 1997). Filters have also been developed within these classes for different purposes as illustrated in Table 22.

**Table 22: Filter classification by type and purpose (Smith 1997)**

	FIR	IIR
Implementation method	(Convolution)	(Recursion)
Purpose		
Time domain (smoothing, DC removal)	Moving average	Single pole
Frequency domain (separating frequencies)	Windowed-sinc	Chebyshev
Custom (Deconvolution)	FIR custom	Iterative design

Four types of filters with different frequency response characteristics exist. These include: low-pass, high-pass, band-pass, and band-reject filters (Smith 1997) with their functions implied in their name. For example, a low-pass filter would remove high frequencies from a signal whereas a band-reject filter would remove frequencies within a specific range. Filter design comprises specification of frequency domain parameters to achieve a desired outcome. Design parameters comprise: frequency response (low-pass, high-pass...), impulse response (IIR or FIR), design method (Chebyshev, Windowed-sinc...), filter order, passband frequency, stopband frequency, passband ripple, and stopband attenuation. These types of filter can be used in combination with one another for specific applications. Figure 58 illustrates an example of a low pass filter and its frequency response.



**Figure 59:** Example of filter frequency response

The passband corresponds to the range of frequencies that are passed through the filter whereas the stopband refers to those that are rejected. The range of frequencies between the stopband and the passband corresponds to the transition band; a ‘quick filter roll-off’ is characterized by a narrow transition band (Smith 1997).

Chebyshev and Windowed-sinc filters can be used to separate signals in the frequency domain. There are four types of Chebyshev filters, which are characterized by their ripple. Type 1 filters allow frequency response ripple in the passband (exemplified in Figure 58), Type 2 filters have ripple in the stopband, elliptic filters correspond to those with a ripple in both the stopband and



the passband, and Butterworth filters are described as maximally flat since the ripple corresponds to 0% (Smith 1997). A comparison of these filters revealed that the Windowed-sinc had a better stopband attenuation and increased flexibility but was much slower than the Chebyshev filter (Smith 1997). The use of a Butterworth IIR filter was investigated because of its lack of ripple and it was determined that the filtering capabilities were acceptable; thus this was the type employed in the development of the disaggregation method.

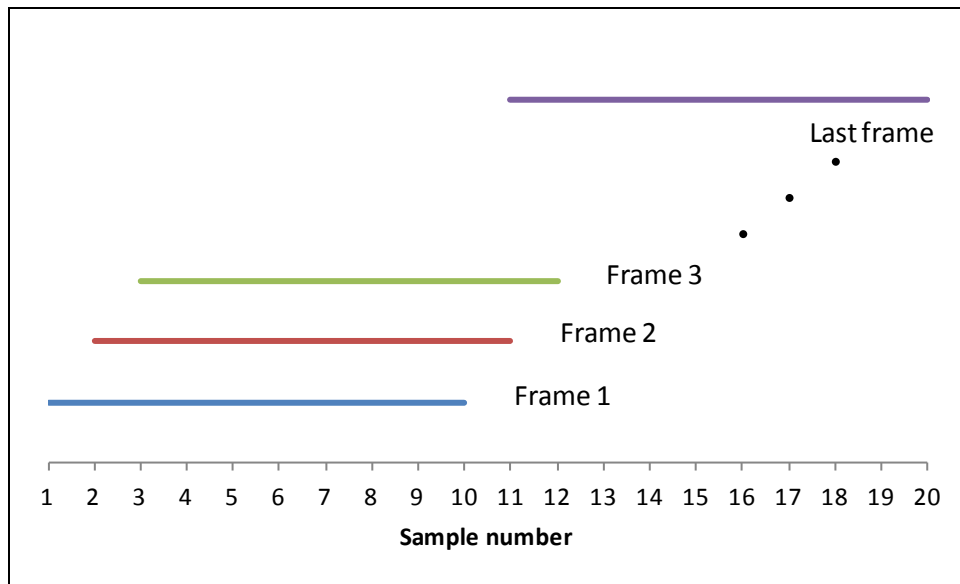
The first step in designing the filter corresponded to determining the frequencies associated with a specific electricity end-use. In the methodology proposed herein, this was achieved by modeling the electricity consumption of a piece of equipment, based on its theoretical load signature. Then an electricity signal corresponding to a particular use for a given duration was derived by repetition of this cycle. Some loads can have several cycles during one day (i.e. hoisting), while other end-uses in a mine may operate at a lower frequency (i.e. mine backfill plants operating in batch mode at each shift). Thus it should be noted that modeled signal should be sufficiently long to include 2 complete cycles for the activity to determine the periodicity of electricity consumption from this end-use. Model parameters to account for operational variability of the equipment were used to alter the individual cycles in the synthesized electricity signal. Fourier transform algorithms are more efficient with signal lengths that correspond to an integer power of 2 (Vetterling, Teukolsky et al. 1992) thus the length of the synthesized signal was chosen to comprise a total of 128 samples.

The modeled consumption was then compared to periods of the actual aggregated time domain electricity signal where the specific equipment was operational, and the variability parameters were changed until the synthesized signal and the actual became comparable. Then FFT was used to transform the synthesized time domain signal to the frequency domain, which allowed

the identification of the frequencies associated with this end-use activity. The resulting filter can be said to be ‘smart’ because the specialist information contained within the model makes the filter expectation guided.

The identified frequencies were used to design a filter to remove these frequencies from the aggregated electricity signal, with the use of the `designfilt` function and the Filter Design & Analysis Tool in MATLAB® (The MathWorks Inc. 2014). A graphical representation of the filter frequency response superimposed on the frequency spectrum of the aggregated electricity consumption permitted visual determination of whether adjustments to the filter design parameters were necessary to remove / attenuate the frequencies of one specific end-use.

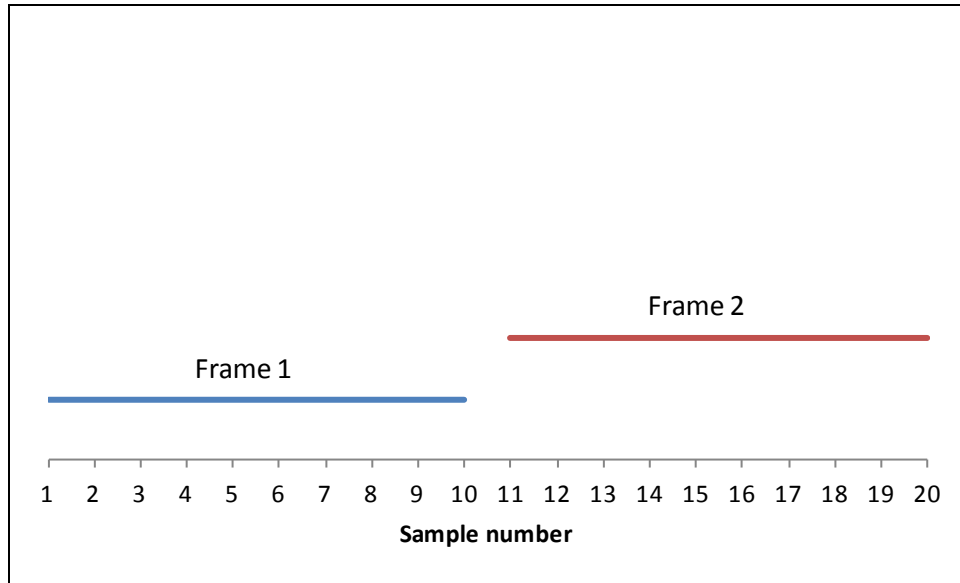
Next, an analysis was conducted to identify the periods in the aggregated time domain signal where the specific end-use was in operation. This was achieved with the use of the Neural Network Pattern Recognition procedure available in MATLAB®. A total of 48 periods of same duration as those from the synthesized signal in the previous step were extracted from the aggregated time domain signal, where the specific end-use to be filtered was operating in only half of these periods. These segments were used as the input data to train the Neural Network to identify the operating state of the specific end-use to be filtered. The output of the Neural Network was used in a ‘sliding’ frame by frame analysis of the aggregated electricity signal to classify each sampling interval based on the probability of operation of the specific end-use. The frame duration in this analysis was the same as that used in the previous steps. For example, Figure 59 shows a ‘sliding’ frame by frame analysis of a signal comprising a total of 20 samples, each frame length is 10 samples and advances by one sample until the entire signal is analyzed. It should be noted that in the actual case study the total number of samples corresponded to 40,320 and each frame comprised 128 samples.



**Figure 60: Diagram illustrating 'sliding' frame by frame analysis**

The use of a 'sliding' frame by frame analysis provided a smoother transition between frames where the activity to be filtered was operating and those where it was not. Alternatively, the use of successive frames with no overlap would have resulted in sharp transitions between frames where the probability of operation varied. For example, use of the Neural Network returned the operating probability of a specific activity within each frame, thus without an overlapping analysis a constant probability value would be used for the entire frame, whereas in the 'sliding' analysis the probability value changed gradually.

Subsequently, a frame by frame analysis was conducted and the designed filter was applied to the frames where the specific end-use was operating. This frame by frame analysis differs from the 'sliding' frame by frame because there is no overlap between the frames; each frame begins at the sample number following the last sample number in the previous frame, illustrated in Figure 60.



**Figure 61: Diagram illustrating a frame by frame analysis**

It should be noted that the frame duration in this stage corresponded to the same length as those in the previous steps to ensure that the spectra contained the same frequency bins to facilitate comparison. In Fourier analysis the frequency resolution ( $\Delta f$ ) is determined as follows (Stanley 2005):

1. Calculate the period  $T$  or the length of the signal (total sampling time)

$$T = N\Delta t$$

where  $N$  is the number of samples in the signal, and  $\Delta t$  is the time interval between samples.

2. Calculate the frequency resolution  $\Delta f$  (width of frequency bins)

$$\Delta f = \frac{1}{T}$$

A signal with  $N$  samples will have  $N/2+1$  equally spaced frequency bins from 0 to  $0.5 \times \text{sampling rate}$  (Smith 1997), where the sampling rate corresponds to  $1/\Delta t$ . Thus the frequency scale and resolution of signals of different lengths will be different and the values for the frequency axis may be different, which would impact spectral comparisons.

Windowing is a commonly used signal processing technique that removes the discontinuities introduced from repetition of a finite signal by tapering the ends of the signal to zero (Smith 2008). A Hanning window can be used for such a purpose; this multiplies the start of a signal by zero and the scaling factor gradually increases to 1 at the center of the signal, then decreases gradually to zero at the end of the signal. This window is applied to frames of a signal where these frames have a 50% overlap so that the sum of the corresponding samples in each frame return the original signal (Boll 1979). The use of a window was not used in the methodology proposed herein because the use of overlapping frames may have resulted in instances with discrepancies between the overlapping samples in successive frames. This would occur where the probability of operating state of an activity would transition from values greater than 50% to lower than 50%, thus one frame would be filtered whereas the next one would not be filtered. Furthermore, as there is no overlapping section at the start of the first frame and the end of the last frame, this information would be discarded since it does not correspond to the original signal. This may not be significant for high frequency activities (i.e. hoisting), but for low frequency activities (i.e. batch mode backfilling) a larger proportion of information would be lost.

Caution must be used during the filter application since the phase may be non-linear (Smith 1997), which could thus affect the information contained in the time domain by shifting the

signal along the time axis. This is important because information pertaining to the location of events in a time domain signal is contained in the phase of its corresponding frequency domain spectra (Smith 1997). In an energy management context, this outcome would not be suitable because it is imperative to know when energy consumption occurs for implementation of: i) optimized schedules to minimize electricity use during peak rate periods or ii) demand management initiatives such as peak shaving or load shifting. This issue was mitigated with the use of bidirectional filtering using the 'filtfilt' function in MATLAB which filters the filter output in the opposite direction to counteract the filter delay (Widmann, Schroger et al. 2014).

The filtered signal comprised the aggregated electricity use from all remaining end-uses, thus subtraction of the filtered signal from the original time domain signal provided a time domain representation of the electricity consumption of the filtered end-use.

Electricity consumption from additional end-uses could be determined by iteration of the aforementioned steps, where the total aggregated electricity signal would correspond to the filtered time domain signal from the previous iteration. Figure 61 illustrates the steps from the proposed top down methodology for disaggregation of an electricity signal.

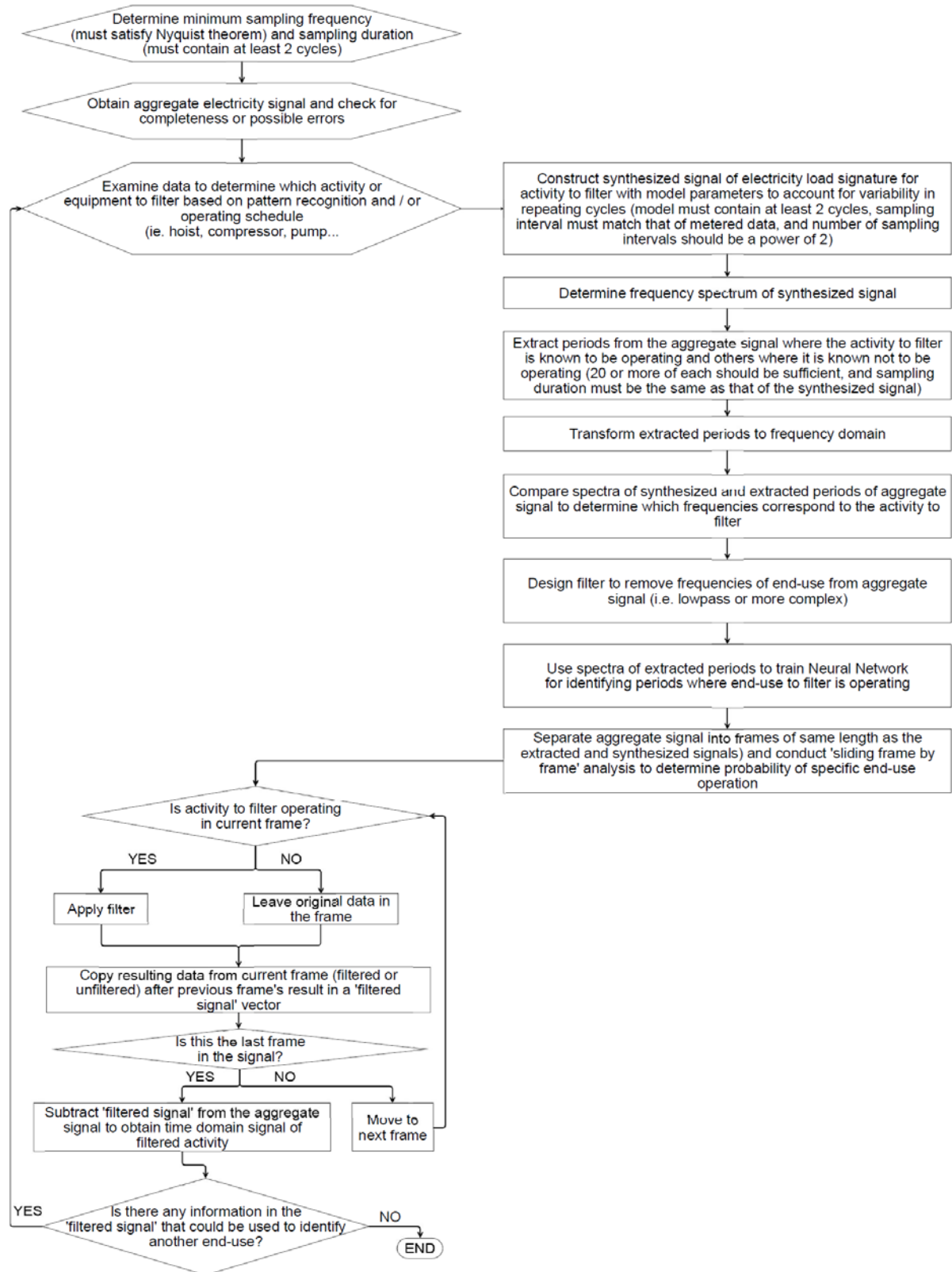


Figure 62: Overview of proposed top down electricity disaggregation method

### **9.3 Isolation of the electricity consumption of a mine hoist from a mine's total electricity meter data**

The proposed top down methodology, described in the previous section, was applied to Garson Mine, which is an underground mine owned and operated by Vale. This section will describe the application of the 'smart' disaggregation methodology to extract the mine's hoist electricity consumption from the mine's total electricity signal.

#### **9.3.1 Establishing the minimum sampling interval**

The first step consisted of determining the minimum sampling interval for the aggregated electricity signal. The mine's end-uses were categorized and the corresponding cycle time for each of these was estimated for a 24 hour period, consisting of two 12 hour shifts per day, illustrated in Table 23 prepared from data obtained from Mallett (2014). This information was used to determine the minimum sampling frequency of the electricity signal required to satisfy the Nyquist sampling theorem.



**Table 23: Time and frequency of Garson Mine end-uses**

End use	Time/cycle (hours)	Time/cycle (minutes)	Time/cycle (seconds)	Frequency (Hz)
Main ventilation <sup>16</sup>	24	1,440	86,400	1.16E-05
Aux. ventilation	24	1,440	86,400	1.16E-05
Skip hoist	0.04	2.37	142	7.04E-03
Cage hoist	0.02 - 0.07	1.18 - 4.00	71 - 245	1.41E-02 - 4.08E-03
Paste plant	12	720	43,200	2.31E-05
Backfill plant	12	720	43,200	2.31E-05
Pumping	1	60	3,600	2.78E-04
Crushing	12	720	43,200	2.31E-05
Compressed air <sup>17</sup>	24	1,440	86,400	1.16E-05
Mining activities	12	720	43,200	2.31E-05
Surface facilities	12	720	43,200	2.31E-05

Table 23 shows that the end-use with the highest frequency corresponded to the cage hoist with a cycle time of 71 seconds, which translated to 0.028 Hz. Thus the minimum sampling interval to detect all end-uses at Garson Mine corresponded to 35 seconds. The sampling intervals for the installed meters at the mine were 15 seconds and 15 minutes; therefore the use of the 15 second interval meter data satisfied the Nyquist sampling theorem and was used in the disaggregation method.

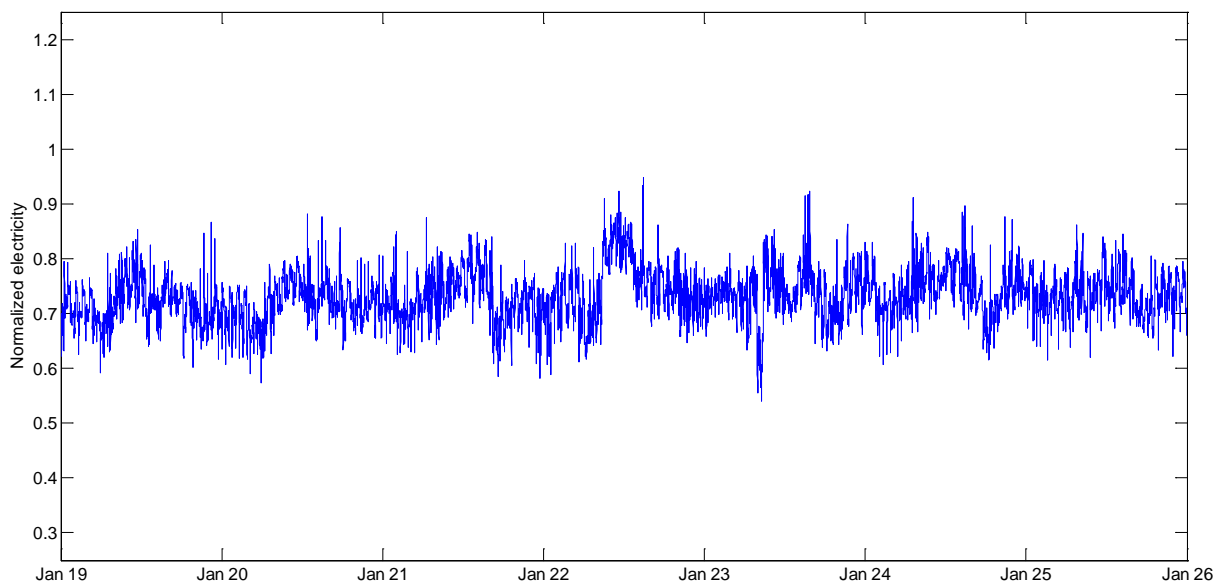
<sup>16</sup> Ventilation is shown as a baseload but electricity use from ventilation systems in mines equipped with ventilation on demand would modulate to match the demand for fresh air

<sup>17</sup> Compressors at this site are part of the baseload, but in mines where compressor supply exceeds demand and there is sufficient storage capacity electricity use would modulate. Modulation could also be indicative of a leak-free compressed air system.

A total of 14 weeks of aggregated electricity consumption data gathered at a 15 second interval was obtained for Garson Mine from Vale’s data historian system for development of the proposed disaggregation methodology. The periods comprised one week for each month, one week for the Holiday period and one week for the scheduled maintenance shutdown period. This would allow distinction of electricity use between maintenance and production periods, as well as seasonal differences.

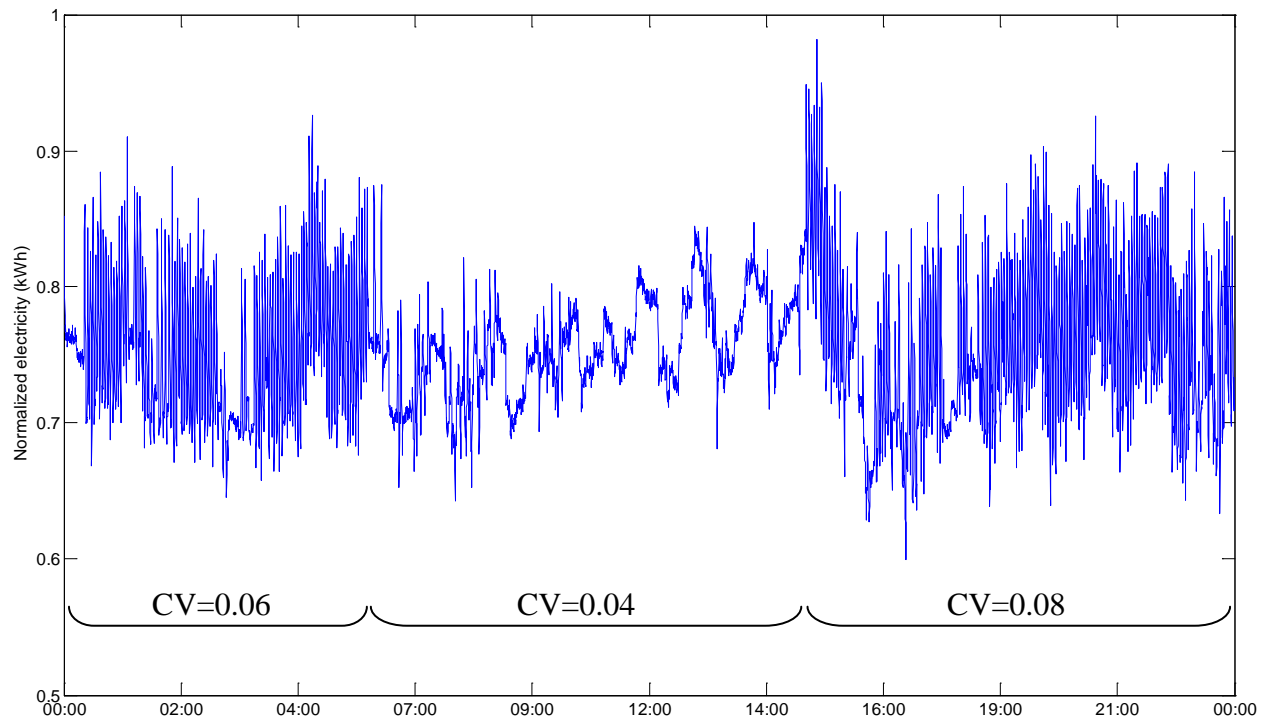
### 9.3.2 Determining which activity to filter

Examination of the aggregate signal for an entire week did not readily distinguish any specific activity as illustrated in Figure 62, which shows the normalized electricity use at Garson Mine for the week of January 19 to 26. It should be noted that all data presented in this section has been normalized based on the maximum corresponding values in the dataset due to the sensitive nature of the information presented. The native units for this data were kWh/15 seconds.



**Figure 63: Normalized aggregated electricity consumption at Garson Mine for the week of January 19 to 26**

However, examination of data on a daily basis revealed that some intervals within this period appeared to have greater variability than others, as exemplified in Figure 63 which shows the data for January 21 and the coefficient of variance for 3 segments (standard deviation divided by the mean).



**Figure 64: Aggregate electricity consumption at Garson Mine for January 21**

Examination of the electricity consumption for a 32 minute segment during these intervals revealed a distinct pattern that was recognized as that corresponding to a repeating hoist cycle. Figure 64 shows a 32 minute segment of the aggregate data for the week of January, comprising 128 samples, which corresponded to 10 hoist cycles, whereas Figure 65 shows the power versus time diagram of one cycle from a cylindrical drum winder from (Walker 1988).

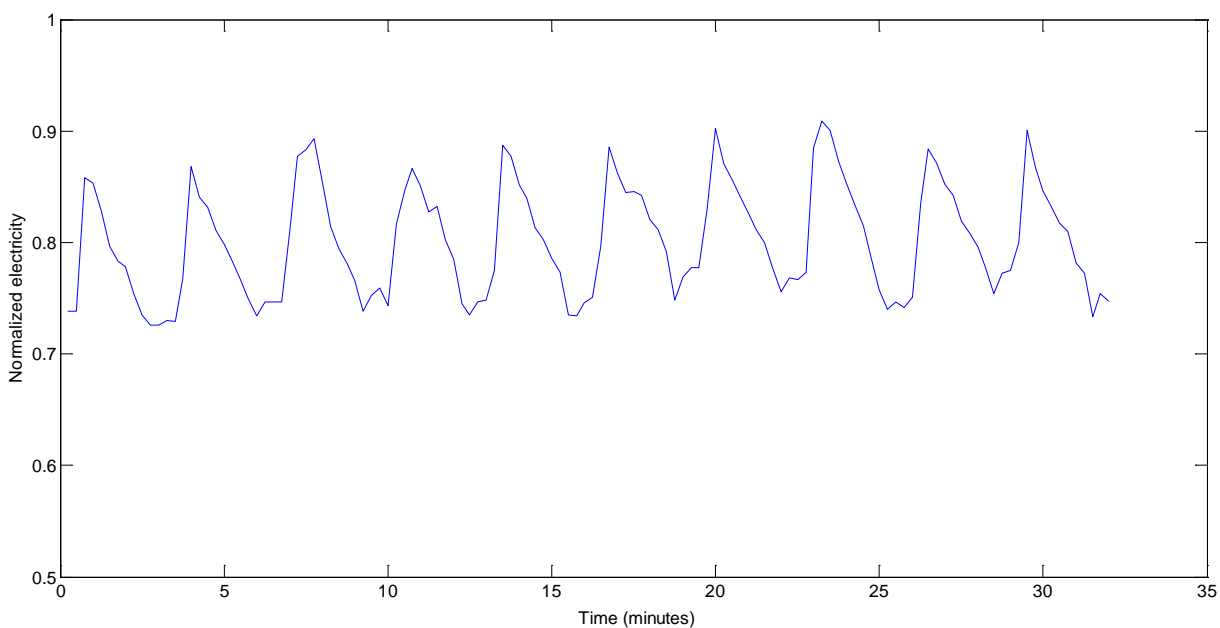


Figure 65: Segment of aggregate electricity use at Garson Mine for a 32 minute interval

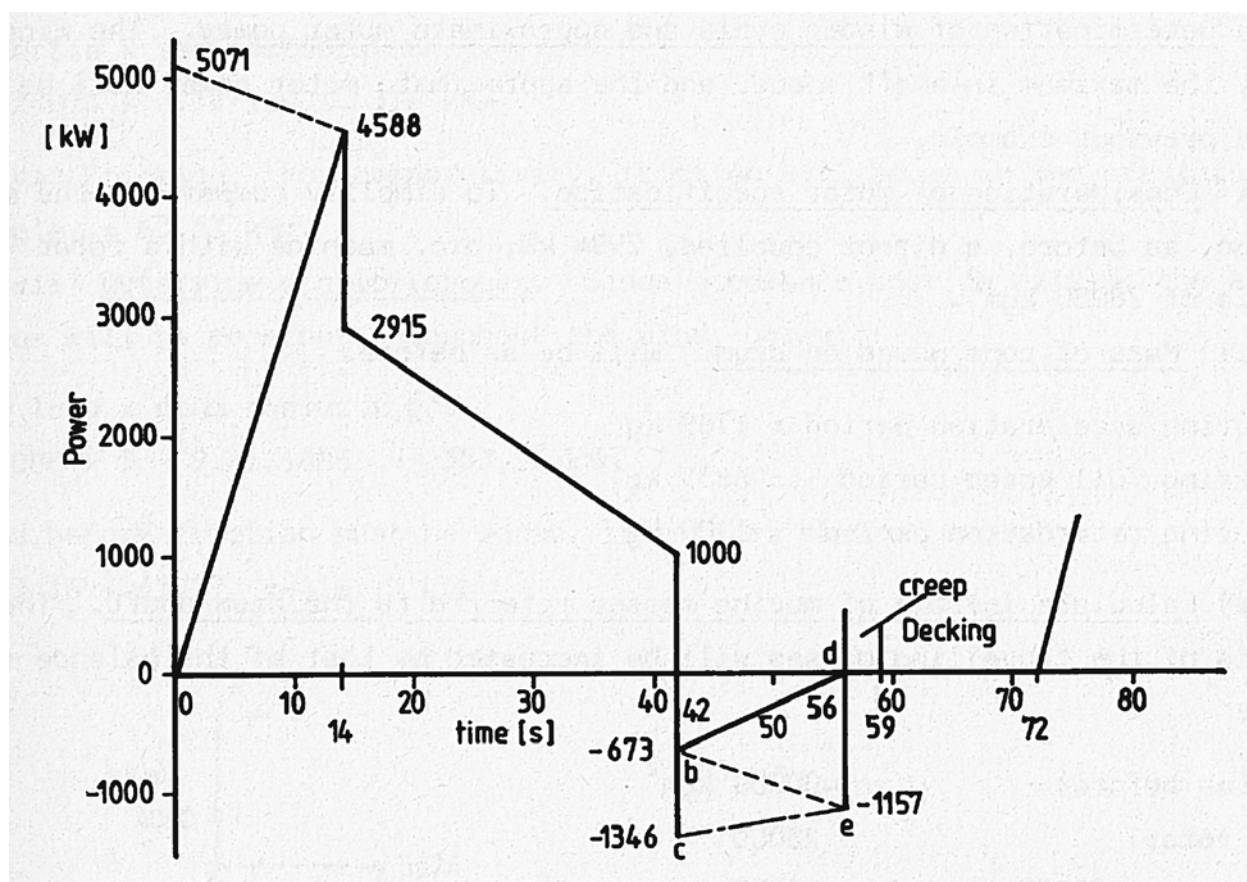
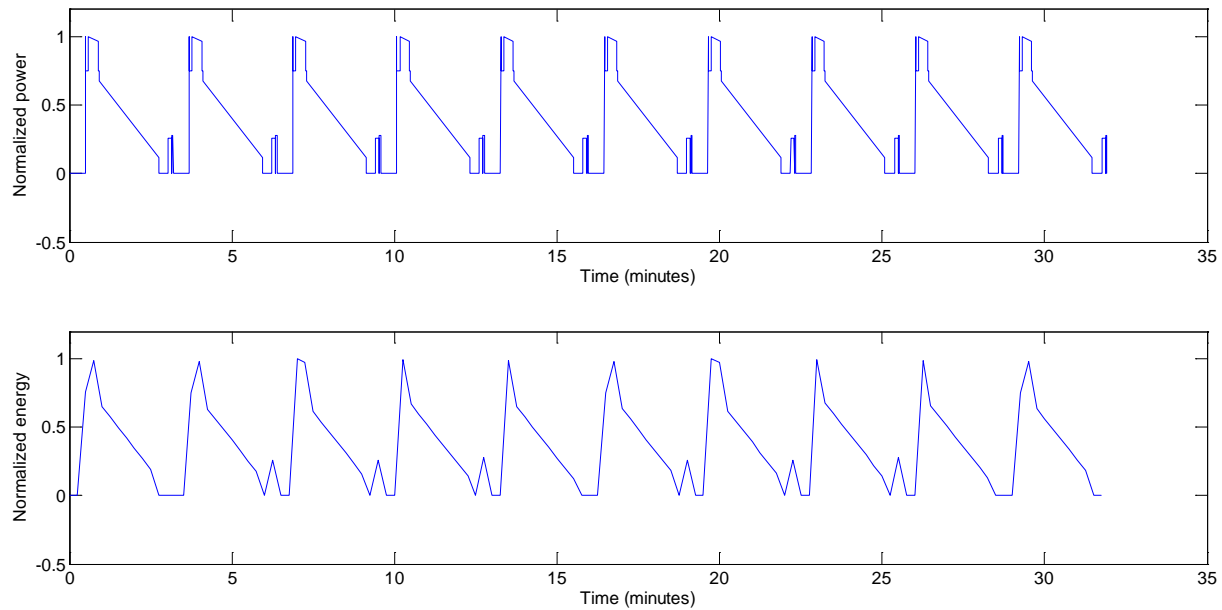


Figure 66: Power / time diagram of cylindrical drum winder (Walker 1988)

Variations in the pattern shown in Figure 64 result from operational variability of the hoist due to different: i) loading time, ii) unloading times, iii) payload weight and, iv) hoist speed. Further variations may be due to electricity loads from other equipment starting and stopping at different times within the hoist cycles.

The theoretical load signature curve for the Garson Mine hoist, parameterized from logged data from the control system (Mallett 2014) was repeated for 10 cycles. During the braking stage of the cycle, it was shown by the power curve in Walker (1988) and from the control system that power can be generated; however since this regenerative power was not used at Garson Mine, adjustments to the section of the curve corresponding to the braking stage were made. Then interpolated values of the data sampled at 15 second intervals were determined and converted to energy values. Figure 66 shows the normalized power and energy curves for 10 cycles.



**Figure 67: Hoist power and energy load signature curves for a 32 minute period**

The pattern illustrated in Figure 64 resembled that of the lower graph of Figure 66. Thus it was hypothesized that the variability in the composite electricity consumption signal could be attributed to the hoist.

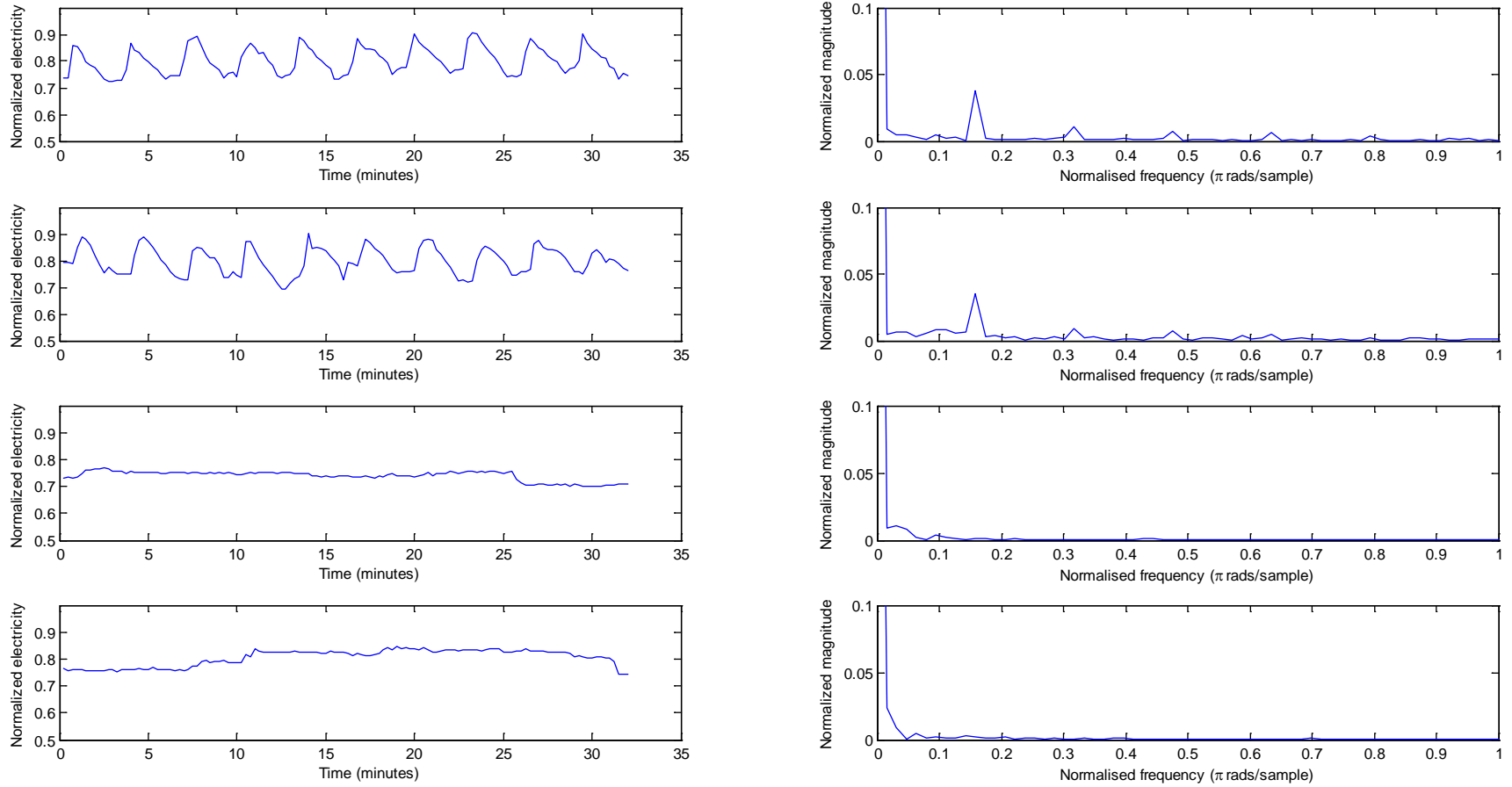
This assumption was confirmed with external knowledge of the hoist operating schedule, which at Garson Mine corresponded to operation between 3:00 PM and 7:00 AM to minimize electricity use during peak rate periods (Mallett 2014). Figure 63 showed the aggregate electricity consumption at Garson Mine for a 24 hour period which illustrates a different consumption pattern during the period when the hoist operation may be curtailed.

Thus the hoist was selected as the first end-use to extract from the aggregate electricity signal at Garson Mine. This selection was determined with the use of expert knowledge, such as the generic load pattern of a hoist coupled with basic information on the operating schedule.

Removal of the hoist signal may facilitate subsequent identification of other end-uses that may currently be ‘masked’ by the hoist electricity use.

### **9.3.3 Determination of probability of hoist operating state**

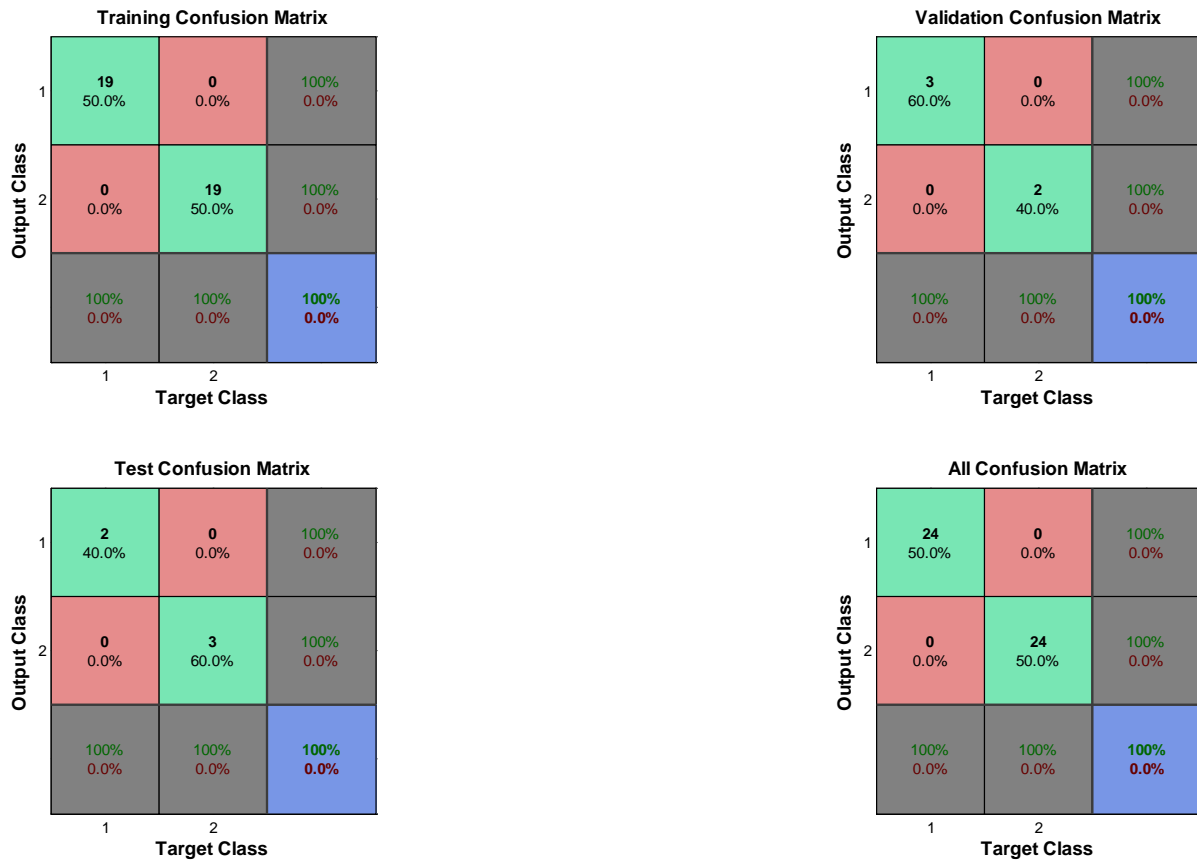
Although the hoist at Garson Mine is scheduled to operate between 3:00PM and 7:00AM, there may be some deviations to the schedule to meet production schedules. Identification of periods when the hoist is operating may be readily discerned by examination of the aggregate signal but this may be time consuming for large datasets. This task may be facilitated by defining criteria so that a computer can be used. Thus the hoist operating state was determined with the use of the Neural Pattern Recognition algorithm in MATLAB® (The MathWorks Inc. 2014) to identify the sampling frames when the filter would be applied. The first step corresponded to the extraction of four 32 minute segments for every week of data obtained, each comprising 128 points, where the hoist was known to be operating in two of these segments and know not to be operating in the other two periods. Then the frequency domain spectra of these segments were determined. Figure 67 shows the signals and corresponding spectra for the extracted periods from the January data. The extracted segments for the other periods are included in Appendix A.



**Figure 68: Frames extracted from January data to train Neural Network**



The magnitude values shown in the frequency spectra of the extracted periods were used as the input values to train the Neural Network to detect whether the hoist was operating at a given sampling interval. The 48 input samples were randomly divided to include 38 samples for the Neural Network training stage, 5 samples for the validation, and 5 samples for testing. The network was trained using scaled conjugate gradient backpropagation and the Network Architecture comprised a total of three sigmoid hidden layers. Demuth *et al* (2008) provide more details on the methodology employed. A so-called ‘confusion matrix’ plot shown in Figure 68 illustrates the types of errors encountered during the training stage (Demuth, Beale et al. 2008). It can be seen that the Neural Network was 100% capable of determining the operating state of the hoist from the blue cells in the bottom right corner of each matrix.



**Figure 69: Neural Network confusion matrix**

The output parameters from the trained Neural Network were then used to determine the probability of the hoist operation for each sample of the signal for an entire week using a sliding frame by frame analysis. Each frame comprised 128 samples, and the probability of hoist operation corresponded to that of the sample in the center of the frame. Then the frame was shifted forward in time by one sample and the probability of the next frame was determined. The probability of hoist operation for the samples at the start and at the end of the sampling period were assumed to correspond to those from the first and last points respectively that were determined with the sliding frame by frame analysis. The results are illustrated in Figure 69. The

blue line at the bottom of the figure corresponds to the aggregate electricity consumption for Garson Mine for a one week period. The green line at the top of the figure shows the corresponding probability of hoist operation for which the values are read on the axis on the right. For example, a value of 1 indicates that the probability that the hoist was operating at that time was 100% as determined by the trained Neural Network. Conversely, a value of 0 indicates that the hoist was not operating, and the values between 0 and 1 correspond to probabilities between 0 and 100% for the hoist operation. Hence a value of 0.5 would indicate a 50% probability that the hoist was running.

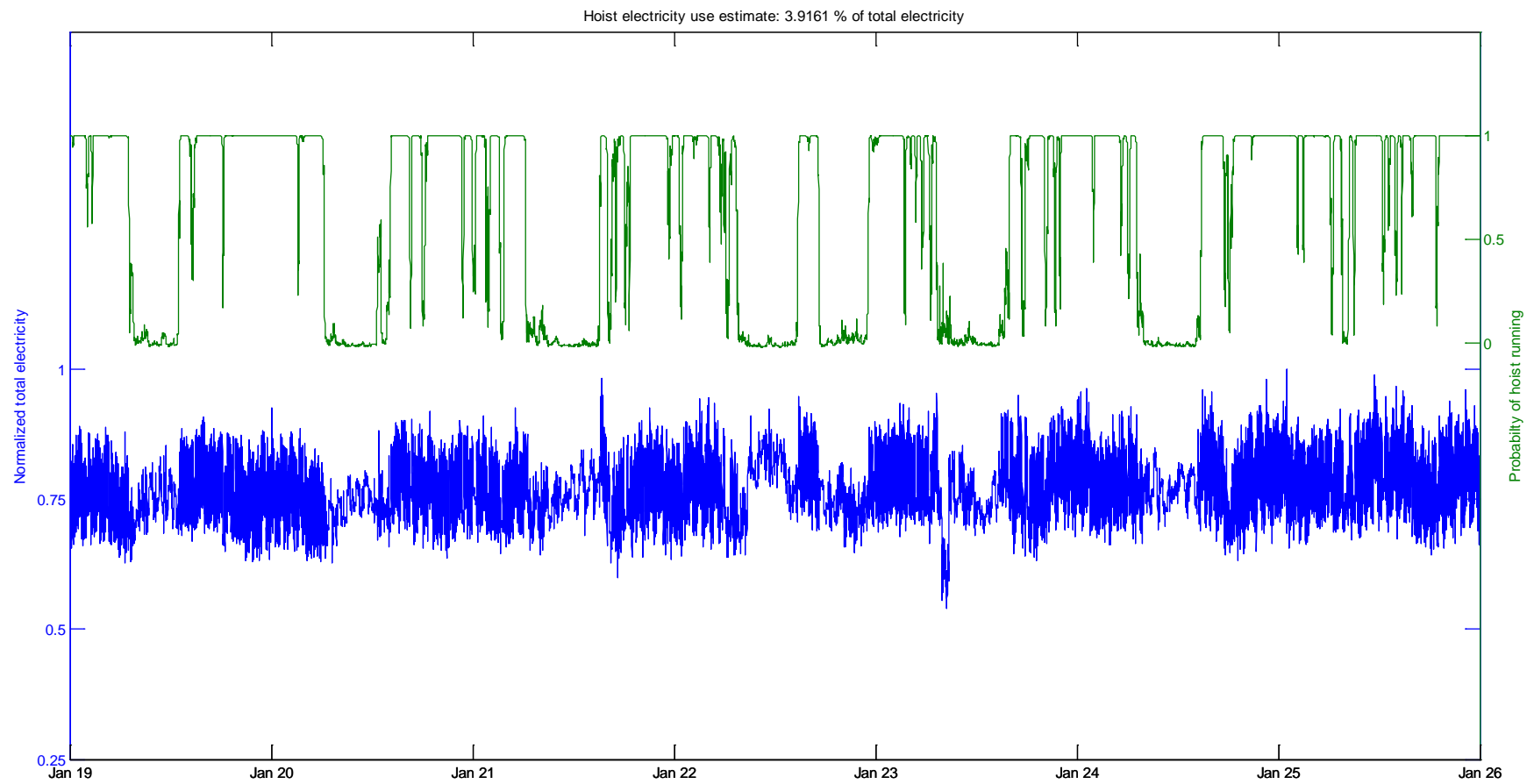
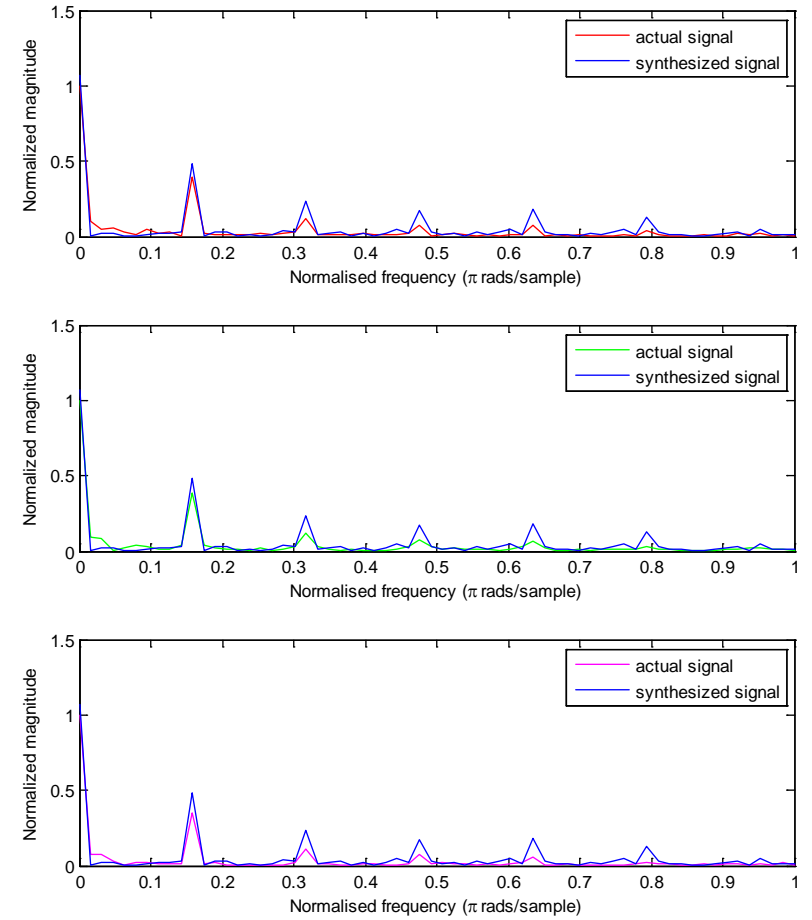
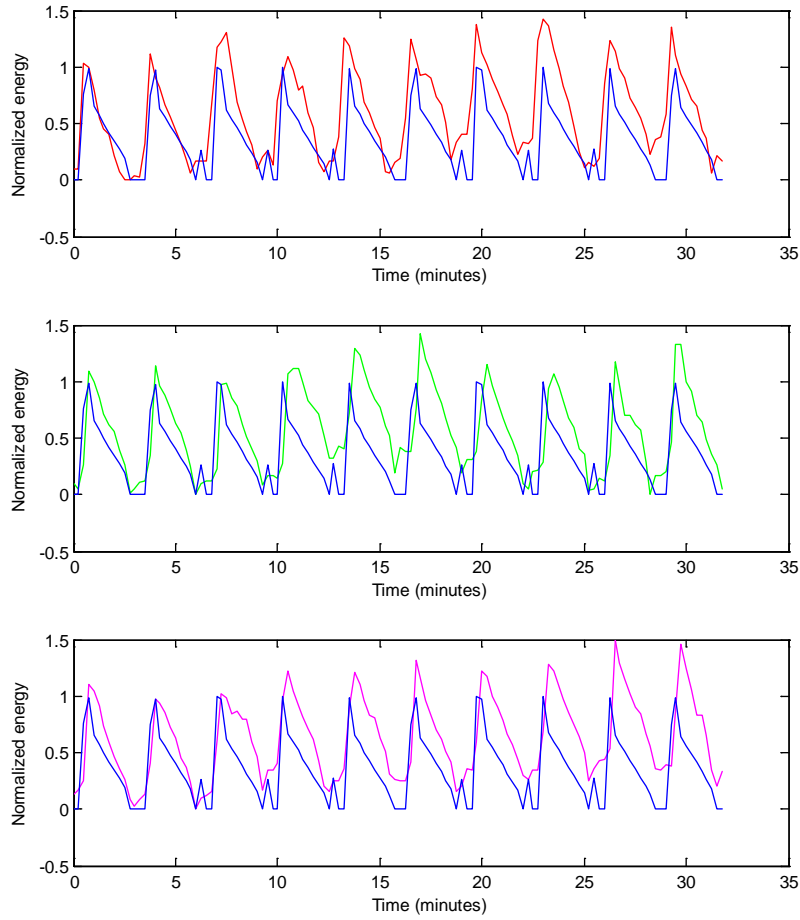


Figure 70: Aggregated electricity signal and probability of hoist operating for January 19 to 26

An estimate of the proportion of total electricity consumption was determined by counting the number of 15 second sampling intervals where the probability of the hoist operating was greater than 50%. Then this value was multiplied by the average electricity consumption per 15 second interval determined from the synthesized hoist electricity load signature, which was presented in Figure 66. The values obtained for the electricity consumption of the hoist from this estimate were compared to those subsequently obtained with the use of a filter.

#### **9.3.4 Designing the filter**

Examination of the spectra derived from the frame samples of the synthesized hoist signal indicated which frequencies were associated with the hoist electricity consumption. These were compared to the corresponding spectra of segments of the aggregate electricity demand signal illustrated in Figure 70. As there was variability in the patterns of the actual hoist cycles, three segments of the aggregate data were randomly selected to ensure that the spectra of these signals were comparable to that of the synthesized signal. It should be noted that the baseline of the aggregate electricity signal was adjusted by subtracting a constant value from electricity data for the entire period so that the minimum value in each frame would be zero. This was done to allow superimposition of the synthesized hoist and actual electricity consumption signals to facilitate comparison. Examination of the distinctions between the periods where the hoist was known to be operating and those when the hoist was not operating used in the Neural Network training provided further confirmation of the frequencies associated with the hoist. The top two spectra on the right in Figure 67 and Appendix A show that peaks at frequencies corresponding to 0.16, 0.32, 0.48, 0.63, 0.79, and 0.95  $\pi$  rad/sec were present when the hoist was operating.



**Figure 71: Comparison of synthesized hoist and actual hoist signals**

Examination of the spectra corresponding to the periods used to train the Neural Network where the hoist was known not to be operating also revealed that there did not appear to be many sizeable peaks at frequencies greater than  $0.2 \pi$  rads/sec. It was decided that a lowpass filter could be used to extract the hoist electricity consumption from the aggregated electricity signal since those corresponding to the hoist were at the higher frequencies. The parameters used to design the filter to remove the hoist frequencies from the aggregated signal are presented in Table 24 and the filter frequency response is illustrated in Figure 71.

**Table 24: Lowpass filter design parameters for extraction of hoist electricity consumption**

Parameter	Value
Response type	Lowpass IIR
Method	Butterworth
Passband frequency	$0.1 \pi$ rads/sec
Stopband frequency	$0.2 \pi$ rads/sec
Passband ripple	1 dB
Stopband attenuation	60 dB
Band to match exactly	Stopband

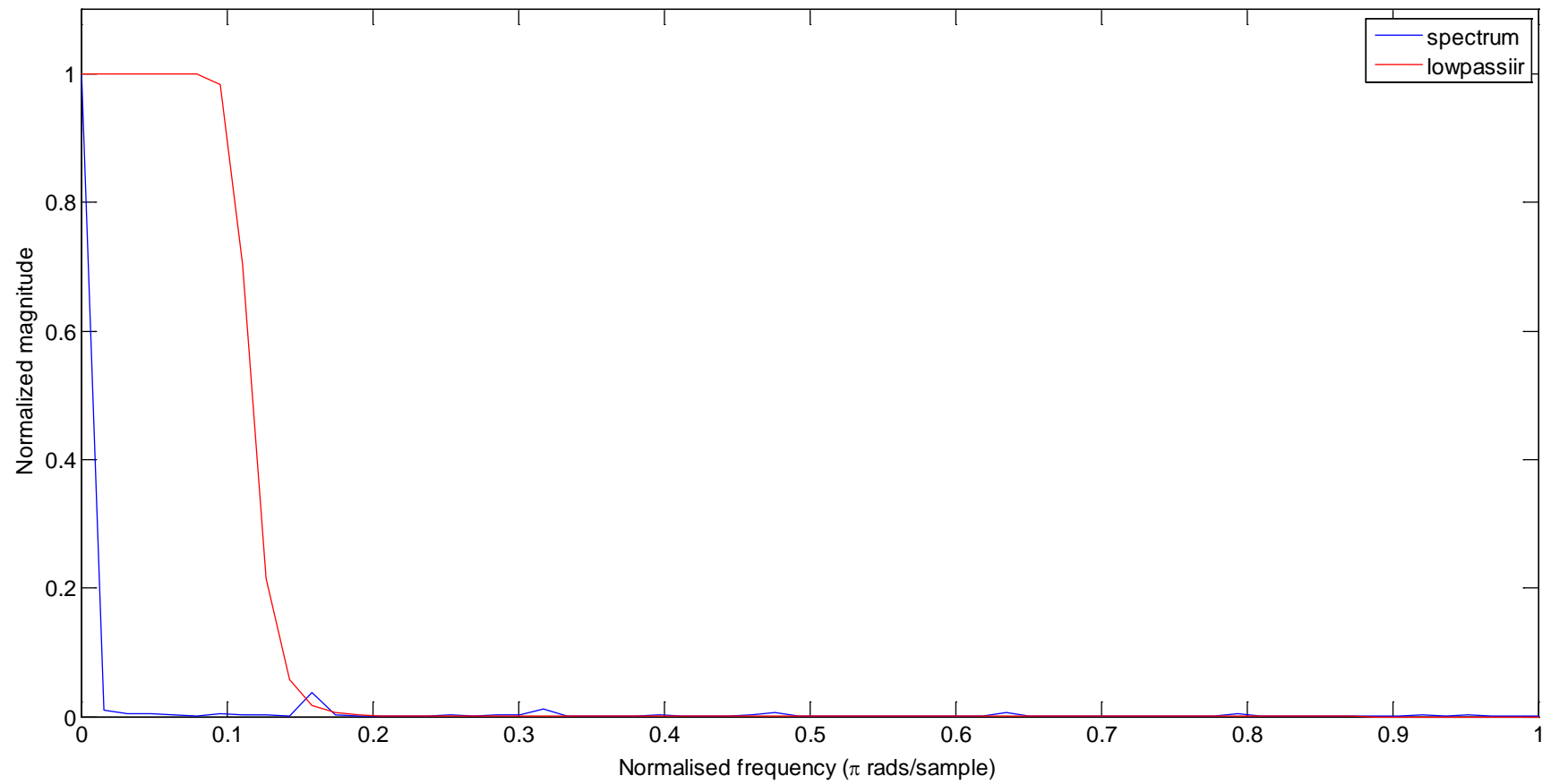


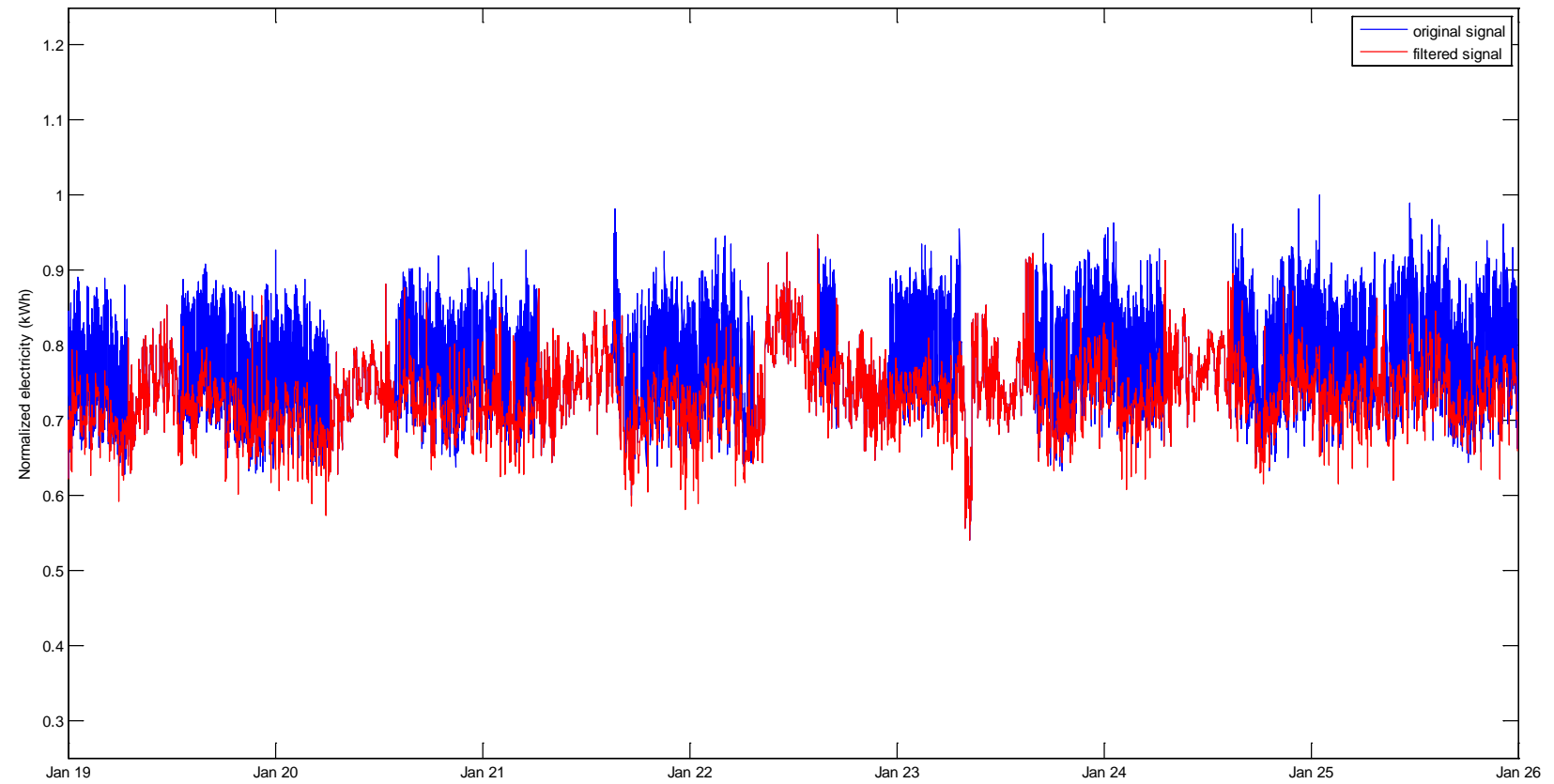
Figure 72: Butterworth filter frequency response for Garson Mine hoist electricity extraction



It can be seen from Figure 71 that the magnitude values corresponding to the peak between  $0.1$  and  $0.2 \pi$  rads/sample would not be completely removed by the filter designed with these parameters. This was intentional since examination of the spectra in Figure 67 and Appendix A showed that the magnitude values at these frequencies for the periods where the hoist was not operating were not always zero. Thus an attempt was made to develop a filter that would attenuate this peak but not completely eliminate it.

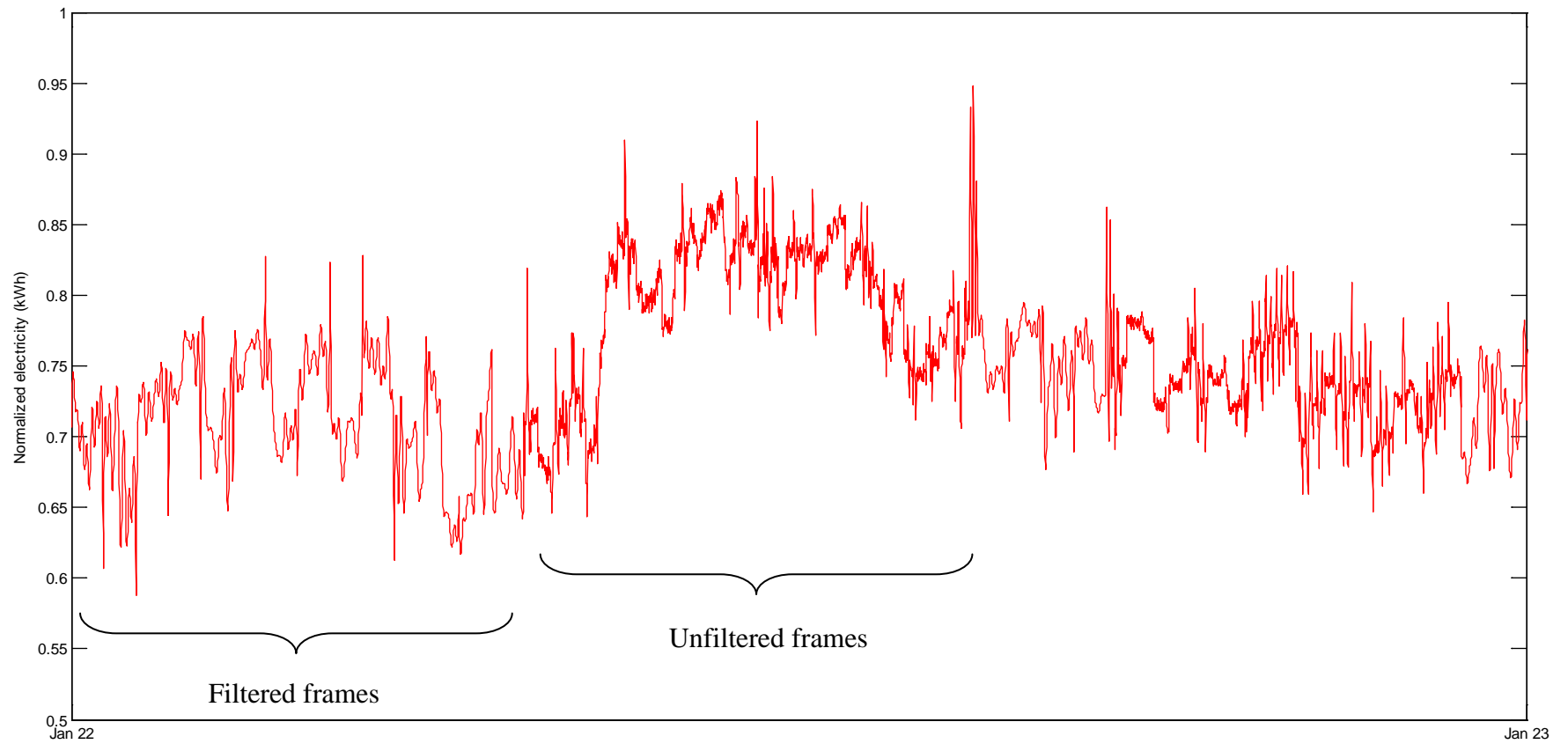
### 9.3.5 Applying the filter

The filter designed in the previous step was then applied to the aggregate electricity signal for periods where the hoist was operating. First the signal was separated into frames each comprising 128 samples. Then the probability of hoist operation was used to determine to which frames the filter should be applied. A threshold value of 0.5 was applied in the frame by frame analysis, whereby the filter was only applied to the frames where the combined probability of the hoist operating for each point within that specific 32 minute period was greater than 50%. A threshold value of 50% was chosen because this would provide a balance between application of the filter to frames where the hoist was operational during a portion of the time. Use of a higher value would have reduced the number of frames where the filter was applied, leaving more of the hoist signal in the filtered signal. Conversely a lower threshold would have applied the filter to more frames with partial hoist operation, thus attenuating some of the high frequencies that are not associated to the hoist. Figure 72 illustrates the resulting filtered electricity signal from Garson Mine after the filter was applied to frames where the probability of hoist operation was greater than 50% to remove the hoist consumption from the aggregate signal. The original aggregate signal is also included with both series were treated with the same normalization.



**Figure 73: Garson Mine electricity signal after hoist filter application overlaid on original aggregate electricity signal**

It can be seen from Figure 72 that the variability associated with the hoist electricity consumption was reduced after application of the filter. A comparison of sections of the signal in Figure 72 where the filter was applied with other frames that remained unfiltered shows that there does not appear to be much difference between the filtered and unfiltered sections of the signal. The difference between the filtered and unfiltered frames could be quantified by comparison of their spectra. However, examination of one daily segment of the filtered signal revealed that the filtered frames appear to have less noise, which corresponded to the removal of the high frequencies during the filtering stage of the methodology. Figure 73 shows the filtered signal for January 22<sup>nd</sup>, where the first part of the signal was filtered and the center was not filtered for the hoist extraction.



**Figure 74: Electricity signal at Garson Mine after hoist filter application for January 22**

It can be seen by comparison of the filtered frame with unfiltered frame from Figure 73 that the use of a lowpass filter may have removed too much of the high frequency components from the aggregate signal. This may be rectified by:

- i) means of adjustments to the filter design parameters such as with the use of a custom bandstop filter to attenuate specific frequency components,
- ii) or use of a different signal processing technique such as spectral subtraction which is employed to remove noise from audio signals.

Use of a more selective method to filter the hoist from the aggregate signal may improve the disaggregation method.

### **9.3.6 Determination of hoist electricity consumption**

The hoist electricity consumption signal was then derived by subtraction of the filtered signal from the original aggregate signal. The resulting hoist electricity consumption signal is illustrated in Figure 74 along with the probability of the hoist operating state. Figure 75 shows a 32 minute segment of the hoist electricity consumption signal extracted from the aggregate signal. It can be seen from the load signature shown in Figure 75 that the applied filter has appeared to have successfully extracted the hoist electricity consumption from the aggregate signal because the load signature resembled that of the synthesized hoist signal in Figure 66. This could be quantified by comparison of the spectra for the extracted period with that of the synthesized hoist.

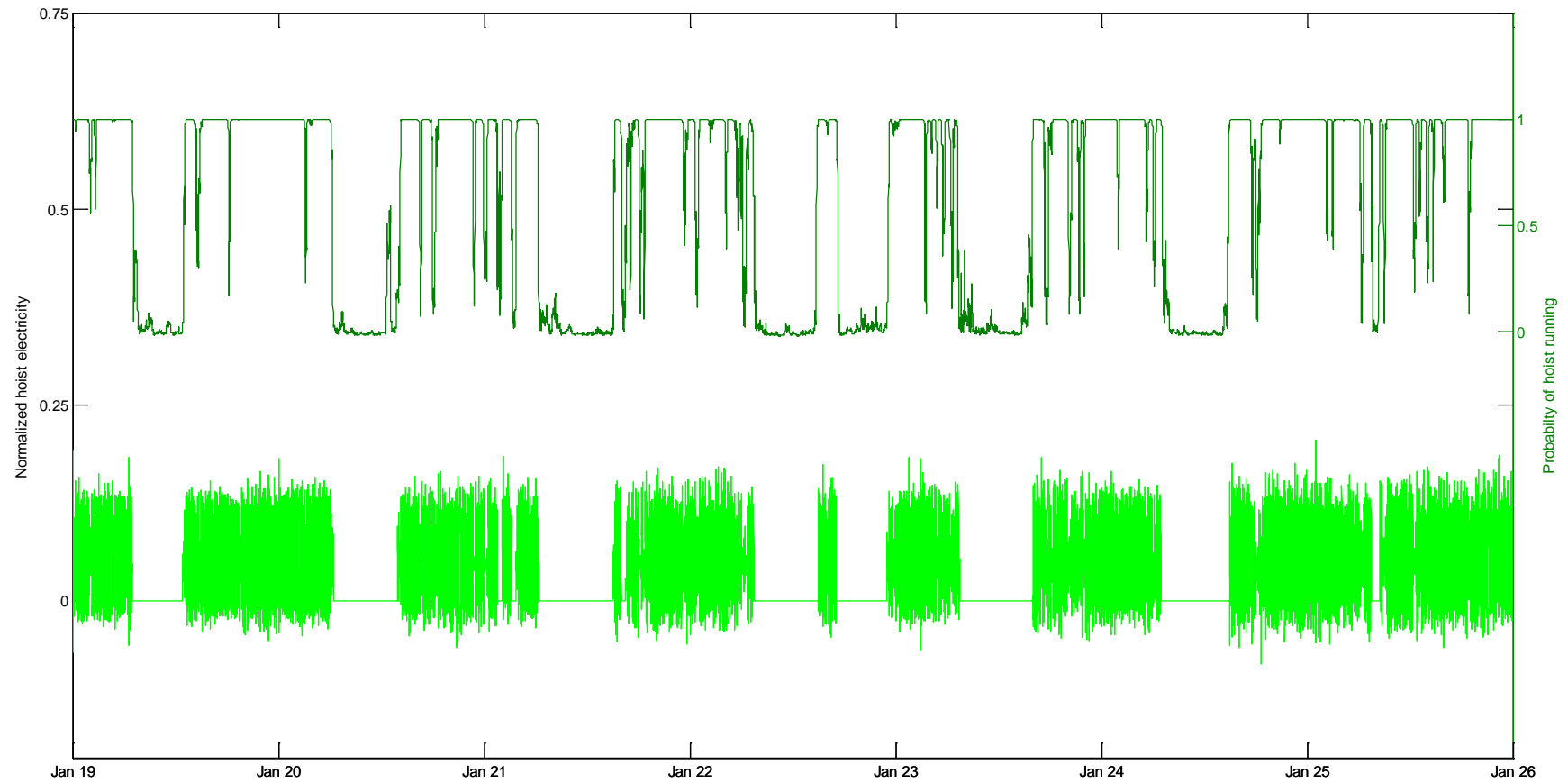


Figure 75: Extracted hoist consumption signal from aggregate electricity signal at Garson Mine for January 19 to 26

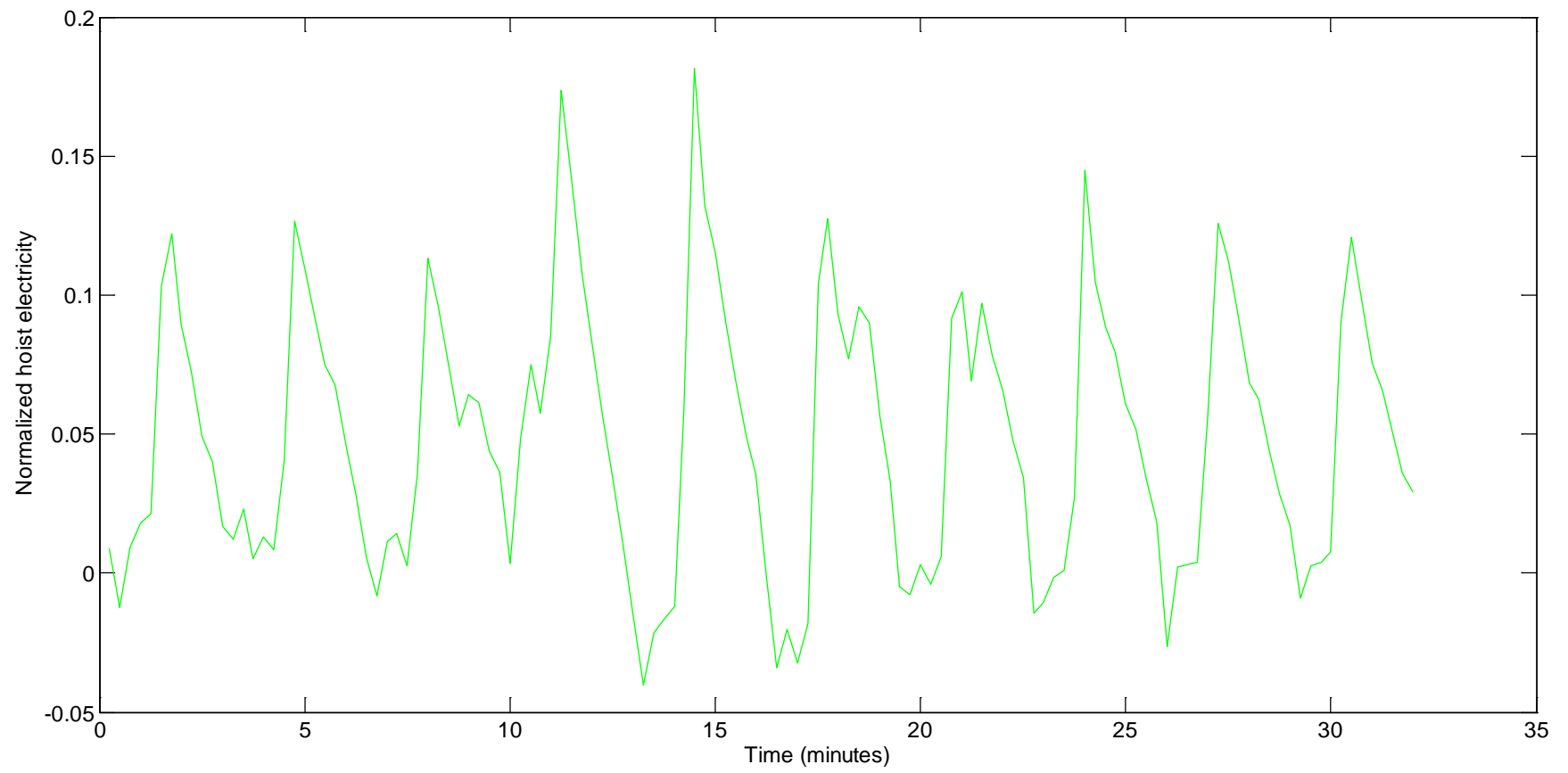


Figure 76: Extracted hoist signal from aggregate electricity signal at Garson Mine (32 minute segment)

The total electricity use from the hoist for the week of January 19 to 26 was then calculated by summing the electricity use from the hoist for each 15 second interval within this period, which allowed determination of the proportion of total electricity use attributable the hoist.

While the methodological development was exercised using January data, the disaggregation methodology was applied to all other periods of aggregated electricity consumption data that was provided for this study. A summary of the results is presented in Table 25, and Appendix B presents an overview of the analysis for each period.



**Table 25: Proportion of total electricity used by the hoist at Garson Mine for various periods**

Period	Hoist electricity consumption estimate (% of total)	
	From average consumption <sup>18</sup>	From filtered signal
January	3.92	4.13
February	3.54	3.55
March	3.75	3.86
April	3.91	3.98
May	2.15	2.20
June	3.88	3.96
July	2.68	2.80
August	2.44	2.43
September	3.00	3.04
October	3.40	3.47
November	3.42	3.46
December	2.66	2.73
Holidays	2.14	2.22
Shutdown	0.18	0.10
Average of 12 months <sup>19</sup>	3.23	3.30

The results presented in Table 25 show that both methods used for estimation of the proportion of total electricity from the hoist provided similar values but those derived from counting the number of 15 second intervals where the probability of the hoist operation was greater than 50% yielded slightly lower results for the weeks excluding Holidays and Shutdown periods.

An energy audit conducted at Garson Mine established that the proportion of electricity consumed by the hoist corresponded to 3.41 % of total electricity (Mallett 2014), thus this

<sup>18</sup> The values in this column were estimated by multiplication of the number of 15 second intervals where the probability of hoist operation was greater than 50% with the average hoist electricity consumption from the synthesized hoist signal.

<sup>19</sup> Excluded Holidays and Shutdown periods

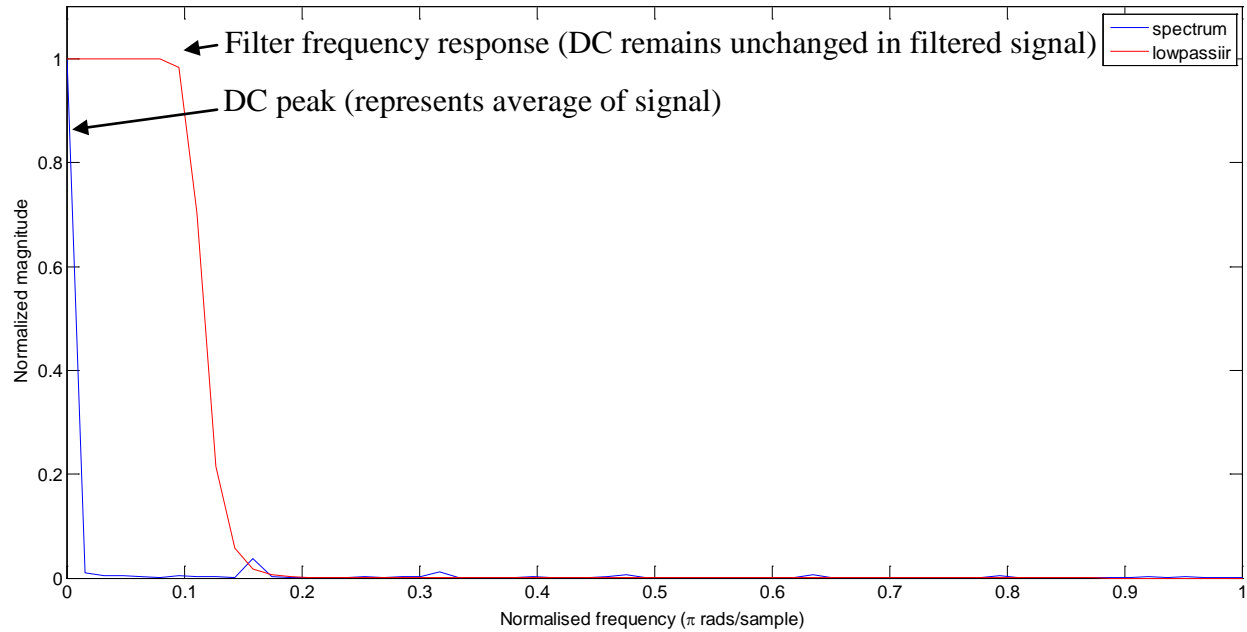
provides confidence in the values determined by the disaggregation method developed as part of this work.

### **9.3.7 Issues with the proposed disaggregation methodology and suggested future refinements**

It was assumed that the discrepancies between both methods used to estimate the electricity use from the hoist could be due to the use of the average hoist cycle electricity consumption value derived from the synthesized load curve for 10 cycles. The energy use from the hoist would vary based on the amount of material being lifted, thus a refined average electricity consumption value that considered the mass of material could provide results between both methods that would be more similar. Alternatively, it is possible that the filter removed data from frequencies that did not belong to the hoist, and thus overestimated the electricity consumption from this end-use. This may be due to the application of a lowpass filter or due to the filtering of frames with partial or intermittent hoist operation.

Examination of the extracted hoist signal from all the assessed periods showed that although regenerated power was not used at Garson Mine, there were some negative electricity consumption values. This was because for some intervals the values from the filtered signal were greater than those from the original aggregate signal. It is estimated that this was because application of the filter did not remove the average consumption of the hoist from the aggregated signal when producing the filtered signal, thus the average consumption derived from the synthesized hoist signal was subtracted from the filtered signal. This can be explained with the use of the diagram in Figure 76 which shows that the DC component (first peak in the spectra which corresponds to the average value of the time domain signal) remained unchanged in the

filtered signal because it was multiplied by 1. Since the filter was designed to remove the electricity consumption of the hoist from the aggregate signal, the average hoist cycle consumption derived from the synthesized hoist signal was subtracted from each of the frames where the filter was applied to obtain the filtered signal.



**Figure 77: Butterworth frequency response for Garson Mine hoist electricity extraction**

The cage hoist at Garson Mine is used to transport workers and supplies underground to and from four levels of different depths. The total time required for one cycle to the shallowest level corresponded to 71 seconds whereas the time to the deepest level was 245 seconds. Examination of the daily cage hoist schedule revealed that 93% of the 29 trips were to the deeper levels, and that the time interval between trips was not constant. Thus the load signature of the individual cycles would be different and the daily pattern for the cage hoist electricity consumption would not be periodic. Knowledge of the cage hoist schedule and the various load signatures would be

required in the disaggregation method, however it may be difficult to discern between the cage and the skip hoist due to their similar load signatures.

Comparison of the filtered signal for all the periods assessed during this study revealed that there were similar patterns that repeated in the different weeks. All of the periods began on a Saturday and ended on a Friday, therefore some activities seemed to occur at the same time every week. Thus discussions with mining personnel may provide clues to assist in the identification of these activities for subsequent iterations of the disaggregation methodology. Examination of periods with lower electricity use such as the scheduled maintenance shutdown period may be useful to identify the load signature of some equipment because of the reduced number of operating equipment.

The use of regenerated power during the braking stage of the hoist cycle was investigated and it was estimated that the potential electricity savings would correspond to roughly 6.7% of the electricity consumed by the hoist. However, since this activity only accounted for about 3% of total electricity use at the mine, this would only translate to total electricity savings of 0.2%.

Thus the savings potential from this measure may be considered negligible. Furthermore, periodic regeneration of electricity for short durations may cause issues in the electrical system at the mine, which may be overcome by storing the regenerated electricity but this would increase the investment for this potential energy conservation measure.

The analysis presented in this chapter indicated that an electricity signal from a mine could be disaggregated to extract the electricity use from the hoist. This was achieved with the use of information from both the time and frequency domains, combined with expert knowledge of electricity load signature and operating schedule for the hoist.

Recursive application of the methodology developed during this study could be used to estimate the electricity consumption of other end-uses, where the aggregate signal would correspond to the filtered signal of the previous iteration. It is anticipated, with knowledge of the operating schedule of the remaining end-uses from Table 23, that the next end-use extracted for Garson Mine may correspond to pumping. The disaggregation methodology for this activity would have to consider the storage capacity, flowrates from groundwater, precipitation, and control measures used to activate the pumps to derive the load signature. Thus the next iteration may be more challenging than the hoist extraction.

Although some issues have been identified with the methodology developed during this study, refinements with additional work could address these shortcomings. Future research should investigate enhancement of the filter design parameters or the use of spectral subtraction to reduce or eliminate the misallocation of frequencies to various end-uses. Nonetheless, a disaggregation methodology was developed during this work that could be applied to estimate the electricity use of a hoist in an underground mine and subsequent reiterations could estimate other end-use electricity consumption.

## **10 Improved energy audit and data interpretation and their impact on production patterns and profitability**

### **10.1 Introduction**

With milling costs representing 43 to 45% of total costs for a mining operation (Curry, Ismay et al. 2014), mills present an excellent opportunity for managing expenditures within the mining sector. It was also reported that in a mineral processing plant, comminution energy consumption may correspond to as much as 60% of total energy (Sayadi, Khalesi et al. 2014), which provides incentive to improve efficiencies in these plants. As efficiencies for comminution processes correspond to 1-2% and grinding at 2-3% (Sadrai, Meech et al. 2011), there appears to be significant room for improvement. Methods for improving efficiencies in milling have been investigated and a summary illustrating the various research areas was presented in Curry *et al* (2014). These included: pre-concentration, more efficient grinding technologies, and coarse particle separation.

In 2008, an energy audit was conducted at Vale's Clarabelle Mill by Byron Landry & Associates in order to identify potential energy savings (Landry 2009), precipitated by rising energy costs and market conditions. A review of this work was undertaken to gain a better understanding of energy use in mineral processing facilities and to determine whether additional energy and cost savings existed at Clarabelle Mill. Furthermore, an analysis was conducted for the 2012 census year to determine potential cost savings that could arise due to a revised Ontario billing rate structure, implemented in 2011. The analysis was also extended to other metal ore milling facilities operating in Ontario to determine the possible savings that could be achieved across the industry.

## **10.2 Clarabelle Mill flowsheet and process description**

Clarabelle Mill has been in operation since 1971 (Pickett, Hall et al. 1978) and processes ore from various Vale and QuadraFNX mines (now KGHM International) (Barrette, Taylor et al. 2012). Flowsheet design and modifications have been described in various books, journal and conference publications (Pickett, Hall et al. 1978, Tenbergen, Throssell 1989, Damjanovic, Goode et al. 2000, Xu, Wilson 2000, Kerr, Bouchard et al. 2003, Doucet, Price et al. 2010, Barrette, Taylor et al. 2012). The process flowsheet in place at the time of the 2008 energy audit consisted of a comminution stage followed by a flotation circuit.

A simplified illustration of the comminution circuit, produced from the aforementioned sources, is presented in Figure 77 whereas the flotation circuit is illustrated in Figure 78.





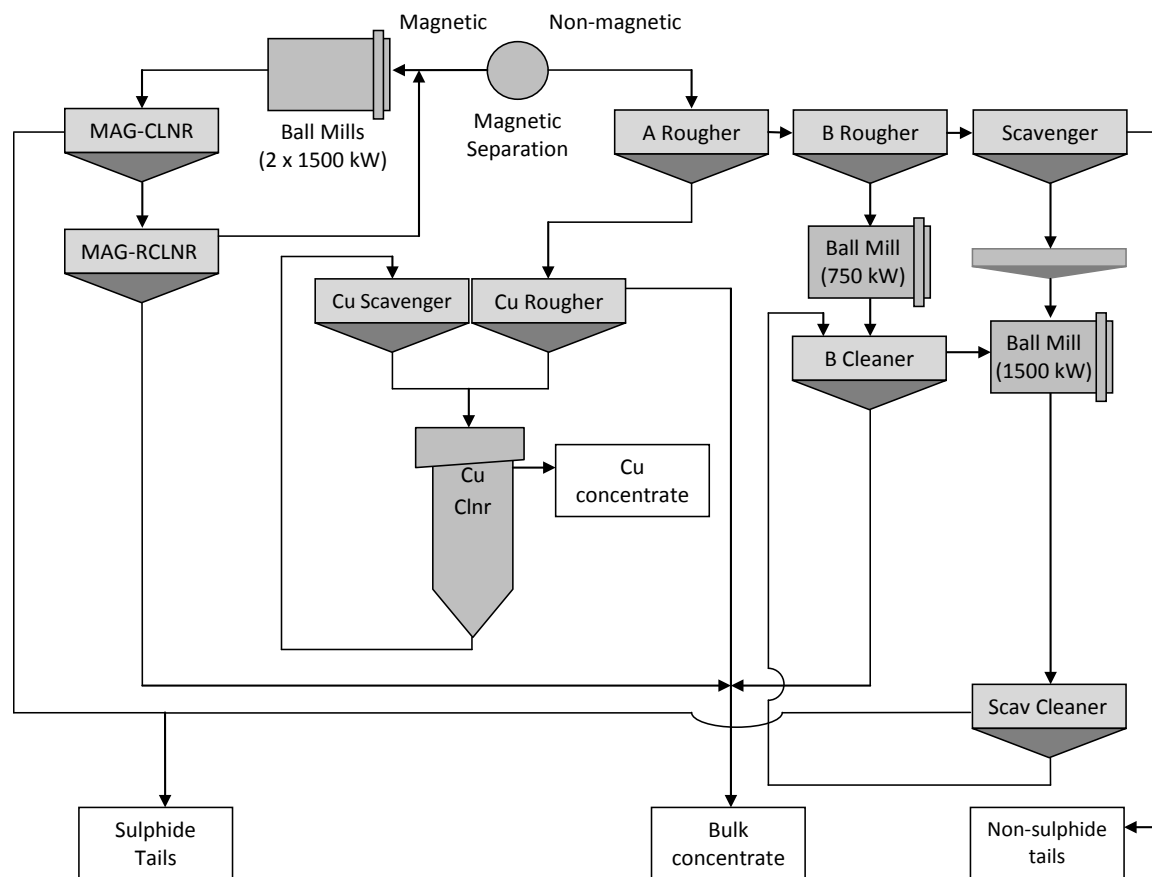


Figure 79: Flotation circuit flowsheet in 2008 (Lawson, Xu 2011)

The comminution stage comprised two routes: a SAG mill circuit, and a crushing and grinding circuit, controlled by an Expert Grinding Control System. Throughput was maximized through the SAG circuit, which can process half of the ore based on total mill design capacity. When throughput exceeded the SAG capacity, ore was processed via the alternate crushing and grinding circuit. The crushing and grinding is performed by four lines of standard and shorthead crushers followed by two rod mills (Damjanovic, Goode et al. 2000, Kerr, Bouchard et al. 2003). Subsequently, the ore from both circuits is fed to five ball mills, which are equipped with cyclones, where the cyclone overflow is pumped to the magnetic separation stage of the mill.

Once the magnetic and non-magnetic fractions are divided, various flotation circuits further separate the minerals from the waste. The result is the production of a copper concentrate which is sold to market and a bulk nickel concentrate which is fed to a smelter for further refining (Lawson, Xu 2011).

Lawson (2011) stated that after 2008, the ball mills were removed from the non-magnetic flotation stages; the 1500 kW ball mill was moved to the comminution circuit whereas the 750 kW ball mill was damaged and thus retired from operation. Although the flowsheets between 2008 and 2012 differed, the equipment used at the facility was the same with the exception of the 750 kW ball mill in the latter year. It is estimated that the impact of this difference is negligible for the purpose of the energy analysis because the retired ball mill demand corresponded to less than 5% of the plant total demand.

### **10.3 Electricity audit**

#### **10.3.1 Review of past audit**

In 2008, a significant amount of effort was applied from Landry and Vale personnel to collect the data for the Clarabelle Mill audit. The dataset consisted of historical values retrieved from the company's PI system, which allowed calculation of electricity use for each piece of equipment, on an hourly basis for the entire year. The data was organized into 12 equipment categories which included: SAG mill, Ball mills, Rod mills, Crushers, Agitators, Pumps, Blowers, Compressors, Fans, Conveyors, Heat trace, and Misc. process. The collated values consisted of: energy (kWh), current (Amps) or run time (hours). Subsequently, the non-energy data was converted to energy units and the hourly values were summed to obtain annual consumption for each piece of equipment.

Detailed data analysis ensued, as part of the energy audit process, to examine areas for potential savings. The following ten opportunities for reducing electricity consumption at the plant by 5% were identified, with payback periods ranging from zero to nine years (Landry 2009):

- Optimize blower operating sequence to maximize use of more efficient units
- Minimize idling of conveyors
- Utilize process control measures on main sumps
- Refine SAG mill process control system
- Reduce compressed air leaks
- Implement motor rewind and replacement strategy
- Optimize amount of water use in the crushing section of the plant
- Replace existing light fixtures with more efficient units
- Exploit energy in tailings pond discharge with installation of micro-hydro turbine
- Replace fluid coupling pump drives with more efficient variable frequency drives

All of the aforementioned measures were considered as good candidates from an energy management standpoint, where implementation could deliver electricity savings. Subsequently, a review of the audit was conducted to gain a better understanding of how electricity is consumed in a mineral processing facility and to possibly identify additional energy savings.

### **10.3.2 Converting collected data into energy values**

Some of the data gathered during the electricity audit of the plant consisted of hourly electricity consumption that could be summed to obtain the annual consumption. Specifically, 72% of the electricity consumption data was allocated in this manner. This indicates that there is minimal

uncertainty for most of the data in the audit since no assumptions or calculations were required for this portion of the data.

Conversely, for other pieces of equipment, the hourly kWh consumption data was not available therefore conversions were employed to calculate the annual electricity consumption for the equipment in question.

For some equipment, current (Amps) values were recorded on an hourly basis which were converted to hourly energy (kWh) values using voltage, power factor and operating hours following the equations from Capehart *et al* (2012 p.268-269) for single-phase and three-phase motors. The proportion of electricity use that was calculated from the conversion of current to energy corresponded to 18.4% of total electricity data.

Power factor values vary depending on the rated capacity and load of a motor and can either be leading or lagging. It should be noted that facility power factor values are not the same as those of the individual equipment and that the individual power factor values should be used when available. Synchronous motors provide power factor correction to the facility (Thumann, Mehta 2008) and since large motors of this type were in use at Clarabelle Mill, a conservative value of 0.85 for the facility was used in this audit due to the lack of individual values.

Where run time data was gathered, voltage, current and power factor estimates were used to calculate the annual energy consumption for single-phase and three-phase motors as per Capehart *et al* (2012 p.268-269). The proportion of total electricity that was calculated from run time data corresponded to 6%.

For some equipment no hourly data was collected; this included 43 pumps where an annual use factor of 75% was estimated, which corresponded well with the average annual use of other pumps. Calculation of the electricity consumption for these pumps (corresponding to 17% of total electricity consumed by all pumps, or 3.6% of total electricity consumption) was achieved by using the rated capacity and an estimate for the voltage were used to calculate a value for the current. Then using these estimates and the power factor value, corresponding to that assumed for the other equipment, in the equations from Capehart *et al* (2012 p.268-269) permitted to estimate the electricity consumption from these pumps.

### **10.3.3 Applying a top-down / bottom-up approach**

Up to this point the analysis consisted of a bottom-up approach, where energy consumption from individual components was summed to estimate the total annual electricity consumption at Clarabelle Mill. Comparison of this amount to the actual total electricity supplied to the facility (top-down component) indicated that 8.8% of total electricity was unallocated, which left uncertainty. This variance was deemed significant and so precipitated a more detailed review in order to allocate this portion of electricity within the milling operation to gain full understanding of how electricity is consumed at the plant. An energy balance ensures that allocated energy consumption is not over or underestimated and allows validation of assumptions made within the bottom-up approach. The use of a top-down / bottom-up methodology provides an opportunity for reconciliation and increases confidence in the values and the results obtained during an energy audit.

Table 26 presents solutions to issues identified with the bottom-up audit during the data reconciliation process. For example, during the original audit some of the equipment at the mill

was omitted, which is listed in Table 27. Table 28 shows the corrected and final electricity allocation to each equipment category, including allocation to excluded equipment in the original audit.

**Table 26: Data reconciliation issues and solutions**

Issue	Solution
Missing or corrupt data for certain periods	It was determined whether the equipment was running during these periods by examining the throughput data. If the equipment was in use, a use factor (number of missing values/number of collected values) was used to prorate the annual electricity consumption for a complete year.
Assumed current and voltage values	The available equipment rating (kW) from the inventory list was examined for agitators, pumps, blowers, compressors, fans, conveyors, heat trace, and misc. process equipment to confirm that the estimated current, voltage and power factor values used in the assessment were acceptable. In some instances the calculated demand values (kWh/h) exceeded the rated capacity (kW) therefore the assumed current (Amps) values were replaced with values calculated from the equipment power rating using the equations from Thumann and Mehta (2008 p.62). For one of the pumps where hourly current data was provided and thus was not altered, the average annual load (kWh/h) exceeded the rated capacity (kW) of the pump therefore the assumed voltage value was reduced to the next highest voltage supplied to the facility. The result of the modified current and voltage values was that the average load was less than the rated capacity. This represents a potential source of error or uncertainty therefore it was recommended that these parameters should be measured.
Use of facility power factor	The power factor for a facility varies when inductive and capacity loads are turned on or off, thus using a constant facility power factor for individual equipment represents a source of uncertainty where it is used to calculate electricity consumption. Measurement of the power factor for each piece of equipment would provide a more accurate representation of the bottom-up electricity consumption values calculated during the audit. Use of the average facility power factor value may over- or under-estimate the electricity consumption of the individual pieces of equipment. During this audit, 26% of the electricity use at the facility was calculated using the average plant power factor value.

---

Omission of equipment categories	It was observed that lighting was not included in the allocated electricity consumption. Therefore the lighting consumption was allocated based on a cursory survey presented in section 3.9 of Landry (2009). The lighting audit was conducted in areas of the plant that were easily accessible therefore not all lights were included, thus this represents a possible source of error.
Omission of individual equipment	The final stage in the reconciliation step consisted of a comparison of the equipment inventory and the equipment for which electricity was allocated. It revealed a total of 80 items of various types, representing a total rating of 5,706 kW, that were not included in the original audit. Table 27 shows a summary of the excluded equipment. The remaining unallocated electricity consumption, after corrections were applied as described in this section, was distributed to the various equipment categories based on the % of total kW excluded values from Table 27. For example, 71% of the total unallocated electricity consumption was allocated to the pumps category.

---



Table 27: Equipment excluded from 2008 audit

Equipment category	Number of items	Rating (kW)	% of Total kW excluded
Ball mills	0	0	0
Blowers	2	298	5
Compressors	0	0	0
Conveyors	6	127	2
Crushers	0	0	0
Fans	19	582	10
Misc. Process	13	643	11
Pumps	40	4,057	71
Rod mills	0	0	0
<b>Total</b>	<b>80</b>	<b>5,706</b>	<b>100</b>

Table 28: Electricity allocation and reconciliation summary<sup>20</sup>

	<b>Electricity consumption (Landry 2009)</b>	<b>Corrected electricity consumption</b>	<b>Unallocated consumption</b>	<b>Final electricity consumption</b>
Equipment Category			% Accounted	
SAG	21.4	24.0		24.0
Rod Mills	6.6	7.0		7.0
Ball Mills	32.4	34.7		34.7
Crushers	1.7	0.8		0.8
Agitators	0.8	0.9		0.9
Pumps	20.4	19.8	3.2	22.9
Blowers	1.5	1.6	0.2	1.8
Compressors	1.1	1.1		1.1
Fans	0.7	0.6	0.5	1.0
Conveyors	3.8	4.2	0.1	4.3
Heat trace	0.1	0.1		0.1
Misc. Process	0.6	0.7	0.5	1.2
Sub-total	91.2	95.2	4.4	99.7
Lighting		0.3		0.3
Sub-total		95.6		100.0
Unallocated	8.8	4.4		0.0
<b>Total</b>	<b>100.0</b>	<b>100.0</b>		<b>100.0</b>

<sup>20</sup> Total may not match the sum of individual values due to rounding

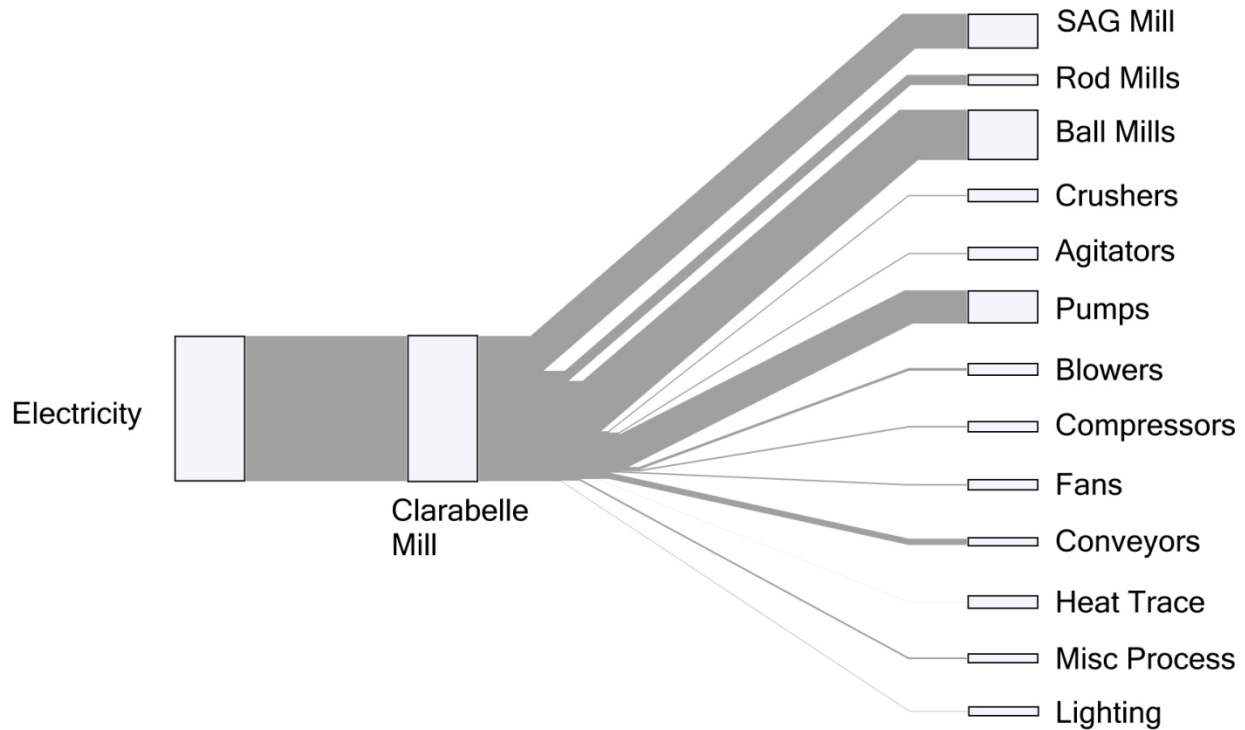
It can be observed from Table 28 that the corrections made to the calculations to allocate the electricity consumption to the various equipment categories did not produce significant changes to the percent allocation of each equipment category however the sum of these minor changes resulted in reducing the unallocated electricity from 8.8% to 4.4%. An investigation of excluded equipment from the audit allowed distribution of the unallocated electricity to its respective categories, which resulted in complete allocation of all electricity supplied to the mill.

Although the material covered in this section may seem pedestrian or of routine detail, it is important to understand the practice of energy management in addition to the theory; this is the level of scrutiny and attention to detail that is required for a thorough and reliable energy assessment. Using only the top-down approach does not provide a full understanding of energy use at a facility. Conversely, the bottom-up method used on its own does not instill confidence in the energy audit values because of the lack of reconciliation; assumed values could be incorrect, and / or data may be missing. The use of both methods together provides more accurate audit values which in turn increases confidence in estimated savings from proposed energy conservation measures. The top-down / bottom-up methodology may be used as part of a continuous improvement process such as that found in the ISO 50001 energy management standard (International Organization for Standardization 2011b).

#### **10.3.4 Energy analysis**

An understanding of energy use is important to identify areas where efforts should be focused for savings. Sankey diagrams are useful to show how energy is used in a process plant since the widths of the bands are proportional to the amounts of energy they represent. A Sankey diagram

was created to illustrate the energy flows at Clarabelle Mill using the audited 2008 annual electricity data, and is shown in Figure 79.



**Figure 80: Clarabelle Mill Sankey diagram for 2008**

It can be observed that the processes consuming the most energy comprise the SAG mill, ball mills and pumps which correspond to areas which may provide opportunities to reduce energy consumption with further investigation.

### 10.3.5 Part-load efficiency curve

An understanding of the variables that affect demand and energy consumption is essential in energy management to benchmark and improve efficiency. In advance of the audit, it was known that operation of equipment at part-load conditions can have a negative effect on energy efficiency (Doty, Turner 2009) which in mineral processing operations can be the result of

changes in throughput. An investigation of the influence of throughput on demand and energy consumption ensued to investigate the correlation. The throughput was examined in terms of % design capacity, which corresponded to the percentage of tonnes of ore processed on an hourly basis with respect to the plant's hourly design capacity.

A model relating the average hourly demand (MWh/h) and hourly throughput (% design capacity) for 2008 is presented in Figure 80. The upper and lower 95% confidence intervals were calculated following the procedure outlined in Brown (2001). It should be noted that throughput below 5% of design capacity was excluded from the analysis; these instances mostly corresponded to the scheduled maintenance shutdown period. Furthermore, the hourly demand values were normalized against the maximum value due to the sensitivity of the information presented.

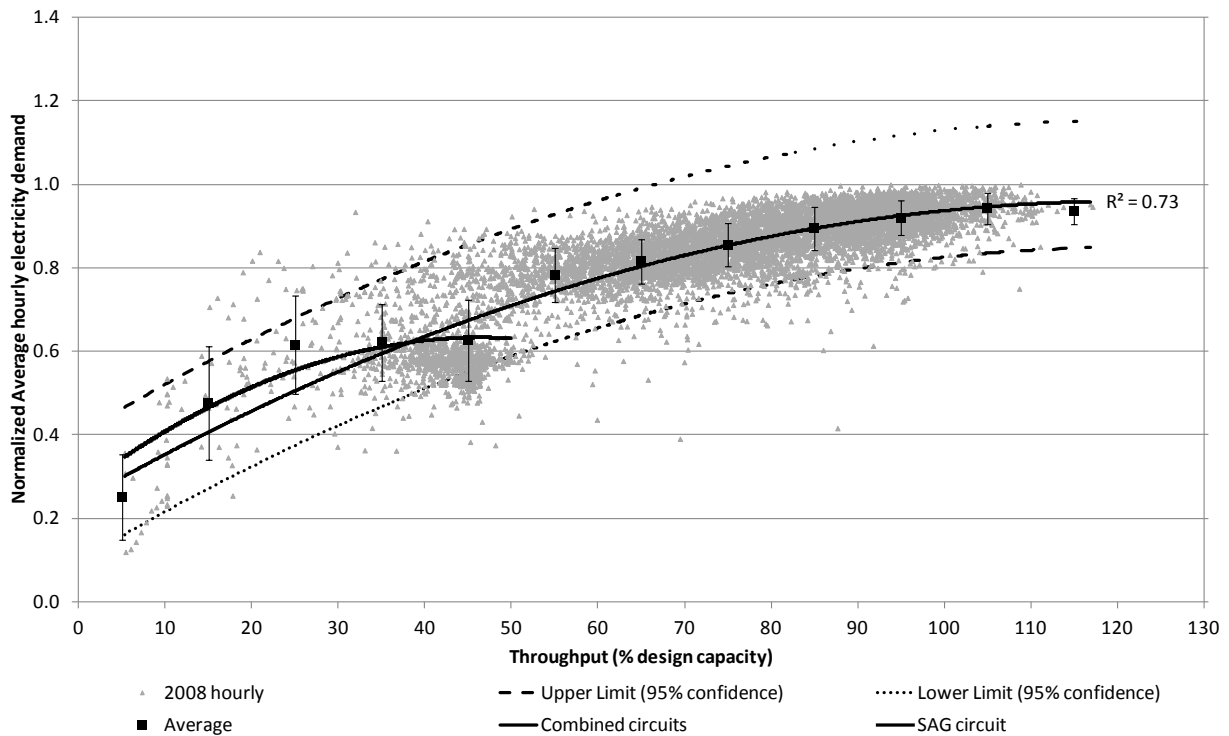
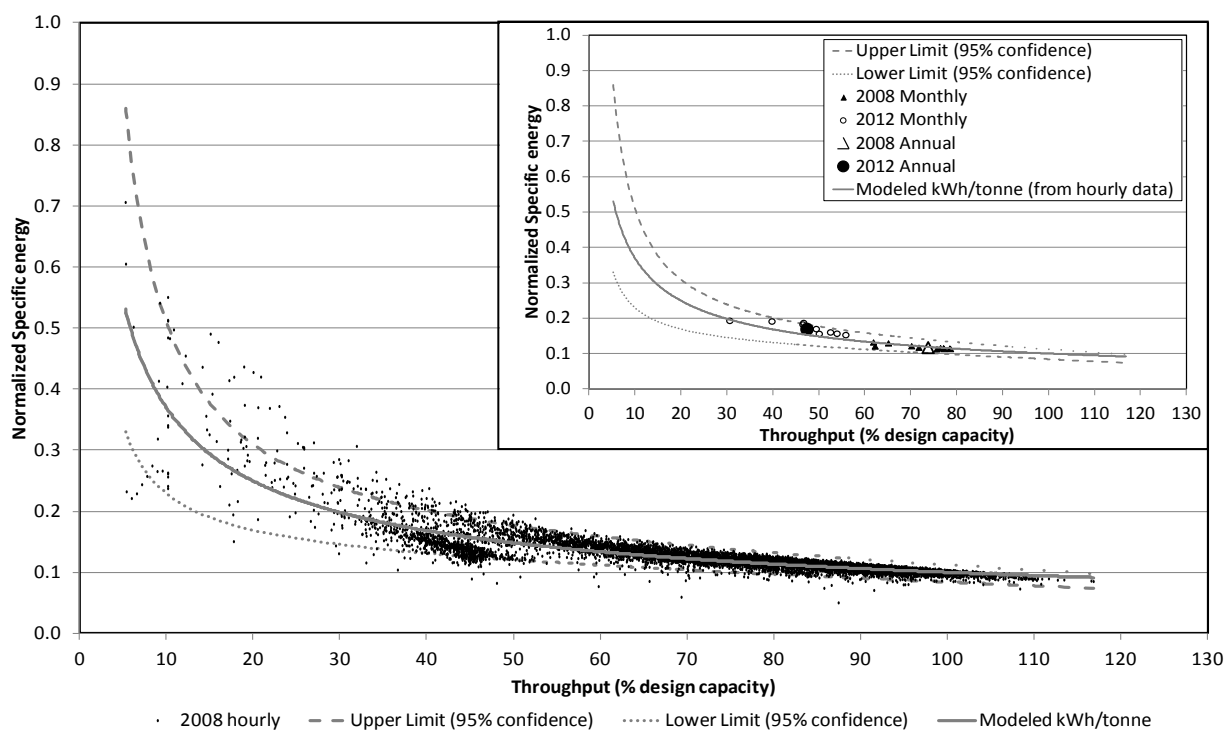


Figure 81: Normalized average hourly electricity demand versus throughput expressed as % design capacity

It can be observed from Figure 80 that electricity demand increases with throughput and that the relation between these variables is not linear. There is also greater variability in demand at lower throughput, illustrated by the error bars for the average of each % design capacity interval. It can also be observed that there are two distinct clusters of the hourly data, disjoint at around 50% design capacity. It is presumed that the data at the lower range represented the use of the SAG mill circuit alone, whereas the data at throughput values greater than 50% design capacity corresponded to the parallel operation of both the SAG, and crushing and grinding circuits. For the purpose of this study, the composite curve represented by all data was used.

A model for specific energy consumption was produced using the modeled MWh/h and hourly throughput expressed as % design capacity and is presented in Figure 81. The specific energy consumption data was normalized against the model value at 100% design capacity due to the sensitive nature of the information. The inset in Figure 81 shows the monthly and annually aggregated data from 2008 and 2012 with the part-load model and confidence limits derived from hourly data. The correlation between the hourly model and the monthly and annual data illustrate that a part-load analysis can be undertaken at facilities where hourly data is not available.



**Figure 82: Normalized specific energy consumption versus throughput expressed as % design capacity (hourly, monthly and annual data)**

It can be observed from Figure 81 that at low throughput, the specific energy consumption increased rapidly which is consistent with prior understanding of part-load electricity consumption. Furthermore, operation of the mill at design capacity is the most efficient in terms of electricity consumption per tonne of ore milled.

#### 10.4 Potential energy conservation at Clarabelle Mill

Energy savings opportunities were investigated using the models and information from Figure 80 and Figure 81. The investigation focused on the potential savings which could arise by modifying the existing schedule so that the facility operated at 100% of design capacity, while maintaining the original monthly and annual production. Practically, this corresponds to altering shift operating patterns and was motivated by noting that this rate of production corresponded to the lowest energy consumption per tonne of ore. Although specific energy consumption was

lower at throughputs greater than 100%, these points were not selected as the target as it was unknown if these production rates could be sustained. To take advantage of time-of-use rates (TOU), operating time was maximized during off-peak electricity periods, which occurred on weekends as well as weekdays from 7PM to 7AM. Although these circumstances are specific to Clarabelle Mill, such considerations feature in many jurisdictions and so there is no great loss of generality. The remaining hours necessary to meet actual production were scheduled during on-peak hours. The analysis was conducted on a monthly basis to provide schedule flexibility, which was also useful since 2012 monthly electricity data was available and thus allowed a comparison of the 2008 and 2012 results. Implementation of a daily intermittent schedule may not be practical or technically feasible but would offer the most electricity cost savings by taking advantage of TOU rates. Alternatively, a weekly intermittent schedule would also deliver savings with respect to electricity consumption per tonne of ore milled.

It should also be noted that during consideration of these revisions to the operating schedule, a base load of 10% of total electricity consumption was included during periods of no production to account for equipment that must operate regardless of production. These could include ventilation systems, agitators and heat trace, among others. Investigation of the electricity data from the energy balance in Figure 79 revealed that consumption of all mills and crushers corresponded to 67% of total electricity at Clarabelle Mill. The remaining 33% of electricity was consumed by pumps, fans, blowers and agitators among other types of equipment. Assuming that all agitators, blowers, fans, heat trace, misc. process and lights remain in operation during periods of no production this would only correspond to 5% of total electricity but a base load estimate of 10% was applied during the analysis. This reflects the fact that some of the pumps



and conveyors of the plant could be running during periods of no production. A summary of the 2008 annual results are presented in Table 29.

**Table 29: Potential savings from optimized TOU schedule and throughput - 2008 analysis**

	<b>Actual</b>	<b>Optimal Point</b>	<b>Upper Limit (95% confidence)</b>	<b>Lower Limit (95% confidence)</b>
Average throughput (% design capacity)	74	100	100	100
Savings vs actual (kWh/tonne)	--	14%	1%	26%

It can be observed from Table 29 that 1%, 14% and 26% savings could be achieved for operation at minimum specific energy consumption at the upper limit, optimal and lower limit respectively.

Subsequently the analysis was repeated with 2012 monthly data. It should be noted that February and September of 2012 had low production due to operating challenges and maintenance shutdown respectively, therefore these months were excluded from the analysis. Table 30 shows the results from the optimized schedule and lower specific energy consumption.

**Table 30: Potential savings from optimized TOU schedule and throughput – 2012 monthly analysis**

	<b>Actual</b>	<b>Optimal Point</b>	<b>Upper Limit (95% confidence)</b>	<b>Lower Limit (95% confidence)</b>
Average throughput (% design capacity)	47	100	100	100
Savings vs actual (kWh/tonne)	--	36%	27%	45%

Table 30 shows that in 2012 if Clarabelle Mill had been operated at 100% of design capacity at all times when operating, the recorded annual production could have been achieved by operating an average of 11 hours per day which could all be scheduled during off-peak electricity rate hours. The potential savings resulting from this scenario ranged from 36-45%; undoubtedly investigation of the feasibility of implementing this option would be valuable. Although the reasons for which throughput at the mill during these years was lower than design capacity are unknown, market conditions, operational challenges, unplanned maintenance and reduced ore supply from mines could be possible explanations.

### **10.5 Demand charges in Ontario via 5CP billing**

Electricity prices in Ontario vary based on supply and demand; the Independent Electricity Supply Operator (IESO) manages bids from generators to supply electricity as well as offers from consumers to reduce consumption in order to meet the forecast demand at the lowest available price (IESO 2013d). Subsequently, as demand increases so does the price of electricity (IESO 2013c).

Electricity rates in Ontario comprise various components including the Hourly Ontario Energy Price (HOEP) and Global Adjustment (GA) charges (IESO 2013b). The wholesale price or Market Clearing Price (MCP) in Ontario is determined every five minutes by the IESO and is established by offers from dispatchable facilities as well as supply and demand from non-dispatchable facilities (IESO 2013c). The Hourly Ontario Energy Price (HOEP) corresponds to the hourly average of the five minute MCP, and is used as the wholesale electricity price. The GA is calculated on a monthly basis and corresponds to the difference between the market price and payments made to regulated and contracted generators as well as demand management initiatives (IESO 2013b).

Demand response can be used by facilities to manage electricity costs by reducing or shifting electricity use during peak demand periods. Motivation for demand response participation in Ontario may be through programs which offer financial incentives for lowering demand or via billing rate structures where customers are invoiced based on their allocation of peak demand, such as the coincident peak (CP) pricing scheme in Ontario (IESO 2013a).

As of January 2011, customers with an average peak demand exceeding five MW were considered 'Class A' customers. The threshold for classification as a Class A customer was lowered on May 1, 2014 to three MW for certain industry sectors defined within the North American Industry Classification System (NAICS), of which the mining industry was included (Government of Ontario 2014). Class A customers are those for whom the portion of the GA they are required to pay corresponds to the percentage of their peak demand for the five peak hours, each on a different day of a twelve month base period, thus termed the 5CP. The base period corresponds to May 1 (Year X) to April 30, (Year X+1). The adjustment or billing period, where the peak demand factor is applied to calculate the monthly demand charges corresponds to

July 1 (Year X+1) to June 30, (Year X+2) (IESO 2014b). For example, the peak factor determined during the May 1, 2012 to April 30, 2013 base period would be applied to the monthly GA amounts from July 1, 2013 to June 30, 2014.

## 10.6 Potential demand savings in Ontario

Scheduling production during off-peak hours would result in GA savings by minimizing consumption during the 5CP hours, which normally occur during the on-peak period. An analysis of the potential savings arising from operating at a base load of 10% of total electricity during on-peak periods was conducted. The 5CP hours for 2012 were used however the corresponding adjustment billing period occurring from July 1, 2013 to June 30, 2014 has not yet taken place therefore the global adjustment amounts were not available. Hence, the global adjustment amounts for July 1, 2012 to June 30, 2013 were used in the analysis. It should be noted that 5CP savings were not calculated for 2008 since this billing structure was not in place during that year. Table 31 shows the monthly GA amounts from 2011 to 2013 whereas Table 32 shows the coincident peak hours in the 2012-13 base period.

**Table 31: Monthly GA amounts from 2011 to 2013 (IESO 2014a)**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total <sup>21</sup>
	(million CAD\$)												
2011	469	394	428	440	498	423	392	426	391	457	451	541	5,310
2012	512	550	667	595	578	585	422	485	479	546	575	463	6,456
2013	609	528	555	615	657	725	610	700	657	634	847	592	7,727

<sup>21</sup> Total may not match the sum of individual values due to rounding.

**Table 32: Coincident peaks for base period May 1, 2012 to April 30, 2013 (IESO 2014b)**

Rank	Date	Hour Ending	Total (MW)
1	17/7/2012	16	24,465.231
2	4/7/2012	17	23,799.628
3	20/6/2012	16	23,869.930
4	23/7/2012	14	23,813.176
5	6/7/2012	16	23,471.131
Average			23,883.819

From Table 31 it can be observed that the total GA amount for the adjustment period corresponding to July 1, 2012 to June 30, 2013 totaled 6,656.8 million\$. Using the hourly average peak demand from Table 32 it was estimated that demand charges based on the 5CP billing structure corresponded to 278,716 \$/MW. Table 33 illustrates the potential savings which could be achieved by a 90% demand reduction during the 5 peak hours for various sized facilities.

**Table 33: Potential 2012 demand response savings for various sized facilities in Ontario**

Average Mill Demand (MW)	Demand Response Baseload (MW)	Demand Response Reduction (MW)	Annual savings (million CAD\$)
3	0.3	2.7	0.8
5	0.5	4.5	1.3
7.5	0.8	6.8	1.9
10	1.0	9.0	2.5
12.5	1.3	11.3	3.1
15	1.5	13.5	3.8
17.5	1.8	15.8	4.4
20	2.0	18.0	5.0
22.5	2.3	20.3	5.6
25	2.5	22.5	6.3

It can be observed from Table 33 that substantial financial benefit could result from modifications to the schedule to maximize production during off-peak hours to reduce electricity consumption during periods affecting the global adjustment charges. It should be noted that these results included only the global adjustment demand savings.

Some companies have implemented protocols to minimize electricity demand and corresponding GA charges involving campaigns of 100 anticipated peak hours per year or more.

Implementation of an intermittent schedule to minimize specific energy consumption (kWh/tonne of ore milled) would not affect these protocols because even a facility operating at

90% design capacity could have a total of 876 hours per year to respond to projected peaks without affecting production.

## **10.7 Extension of analysis to other milling facilities in Ontario**

### **10.7.1 Development of part-load curve**

A model of specific energy consumption (kWh/tonne milled) versus throughput (% design capacity) was developed for a base metal milling facility, from hourly electricity and throughput data for one census year; the purpose was to examine how electricity consumption varied with throughput. The analysis boundaries included all processes from crushing to concentrate production.

A list of metal (gold, base metal and platinum) mines operating in Ontario during 2012 was established from the Ontario Mining and Exploration Directory (Ontario Prospectors Association 2012) and the Mining Association of Canada's Facts & Figures (Mining Association of Canada 2013). Subsequently, data were collected comprising the following for each milling operation: commodity, flowsheet, design capacity, and annual throughput; the throughput expressed as % design capacity was calculated from the last two by considering plant utilization. For example some facilities reported having a two week scheduled maintenance shutdown period. Therefore the annual design capacity was calculated by multiplying the design tonnes per day by 352 days per year (366-14). Table 34 shows a summary of the Ontario milling facilities examined for this study. It should be noted that Liberty Mines Inc. Redstone Mill was not included in the survey due to intermittent operation in 2012.

**Table 34: Summary of Ontario milling facilities (numbers in brackets correspond to data sources – refer to bibliography)**

Company	Mill	Commodity (1)	Comminution	Separation	Design Capacity (tonnes per day)	Annual Throughput (2012)	% design capacity
Vale	Clarabelle	Ni, Cu, Co, PGM ,Au, Ag, Se, Te	SABC (2)	Flotation (2)	36,300 (3)	5,740,700 <sup>22</sup> (4,5)	47
Xstrata Nickel <sup>23</sup>	Strathcona	Ni, Cu, Co, PGM, Au, Ag, Se, Te	Rod / Ball mill (2)	Flotation (2)	7,534 (6)	2,029,753 (7)	74
Xstrata Zinc Canada <sup>24</sup>	Kidd Creek	Cu, Zn, Ag, Se, Te, In, Cd	Rod / Ball mill (2)	Flotation (2)	12,329 (8)	2,268,672 (7)	50
North American Palladium	Lac des Iles	PGM, Ni, Au, Cu, Co	SABC and vertimill (9)	Flotation (9)	15,000 (9)	2,063,260 (10)	75

<sup>22</sup> Includes ore from Vale and KGHM mines processed at Clarabelle Mill

<sup>23</sup> Now Sudbury Integrated Nickel Operations – a Glencore Company

<sup>24</sup> Now Kidd Operations – a Glencore Company



St Andrew Goldfields Ltd.	Holt	Au, Ag	SABC (11)	CIL-EW (11)	3,000 (11)	897,508 (12)	82
Kirkland Lake Gold Inc.	Macassa	Au, Ag	Ball mill (13)	CIP (14)	1,315 (14)	275,840 (15)	59
Brigus Gold Corp.	Black Fox	Au	Ball mill (16)	CIC, CIL, CIP (16)	2,200 (17)	735,573 (18)	91
Lake Shore Gold Corp.	Bell Creek	Au	Ball mill (19)	CIL, CIP (19)	2,000 (19)	719,298 (20)	98
Goldcorp Inc.	Dome	Au	Rod / Ball mill (21)	CIP (21)	11,000 (21)	4,162,438 (22)	103
Richmont Mines Inc.	Island Gold	Au	Ball mill (23)	CIP (24)	850 (24)	246,743 (25)	81
Wesdome Gold Mines Ltd.	Eagle River	Au	Ball mill (26)	Merril- Crowe (27)	1,000 (27)	219,935 (28)	120

Barrick Gold Corp.	Hemlo	Au	SABC (2)	CIP (2)	10,000 (29)	3,080,799 (30)	84
Goldcorp Inc.	Musselwhite	Au, Ag	Rod / Ball mill (2)	CIP (2)	4,500 (31)	1,299,600 (22)	79
Goldcorp Inc.	Red Lake	Au, Ag	Ball / vertimill (32)	CIP (32)	3,100 (33)	858,100 (22)	76
	Campbell		Rod/ball mill (32)	Flotation, CIP, CIL (32)			
Total					110,129	24,571,519	61

Electricity data was then requested from each of these operations, however not all facilities responded to the request, whereas others were unable to fulfill the request due to insufficient sub-metering between the mine and the mill.

In the absence of electricity data for each of the milling facilities, the part-load curve from Clarabelle Mill was used in conjunction with cost estimate models (Western Mine 2006) to assess the potential savings from other milling facilities in Ontario with similar flowsheets. These included Strathcona and Kidd Creek mills, both operating a comminution circuit, followed by flotation. It was assumed that part-load operation of these facilities would be similar to that of Clarabelle Mill. However, the cost estimate models (Western Mine 2006) were used to estimate the scale effect due to these facilities having different design capacities.

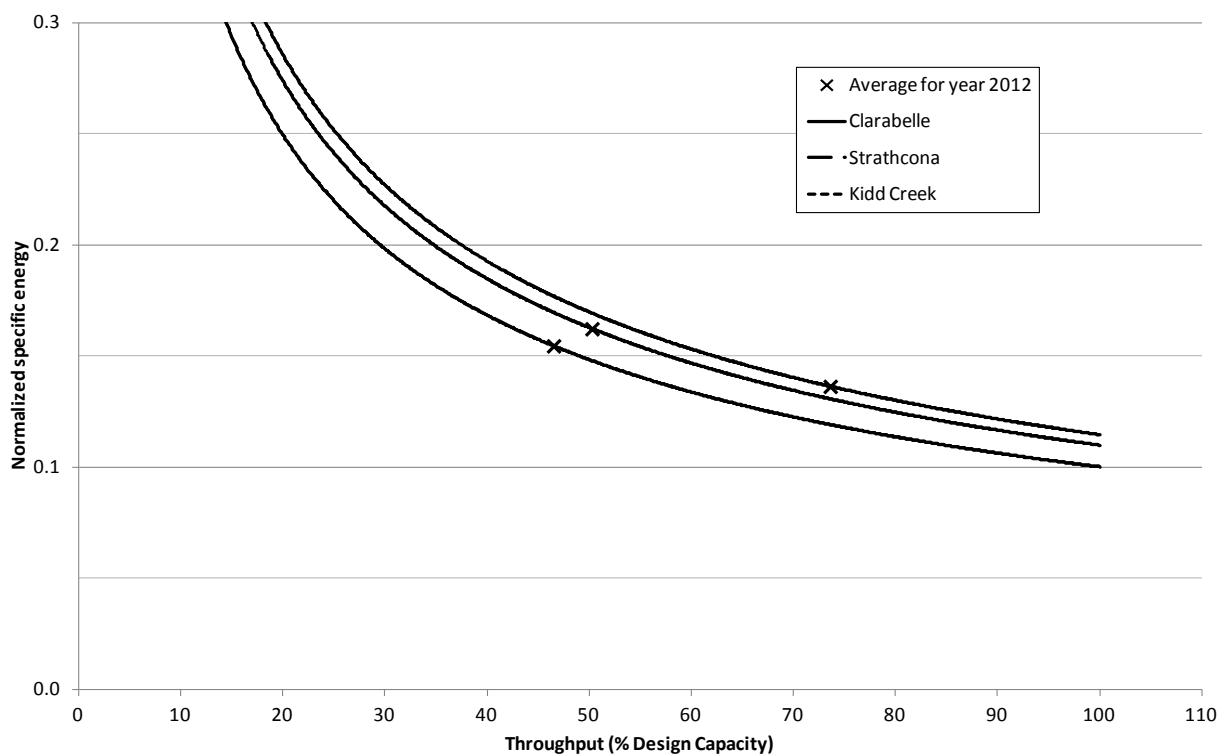
Electricity consumption in kWh/day for a flotation mill with two products was obtained from the Mining Cost Service Manual (Western Mine 2006) for mills with design capacities ranging from 100 to 80,000 tonnes per day. These values were then converted to specific energy requirements in kWh/tonne for each throughput value. Subsequently, a model was developed to estimate how specific energy consumption (kWh/tonne) varied with design capacity (tonnes/day). Then using a method adapted from Pascoe (1992) and Remer *et al* (2008), specific electricity consumption at design capacity was estimated for Strathcona and Kidd Creek mills, scaled down from the Clarabelle Mill model, as illustrated in (24).

$$kWh/tonne_B = kWh/tonne_A \left( \frac{C_B}{C_A} \right)^x \quad (24)$$

where  $kWh/tonne_B$  and  $C_B$  corresponded to the specific energy and design capacity of the unknown plant,  $kWh/tonne_A$  and  $C_A$  corresponded to the respective Clarabelle Mill values and

$x$  was the slope of the model derived from the logarithm of specific energy and capacity from Western Mine (2006) data.

It was estimated that due to economies of scale, Strathcona and Kidd mills consumed 14.5% and 9.7% more electricity per tonne milled than Clarabelle Mill, at design capacity. Therefore, with reference to Figure 83, the part-load curve derived for Clarabelle Mill was shifted upward on the vertical axis by these proportions to estimate part-load operation of these facilities. The results are presented in Figure 83 where the average annual values are represented with an 'x'. It should be noted that due to the sensitive nature of the information presented, the values were normalized with respect to Clarabelle Mill at 100% design capacity.



**Figure 83: Normalized specific energy versus throughput expressed as % design capacity for flotation mills in Ontario**

Observation of Figure 82 revealed that part-load operation of a mill can lead to a loss of economies of scale; according to the models, Strathcona Mill which corresponds to the smallest facility examined had the lowest specific electricity consumption, which is the opposite of what would be expected. It was also realized that consideration of throughput is important for benchmarking purposes. For example, comparison of unit electricity consumption before and after implementation of an energy efficiency measure is only fair when both periods examined were operated at the same throughput, otherwise it may be difficult to assess the impact of an initiative on the energy use.

#### **10.7.2 Savings estimate for flotation mills**

Using the respective models from Figure 82 and the % design capacity values from Table 34, potential reductions in energy consumed for census year 2012 were estimated for Strathcona and Kidd Creek mills. Specific energy consumption savings were estimated by operating each mill at design capacity to achieve actual reported annual throughput. The results are presented in Table 35. The results for Clarabelle Mill are also presented for comparative purposes. The reductions in energy consumed translate into reduced energy costs, but not proportionally due to time-of-use pricing schemes. The savings would be greater if mill operation was maximized during off-peak rate hours.

**Table 35: Potential savings from full-load operation for flotation mills in Ontario**

Mill	% design capacity	% savings
Clarabelle	47	36
Strathcona	74	16
Kidd Creek	50	32

Additional electricity cost savings arising from load shifting could be obtained by these facilities, by conserving demand within the 5CP billing rate structure in Ontario. Assuming that a 10% base load was consumed during periods of no production, it was estimated that the total demand savings in 2012 from these 3 facilities would total 39 MW, corresponding to over \$10 million, in addition to the electricity savings from Table 35.

It was not possible to derive a part-load operation model for gold milling facilities due to a lack of information. However, it is estimated that the savings from these facilities would be lower than those from the flotation mills because most gold mills were operating closer to design capacity in 2012. However, this estimate is dependent on the slope of the part-load curve.

Although gold mill throughput in terms of % design capacity was higher than base metal mills in 2012, a steeper curve could result in greater savings for the gold processing facilities.

Conversely, a flat curve would yield a lower difference between part-load and full-load specific energy consumption, thus the savings would also be less. An assessment of the electricity demand reduction during ‘shut down’ periods could not be undertaken due to the lack of detailed electricity data from gold milling facilities, thus the demand charge reductions from the 5CP billing rate could not be estimated.

## 10.8 Discussion of case study findings

An energy audit should not be undertaken simply as a data collection exercise; there needs to be some checks and balances to provide confidence in the values. This is readily achieved with a top-down / bottom-up approach. Although the first iteration of the audit may include assumptions to account for a lack of data, which represent a source of uncertainty, this highlights data gaps that need additional metering. Then the data can be refined, leading to increased confidence in the bottom-up audit values. As the uncertainty in the audit values is reduced confidence grows in understanding energy usage.

During the provincial analysis in this study, several assumptions were made, which may have an effect on the results. For example, it was assumed that all flotation mills had the same form of part-load operating curve and that this shifted on the vertical axis only depending on the design capacity of the facility. Furthermore, mill operation was assumed to be 24 hours per day for 366 days for 2012, unless stated otherwise in the sources reviewed. The reasons for reduced throughput could include: change in ore mineralogy or properties, lower availability from the mine, market conditions, or due to maintenance shutdown (scheduled or emergency). It was assumed in the calculation of % design capacity of the various mills in Table 34 that throughput was less than design capacity due to low availability. In instances where this may not be the case, the potential cost and electricity savings estimated in this study may be lower.

Another model (United States Bureau of Mines, Camm 1991) was also examined for estimating the electricity consumption of operations having different design capacities. Electricity cost estimates in this model were presented in terms of 1989 \$US/short ton but the electricity rate used to derive the model was not provided. This presented a level of uncertainty when estimating

present costs or electricity consumption because either an average index or average electricity rate was required. Although this was intended to be a cost model, it may be more valuable to present electricity consumption in energy units (kWh) because these are constant regardless of time, whereas costs vary with time due to changing tariffs and inflation. In addition, rates vary depending on location therefore presenting energy units in cost models may be more suitable, whether it is for electricity or fuel. For this reason, it was decided to use the Western Mine Cost Service (Western Mine 2006) model in the analysis. Furthermore, the range in throughput values from the Western Mine cost model was larger than that of the United States Bureau of Mines (1991).

The efficiency of comminution processes is low; Sadrai *et al* (2011) reported efficiencies of 1-2% for grinding and 2-3% for crushing, therefore operation of a mill at less than optimal conditions, such as lower throughput than design capacity, may result in even lower efficiencies. The effect of part-load operation of milling facilities was examined during this study and it was identified that electricity consumption could be improved by ensuring that facilities operated at design capacity.

The underlying factors that produce the relationship observed in this study between specific energy consumption and throughput were not investigated. However, it can be hypothesized that the following measures influence the shape of the part-load curve:

- Most of the equipment used in a milling facility is powered by motors, which operation at reduced load leads to lower efficiency (Doty, Turner 2009).
- It is estimated that the mass of ore is small compared to the total mass including the ore, the grinding mill and grinding media. Therefore most of the electricity consumed would



be used to rotate the vessel. So an increase in the amount of ore in the mill would not increase the electricity consumption by the same amount.

- Particle size reduction (grinding) in SAG mills relies on impact and abrasion from steel balls and ore (Wills, Napier-Munn et al. 2006). Thus unless the amount of steel balls is increased when there is less ore in the vessel, the chances of particle collision may be reduced, leading to greater retention time in the mill and thus an increase in the amount of energy required to achieve a specific target grind.

These three mechanisms (and possibly others) manifest as specific energy consumption versus throughput expressed in terms of % design capacity.

North American Palladium's Lac des Iles (LDI) operation has realized that lower throughput resulted in increased specific energy consumption and thus unit costs, therefore they have implemented an operating pattern where the ore beneficiation plant operates for 14 days then shuts down for 14 days and has done so since 2010 (North American Palladium 2013b). This leads one to ponder whether the plant was designed at the right capacity. Although the flowsheet for this facility is similar to that of Clarabelle Mill the potential savings were not included in the analysis of section 7 because of differences in ore mineralogy that may affect electricity consumption. For example, the target grind for the ore at LDI ranged from 80% passing 38 to 74 $\mu$ m depending on the source (North American Palladium 2013a, McCracken, Kanhai et al. 2013) whereas Clarabelle Mill has a target of 80% passing 150  $\mu$ m (Lawson, Xu 2011). Furthermore, in terms of the Bond ball mill work index, the ore at LDI is harder than that treated at Clarabelle: 17.9 kWh/tonne (McCracken, Kanhai et al. 2013) compared to 12.7 kWh/tonne (Damjanovic, Goode et al. 2000). For these reasons, it is unknown whether the part-load operation curve of this facility would be of the same form as that of Clarabelle Mill. But if so, it

is estimated that the operating schedule at LDI realized an energy saving of 33%, a figure that could be compared with those of Table 35.

Others have also investigated inefficiencies arising from part-load operation of individual processes within a mill. Armstrong (1978) examined the possible energy and cost savings associated with maximizing the throughput of a rod mill. During a 26 day examination period, the average specific energy consumption of the rod mill was 3.56 kWh/tonne, whereas the lowest consumption of 3.00 kWh/tonne was consumed when the mill was operated at rated capacity. The study demonstrated 16% reduction in specific energy consumption with the mill operating at maximum throughput, rather than at 61%.

Using the same approach, Armstrong (1980) showed that unit energy consumption increased as throughput decreased in a uranium mine. The difference between the minimum unit energy consumption (kWh/tonne) at rated throughput and that at lower production was defined as “waste energy”. Armstrong showed that elimination of this waste energy by operating at rated throughput rather than at 72% could lessen the specific energy consumption (kWh/tonne) by 10%. This translated to total electricity cost reduction of 14%, with 8% from peak load control and 6% from energy savings.

An analysis during an energy audit at Wesfrob Mines Ltd. (now closed) showed that the relationship between specific electricity consumption (kWh/tonne) and throughput for the total operation as well as for the separate crushing and grinding stages was inversely related (Doyle 1979); energy savings at the mill could be achieved either by increasing the amount of ore extracted from the mines or by reducing the plant operating hours.

In 1979, a survey of energy consumption in 67 Canadian mills was conducted, including six nickel and copper ore mills which reported electricity consumption values ranging from 21 to 42 kWh/tonne of ore milled (Joe 1979). These values were compared to those predicted by the model developed from the Western Mine Cost Service (Western Mine 2006) and it was determined that only two of the values reported by Joe (1979) agreed with predicted values at design capacity; the variance between predicted and reported values for these ranged from 1 to 4%. The four values that did not agree with the predictions were appreciably higher than the model, specifically between 12 and 47%. However, as design capacity was not reported in the survey, it was not possible to determine whether these facilities were operating at part-load, which may explain the reason for higher than expected electricity consumption in these cases.

Matthews and Craig (2013) illustrated the benefits of load shifting in a simulated run-of-mine (ROM) ore milling circuit, operating at 93% capacity. The potential electricity costs savings estimated in this case ranged from \$2.05 to \$9.90 per kg of unrefined platinum, for the low and high tariff periods respectively. These corresponded to savings of 1 to 4 %, however savings for mills operating at even lower throughputs would be greater. The savings reported by Matthews and Craig (2013) were consistent with the model developed in this study; at 93% design capacity it is estimated that electricity consumption was 4% greater than operation at design capacity.

An understanding of electricity billing is important to maximize financial savings from energy management efforts. For tariffs in Ontario, as illustrated in Table 31 significant cost savings can result from accurate prediction of peak demand hours, and scheduling of shutdown periods corresponding to these. Demand response from Class A customers to the 5CP billing structure in Ontario was examined and presented in the appendix of the Ontario Energy Board Market Surveillance Panel Monitoring Report (Ontario Energy Board - Market Surveillance Panel 2013).

It was estimated, by comparison of pre and post-policy consumption, that a reduction of 200 MW was attributed to the 5CP policy, of which the mining sector contributed 30 MW.

Furthermore, demand reduction from the mining sector during the top 1% demand hours was estimated at 52 MW, which indicated that these facilities were responding when there was a chance that a peak demand event would correspond to a coincident peak. Considering that the average hourly demand from the Ontario mining sector corresponds to about 500 MW (Choi, Sen et al. 2011) and that the average throughput from milling facilities was 61% of design capacity in 2012, there appears to still be room for greater response from the mining industry. However, it is hypothesized that demand reductions during peak demand hours may not be maximized from the mining sector for the following reasons:

- Changes in operating schedule could lead to issues with labour relations.
- Intermittent schedule may pose operational challenges. For example it may be difficult to achieve a steady state (temperature, pH...) in certain areas of the process, or shutting down the mill may have a negative impact on downstream stages.
- Costs of shutting down and restarting operations may exceed financial benefits from the demand response pricing scheme.
- Contractual obligations may limit the periods for reduced production.
- Organizations may have difficulty in predicting peaks.
- Smaller facilities that do not qualify as Class A are not incentivized to reduce demand to the same level. Therefore if only a small share of mining companies are classified as Class A customers, this may hinder demand reductions from the sector but this may change as a result of lowering the qualification threshold for Class A customers from 5 MW to 3 MW in 2014.

Response to coincident peak pricing in Texas was investigated by Zarnikau and Thal (2013) who illustrated that large electricity consumers had difficulty with predicting and responding to coincident peaks. The typical response periods corresponded to 2 or 3 hours for a 15 minute peak interval. In the early years of the coincident pricing rate structure, demand reduction during peaks varied more than in the later periods. Furthermore, demand increases were observed for one of the peak periods during the first two years of the program. However, it appeared that consumers implemented strategies for predicting and responding to coincident peaks, which can be explained by the increased demand reduction in the latter period of the 5 years examined.

Coincident peak pricing in Ontario was introduced in 2011. This policy is relatively new, thus customers billed under this structure may still be refining their strategies for maximizing response during peak hours. Over time, demand response from Class A customers may be greater.

A review of the Global Adjustment pricing scheme examined alternative methods of recovering these costs, which included expansion of the current demand response structure to other consumers in Ontario (Navigant Consulting Ltd. 2014). Although it was suggested by Zarnikau and Thal (2013) to expand the coincident pricing rate to smaller users, this may make peak prediction even more difficult. With more users, response may be greater and an anticipated peak may actually shift to a different period. Changes to the billing structure may also not be effective at achieving policy goals. As evidenced by Grubler (2012), short-lived policies were not effective for long- term transitions. This was found by examination of the common characteristics of successful policies from a total of 20 energy technology innovation case studies. Similarly, Noailly and Batrakova (2010) stated that policy uncertainty and frequent changes hindered innovation and investment in building energy efficiency. Consequently, it must

be entertained that changes to the current Ontario electricity pricing scheme could reduce the effectiveness of demand response from firms.

Demand response to coincident peak pricing was also investigated by Liu *et al* (2013) who developed an algorithm to assist data centers in minimizing electricity costs. The proposed strategies to lower peak demand comprised workload shifting and local electricity generation (behind the 'meter'). For mining companies operating at full or high capacity, workload shifting may not be possible. However local electricity generation may present an alternative opportunity for these organizations to lower electricity costs during coincident peaks.

The analysis in this study was conducted with respect to an energy management perspective with a basic knowledge of milling practices. Therefore, prior to implementing the strategies from this study, it would be advisable to consult with plant operators and metallurgists to determine the optimal conditions to balance energy cost savings against operational limits while maintaining acceptable metal recovery. The proposed schedule at Clarabelle Mill, operating 11 hours per day, may not be feasible to implement from an operational or maintenance perspective, but this was the option that would provide maximum energy savings. Alternatively, a schedule such as that implemented at LDI, corresponding to a 7 days on, 7 days off, could be investigated. Although the savings would be lower due to operation during peak hours there still would be savings compared to operation at part-load, especially if the off days coincide with 5CP hours.

As was demonstrated in Choi *et al* (2011), from 2005 to 2008 industrial customers in Ontario implemented load-shifting to reduce consumption during peak rate periods. The amount that milling facilities specifically have responded to the 5CP billing is unknown thus it is possible

that the demand savings estimated in this study have already been realized, but additional opportunities for energy savings still remain.

### **10.9 Concluding remarks for case study**

Energy penalties are incurred when mills are operated at part-load because more electricity per tonne of ore milled is consumed, resulting in higher unit operating costs. The first step in managing energy at a milling facility should correspond to operation at design capacity, ensuring the most efficient use of electricity. For facilities where throughput may be constrained by the mining rate, market conditions, operational challenges, etc., this could entail intermittent operation at 100% design capacity, possibly through alteration of shift patterns. Alternatively, a modular design including parallel lines could offer throughput flexibility without sacrificing electricity use per tonne of ore milled.

Although the most efficient use of electricity occurs when a plant is operated at design capacity, investigation of milling facilities in Ontario revealed that they are not always operated in this manner. The base metal mills were operated between 47 and 74% of design capacity, whereas the gold mills ranged from 59 to 120%.

Potential electricity savings from optimizing the schedule to ensure that the base metal flotation mills in Ontario were always operated at 100% of design capacity could range between 14 and 36%.

An understanding of the billing structure was essential to maximize the financial benefits. These mills could potentially have also reduced their demand charges by 90% in addition to the

electricity savings, by strategically scheduling operation of the mill during non-peak hours, thus lessening demand during coincident peak hours.

Economies of scale can be lost from low throughput at the larger facilities.

For benchmarking, whether assessing the performance of several facilities, or quantifying improvements within a single operation as a result of modifications to the equipment or flowsheet design, only operation at equivalent load values (% design capacity) provides a fair measure for comparison. In the work reported in this Chapter, a third party undertook an energy audit which identified ten opportunities for improvement, amounting to 5% of electricity savings. The work done herein was an audit review which identified further savings of 14% arising from re-profiling the production schedule. If the current arrangement for demand billing is considered, additional cost savings of the same scale were identified. The magnitude of these savings will be important to plant design engineers and plant operators alike.

As part of a continuous improvement process, progressive refinement of energy balances with the use of a top-down / bottom-up analysis approach lead to increased confidence in the audit and a stronger basis for future actions. To complete an accurate energy assessment it was essential to understand the energy data requirements, including the principal controlling factors governing energy consumption, and how this data can be converted into useful information. In theory, energy management methodology seems straightforward, but this work has shown that in practice, a significant amount of effort and analysis was required for a comprehensive and reliable assessment.



## **11 Using mass and energy balances with pinch analysis principles to identify energy savings from waste heat recycling: a case study from a pyrometallurgical mineral processing operation**

Although this Chapter is brief, it is included to complete the examination of energy management in the 'Mine to Bullion' process. The work presents a summary of an improved energy audit and analysis for a pyrometallurgical process and is described in full in Levesque (2011).

In 2008 an energy audit was conducted at Vale's PTI nickel laterite operation in Indonesia. However, this audit concluded at the data gathering stage and omitted the analysis stage; thus the analysis was undertaken as part of a Master's research project. It was hypothesized that a substantial amount of energy was wasted from the pyrometallurgical process employed at this site and that a significant portion of this wasted energy could be captured and used in other stages of the process (Levesque 2011).

Investigation of this hypothesis began with the conversion of energy data gathered by Vale personnel into a Sankey diagram to illustrate the energy flows to the various stages in the process. Subsequently with the use of mass and energy balances, the energy attributed in the various input and output streams of the process, comprising off-gases and slag, was quantified and qualified. Complete details of the audit and analysis stages of the study are presented in Levesque (2011). These energy flows were then added to the Sankey diagram, which illustrated all energy flows at the site, shown in Figure 83.

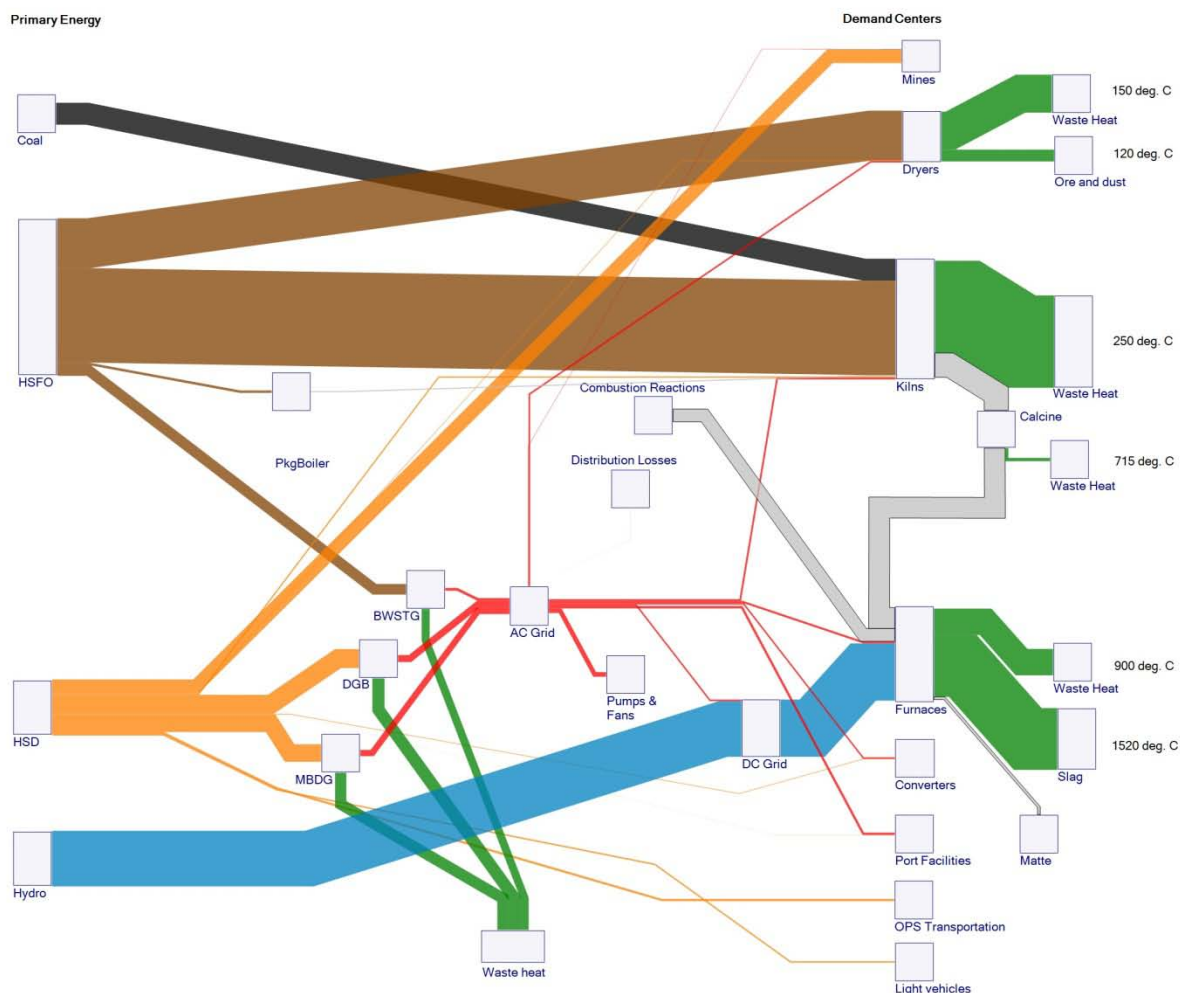


Figure 84: Sankey diagram from a nickel laterite processing operation (Levesque 2011)<sup>25</sup>

It can be seen in Figure 83 that most of the energy in the various stages of the process was released to the atmosphere either via off-gas or slag. With the use of Pinch Analysis principles, sinks where these sources of waste heat could be used to displace primary energy consumption were identified. Figure 84 illustrates the proposed scheme for energy reductions via waste heat recycling.

<sup>25</sup> HSFO: High Sulphur Fuel Oil, HSD: High Speed Diesel, BWSTG: Steam turbine, DGB: Diesel generators

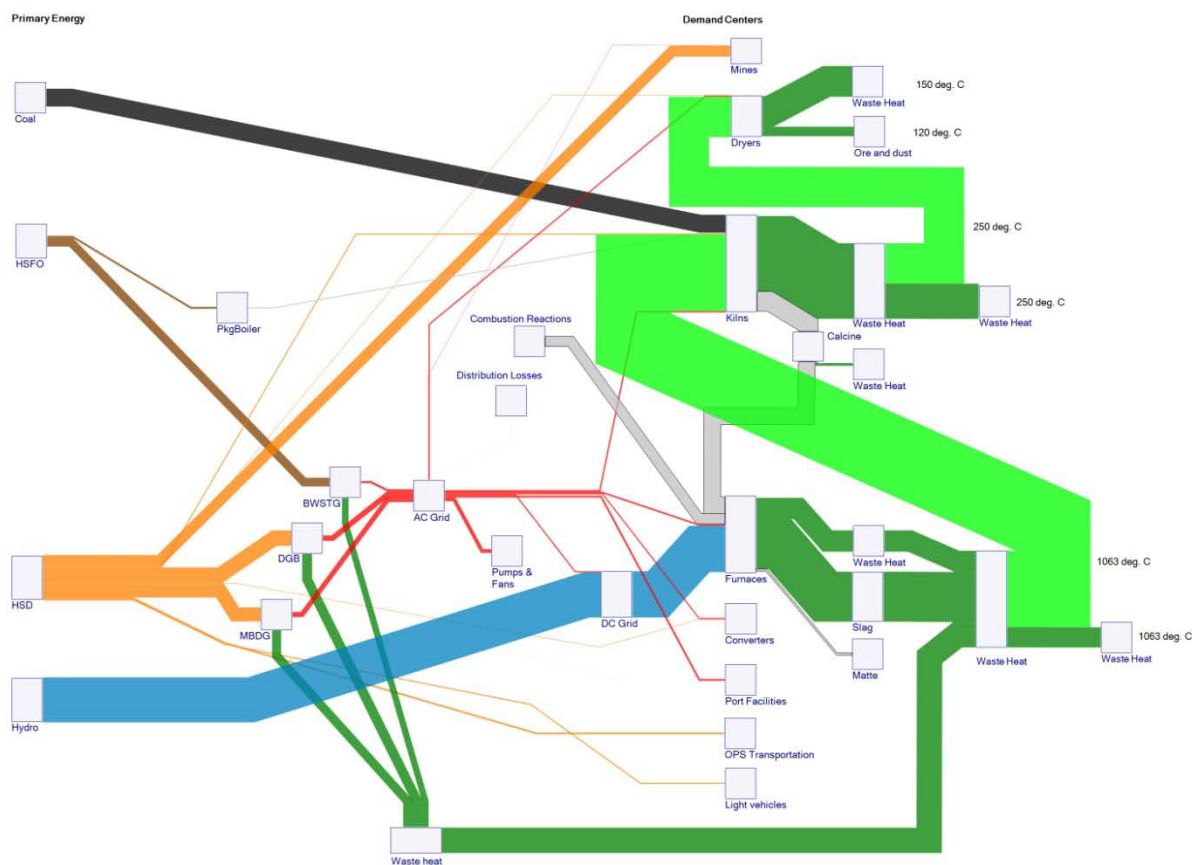


Figure 85: Sankey diagram from a nickel laterite processing operation with waste heat recycling (Levesque 2011)

Waste heat from the diesel generators as well as from the slag and off-gas from the furnaces was used to supply the kilns, and the waste heat from the kilns supplied the dryers, thus displacing HSFO. It can be seen by comparison of Figure 83 and Figure 84 that substantial amounts of primary energy consumption, specifically HSFO could be reduced with the capture and reuse of the various waste heat streams within this nickel laterite process. While it should be noted that technology for waste heat recovery from slag may not yet be commercially available, this analysis illustrated the potential for savings, thus possibly providing incentive for research in this area. Table 36 shows the energy conservation potential of the different energy sources from the proposed waste heat recycling scheme.

**Table 36: Energy savings from proposed waste heat recycling scheme**

Energy source	% savings
Coal	0
HSFO	92
HSD	0
Hydro	0
<b>Total<sup>26</sup></b>	<b>50</b>

Overall, this analysis shows that substantial savings could be achieved with the reduction of waste energy by capturing and reusing this energy in other stages of the process. These energy savings translated to roughly \$140 million dollars (2008 US\$) in annual cost reductions for this site (Levesque 2011).

This study also demonstrated the need to follow through on all stages of an energy audit, and it also showed the importance of assessing the energy associated with mass flows in pyrometallurgical processes. Gathering primary energy use data without the analysis stage and identification of other energy sources will not result in the identification of energy conservation measures. Although this study corresponded to an energy audit for a specific processing route, it can be applicable to other thermal processes within the mining sector such as smelting.

---

<sup>26</sup> It should be noted that the “Total” corresponds to the % total energy savings at the site. The sum of the % savings from the individual energy sources does not equal the “Total” due to the relative proportion of total energy that these correspond to.

## **12 Discussion**

A critical review of energy management progress in the mining sector was conducted by comparing the conservation measures implemented in the 1970's with current initiatives. It was concluded that mining companies were still reporting adoption and implementation of energy conservation innovations of the 1970's. Progress in the energy management sector of mining is thus deemed to be lacklustre.

The main objective for this research was to exemplify parts of a robust energy management methodology for application within the mining sector as a possible solution to address the slow evolution. Various energy management components such as communication, auditing and interpretation were examined, and examples were presented to demonstrate the benefits of the improved energy management methodology.

### **12.1 Improved energy audit and analysis guidelines**

#### **12.1.1 Recommendations for improved energy audits in the mining sector**

Existing energy audit methodologies and guidelines available for energy management were reviewed and assessed for their applicability to the mining sector. Some of the energy audit methodologies were of a general nature and could be applied to many different sectors such as residential, commercial or industrial, whereas other methods were specific to the industrial sector, but all could be applicable to the mining industry.

Although any of the reviewed audit methods could be used in the mining sector, the choice would be dependent on the desired level of detail and accuracy, as well as the available information and resources. For example, conducting a complete bottom-up energy audit in a

mine or mining facility may not be easily achieved in the absence of metered values since a substantial amount of data would be required to estimate the energy consumption from various end-uses. The use of values derived from estimates for appraisal of potential energy conservation measures would then introduce uncertainty in the assessment and possibly increase the risk of implementing the proposed energy conservation initiatives. The energy audit conducted at Garson Mine from Chapter 7 exemplifies this issue. Energy consumption estimates were used in areas lacking meters, thus use of the original estimates may have identified “Underground equipment (drills, bolters...)” electricity use as a priority focus area for potential energy conservation opportunities. But these savings may not be fully realized when the energy use is overestimated. The Garson Mine study also highlighted the importance of a data reconciliation stage in an audit to check estimates which may enhance confidence in the audit values.

Conversely, the use of a top-down method would not produce the same level of detail as the bottom-up audit unless an iterative process was used, whereby the top-down process was repeated until energy consumption from all end-uses within each segment was established.

In the Clarabelle Mill case study of Chapter 10, an energy audit was conducted by a consultant using a bottom-up method, which identified a total of 10 energy conservation measures in various areas of the plant, with a potential for energy savings totaling 5%. However, most of these measures corresponded to areas where energy use was not significant, thus having a minimal impact on total energy use. Alternatively, the top-down energy audit method could have been used to highlight priority focus areas such as the grinding stage, which may have resulted in a different outcome with greater savings. Ultimately, the use of a top-down / bottom-up method to reconcile the data represented a more complete understanding of energy demand at the facility which was used to augment the potential energy savings by 36%.

The reviewed methods in Chapter 4 each presented advantages and disadvantages. Thus the use of a hybrid method combining the strengths of each type of method may be better suited for the mining sector. For instance, the use of an iterative methodology combining the top-down and energy balance methods with the guidelines and tools from the Energy Savings Toolbox and the Energy Efficiency Opportunities Energy-Mass Balance: Mining documents may be beneficial for the mining sector. The top-down method would highlight areas where additional focus would be required, and the energy balance method could be used to allocate energy to various end-uses within these focus areas in the absence of metered data. The energy balance method would also ensure that the sum of the amounts from the individual components match the total energy consumption. The tools and guidelines provided in the Energy Savings Toolbox could be used to assess energy use and identify potential conservation opportunities, especially if combined with the mining-specific guidance included in the EEO Energy-Mass Balance: Mining. For example, the EEO guidance document promoted the use of support variables, which could be incorporated in the Performance Benchmarks presented in the Energy Savings Toolbox. The Musselwhite Mine case study presented in Chapter 3.1.6 illustrated how support variables could be used with energy consumption in an internal benchmarking exercise to assess energy performance within a mine site. This example demonstrated that the use of energy-influencing variables was necessary to establish and measure continuous improvement, thus measurement of these variables in addition to energy use data is necessary.

Another benefit of incorporating the EEO method corresponded to mapping mass flows, which in the mining sector could present potential energy conservation opportunities. In Chapter 11, an example using mass and energy balances in a pyrometallurgical mining operation demonstrated that substantial amounts of energy can be associated with material flows. Quantification of these

energy amounts along with qualification of the heat grade allowed use of pinch analysis principles to link heat sources with heat sinks, thus displacing up to 50% of primary energy sources at a nickel laterite processing operation.

The iterative part of the proposed hybrid method would comprise repeating the process from the energy balance step with the next most important focus area; thus this step may satisfy the continuous improvement aspect of ISO 50001.

### **12.1.2 A novel energy audit method**

A large amount of equipment is used in an underground mine, thus it may not be practical or economical to install meters on all of these. However, in most mines the total electricity use from all equipment is metered and a method of extracting information from this data was developed. Chapter 9 of this work presented a novel disaggregation method that could be used to estimate the electricity consumption from end-uses in the absence of sub-meter data. This information could then be used by decision makers and address the lack of information barrier previously identified.

The novelty of this disaggregation method was the ability to construct the time domain signal representing the electricity use from a mine hoist as a model. Other existing disaggregation methods have been used to estimate the total electricity consumption of an end-use or appliance for a given period by identification of the time when the consumption began and ended, but the energy use at an exact moment was not determined. Knowledge of an equipment's load profile may provide information required for energy management decisions. For example, where a facility is charged for demand, based on peak demand during a fixed period, an understanding of



the disaggregated load profile may be useful for peak shaving or load shifting to lower energy costs.

The method developed and presented in Chapter 9 was exemplified by estimation of the hoist electricity consumption, which contributes to the variability of the total energy demand at the mine. It is presumed that the methodology could be recursively applied to obtain estimates of other variable loads, such as pumps, compressors, or underground equipment. Thus the method may be used to discern the variable loads from the baseload or constant energy demands at a mine.

Although some issues with the developed disaggregation method were identified, it does present a basis whereby further research could improve the method. Successful development and adoption of this methodology would reduce the amount of metered data required for energy audits, thus reducing capital and maintenance costs of sub-metering, as well as costs of data transmission and storage. An energy audit conducted from data gathered from a single meter would result in a simpler and lower cost energy management system.

## **12.2 Improved communication of best practice energy conservation initiatives**

The Australian Government's Energy Efficiency Opportunities (EEO) Act 2006 was a good initiative to enhance industrial energy efficiency for large consumers. However, in 2014, the bill was repealed (The Parliament of the Commonwealth of Australia 2014). It was stated that the program had successfully promoted adoption of energy management as standard practice within industry, thus mandatory regulation was no longer required. Further incentive for energy conservation was also driven by rising energy prices. An underpinning element to the development of the EEO program was to address barriers to identification and adoption of

energy efficiency measures, which corresponded to organizational barriers and the lack of information for decision making. It was stated that for the mining sector “...*when energy prices are low and resource prices are high, energy costs are not considered, because the profits from greater export volumes far exceed the increased energy costs. When energy prices are high and the resource price is low the focus changes to minimizing all operating costs, including energy costs*” (The Parliament of the Commonwealth of Australia 2014). Thus it is unknown whether the abolition of the regulation will sustain the potential for embedded energy management within the mining sector in Australia.

One of the outcomes of the EEO program was the development of the Mining Significant Opportunities Register (Australian Government Department of Resources, Energy and Tourism 2011a), which included several examples of energy conservation measures applicable to the mining sector. A critical review of this register revealed some shortcomings, which were addressed with the development of the Mining Energy Efficiency Best Practice Database (Levesque 2013). The improvements comprised i) a standardized reporting mechanism to facilitate and enhance the identification of relevant information, and ii) a data checking stage prior to inclusion of case studies in the register to ensure that complete and reliable data was included.

Dissemination of best practice may be a good mechanism for enhancing energy performance by addressing the information barrier. However, there are differences between the various mines and processes within the industry, so the savings reported by one site may not be completely indicative of those at another facility. Thus the inclusion of additional support variables such as mine depth, or production amounts would enhance the ability to better estimate the applicability of measures and the potential savings from one site to another. To date, over 40 users have

downloaded a copy of the Mining Energy Efficiency Best Practice Database, and although there is an option to upload case studies, none have been provided. The reason for this is unknown but it can be speculated that it may be due to companies already using numerous other reporting mechanisms such as corporate sustainability reports or corporate websites, or possibly companies don't want to disclose all implemented energy conservation measures to maintain competitiveness.

### **12.3 Improved interpretation for enhanced energy savings and better communication**

Several sources of data were reviewed, which included the CIPEC Canadian Benchmarking studies (Canadian Industry Program for Energy Conservation 2005a, Canadian Industry Program for Energy Conservation 2005b), the US DOE Mining Industry Bandwidth study (U.S. Department of Energy 2007), resources from Statistics Canada and Natural Resources Canada, as well as the Canadian Industrial Energy End-use Data and Analysis Center (CIEEDAC) Energy Use and Related Data reports pertaining to the mining sector (Canadian Industrial Energy End-use Analysis Center (CIEEDAC) var.). The energy data from these sources pertained to the mining sector or sub-sectors thereof but the lack of support variable information hindered the usefulness of the figures. For example, the data presented in Figure 2 seems inconsistent with an understanding of energy use in the mining sector; the data showed that although diesel consumption was increasing, electricity use was declining. One would expect that the consumption from these types of energy would be directly proportional since increased diesel would require additional ventilation to support safe working conditions. From an energy management perspective these data may indicate that mining companies have focused efforts at reducing electricity consumption but that these savings have been eroded or 'spent' through

increased diesel use and higher ventilation load. However, the lack of support variables in the available collated data hinders a sufficiently thorough understanding of energy use in the sector, to support policy development.

Furthermore, use of alternative metrics in the Canadian Underground Benchmarking study suited to the industry, such as that illustrated in the Musselwhite case study in Chapter 3.1.6 of this work which include mine depth, production and heating degree days, could have been useful for setting energy conservation targets for underground mines. It is assumed that the lack of this type of information or an alternative, universally agreed, metric may be a limiting factor in adoption of energy management initiatives in the mining sector since there is no target in sight.

Although establishment of a metric for benchmarking energy use for the sector as a whole may be of limited use, measures on a sub-sectorial basis, by commodity, may enlighten mining companies with respect to their energy performance and may motivate low performers to implement changes or adopt energy management protocols. Conversely, internal benchmarks comparing energy use from a facility for different periods could be useful for monitoring performance and measuring improvements (Natural Resources Canada 2009) but support variables that influence energy use should be included.

The development of baselines or benchmarks would also be useful for demonstrating continuous improvement, as is required in the adoption of the ISO 50001 energy management standard. Regardless of adoption of this standard, establishment of baselines is an underpinning element for participation in rate reduction programs such as the Northern Industrial Electricity Rate Program (NIERP) (Ministry of Northern Development, Mines and Forestry 2010). Thus the use of benchmarks could be applicable in multiple programs and protocols.

The need for appropriate metrics and benchmarking methodologies for comminution processes was identified as a priority during a workshop hosted by the Coalition for Eco-Efficient Comminution (CEEC) (Natural Resources Canada 2015). Possible variables that could be considered for benchmarking comminution processes may include ore hardness, size reduction ratio, and amount of ore processed. Thus, eliminating the influence from these variables on energy use may allow companies to compare and assess the energy performance of various facilities and processing routes. These benchmarks could be used to motivate energy management activities or to help inform which processing method should be adopted at the design stage of the mining cycle.

Although tools such as Portfolio Manager are available for benchmarking energy consumption, water use and greenhouse gas emissions for buildings (United States Environmental Protection Agency 2015, Natural Resources Canada 2014), there are no comparable options for mines. The US Environmental Protection Agency developed Energy Star Energy Performance Indicator for plants to enable benchmarking of industrial facilities, which may assist with establishment of energy conservation targets (US Environmental Protection Agency n.d.). Models which considered variables that influence energy use were developed using production and energy use from census data, against which facilities can compare their energy performance. Scores ranging from 1 to 100 are assigned to participating facilities, where a low score indicated margin for improvement and high scoring facilities were considered energy efficient. Indicators were available for various industrial facilities but mining was not included in the list. Thus, it could be argued that the time has come for development of such tools for this sector.

The use of internal benchmarking (kWh/tonne vs throughput) at Clarabelle Mill during the review of the original energy audit, presented in Chapter 10, identified that lower throughput

periods consumed a greater amount of electricity per tonne of ore processed. It was shown that potential electricity savings corresponding to 36% could be achieved via modification of the operating schedule of the facility while maintaining the same annual throughput. This would ensure that mill operation occurred at design capacity, and thus at the most energy efficient operating point.

In the Clarabelle Mill case study presented in Chapter 10, it was also demonstrated that the financial savings could be enhanced firstly by understanding electricity tariffs and subsequently by using this knowledge in development of revised operating schedules. Substantial cost savings were identified by avoiding electricity demand from milling facilities during peak hours in Ontario.

Sometimes the proposed measures seem simple but their implementation may be challenging. It is possible that facilities are not equipped for these solutions or that they need time to adapt to policies such as the 5CP billing scheme in Ontario. For example, since this tariff structure has been implemented in 2011, the peak hours have occurred during the summer months, but in the 2014-2015 base period, 3 of the 5 peak hours took place during the winter. Therefore it is possible that some facilities may not be prepared for intermittent operation during these months without implementation of mitigation strategies. For example, it may be possible that some pipelines could freeze if pumps were stopped but the use of a heat trace could enable facilities to respond to the 5CP billing structure.

As ventilation corresponded to the mine system that consumed the most amount of energy in an underground mine, this was identified as a priority focus area using the top-down energy audit method. The ventilation case study in Chapter 8 of this work was used to examine potential

energy conservation in auxiliary mine ventilation systems via the use of lower friction plastic ducting.

Implementation of the principles outlined in the Energy Savings Toolbox maximized the energy savings in the ventilation system by matching the usage to the requirements, and maximizing the system efficiency. Matching the use to the need was achieved when consideration was given to the ventilation system as a whole, including the fan and the duct, which delivered energy savings via flowrate control. It was shown that regardless of the type of duct used in a given system, use of a custom fixed-speed fan or a variable speed fan resulted in energy savings compared to the fixed speed counterpart fan, the typical practice. The energy savings from flowrate control ranged from 1% to 58% depending on the final duct length. Duct substitution was used to improve system efficiency with the use of lower friction factor ducting to deliver the same amount or more air to the work area while consuming less energy. It was shown that energy savings from use of the plastic duct ranged from 7% to 66% compared to the use of Layflat ducting. Furthermore, combination of both these energy conservation strategies resulted in additive energy savings, amounting to 56% to 74%, depending on the final duct length.

The case studies presented in Chapter 9 also demonstrated the value of variable speed fans in auxiliary systems with multiple fans by reducing the discontinuity in operating costs introduced by the increased airflow when more than one fan was used in a system. Although the plastic duct always consumed less energy than the other duct types, the cheapest option when considering capital and operational costs depended on the number of fans in the system and the project installation. It was also determined that generalized recommendations for selection of duct types was not possible for underground mines, thus the model developed during this study was made available for users to determine the optimal solution for custom situations.

The work included in Chapter 9 also demonstrated the importance of accurate flowrate measurements and consideration of leakage during ventilation surveys that are used to determine duct friction factors. It was shown that flowrate measurements at proper locations are critical to quantify the actual amount of air flowing through the duct between the pressure measurement locations. Use of a flowrate value recorded at a single location may result in over or underestimation of the flow which will lead to an under or overestimation of the duct friction factor. Furthermore, an assessment method was proposed for validation of the calculated friction factor with the use of asperity height measurements and a Moody diagram, thus providing confidence in the values used for decision making.

## **12.4 Some final thoughts**

The work throughout this doctoral study set out to investigate whether existing resources for energy management were applicable to the mining sector. Review and use of these tools and guidelines has demonstrated that existing energy management protocols can be used to understand energy use and identify potential energy conservation initiatives in the mining sector. However, these established guidelines were not always used and thus the identified energy savings are not being maximized.

Another topic of investigation for this research was to determine how energy management progress could be measured. It was determined that this could be achieved with the use of support variables, which for an underground mine consisted of throughput, mine depth and heating degree days. But why has no one else presented this before? No organization wants to think that they are wasting energy or that their performance is poor so it is suspected that the lack of benchmarking activities may be part of the cause for slow progress in energy management in



the mining sector. However without proper benchmarks to highlight the potential for energy savings and establish targets, there may be no motivation to change behavior with respect to energy management within this sector.

Energy management in the mining sector may be a cyclical activity corresponding to periods of low commodity prices and high energy rates, which imply a short-term view. It is suspected that behavior changes are required in addition to improved guidelines so that short-, medium-, and long-term perspectives are included in energy management decisions so that continuous improvement and energy conservation benefits can be sustained.

## 13 Conclusions

### 13.1 Conclusions

The Garson Mine audit in Chapter 7 resulted in recommendations for an improved energy audit methodology for mines, developed from a combination of existing methods and guidelines. This method was derived by considering the challenges in the mining sector with respect to energy such as little sub-metering and the large amount of equipment used in the industry. Further refinements to the methodology may arise from conducting energy audits at other mines which may lead to the identification of additional improvements.

The improved mine audit from Chapter 7 also highlighted the importance of checking estimates to enhance the accuracy of the audit data. This was illustrated in the data reconciliation step which showed that some of the original audit values were either over or underestimated, and thus may have led to focusing future efforts in the wrong areas. It is recommended that future work may entail development of methods for data reconciliation for specific demand centers within a mine.

Experience has revealed that extensive sub-metering is lacking in older mines, and thus precipitated the development of a method for extracting energy consumption of end-uses from a main mine's electricity meter. It was shown that it is possible to isolate the electricity consumption of a mine hoist from the aggregated signal. Furthermore, construction of the time domain signal of the extracted end-use can be achieved with this novel method, an important piece of information for energy management. Although the method was illustrated using an example to estimate the electricity use of a hoist from an underground mine, future work could entail: i) development of the method for use with other equipment, and ii) an investigation of use

of custom filters. Although it is presumed that the method would be limited to the isolation of electricity use from activities that have a variable load, this information would still be useful to categorize activities that contribute to the electricity baseload and those that vary..

The Musselwhite Mine example illustrated how mines can demonstrate energy management improvement with the use of additional support variables. The work showed that although total annual energy use at this mine increased, energy conservation efforts were effective. However an in-depth statistical analysis using daily, weekly, or monthly data rather than annual figures may be used in the future to refine this example or identify additional support variables. Furthermore, analysis of the support variables that affect energy use of the separate demand centers may also be beneficial to improve understanding of energy use in mines. Improved understanding leads to higher energy savings and enhanced profitability.

The ventilation study in Chapter 8 illustrated a methodology for appraisal of potential energy conservation measures for auxiliary mine ventilation systems. This was achieved with the development of a novel model to assess the techno-economic viability of various fan and duct combinations. The ventilation study illustrated the importance of matching the usage to the need (with a variable speed fan) as well as adoption of energy efficiency measures (lower friction factor duct) to maximize energy savings. Although this case study focused on an auxiliary mine ventilation system, the guidelines would be applicable to other systems in a mine. The model could be further improved with the addition of a fan database whereby the optimal combination could be identified.

Analysis using the auxiliary ventilation model also demonstrated that the use of variable frequency drives in auxiliary mine ventilation systems is useful for systems with more than one fan by reducing the discontinuity in energy use introduced when additional fans are added.

Recommendations for development of a standardized ventilation survey method were proposed for determination of duct friction factors. This method arose from the simulation of a ventilation system which included leakage at the joints between the segments of the system, which highlighted the importance of proper characterization of the flowrate in the duct in deriving a more accurate estimate of the duct friction factor. As there is no data for comparison of leaks from different types of ducts with different joint geometries from a standard method, there is thus a need for testing to determine leakage values that can be used for design purposes as well as an assessment of the quality of installation for existing ventilation systems.

A method for verification of duct friction factor results obtained from ventilation surveys was suggested. It was recommended that this be achieved with the use of asperity height measurements and a Moody diagram. As energy use from ventilation systems in underground mines is substantial so can the energy savings be substantial but there is a need for accurate data so that the best decisions can be made. Additional ventilation surveys for various auxiliary ventilation systems (duct and fan), conducted using a standard methodology would be useful to assess whether the verification method can be extended to other materials.

The Clarabelle Mill study demonstrated that energy savings can be enhanced with improved interpretation. This was shown by examination of the influence of throughput on energy use per tonne of ore milled. An improved understanding of energy-influencing factors and use of an

internal performance benchmark lead to the identification of a potential for 36% electricity savings by adoption of a modified schedule to ensure that operation was at design capacity.

Future work could focus on the examination of barriers or challenges at existing milling facilities to adoption of batch mode operation, such as the effect on downstream processes, or the impact on mineral recovery. The identification of potential barriers could lead to further research to identify solutions to mitigate these issues. Additionally, adoption of design principles that include parallel production lines of lower capacity may eliminate the need for batch-mode operation for new facilities.

The milling study also showed that part-load operation is a factor that needs to be considered when benchmarking facilities. A fair comparison (either internal or external) can only be made when the % design capacity at which a facility was operated is considered. However, this is not the only factor to consider for benchmarking purposes; ore hardness, feed size, and product size are some other variables that could influence energy use in milling plants. Thus it is suggested that a study be conducted to identify and quantify the effect of support variables that could be used to benchmark mills.

The energy audit at Clarabelle Mill was improved with the demonstration of a methodology to reconcile bottom-up and top-down data for improved understanding of energy use. However the accuracy of the metered data is unknown, thus future work could include the development of guidelines for accurate data gathering and a review of metering technology applicable to the mining sector.

This work signposted in Chapter 11 showed the importance of measuring mass flows and their corresponding temperatures to quantify all energy flows within thermal processes found in the

minerals industry. Substantial volumes are present and thus substantial savings can be identified. However the analysis was conducted only for a nickel laterite pyrometallurgical process, and thus should be repeated to quantify the amounts of waste heat contained in the various output streams of other smelters and refineries. Further work could also include a review of commercially available technologies that could be applicable for waste heat recovery in these facilities. Research and development for new technologies for waste heat recovery from slag, should definitely be pursued.

Although there have been several milestone improvements in energy management in the mining sector, it appears that there has not yet been widespread adoption of best practice measures, since these are still being put into practice. There seems to be a need for better dissemination of good practice. Presently, energy conservation measures are mainly communicated via sustainability reports however the task of reviewing all of these is difficult due to the diversity of practice and incomplete reporting. Adoption of the Mining Energy Efficiency Best Practice database with its standardized reporting mechanism will enhance transparency of the mining industry in energy matters and help it maintain its social license to operate. Development of the Best Practice Database has resulted in an improved communication tool for enhanced dissemination of energy conservation opportunities within the mining sector. However adoption of the database to date has been one-sided as no case studies have been uploaded by practitioners or operators for inclusion. Thus to ensure the success of this tool, enhanced promotion of the register with mine energy managers or consultants is recommended. Alternatively, a survey could be conducted to examine the reason for reluctance from mining companies to share best practices whereby possible solutions could be identified to overcome the barriers to sharing best practices.

The review of existing mining energy-related data has revealed that improved reporting with the inclusion of support variables is required for better communication and better interpretation of energy use within the sector. Although the data published for the mining sector and sub-sectors by government and other sources is useful, it does lack in reporting of support variables which are essential for understanding of trends. For example, the data in Figure 2 may be interpreted several ways; industry focus was on electricity savings but these translated to increased use of diesel equipment, or there are more open pit mines in the latter years which contributed to the rise in diesel use. Thus inclusion of support variables as well as timely reporting of data is essential to i) examine, and ii) gain a better understanding of recent trends.

The Canadian government has published statistics relating to the mining industry for many years. Although there is plenty of data, not all the information required for a complete energy efficiency analysis is available. Although CIEEDAC has published energy consumption by source as well as production for sub-sectors within the mining industry, other factors of influence are still needed for a complete energy efficiency assessment.

Innovative solutions will be required for mining companies that are committed to continuous improvement, motivating investment in research and development in energy management. However there are few reliable complete data sets available to researchers on energy use in the mining industry that include factors which influence energy consumption. Consistent benchmarking and reporting is critical for the industry to progress. Otherwise, the advancement of new energy management innovations will be hindered, as resources will be misdirected. A synthesis or audit, not for individual operations or companies, but across the entire mining industry is required to confirm whether best practices are increasing. It appears that innovation in terms of energy management in the mining sector has been slow since companies are still

reporting energy conservation initiatives that were identified during the 1970's. Thus maybe there is a need for an improved curriculum that would highlight energy matters to future mining engineers, which could then be considered during the design stage of a mining project.

Although the data presented herein indicates a lack of progress in energy management in the mining sector as a whole, it is known that some companies have implemented highly sophisticated energy management measures. However these systems still require enhanced interpretation to direct resources to realize their full potential for energy savings.

Will the mining sector be proactive and voluntarily adopt these changes in corporate policy or will it be required to do so through increased regulation? Based on the lack of progress identified from past experiences in the mining sector it is presumed that these changes will likely occur as a result of regulations or from market conditions such as energy rate increases or lower commodity prices.

## **13.2 Contributions**

The main objective of this research was to develop an improved energy management methodology for the mining processing stages from 'Mine to Bullion'. Several contributions have emerged through the steps taken to reach this goal and are presented in the following.

### **13.2.1 Mine**

1. The Garson Mine audit resulted in recommendations for an improved energy audit methodology for mines, developed from a combination of existing methods and guidelines.



2. The improved mine audit also highlighted the importance of checking estimates to enhance the accuracy of the audit data.
3. A methodology was developed to disaggregate the electricity use within a mine for use in the absence of sub-metered data.
4. The Musselwhite Mine example illustrated how mines can demonstrate energy management improvement with the use of additional support variables.
5. The ventilation study illustrated a methodology for appraisal of potential energy conservation measures for auxiliary mine ventilation systems.
6. Recommendations for development of a standardized method for determination of duct friction factors.
7. A method for verification of duct friction factor results obtained from ventilation surveys was suggested.
8. Analysis using the ventilation model demonstrated that the use of variable frequency drives in auxiliary mine ventilation systems is useful for systems with more than one fan by reducing the discontinuity in energy use introduced when additional fans are added.

### **13.2.2 Processing**

9. The Clarabelle Mill study demonstrated that energy savings can be enhanced with an improved interpretation method.

10. This study also showed that part-load operation is a factor that needs to be considered when benchmarking facilities.
11. The energy audit method was improved with the demonstration of a methodology to reconcile bottom-up and top-down data for improved understanding of energy use.

### **13.2.3 Purification**

12. The work in Chapter 11 showed the importance of measuring mass flows and their corresponding temperatures to quantify all energy flows within a thermal process, which could represent substantial amounts and thus substantial savings.

### **13.2.4 All stages from 'Mine to Bullion'**

13. Development of the Best Practice Database has resulted in an improved communication tool for enhanced dissemination of energy conservation opportunities within the mining sector.
14. The review of existing mining energy-related data has revealed that improved reporting with the inclusion of support variables is required for better communication and better interpretation of energy use within the sector.

## **13.3 Future work**

The research undertaken during this work has identified that substantial energy savings could be achieved with the adoption of improved energy management guidelines. Although the work proposed an improved framework, additional work to further improve the method. Suggestions from the various chapters and discussion sections are consolidated in the following.

### 13.3.1 Mine

- Further refinements to the energy audit methodology for mines may arise from conducting audits at other mines which may lead to the identification of additional improvements.
- It is recommended that future work may entail development of methods for data reconciliation for specific demand centers within a mine.
- Although the novel energy audit method illustrated an example to estimate the electricity use of a hoist from an underground mine, future work could entail: i) development of the method for use with other equipment, and ii) an investigation of use of custom filters.
- Benchmarking for underground mines could benefit from an in-depth statistical analysis using daily, weekly, or monthly data rather than annual figures. Additional support variables need to be identified for underground mines and these could include: mine depth, production, heating degree days, cooling degree days, and geothermal gradient. Investigation of the stripping ratio, haulage distances, production, and climate condition could be used to establish benchmarks for open-pit mines. Furthermore, analysis of the support variables that affect energy use of the separate demand centers may also be beneficial to improve understanding of energy use in mines.
- The auxiliary ventilation model developed during this study could be further improved with the addition of a fan database whereby the optimal combination could be identified.
- As there is no data for comparison of leaks from different types of ducts with different joint geometries from a standard method, there is thus a need for testing to determine leakage values that can be used for design purposes as well as an assessment of the quality of installation for existing ventilation systems.

- Since energy use from ventilation systems in underground mines is substantial, so can the energy savings but there is a need for accurate data so that the best decisions can be made. Additional ventilation surveys for various duct types, conducted using a standard methodology would be useful to assess whether the verification method proposed herein can be extended to other materials.
- Future work for energy audits could also include the development of guidelines for accurate data gathering and a review of metering technology applicable infrastructure to the mining sector.

### **13.3.2 Processing**

- Future work could focus on the examination of barriers or challenges at existing milling facilities to adoption of batch mode operation, such as the effect on downstream processes, or the impact on mineral recovery. The identification of potential barriers could lead to further research to identify solutions to mitigate these issues. Additionally, adoption of design principles that include parallel lines may eliminate the need for batch-mode operation for new facilities.
- As was demonstrated during this study, benchmarks are a valuable indicator of performance and can be useful to drive energy management by illustrating the potential for savings. Thus it is suggested that a study be conducted to identify and quantify the effect of support variables that could be used to benchmark mills. For milling facilities the variables could include: ore hardness, production, and size reduction ratio.

### **13.3.3 Purification**

- Further work could also include a review of commercially available technologies that could be applicable for waste heat recovery in pyrometallurgical facilities, as well as research and development for new technologies for waste heat recovery from slag, not yet commercially available.

### **13.3.4 All stages from 'Mine to Bullion'**

- To ensure the success of the Best Practice database enhanced promotion of the register with mine energy managers or consultants is recommended. Alternatively, a survey could be conducted to examine the reason for reluctance from mining companies to share best practices whereby possible solutions could be identified to overcome these barriers.
- Inclusion of support variables as well as timely reporting of data is essential to i) examine, and ii) gain a better understanding of recent trends. Although CIEEDAC has published energy consumption by source as well as production for sub-sectors within the mining industry, other factors of influence are still needed for a complete energy efficiency assessment.
- Additionally, it may be beneficial to understand why energy management in the mining sector is of a cyclical nature; occurring when commodity prices are low. Energy savings exist regardless of metal values thus the industry may not be realizing maximized profits.

## References

- ABB, 2014-last update, ABB commissions Clarabelle mill upgrade for Vale in Canada. Available: <http://www.abb.com/cawp/seitp202/c2baacc29b1dfc9b85257c77004ee178.aspx> [4/30/2015, 2015].
- AKBARI, H., 1995. Validation of an algorithm to disaggregate whole-building hourly electrical load into end uses. *Energy*, **20**(12), pp. 1291-1301.
- AKBARI, H. and KONOPACKI, S.J., 1998. Application of an End-Use Disaggregation Algorithm for Obtaining Building Energy-Use Data. *Journal of Solar Energy Engineering*, **120**(3), pp. 205-210.
- ALLEN, C., 2012. *Applying automation technology to underground ventilation systems*. lecture edn. September 2, Sudbury, Dynamic Earth: CIM Distinguished Lecturers Program.
- AMBROSIO, S., 2012. Steel spiral ducting friction factor determination. *Journal of the Mine Ventilation Society of South Africa*, **65**(2), pp. 12-19.
- AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME), 2015-last update, Standards. Available: <https://www.asme.org/shop/standards#itemName=Energy%20Efficiency,tax=f07c3937-7eb2-4822-8753-17505c152ee2> [02/14/2015, 2015].
- ARMSTRONG, T.B., 1980. Two steps to energy management. *CIM Bulletin*, (March), pp. 154-159.
- ARMSTRONG, T.B., 1978. Energy consumption in mining-milling. *Canadian Mining Journal*, **99**(3),.
- AUSTRALIAN GOVERNMENT DEPARTMENT OF RESOURCES, ENERGY AND TOURISM, 2011a-last update, Energy Efficiency Opportunities - Mining. Available: <http://www.ret.gov.au/energy/efficiency/eeo/industry-sector/mining/Pages/Mining%20Sector.aspx> [03/30/2012] .
- AUSTRALIAN GOVERNMENT DEPARTMENT OF RESOURCES, ENERGY AND TOURISM, 2011b-last update, Energy Efficiency Opportunities Program - About the Program. Available: <http://www.ret.gov.au/energy/efficiency/eeo/about/Pages/default.aspx> [03/30/2012] .
- AUSTRALIAN GOVERNMENT DEPARTMENT OF RESOURCES, ENERGY AND TOURISM, 2010-last update, Energy-Mass Balance: Mining. Available: <http://www.ret.gov.au/energy/efficiency/eeo/resmaterial/Pages/default.aspx> [1/22/2013, 2013].
- BALDWIN, C., 2014. Certifiable gains in efficiency. *CIM Magazine*, **9**(6), pp 46.

BARRETTE, R., TAYLOR, A., DOUCET, J., SHELEGEY, J., SULLIVAN, H. and LAWSON, V., 2012. Applying a customer-based approach at Vale's Clarabelle Mill, *44th Annual Canadian Mineral Processors Operators Conference*, 17-19 January, 2012 2012, CIM, pp. 39.

BARTSCH, E., LAINE, M. and ANDERSEN, M., 2010. The Application and Implementation of Optimized Mine Ventilation on Demand (OMVOD) at the Xstrata Nickel Rim South Mine, Sudbury, Ontario, *HARDCASTLE & MCKINNON*, ed. In: *13th United States / North American Mine Ventilation Symposium*, June 13-17 2010 2010.

BATTELLE COLUMBUS LABORATORIES, 1975. *Energy use patterns in metallurgical and nonmetallic mineral processing (phase 4 - energy data and flowsheets, high-priority commodities)*. Washington: Bureau of Mines U.S. Department of the Interior.

BENNETT, M. and NEWBOROUGH, M., 2001. Auditing energy use in cities. *Energy Policy*, **29**(2), pp. 125-134.

BERGES, M., GOLDMAN, E., MATTHEWS, H., SOIBELMAN, L. and ANDERSON, K., 2011. User-Centered Nonintrusive Electricity Load Monitoring for Residential Buildings. *Journal of Computing in Civil Engineering*, **25**(6), pp. 471-480.

BIRT, B.J., NEWSHAM, G.R., BEAUSOLEIL-MORRISON, I., ARMSTRONG, M.M., SALDANHA, N. and ROWLANDS, I.H., 2012. Disaggregating categories of electrical energy end-use from whole-house hourly data. *Energy and Buildings*, **50**(0), pp. 93-102.

BOART LONGYEAR, 2014-last update, 2014 Drilling Equipment Product Line. Available: [http://app.boartlongyear.com/brochures/Rig\\_Catalog\\_English\\_Feb\\_28\\_2014.pdf](http://app.boartlongyear.com/brochures/Rig_Catalog_English_Feb_28_2014.pdf) [6/5/2015, 2015].

BOLL, S.F., 1979. Suppression of acoustic noise in speech using spectral subtraction. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, **ASSP-27**(2), pp. 113-120.

BP, 2012-last update, Historical Data. Available: [http://www.bp.com/liveassets/bp\\_internet/globalbp/globalbp\\_uk\\_english/reports\\_and\\_publications/statistical\\_energy\\_review\\_2011/STAGING/local\\_assets/spreadsheets/statistical\\_review\\_of\\_world\\_energy\\_full\\_report\\_2012.xlsx](http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/spreadsheets/statistical_review_of_world_energy_full_report_2012.xlsx) [10/12/2012].

BROWN, A.M., 2001. A step-by-step guide to non-linear regression analysis of experimental data using a Microsoft Excel spreadsheet. *Computer methods and programs in biomedicine*, **65**(3), pp. 191-200.

BROWNLEE, C., 2012. *OMA Energy Committee*. email edn.

CANADA DEPARTMENT OF TRADE AND COMMERCE, 1945. *Chronological Record of Canadian Mining Events from 1604 to 1943 and Historical Tables of the Mineral Production of Canada*. Ottawa: Edmond Cloutier.

CANADA DEPARTMENT OF TRADE AND COMMERCE, 1939. *Historical Tables of the Mineral Production of Canada*. Ottawa: J.O. Patenaude.

CANADA MINING INNOVATION COUNCIL (CMIC), 2010. *Report on the opportunities for demand management in Canadian mining and metalurgical facilities*. 18 pages edn.

CANADIAN INDUSTRIAL ENERGY END-USE ANALYSIS CENTER (CIEEDAC), var.-last update, Energy use and related data: Canadian Mining and Metal Smelting and Refining Industires, 1990-various. Available: <http://www2.cieedac.sfu.ca/publications> [04/25/2013].

CANADIAN INDUSTRIAL ENERGY END-USE ANALYSIS CENTER (CIEEDAC), 2013-last update, CIEEDAC Database on Energy, Production and Intensity Indicators for Canadian Industry. Available: <http://www3.cieedac.sfu.ca/CIEEDACweb/mod.php?mod=NAICSPublic&menu=1602> [04/25/2012].

CANADIAN INDUSTRY PROGRAM FOR ENERGY CONSERVATION, 2005a. *Benchmarking the Energy Consumption of Canadian Open-Pit Mines*. Ottawa: Natural Resources Canada.

CANADIAN INDUSTRY PROGRAM FOR ENERGY CONSERVATION, 2005b. *Benchmarking the Energy Consumption of Canadian Underground Bulk Mines*. Ottawa: Natural Resources Canada.

CANADIAN INSTITUTE FOR ENERGY TRAINING, 2006. *Energy Codes and Standards*. Certified Energy Manager Training edn. The Association of Energy Engineers.

CAPEHART, B.L., TURNER, W.C. and KENNEDY, W.J., 2012. *Guide to energy management*. 7th edn. Lilburn, GA: Fairmont Press.

CHANG, H., YANG, H. and LIN, C., 2008. Load identification in neural networks for a non-intrusive monitoring of industrial electrical loads. In: W. SHEN, J. YONG, Y. YANG, J.P. BARTHES and J. LUO, eds, *Computer Supported Cooperative Work in Design IV, 11th International Conference, CSCWD 2007, Melbourne, Australia, April 26-28, 2007. Revised Selected Papers*. Springer, pp. 664-674.

CHOI, W., SEN, A. and WHITE, A., 2011. Response of industrial customers to hourly pricing in Ontario's deregulated electricity market. *Journal of Regulatory Economics*, **40**(3), pp. 303-323.

CLEAN ENERGY MINISTERIAL, 2014-last update, Global energy management system implementation: Case study New Gold New Afto Mine. Available: [http://www.cleanenergyministerial.org/Portals/2/pdfs/GSEP\\_EMWG\\_New-Gold\\_case-study.pdf](http://www.cleanenergyministerial.org/Portals/2/pdfs/GSEP_EMWG_New-Gold_case-study.pdf) [December 15, 2014].

COOREMANS, C., 2011. Make it strategic! Financial investment logic is not enough. *Energy Efficiency*, **4**(4), pp. 473-492.



CUBEX LTD., nd.-last update, Orion specification sheet. Available: <http://www.cubex.net/cubex/wp-content/uploads/403-10-r13-orion-spec-sheet.pdf> [6/4/2015, 2015].

CUBEX LTD., 2010a-last update, Aries Technical Specification. Available: <http://www.cubex.net/cubex/wp-content/uploads/Cubex-Aries-Specification-March-22-2010.pdf> [6/4/2015, 2015].

CUBEX LTD., 2010b-last update, Cubex Underground Drills R110 Booster Specifications. Available: <http://www.cubex.net/cubex/wp-content/uploads/R110-Specifications-Completed-03-22-2010.pdf> [6/5/2015, 2015].

CULLAIN, J.G., 1979. Energy conservation at Inco metals company: compressed air in underground mining. *CIM Bulletin*, **72**(811), pp. 70-73.

CURRY, J.A., ISMAY, M.J.L. and JAMESON, G.J., 2014. Mine operating costs and the potential impacts of energy and grinding. *Minerals Engineering*, **56**, pp. 70-80.

DA CUNHA, I.F., 2007-last update, Implementing a sustainable compressed air leak program - Lessons learned and best practices. Available: [http://www.oma.on.ca/en/publications/resources/Compressed\\_Air\\_Final\\_070919.pdf](http://www.oma.on.ca/en/publications/resources/Compressed_Air_Final_070919.pdf) [03/12/2012].

DAMJANOVIC, B., GOODE, J.R. and CANADIAN INSTITUTE OF MINING, METALLURGY AND PETROLEUM, 2000. *Canadian Milling Practice CIM Special Volume 49*. Montreal: Canadian Institute of Mining, Metallurgy and Petroleum.

DE LA HARPE, J.H., CHESSOR, E. and DU PLESSIS, J.J.L., 2014. Chapter 7 Basic Fan Engineering. In: J.J.L. DU PLESSIS, ed, *Ventilation and Occupational Environmental Engineering in Mines*. 3rd edn. Johannesburg: Mine Ventilation Society of South Africa, pp. 109.

DEBEERS CANADA, ca. 2011-last update, 2010 Report to Society Canada. Available: [http://www.debeerscanada.com/files\\_3/publications.php](http://www.debeerscanada.com/files_3/publications.php) [03/14/2012].

DEMUTH, H., BEALE, M. and HAGAN, M., 2008. *Neural network toolbox™ 6 User's guide*. Natick, MA: The MathWorks, Inc.

DESHPANDE, M.V., 1966. *Elements of Electrical Power Station Design*. Great Britain: Pitman.

DESOUZA, E., 2004. Auxiliary ventilation operation practices, R. GANGULI and S. BANDOPADHYAY, eds. In: *Mine Ventilation: Proceedings of the 10th US/North American Mine Ventilation Symposium*, 16-19 May 2004, A.A. Balkema Publishers, Taylor & Francis Routledge, pp. 341-349.

DIAVIK DIAMOND MINE, n.d.-last update, Infrastructure. Available: [http://www.diavik.ca/ENG/ouoperations/565\\_infrastructure.asp](http://www.diavik.ca/ENG/ouoperations/565_infrastructure.asp) [03/12/2012].

DOTY, S. and TURNER, W.C., 2009. *Energy Management Handbook*. 7th edn. Lilburn, GA: The Fairmont Press.

DOUCET, J., PRICE, C., BARRETTE, R. and LAWSON, V., 2010. Evaluating the effect of operational changes at the vale canada clarabelle mill, 2010, Metallurgical Society of CIM, pp. 373-380.

DOYLE, D.M., 1979. Approach to energy management at Falconbridge nickel mines Limited *CIM Bulletin*, **72**(810), pp. 82-91.

DUCKWORTH, I.J., LOOMIS, I. and PROSSER, B., 2012. Fifteen years of resistance data collected at Freeport Indonesia, F. CALIZAYA and M. NELSON, eds. In: *14th U. S. /North American Mine Ventilation Symposium*, 30 June 2012, University of Utah.

DUCKWORTH, I.J. and LOWNDES, I.S., 2003. Modelling of auxilliary ventilation systems. *Transactions of the Institutions of Mining and Metallurgy, Section A: Mining Technology*, **112**(2), pp. A105-A113.

ECKELMAN, M.J., 2010. Facility-level energy and greenhouse gas life-cycle assessment of the global nickel industry. *Resources, Conservation & Recycling*, **54**(4), pp. 256-266.

EGARTER, D., SOBE, A. and ELMENREICH, W., 2013. Evolving non-intrusive load monitoring. In: A.E.A. ESPARCIA-ALCAZAR, ed, *Applications of Evolutionary Computation, 16th European Conference, EvoApplications 2013, Vienna, Austria, April 3-5, 2013. Proceedings*. Springer, pp. 182-191.

ENERGY MINES AND RESOURCES CANADA, various-last update, Energy Management Series [Homepage of Office of Energy Efficiency], [Online]. Available: <http://oee.nrcan.gc.ca/commercial/energy-management-series/6030> [6/3/2012].

FARHAT, A.A. and UGURSAL, V.I., 2010. Greenhouse gas emission intensity factors for marginal electricity generation in Canada. *International Journal of Energy Research*, **34**(15), pp. 1309-1327.

FARINACCIO, L. and ZMEUREANU, R., 1999. Using a pattern recognition approach to disaggregate the total electricity consumption in a house into the major end-uses. *Energy and Buildings*, **30**(3), pp. 245-259.

FEDERAL, PROVINCIAL AND TERRITORIAL SOCIAL LICENCE TASK GROUP, 2010-last update, Mining Sector Performance Report 1998-2008. Available: [http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/minerals-metals/files/pdf/mms-smm/pubr-pubr/pdf/EMMC\\_english.pdf](http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/minerals-metals/files/pdf/mms-smm/pubr-pubr/pdf/EMMC_english.pdf) [03/08/2012].

FIRTH, S., LOMAS, K., WRIGHT, A. and WALL, R., 2008. Identifying trends in the use of domestic appliances from household electricity consumption measurements. *Energy and Buildings*, **40**(5), pp. 926-936.

FITZPATRICK, P., FONSECA, A. and MCALLISTER, M.L., 2011. From the Whitehorse Mining Initiative Towards Sustainable Mining: lessons learned. *Journal of Cleaner Production*, **19**(4), pp. 376-384.

FLOWER, J.R. and LINNHOFF, B., 1978. Synthesis of heat exchanger networks - 2. Evolutionary generation of networks with various criteria of optimality. *AIChE Journal*, **24**(4), pp. 642-654.

FLSMIDTH, 2013-last update, FLSmidth Smelting equipment. Available: <http://www.flsmidth.com/en-US/Industries/Categories/Products/Pyroprocessing/Smelting+equipment/Smelting+equipment> [4/30/2015, 2015].

FONSECA, A., MCALLISTER, M.L. and FITZPATRICK, P., 2014. Sustainability reporting among mining corporations: a constructive critique of the GRI approach. *Journal of Cleaner Production; Special Volume: The sustainability agenda of the minerals and energy supply and demand network: an integrative analysis of ecological, ethical, economic, and technological dimensions*, **84**, pp. 70-83.

FRANK, R., BERNANKE, B., OSBERG, L., CROSS, M. and MACLEAN, B., 2012a. *Principles of Macroeconomics*. 4th Cdn ed. edn. Toronto, Canada: McGraw-Hill Ryerson.

FRANK, R., BERNANKE, B., OSBERG, L., CROSS, M. and MACLEAN, B., 2012b. *Principles of Microeconomics*. 4th Cdn ed. edn. Toronto, Canada: McGraw-Hill Ryerson.

FYTAS, K., PERREAULT, S. and DAIGLE, B., 2000. EOLAVAL, a mine ventilation planning tool, G.N. PANAGIOTOU and T.N. MICHALAKOPOULO, eds. In: *Mine Planning and Equipment Selection 2000 (MPES) - Proceedings of the Ninth International Symposium*, 6-9 November 2000 2000, A.A. Balkema Publisher, pp. 51.

G+ INDUSTRIAL PLASTICS INC., nd. *G+ Speed Air Duct*. Promotional poster edn.

G+ INDUSTRIAL PLASTICS INC., 2014-last update, Ventilation. Available: <http://www.plastiquesgplus.com/en/ventilation> [March 28, 2014].

GILLIES, A.D. and WU, H.W., 1999. A comparison of air leakage prediction techniques for auxiliary ventilation ducting systems, JERRY CHEN-JEN TIEN, ed. In: *Proceedings 8th US mine ventilation symposium*, June 11- 17 1999, University of Missouri-Rolla Press, pp. 681.

GLOBAL REPORTING INITIATIVE, ca. 2013-last update, What is GRI?. Available: <https://www.globalreporting.org/information/about-gri/what-is-GRI/Pages/default.aspx> [02/07/2015, 2015].

GLOBAL REPORTING INITIATIVE, ca. 2012-last update, Sustainability Disclosure Database - Search. Available: <http://database.globalreporting.org/search> [10/31/2012, 2012].

GLOBAL REPORTING INITIATIVE, 2011-last update, Sustainability Reporting Guidelines Version 3.1. Available: <https://www.globalreporting.org/resource/library/G3.1-Sustainability-Reporting-Guidelines.pdf> [07/04/2012].

GLOBAL REPORTING INITIATIVE, 2010-last update, Mining and Metals Sector Supplement. Available: <https://www.globalreporting.org/reporting/sector-guidance/mining-and-metals/Pages/default.aspx> [11/1/2012].

GOLDCORP, ca. 2011-last update, Musselwhite - Overview & Operating Highlights. Available: <http://www.goldcorp.com/Unrivalled-Assets/Mines-and-Projects/Canada-and-US/Operations/Musselwhite/Overview-and-Operating-Highlights/default.aspx> [3/16/2012].

GOLDCORP, ca. 2010-last update, Musselwhite Mine Sustainability Report 2008-2009. Available: [http://csr.goldcorp.com/2010/docs/2009\\_musselwhite.pdf](http://csr.goldcorp.com/2010/docs/2009_musselwhite.pdf) [03/09/2012].

GOLDCORP, ca. 2005-last update, Musselwhite Mining. Available: <http://209.89.176.189/operations/musselwhite/mining/> [3/16/2012, 2012].

GOLDCORP, 2011-last update, Rockbreaking News. Available: <http://www.porcupinegoldmines.ca/en/latestnewsletter.asp> [10/16/2012].

GOLDCORP, 2010-last update, Energy Initiatives at Musselwhite. Available: [http://csr.goldcorp.com/2010/6\\_energy.php#3](http://csr.goldcorp.com/2010/6_energy.php#3) [3/22/2012].

GOVERNMENT OF ONTARIO, 2014-last update, Ontario Regulation 126/14 [Homepage of Ontario], [Online]. Available: [http://www.e-laws.gov.on.ca/html/source/regs/english/2014/elaws\\_src\\_regs\\_r14126\\_e.htm](http://www.e-laws.gov.on.ca/html/source/regs/english/2014/elaws_src_regs_r14126_e.htm) [May 8, 2014].

GRUBLER, A., 2012. Energy transitions research: Insights and cautionary tales. *Energy Policy*, **50**(0), pp. 8-16.

GUERIN, T., 2006. A survey of sustainable development initiatives in the Australian mining and minerals industry. *Minerals and Energy - Raw Materials Report*, **20**(3-4), pp. 11-44.

HALL, J.A. and LIEDTKA, S.L., 2007. the Sabanes-Oxley Act: Implications for Large-Scale IT Outsourcing. *Communications of the ACM*, **50**(3), pp. 95-100.

HALL, E.H., HANNA, W.T., REED, L.D., VARGA JR., J., WILLIAMS, D.N., WILKES, K.E., JOHNSON, B.E., MUELLER, W.J., BRADBURY, E.J. and FREDERICK, W.J., 1975. *Evaluation of the theoretical potential for energy conservation in seven basic industries*. Columbus: Battelle Columbus Laboratories;.

HARR, M.E., 1987. *Reliability-based design in civil engineering*. United States of America: McGraw Hill.

HARRIS, J.H. and ARMSTRONG, T.B., 1979. Electrical energy management Inco metals company Shebandowan Mine. *CIM Bulletin*, **72**(812), pp. 66-72.

HARTMAN, H.L. and MUTMANSKY, J.M., 2002. *Introductory mining engineering*. Second edition edn. New Jersey, U.S.A.: John Wiley & Sons.

HASANBEIGI, A. and PRICE, L., 2010-last update, Industrial Energy Audit Guidebook: Guidelines for Conducting an Energy Audit in Industrial Facilities [Homepage of Ernest Orlando Lawrence Berkeley National Laboratory], [Online]. Available: [http://minotaur.lbl.gov/china.lbl.gov/sites/china.lbl.gov/files/LBNL-3991E.Industrial%20Energy%20Audit%20Guidebook\\_0.pdf](http://minotaur.lbl.gov/china.lbl.gov/sites/china.lbl.gov/files/LBNL-3991E.Industrial%20Energy%20Audit%20Guidebook_0.pdf) [04/01, 2013].

HAUTA, R., 2015. *MacLean drilling time*. email edn.

HAYS, R.M., 1990. Trucks. In: B.A. KENNEDY, ed, *Surface Mining*. 2nd edition edn. Littleton, CO, USA: Society of Mining, Metallurgy, and Exploration, pp. 672-691.

ICMM, 2015-last update, Member performance. Available: <http://www.icmm.com/members/member-performance> [5/25/2015, 2015].

ICMM, 2013-last update, The cost of carbon pricing: competitiveness implications for the mining and metals industry. Available: <http://www.icmm.com/publications> [26 September, 2013].

ICMM, 2012a-last update, 10 principles. Available: <http://www.icmm.com/our-work/sustainable-development-framework/10-principles> [10/31/2012].

ICMM, 2012b-last update, About ICMM. Available: <http://www.icmm.com/> [07/03/2012].

ICMM, 2012c-last update, Member companies. Available: <http://www.icmm.com/members> [10/31/2012].

ICMM, 2012d-last update, Our History. Available: <http://www.icmm.com/about-us/icmm-history> [10/31/2012].

ICMM, 2012e-last update, Public reporting. Available: <http://www.icmm.com/our-work/sustainable-development-framework/public-reporting> [11/2/2012].

IESO, 2014a-last update, Global Adjustment. Available: [http://www.ieso.ca/imoweb/b100/b100\\_GA.asp](http://www.ieso.ca/imoweb/b100/b100_GA.asp) [February 19, 2014].

IESO, 2014b-last update, Global Adjustment for Class A. Available: <http://www.ieso.ca/Pages/Participate/Settlements/Global-Adjustment-for-Class-A.aspx> [February 19, 2014].

IESO, 2013a-last update, Demand Response. Available: [http://www.ieso.ca/imoweb/siteShared/managing\\_demand.asp?sid=bi](http://www.ieso.ca/imoweb/siteShared/managing_demand.asp?sid=bi) [8/1/2013, 2013].

IESO, 2013b-last update, Electricity Charges Explained. Available: <http://www.ieso.ca/imoweb/role/wholesaleCharges.asp> [8/1/2013, 2013].

IESO, 2013c-last update, Energy Market Overview. Available: <http://www.ieso.ca/imoweb/mktOverview/mktOverview.asp> [8/1/2013, 2013].

IESO, 2013d-last update, Why Wholesale Prices Fluctuate. Available: [http://www.ieso.ca/imoweb/businessIndustry/bi\\_wholesale\\_price2.asp](http://www.ieso.ca/imoweb/businessIndustry/bi_wholesale_price2.asp) [8/1/2013, 2013].

INSTITUTE FOR INDUSTRIAL PRODUCTIVITY, 2012-last update, Tools. Available: <http://www.iipnetwork.org/tools> [6/15/2012].

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2011a-last update, Discover ISO. Available: [http://www.iso.org/iso/about/discover-iso\\_isos-name.htm](http://www.iso.org/iso/about/discover-iso_isos-name.htm) [09/07/2011].

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2011b-last update, Energy management systems - Requirements with guidance for use. Available: [http://www.iso.org/iso/iso\\_catalogue/catalogue\\_tc/catalogue\\_detail.htm?csnumber=51297](http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=51297) [July 22, 2011].

JAMES, B., 1978. Energy efficiency - high of low priority for management in the industrial minerals industry? *CIM Bulletin*, **71**(800), pp. 97-103.

JENKINS, H. and YAKOVLEVA, N., 2006. Corporate social responsibility in the mining industry: Exploring trends in social and environmental disclosure. *Journal of Cleaner Production*, **14**(3-4), pp. 271-284.

JOE, E.G., 1979. Energy consumption in Canadian mills. *CIM Bulletin*, **72**(806), pp. 147-151.

KERR, A., BOUCHARD, A.P., TRUSKOSKI, J., BARRETT, J. and LABONTE, G., 2003. The "Mill Redesign Project" at Inco's Clarabelle mill. *CIM Bulletin*, **96**(1075), pp. 58-66.

KIM, H., MARWAH, M., ARLITT, M., LYON, G. and HAN, J., 2011. Unsupervised Disaggregation of Low Frequency Power Measurements. *Society for Industrial and Applied Mathematics*, pp. 747-758.

LAMBERT, E.H., 1973. Energy conservation for the mining industry. *CIM Bulletin*, **66**(738), pp. 69-74.

LANDRY, B.J., 2009. *Energy Survey Report Calarabelle Mill Vale Inco Ltd.* Draft Report edn. Byron J. Landry & Associates.

LAWSON, V. and XU, M., 2011. Float it, clean it, depress it - Consolidating the separation stages at Clarabelle Mill, *Metallurgical Plant Design and Operating Strategies, METPLANT 2011, August 8, 2011 - August 9, 2011*, Australasian Institute of Mining and Metallurgy, pp. 589-601.

LCG MANAGEMENT GROUP, 2009-last update, Investigation of Current Research Related to the Reduction of Energy Usage in Mines Through Recycling, Reuse, and Other Means. Available: <http://www.miningexcellence.ca/doc/b0410238-4883-44e7-858f-a97f3d924501> [09/26/2011].

LE ROUX, W., 1979. *Mine ventilation notes for beginners*. Third edition edn. South Africa: Mine Ventilation Society of South Africa.

LEVESQUE, M., 2013-last update, Mining Energy Efficiency Best Practice Database. Available: [http://www.mirarco.org/scripts/Mining\\_EE\\_Best\\_Practice/index.php](http://www.mirarco.org/scripts/Mining_EE_Best_Practice/index.php) [08/09/2013, 2013].

LEVESQUE, M.Y. and MILLAR, D.L., 2015a-last update, Auxiliary mine ventilation cost assessment model [Homepage of Laurentian University], [Online]. Available: <http://dx.doi.org/10.14285/10219/2301> [02/10, 2015].

LEVESQUE, M. and MILLAR, D.L., 2013. A best practice database for energy management in the minerals industry, *World Mining Congress*, 11-15 August 2013, Canadian Institute of Mining, Metallurgy and Petroleum.

LEVESQUE, M., 2011. *Understanding Mine Heat - Sankey Diagrams for Nickel Production from Laterite Ore*, Laurentian University.

LEVESQUE, M.Y. and MILLAR, D.L., 2015b. The link between operational practices and specific energy consumption in metal ore milling plants – Ontario experiences. *Minerals Engineering*, **71**(0), pp. 146-158.

LEVESQUE, M., MILLAR, D. and PARASZCZAK, J., 2014. Energy and mining – the home truths. *Journal of Cleaner Production*, **84**(0), pp. 233-255.

LI, G., KOCSIS, C. and HARDCASTLE, S., 2011. Sensitivity analysis on parameter changes in underground mine ventilation systems. *Journal of Coal Science and Engineering*, **17**(3), pp. 251-255.

LIANG, J., NG, S.K.K., KENDALL, G. and CHENG, J.W.M., 2010a. Load signature study part I: Basic concept, structure, and methodology. *IEEE Transactions on Power Delivery*, **25**(2), pp. 551-560.

LIANG, J., NG, S.K.K., KENDALL, G. and CHENG, J.W.M., 2010b. Load signature study part II: Disaggregation framework, simulation, and applications. *IEEE Transactions on Power Delivery*, **25**(2), pp. 561-569.

LINNHOFF, B., 1993. Pinch analysis - a state-of-the-art overview. *Chemical Engineering Research and Design*, **71**, pp. 503-522.

LINNHOFF, B. and HINDMARSH, E., 1983. Pinch design method for heat exchanger networks. *Chemical Engineering Science*, **38**(5), pp. 745-763.

LINNHOFF, B. and FLOWER, J.R., 1978. Synthesis of heat exchanger networks - 1. systematic generation of energy optimal networks. *AIChE Journal*, **24**(4), pp. 633-642.

LIU, Z., WIERMAN, A., CHEN, Y., RAZON, B. and CHEN, N., 2013. Data center demand response: Avoiding the coincident peak via workload shifting and local generation. *Performance Evaluation*, **70**(10), pp. 770-791.

LYNN, P.A., 1989. *An introduction to the analysis and processing of signals*. 3rd edition edn. Houndmills, Basingstoke, Hampshire, London: Macmillan Education Ltd.

MALLET, R., 2014. *Garson Mine Energy Audit*. Masters (M.Eng.) project in Natural Resources Engineering edn. Sudbury, Canada: Laurentian University.

MANIAN, V.S., 1974. Energy efficiency brings economies. *Canadian Mining Journal*, **95**(9), pp. 37, 58-37, 58.

MARCEAU, M.L. and ZMEUREANU, R., 2000. Nonintrusive load disaggregation computer program to estimate the energy consumption of major end uses in residential buildings. *Energy Conversion and Management*, **41**(13), pp. 1389-1403.

MASON, J.K., WHITE, G.D., O'BRIEN, M.S. and KOMAR, C., 2003. *Report of Activities 2002*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report edn. Thunder Bay North District; Ontario Geological Survey, Open File Report 6111.

MASON, J.K., WHITE, G.D., SCOTT, J.F., O'BRIEN, M.S. and KOMAR, C., 2002. *Report of Activities 2001*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report edn. Thunder Bay North District; Ontario Geological Survey, Open File Report 6080.

MATTHEWS, B. and CRAIG, I.K., 2013. Demand side management of a run-of-mine ore milling circuit. *Control Engineering Practice*, **21**(6), pp. 759-768.

MCCRACKEN, T., KANHAI, T., BRIDSON, P., MCBRIDE, W.R., SMALL, K. and PENNA, D.N., January 31, 2013-last update, Technical Report Lac des Iles Mine, Ontario, Incorporating Prefeasibility Study Offset Zone Phase I [Homepage of Tetra Tech], [Online]. Available: <http://www.nap.com/investors/investor-briefcase/default.aspx> [November 28, 2013].



MCLELLAN, B.C., CORDER, G.D., GIURCO, D.P. and ISHIHARA, K.N., 2012. Renewable energy in the minerals industry: a review of global potential. *Journal of Cleaner Production*, **32**(0), pp. 32-44.

MCPHERSON, M.J., 1993. *Subsurface ventilation and environmental engineering*. 1 edn. London: Chapman and Hall.

MECANICAD, nd.-last update, Ventilation. Available: <http://mecanicad.ca/en/content/ventilation> [6/7/2015, 2015].

METKEMEYER, L., 2012. Improving copper recovery in heap leaching cycles in hydrometallurgical plants by solar heating, WIERTZ, J. & FILIPPO, G., ed. In: *Enermin2012: 2nd International Seminar on Energy Management in the Mining Industry*, 10-12 September 2012 2012, Gecamin.

MEYER, C.F., 1990. Determining the friction losses of underground ventilation ducting. *Journal of the Mine Ventilation Society of South Africa*, **43**(10), pp. 191-195.

MILLAR, D.L., LEVESQUE, M., LYLE, G. and BULLOCK, K., 2012. Enabling progressive energy management practice for minerals operations. *CIM Journal*, **3**(3), pp. 178-184.

MINE VENTILATION SERVICES, 2003. *DuctSIM User's Manual*. Version 1.0b edn.

MINERALS AND METALS SECTOR OF NATURAL RESOURCES CANADA AND THE NATIONAL ENERGY BOARD, 2012. *Principal Mineral Areas of Canada, Sixty-first Edition, 2011*. Geological Survey of Canada, Map 900A, scale 1: 6 000 000.

MINING ASSOCIATION OF CANADA, 2013-last update, F&F 2012 Facts & Figures of the Canadian Mining Industry. Available: <http://www.mining.ca/site/index.php/en/> [1/31/2013].

MINING ASSOCIATION OF CANADA, 2012a-last update, Energy and GHG Emissions Management Guidance Document. Available: <http://www.mining.ca/site/index.php/en/towards-sustainable-mining/performance-measures-a-protocols.html> [11/1/2012].

MINING ASSOCIATION OF CANADA, 2012b-last update, Energy and GHG Emissions Management Protocol. Available: <http://www.mining.ca/site/index.php/en/towards-sustainable-mining/performance-measures-a-protocols.html> [11/1/2012].

MINING ASSOCIATION OF CANADA, 2011a-last update, Members. Available: <http://www.mining.ca/site/index.php/en/about-us/members.html> [11/1/2012].

MINING ASSOCIATION OF CANADA, 2011b-last update, Performance Measures and Protocols. Available: <http://www.mining.ca/site/index.php/en/towards-sustainable-mining/performance-measures-a-protocols.html> [07/03/2012].

MINING ASSOCIATION OF CANADA, 2011c-last update, Towards Sustainable Mining. Available: <http://www.mining.ca/site/index.php/en/towards-sustainable-mining.html> [07/03/2012].

MINING ASSOCIATION OF CANADA, 2011d-last update, TSM Progress Report. Available: <http://www.mining.ca/site/index.php/en/towards-sustainable-mining/progress-reports.html> [11/1/2012].

MINISTRY OF NORTHERN DEVELOPMENT, MINES AND FORESTRY, 2010-last update, Northern Industrial Electricity Rate Program (NIER Program) Program Rules. Available: [http://www.mndmf.gov.on.ca/northern\\_development/business\\_support/northern\\_industrial\\_electricity\\_rate\\_program\\_e.asp](http://www.mndmf.gov.on.ca/northern_development/business_support/northern_industrial_electricity_rate_program_e.asp) [09/15/2011].

MUDD, G.M., 2010. Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, **38**(1-2), pp. 9-26.

MUDD, G.M., 2007. Global trends in gold mining: Towards quantifying environmental and resource sustainability. *Resources Policy*, **32**(1-2), pp. 42-56.

NAPIER-MUNN, T., 2015. Is progress in energy-efficient comminution doomed? *Minerals Engineering; Special issue: Comminution*, **73**, pp. 1-6.

NATURAL RESOURCES CANADA, nd-last update, Comprehensive Energy Use Database Industrial Sector Disaggregated Industries Canada (2012) [Homepage of Office of Energy Efficiency], [Online]. Available: [http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends\\_id\\_ca.cfm](http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive/trends_id_ca.cfm) [5/22/2015, 2015].

NATURAL RESOURCES CANADA, ca. 2014-last update, Energy Use Data Handbook Tables. Available: [http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/handbook\\_aaa\\_ca.cfm](http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/handbook/handbook_aaa_ca.cfm) [4/29/2015, 2015].

NATURAL RESOURCES CANADA, ca. 2013a-last update, Energy Use Data Handbook Tables [Homepage of Natural Resources Canada], [Online]. Available: [http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/handbook\\_totalsectors\\_ca.cfm?attr=0](http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/handbook_totalsectors_ca.cfm?attr=0) [06/02/2013, 2013].

NATURAL RESOURCES CANADA, ca. 2013b. *RETScreen Plus*.

NATURAL RESOURCES CANADA, 2015-last update, Heads Up CIPEC – Volume 19, Issue 1. Available: <http://www.nrcan.gc.ca/energy/efficiency/industry/technical-info/library/newsletter/14406#s7> [2/19/2015, 2015].

NATURAL RESOURCES CANADA, 2014-last update, Why ENERGY STAR Portfolio Manager?. Available: <http://www.nrcan.gc.ca/energy/efficiency/buildings/energy-benchmarking/whypm/3729> [2/12/2015, 2015].

NATURAL RESOURCES CANADA, 2012a. *General Review of the Mineral Industries*. Catalogue no. 26-201-X. 2010 Edition edn.

NATURAL RESOURCES CANADA, 2012b. *Heads Up CIPEC Newsletter*. newsletter edn. June 1, 2012 ed. Vol. XVI, No. 11.

NATURAL RESOURCES CANADA, 2011a-last update, Canadian Industry Program for Energy Conservation (CIPEC). Available: <http://oee.nrcan.gc.ca/industrial/cipec/13673> [3/7/2012].

NATURAL RESOURCES CANADA, 2011b-last update, Canadian Minerals Yearbook (CMY) | Minerals and Metals Sector. Available: <http://www.nrcan.gc.ca/minerals-metals/business-market/canadian-minerals-yearbook/4070> [9/16/2013].

NATURAL RESOURCES CANADA, 2009-last update, Energy Savings Toolbox - An Energy Audit Manual and Tool. Available: <http://www.nrcan.gc.ca/energy/efficiency/industry/cipec/5161> [04/23/2013, 2013].

NATURAL RESOURCES CANADA, 2003-last update, Pinch Analysis: For the efficient use of energy, water & hydrogen. Available: <http://canmetenergy.nrcan.gc.ca/industrial-processes/industrial-systems-optimization/publications/206> [06/07/2012].

NAVIGANT CONSULTING LTD., January 23, 2014-last update, Global Adjustment Review. Available: [http://www.ieso.ca/imoweb/pubs/consult/se106/se106-20140128-Global\\_Adjustment\\_Review\\_Report.pdf](http://www.ieso.ca/imoweb/pubs/consult/se106/se106-20140128-Global_Adjustment_Review_Report.pdf) [January 31, 2014].

NICKELL, C., G. and DENYER, C., 2007. An Introduction to SAS 70 Audits. *Benefits Law Journal*, **20**(1), pp. 58-68.

NOAILLY, J. and BATRAKOVA, S., 2010. Stimulating energy-efficient innovations in the Dutch building sector: Empirical evidence from patent counts and policy lessons. *Energy Policy*, **38**(12), pp. 7803-7817.

NORGATE, T. and HAQUE, N., 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production*, **18**(3), pp. 266-274.

NORTH AMERICAN PALLADIUM, 2013a-last update, 2009 Annual Report. Available: <http://www.nap.com/investors/Financial-Reports/default.aspx> [11/14, 2013].

NORTH AMERICAN PALLADIUM, 2013b-last update, 2012 Annual Report. Available: <http://www.nap.com/investors/Financial-Reports/default.aspx> [11/14, 2013].

ONDER, M., SARAC, S. and CEVIK, E., 2006. The influence of ventilation variables on the volume rate of airflow delivered to the face of long drivages. *Tunnelling and Underground Space Technology*, **21**(5), pp. 568-574.

ONTARIO ENERGY BOARD - MARKET SURVEILLANCE PANEL, June, 2013-last update, Monitoring Report on the IESO-Administered Electricity Markets for the period from May 2012 - October 2012, Appendix. Available: <http://www.ontarioenergyboard.ca/OEB/Industry/About> the OEB/Electricity Market Surveillance/Market Surveillance Panel Reports [7/18/2013, 2013].

ONTARIO PROSPECTORS ASSOCIATION, 2012-last update, Ontario Mining and Exploration Directory 2012. Available: <http://www.mndm.gov.on.ca/en/news/mines-and-minerals/ontario-mining-exploration-directory-2012> [November 14, 2013].

PARASZCZAK, J., FYTAS, K. and LAFLAMME, M., 2014. Feasibility of Using Electric Trucks in Deep Metal Mines. *Mine Planning and Equipment Selection*. Springer, pp. 1265-1275.

PARASZCZAK, J. and FYTAS, K., 2012. Renewable energy sources - a promising opportunity for remote mine sites? *International Conference on Renewable Energies and Power Quality (ICREQP'12)*, March 28-30 2012 2012.

PASCOE, R.D., 1992. Capital and operating costs of minerals engineering plants - a review of simple estimation techniques. *Minerals Engineering*, **5**(8), pp. 883-893.

PAWLIK, K.E., CAPEHART, L.C. and CAPEHART, B.L., 2002. "Energy Balancing": How to Use the Energy Balance Data You Have Collected TO MAKE FINANCIAL DECISIONS. *Strategic Planning for Energy and the Environment*, **21**(3), pp. 58-80.

PAWLIK, K.E., CAPEHART, L.C. and CAPEHART, B.L., 2001. Analyzing Facility Energy Use: A Balancing Act. *Strategic Planning for Energy and the Environment*, **21**(2), pp. 8-33.

PERDAN, S. and AZAPAGIC, A., 2011. Carbon trading: Current schemes and future developments. *Energy Policy*, **39**(10), pp. 6040-6054.

PEREZ, F. and SANCHEZ, L.E., 2009. Assessing the Evolution of Sustainability Reporting in the Mining Sector. *Environmental Management*, **43**(6), pp. 949.

PERRY, R.H., GREEN, D.W. and MALONEY, J.O., 1997. *Perry's chemical engineers' handbook*. 7th edn. New York: McGraw-Hill.

PICKETT, D.E., HALL, W.S. and SMITH, G.W., 1978. *Milling practice in Canada*. Montréal, Qué.: Canadian Institute of Mining and Metallurgy.

PIRAINO, G., RIMAWI, E. and CERNY, A., 2012. 25+MWth solar heating commercially viable for solvent extraction electrowinning (SX-EW) and heap leaching, WIERTZ, J. & FILIPPO, G., ed. In: *Enermin2012: 2nd International Seminar on Energy Management in the Mining Industry*, 10-12 September 2012 2012, Gecamin.

RAMIREZ, R.W., 1985. *The FFT, fundamentals and concepts*. Englewood Cliffs, NJ: Prentice-Hall.

REMER, D.S., LIN, S., YU, N. and HSIN, K., 2008. An update on cost and scale-up factors, international inflation indexes and location factors. *International Journal of Production Economics*, **114**(1), pp. 333-346.

RIO TINTO, ca. 2010-last update, Diavik Diamond Mine 2010 Sustainable Development Report. Available: <http://www.diavik.ca/ENG/resources/661.asp> [03/13/2012].

RIO TINTO, 2013-last update, Wind farm. Available: [http://www.diavik.ca/ENG/ouoperations/565\\_wind\\_farm.asp](http://www.diavik.ca/ENG/ouoperations/565_wind_farm.asp) [03/07, 2013].

ROSENQVIST, J., THOLLANDER, P., ROHDIN, P. and SODERSTROM, M., 2012. Industrial Energy Auditing for Increased Sustainability: Methodology and Measurements. In: A. GEBREMEDHIN, ed, *Sustainable Energy - Recent Studies*. InTech, pp. Chapter 5.

SADRAI, S., MEECH, J.A., TROMANS, D. and SASSANI, F., 2011. Energy efficient comminution under high velocity impact fragmentation. *Minerals Engineering*, **24**(10), pp. 1053-1061.

SANDVIK MINING AND CONSTRUCTION, 2007-last update, DL410-10 Technical Specification. Available: [http://www.mc.sandvik.com/SANDVIK/1281/Internet/MANorway/SE03605.NSF/Alldocs/Products\\*5CDrill\\*rigs\\*and\\*rock\\*drills\\*5CUnderground\\*drill\\*rigs\\*5CProduction\\*drill\\*rigs\\*2ADL410\\*2D10/\\$FILE/7-6100-F \(DL410-10\).pdf](http://www.mc.sandvik.com/SANDVIK/1281/Internet/MANorway/SE03605.NSF/Alldocs/Products*5CDrill*rigs*and*rock*drills*5CUnderground*drill*rigs*5CProduction*drill*rigs*2ADL410*2D10/$FILE/7-6100-F%20(DL410-10).pdf) [6/5/2015, 2015].

SAYADI, A.R., KHALES, M.R. and KHOSFARMAN, M., 2014. A parametric cost model for mineral grinding mills. *Minerals Engineering*, **55**(0), pp. 96-102.

SCALES, M., 2007. Musselwhite mine & mill. *Canadian Mining Journal*, (June ed.), **128**(5), pp. 21-22.

SCOTT, G.D., 2008. *Energy Conservation Opportunities in Ontario's Mining Industry*. report edn. July 7 2008: Ontario Mining Association's Energy Committee.

SIROIS, L., 1993. *Energy Efficiency R&D Opportunities in the Mining and Metallurgy Sector, Phase 1 - Scoping Study*. CANMET Contract No. EA9710-2-1. 2012. Ottawa, Ontario: Efficiency and Alternative Energy Technology Branch, CANMET, Natural Resources Canada, NRCan.

SMITH, H., 2008. *Modelling for resource and environmental impact assessments of wave farms*, University of Exeter.

SMITH, S.W., 1997. *The scientist & engineer's guide to digital signal processing*. 1 edn. San Diego, Calif: California Technical Pub.

SMYK, M.C., WHITE, G.D., HINZ, P. and KOMAR, C., 2009. *Report of Activities 2008*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6233.

SMYK, M.C., WHITE, G.D., MAGEE, M.A. and KOMAR, C., 2006. *Report of Activities 2005*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6181.

SMYK, M.C., WHITE, G.D., MAGEE, M.A. and KOMAR, C., 2005. *Report of Activities 2004*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6147.

SMYK, M.C., WHITE, G.D., MAGEE, M.A. and KOMAR, C., 2004. *Report of Activities 2003*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6128.

SMYK, M.C., WHITE, G.D., PUUMALA, M.A., HINZ, P. and KOMAR, C., 2008. *Report of Activities 2007*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6217.

SMYK, M.C., WHITE, G.D., PUUMALA, M.A., MAGEE, M.A. and KOMAR, C., 2007. *Report of Activities 2006*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6201.

SMYK, M.C. and WHITE, L., H.C., 2010. *Report of Activities 2009*. Resident Geologist Program, Thunder Bay North Regional Resident Geologist Report: Thunder Bay North District edn. Ontario Geological Survey Open File Report 6245.

SONNEMANN, G.W., SCHUHMACHER, M. and CASTELLS, F., 2003. Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator. *Journal of Cleaner Production*, **11**(3), pp. 279-292.

STANLEY, W.D., 2005. *Technical analysis and applications with MATLAB*. Clifton Park, NY: Thomson Delmar Learning.

STATISTICS CANADA, var.a-last update, General Review of the Mineral Industries, Mines, Quarries and Sand Pits. Catalogue no. 26-201-X [Homepage of Ottawa], [Online]. Available: <http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=26-201-X&chropt=1&lang=eng> [9/12/2013].

STATISTICS CANADA, var.b-last update, Non-metal Mines, Catalogue no. 26-224-XIB. Available: <http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=26-224-XIB&lang=eng> [9/12/2013].

STATISTICS CANADA, var.c-last update, Report on Energy Supply Demand in Canada. Catalogue no. 57-003-X [Homepage of Ottawa], [Online]. Available: <http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=57-003-X&chropg=1&lang=eng> [9/12/2013].

STATISTICS CANADA, var-last update, Metal Ore Mining, Catalogue no. 26-223-X. Available: <http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?lang=eng&catno=26-223-X> [9/12/2013].

STATISTICS CANADA, 2015/01/22, 2015-last update, CANSIM - 326-0021 - Consumer Price Index. Available: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=3260021&paSer=&pattern=&stByVal=1&p1=1&p2=37&tabMode=dataTable&csid=> [4/29/2015, 2015].

STATISTICS CANADA, 2013-last update, CANSIM - Canadian socioeconomic database from Statistics Canada. Available: <http://www5.statcan.gc.ca/cansim/a01?lang=eng> [4/25/2013, 2013].

STATISTICS CANADA, 2012. *North American Industry Classification System (NAICS) Canada Catalogue no. 12-501-X*. Ottawa, Canada: Minister of Industry.

STATISTICS CANADA, 1999-last update, Historical Statistics of Canada : Chronological index. Available: <http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=11-516-X&chropg=1&lang=eng#issue1983001> [9/13/2013].

STERLING, D., 2010. Identifying Opportunities to reduce the consumption of energy across Mining and Processing Plants, *World Energy Congress 2010*, September 12-16 2010 2010.

STREETER, V.L. and WYLIE, E.B., 1983. *Fluid mechanics*. International Student Edition edn. Tokyo, Japan: McGraw-Hill.

TAMROCK, 2000. *TamrockProduct Catalogue- Robolt series technical data sheet*.

TAMROCK, 1995. *TamrockProduct Catalogue- Drills - Solo series*.

TARDIF, D., PAQUET, A. and MILLER, F., 2010. Exploration drift ventilation project at Mine Casa Berardi - A new and more economical solution, HARDCASTLE & MCKINNON, ed. In: *13th U.S./North American Mine Ventilation Symposium*, June 13-16 2010 2010, MIRARCO, pp. 243.

TECK, ca. 2007-last update, Sustainability Summary Hemlo Operations. Available: <http://www.teck.com/Generic.aspx?PAGE=Teck+Site%2fResponsibility+Pages%2fSustainability+Pages%2fReport+Archive&portalName=tc> [03/22/2012].

TENBERGEN, R.A. and THROSSELL, M.A., 1989. Semi autogenous-ball mill-crushing circuit selection for Inco's mills rationalization, A.L. MULAR and G.E. AGAR, eds. In: *Advances in*

*autogenous and semiautogenous grinding technology*, 25-27 September 1989, Dept. of Mining and Mineral Process Engineering, University of British Columbia, pp. 253.

THE ASSOCIATION OF ENERGY ENGINEERS, nd. *Comprehensive five day training program for Certified Energy Managers course manual*. Atlanta, Georgia, USA: The Association of Energy Engineers.

THE GLOBE AND MAIL, 2010-last update, Teck, Suncor partner on wind power project. Available: <http://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/teck-suncor-partner-on-wind-power-project/article1718742/> [05/31/2012].

THE MATHWORKS INC., 2014. *MATLAB Release 2014a*. R2014a edn. Natick, Massachusetts, United States: The MathWorks Inc.

THE MINING ASSOCIATION OF CANADA, ca. 2015-last update, Facts and Figures 2014. Available: [http://mining.ca/sites/default/files/documents/Facts\\_and\\_Figures\\_2014.pdf](http://mining.ca/sites/default/files/documents/Facts_and_Figures_2014.pdf) [6/11/2015, 2015].

THE PARLIAMENT OF THE COMMONWEALTH OF AUSTRALIA, 2014-last update, Energy Efficiency Opportunities (Repeal) Bill 2014 Explanatory Memorandum. Available: [http://www.aph.gov.au/Parliamentary\\_Business/Bills\\_Legislation/Bills\\_Search\\_Results/Result?bId=r5232](http://www.aph.gov.au/Parliamentary_Business/Bills_Legislation/Bills_Search_Results/Result?bId=r5232) [3/10/2015, 2015].

THUMANN, A. and MEHTA, D.P., 2008. *Handbook of energy engineering*. 6th edn. Lilburn, GA: Fairmont Press ;Boca Raton, FL.

TITTMAN, D.W., 1977. ENERGY CONSERVATION AT ERIE MINING CO. *Mining Congress Journal*, **63**(12), pp. 37-41.

TOLLINSKY, N., 2011-last update, Idling alternative cuts diesel consumption [Homepage of Sudbury Mining Solutions Journal, December Issue], [Online]. Available: <http://www.sudburyminingsolutions.com/idling-alternative-cuts-diesel-consumption.html> [06/28/2012].

TORAÑO ÁLVAREZ, J., RODRÍGUEZ DÍEZ, R., CUESTA GUTIÉRREZ, A. and DIEGO ÁLVAREZ, I., 2002. A computer program for calculating ventilation in tunnelling works based on an explicit method. *Tunnelling and Underground Space Technology*, **17**(3), pp. 227-236.

TRAPANI, K. and MILLAR, D.L., 2013. Proposing offshore photovoltaic (PV) technology to the energy mix of the Maltese islands. *Energy Conversion and Management*, **67**, pp. 18-26.

TUAZON, D., CORDER, G., POWELL, M. and ZIEMSKI, M., 2012. A practical and rigorous approach for the integration of sustainability principles into the decision-making processes at minerals processing operations. *Minerals Engineering*, **29**, pp. 65-71.



U.S. DEPARTMENT OF ENERGY, 2007-last update, Mining Industry Energy Bandwidth Study. Available: [http://www1.eere.energy.gov/manufacturing/industries\\_technologies/mining/pdfs/mining\\_bandwidth.pdf](http://www1.eere.energy.gov/manufacturing/industries_technologies/mining/pdfs/mining_bandwidth.pdf) [05/28/2012].

U.S. ENERGY INFORMATION ADMINISTRATION, 2011-last update, Frequently Asked Questions - How much electricity is lost in transmission and distribution in the United States?. Available: <http://205.254.135.7/tools/faqs/faq.cfm?id=105&t=3> [07/03/2012].

U.S. GOVERNMENT PRINTING OFFICE, 2002-last update, Public Law 107 - 204 - Sarbanes-Oxley Act of 2002. Available: <http://www.gpo.gov/fdsys/pkg/PLAW-107publ204/content-detail.html> [4/16/2012].

UGURSAL, I., 2014. *Underground mining equipment*. Photograph taken during site visit edn. Sudbury, Canada.

UNITED NATIONS GLOBAL COMPACT, 2011-last update, UN Global Compact Brochure - Corporate Sustainability in The World Economy. Available: <http://www.unglobalcompact.org/AboutTheGC/index.html> [07/3/2012].

UNITED NATIONS GLOBAL COMPACT, 2010-last update, GRI and UN Global Compact Forge New Alliance. Available: <http://www.unglobalcompact.org/news/50-06-24-2010> [11/31/2012].

UNITED STATES BUREAU OF MINES and CAMM, T.W., 1991. *Simplified cost models for prefeasibility mineral evaluations*. Washington, DC: U.S. Dept. of the Interior, Bureau of Mines.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2015-last update, Use Portfolio Manager. Available: <http://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager> [2/12/2015, 2015].

UNIVERSITY OF TORONTO, ONTARIO, LAURENTIAN UNIVERSITY and CANADIAN COMMITTEE ON ELECTROTECHNOLOGIES, 1989. *Energy efficient technologies in the mining and metals industry*. Toronto, Ont.: Ministry of Energy.

US ENVIRONMENTAL PROTECTION AGENCY, n.d.-last update, ENERGY STAR Energy Performance Indicators for plants. Available: <http://www.energystar.gov/buildings/facility-owners-and-managers/industrial-plants/measure-track-and-benchmark/energy-star-energy?s=mega> [3/10/2015, 2015].

VALE, ca. 2010-last update, 2010 Sustainability Report. Available: <http://nickel.vale.com/sustainability/reports/default.aspx> [04/12/2012].

VENTILATION ENGINEER, 2015. *k Factor Comparison Generic*. email edn.

VETTERLING, W.T., TEUKOLSKY, S.A. and PRESS, W.H., 1992. *Numerical recipes in C*. Second Edition edn. Cambridge: Press Syndicate of the University of Cambridge.

VOGT, Y., 2003. Top-down Energy Modeling. *Strategic Planning for Energy and the Environment*, **22**(4), pp. 64-79.

VUTUKURI, V., 1984. Design of auxiliary ventilation systems for long drivages, *Fifth Australian Tunneling Conference*, 22-24 October 1984, Institution of Engineers, Australia, pp. 73.

VUTUKURI, V., 1983. Air leakage in ventilation ducting and the design of auxiliary ventilation systems. *Mining Engineer*, **143**, pp. 37-43.

VUTUKURI, V.S., 1993. Appraisal of accuracy of various formulas for the design of a simple auxiliary ventilation system, *Proceedings of the 6th US Mine Ventilation Symposium, June 21, 1993 - June 23, 1993*, Publ by SME, pp. 145-150.

WALKER, J. and HOWARD, S., 2002. *Finding the way forward*. Nottingham, UK: Russell Press Ltd.

WALKER, S.C., 1988. Mine winding and transport. *Advances in Mining Science and Technology*. Amsterdam: Elsevier Pub. Co, pp.307.

WANG, H.Q., CHEN, S.Q. and CHEN, T., 2010. Study of energy saving of long distance tunnelling fan with frequency control in coal mines. *Transactions of the Institutions of Mining and Metallurgy, Section A: Mining Technology*, **119**(1), pp. 42-45.

WANG, S., YAN, C. and XIAO, F., 2012. Quantitative energy performance assessment methods for existing buildings. *Energy and Buildings*, **55**(0), pp. 873-888.

WENZL, K.H.B., 1978. Inco metals company, Ontario division, energy management program. *Canadian Mining Journal*, **99**(3), pp.11.

WESTERN MINE, 2006. *Mining Cost Service*. Vol. 1 edn. Washington, USA: Schumacher, Otto.

WIDMANN, A., SCHROGER, E. and MAESS, B., 2014. Digital filter design for electrophysiological data - a practical approach. *Journal of neuroscience methods*, (In Press),.

WILLS, B.A., NAPIER-MUNN, T., WILLS, B.A. and JULIUS KRUTTSCHNITT MINERAL RESEARCH CENTRE, 2006. *Wills' mineral processing technology :an introduction to the practical aspects of ore treatment and mineral recovery*. 7th edn. Amsterdam: Elsevier/Butterworth-Heinemann.

WINGENDER, J.R. and WOODROOF, E.A., 1997. When firms publicize energy management projects their stock prices go up. *Strategic Planning for Energy and the Environment*, **17**(1), pp. 38-51.

WORKPLACE SAFETY NORTH, 2011. *Auxiliary Mine Ventilation Manual*. v 1.3 edn. Ontario.

WU, H.W. and GILLIES, A.D., 2014. A comparison of predicted performance of auxiliary ventilation ducting systems, F. VON GLEHN and M. BIFFI, eds. In: *Proceedings of the tenth international mine ventilation congress*, 2-8 August 2014, The Mine Ventilation Society of South Africa, pp. 533.

XIAO, Z. and VIEN, A., 2003. Limitations of variance analysis using propagation of variance. *Minerals Engineering*, **16**(5), pp. 455-462.

XSTRATA, ca. 2007-last update, Sustainability Report 2007. Available: [http://www.xstrata.com/content/assets/pdf/x\\_sustainability\\_2007.pdf](http://www.xstrata.com/content/assets/pdf/x_sustainability_2007.pdf) [03/26/2012].

XSTRATA NICKEL, ca. 2010-last update, Xstrata Nickel Sustainability Report 2010 Sudbury Operations. Available: [http://www.xstratanickel.com/EN/Publications/Sustainable%20Development/Xstrata%20Nickel%20Sustainability%20Report%202010\\_Sudbury.pdf](http://www.xstratanickel.com/EN/Publications/Sustainable%20Development/Xstrata%20Nickel%20Sustainability%20Report%202010_Sudbury.pdf) [10/09/2012].

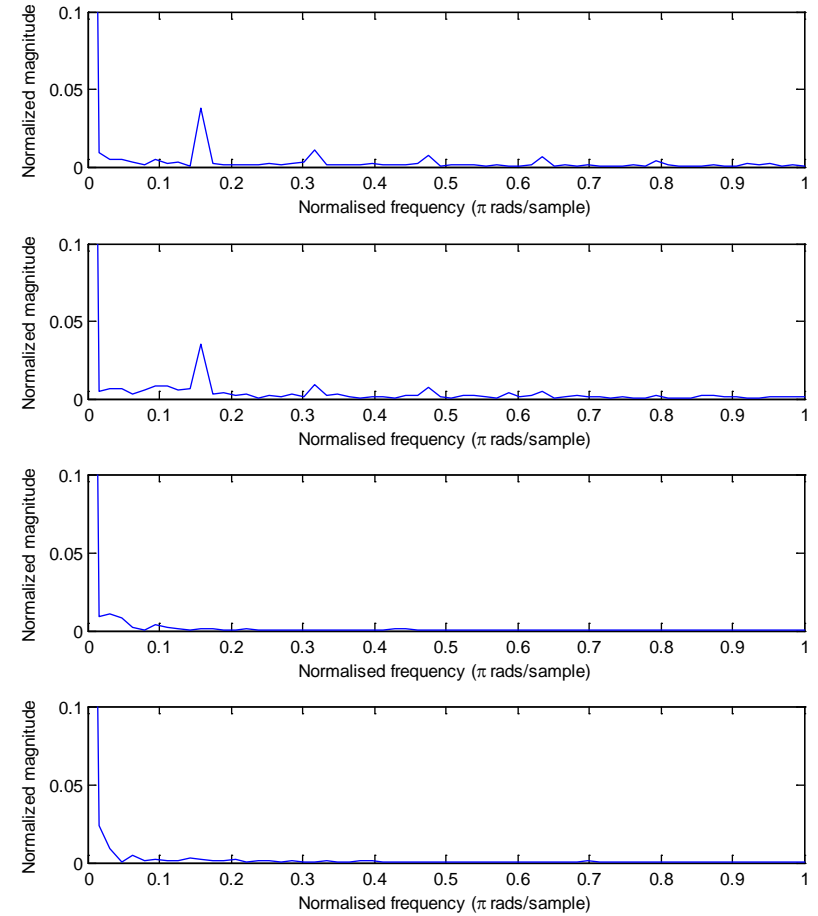
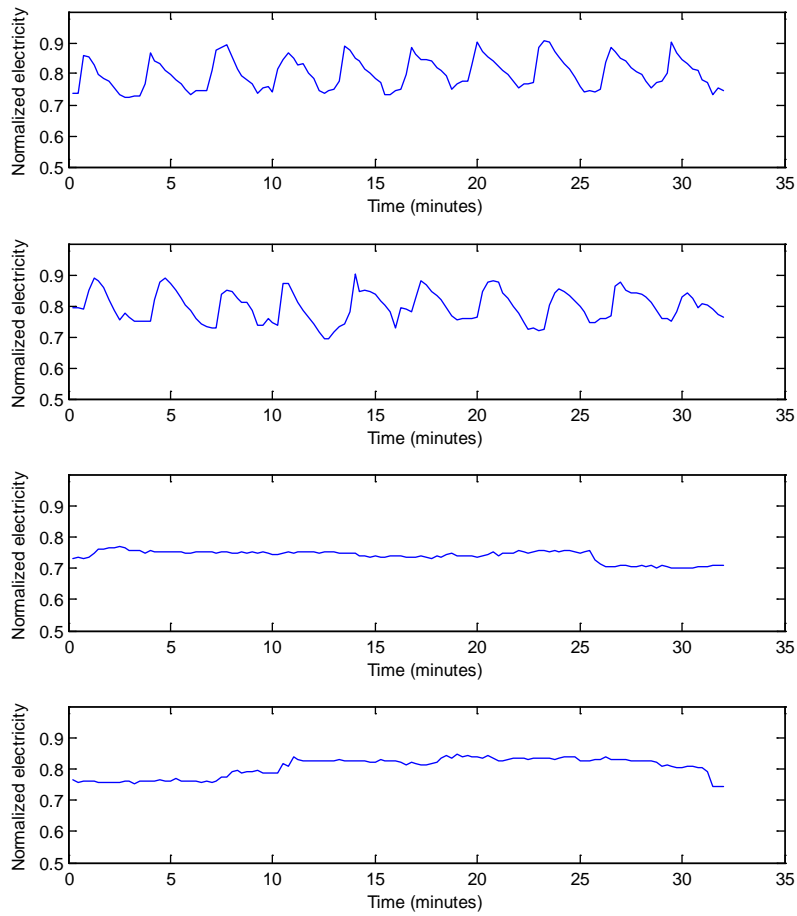
XU, M. and WILSON, S., 2000. Investigation of seasonal metallurgical shift at Inco's clarabelle mill. *Minerals Engineering*, **13**(12), pp. 1207-1218.

YAN, C., WANG, S. and XIAO, F., 2012. A simplified energy performance assessment method for existing buildings based on energy bill disaggregation. *Energy and Buildings*, **55**(0), pp. 563-574.

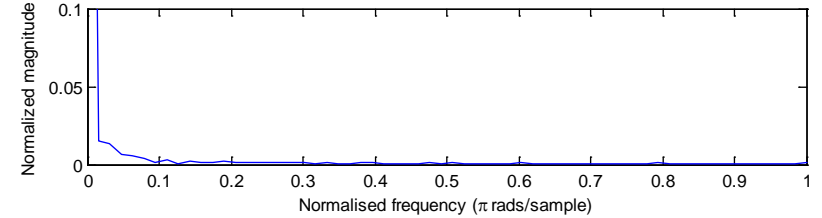
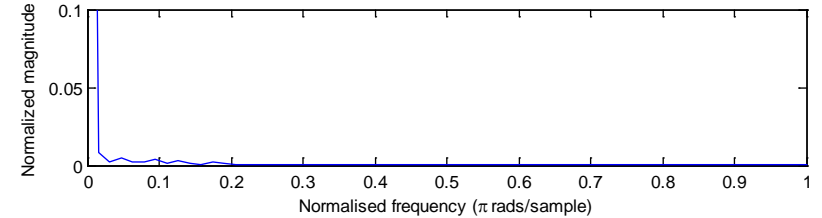
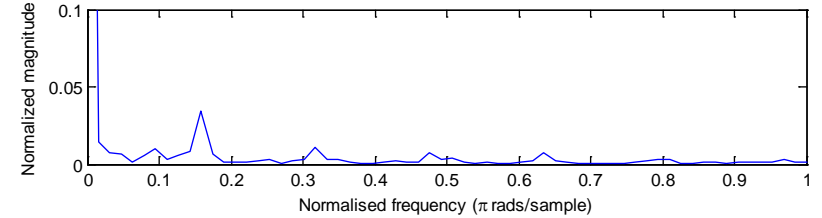
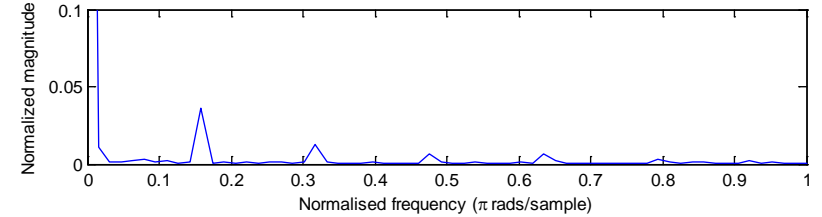
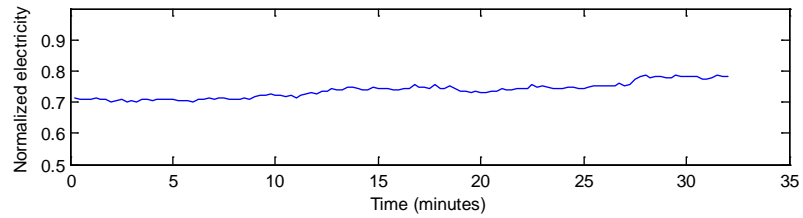
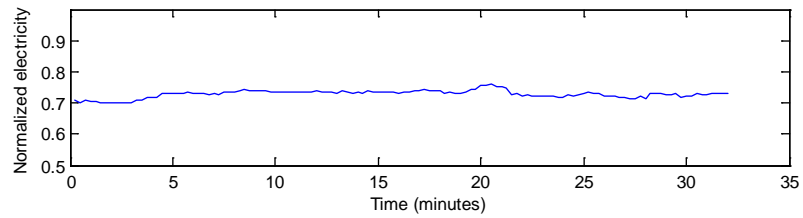
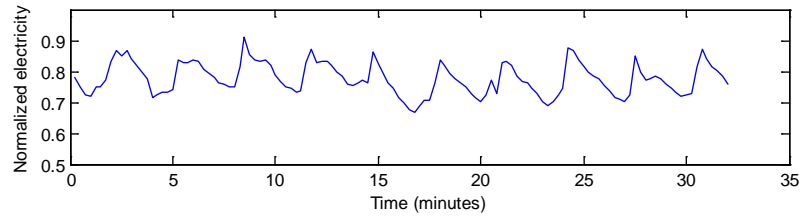
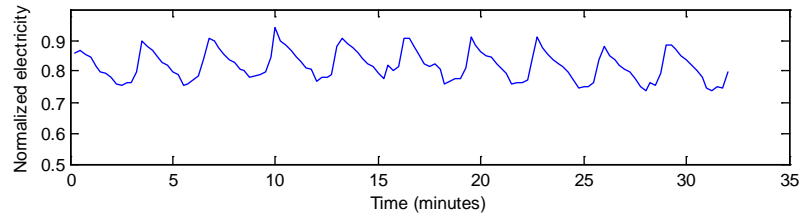
ZARNIKAU, J. and THAL, D., 2013. The response of large industrial energy consumers to four coincident peak (4CP) transmission charges in the Texas (ERCOT) market. *Utilities Policy*, **26**(0), pp. 1-6.

ZOHA, A., GLUHAK, A., IMRAN, M.A. and RAJASEGARAR, S., 2012. Non-Intrusive Load Monitoring Approaches for Disaggregated Energy Sensing: A Survey. *Sensors*, **12**(12), pp. 16838-16866.

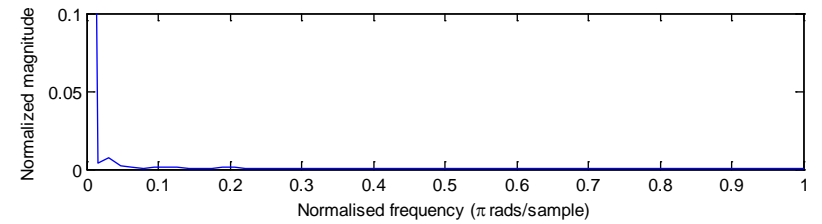
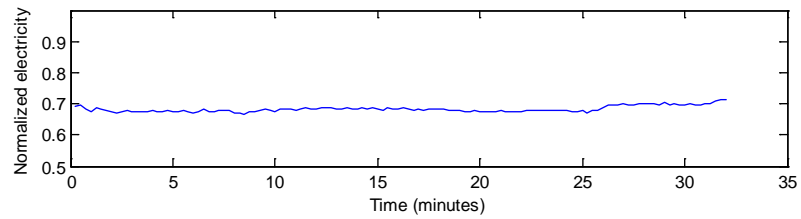
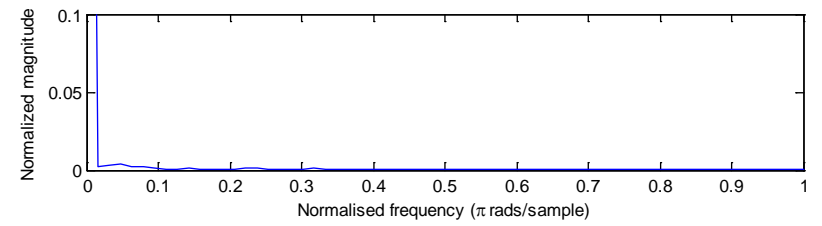
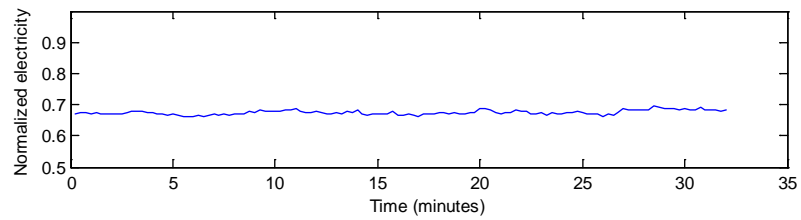
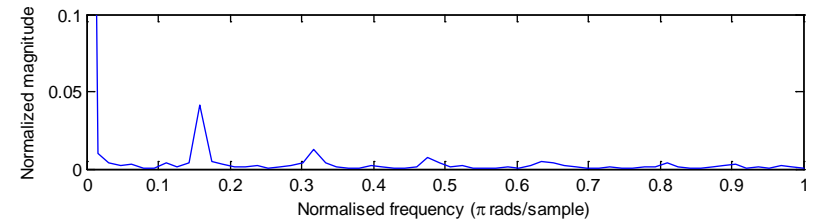
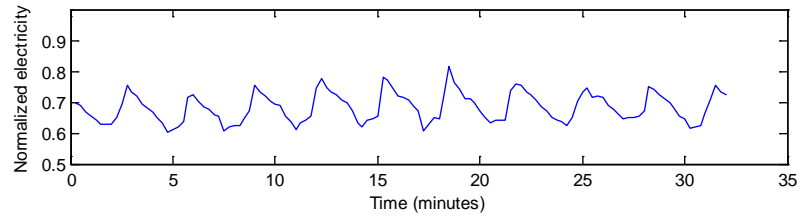
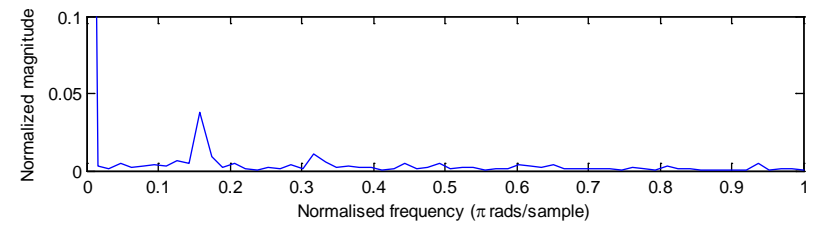
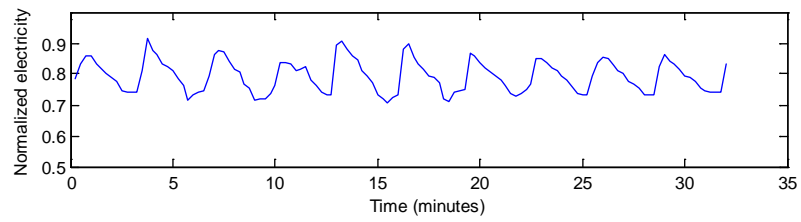
**Appendix A – Frames extracted from different months of the aggregated signal to train Neural Network for identification of hoist operating probability**



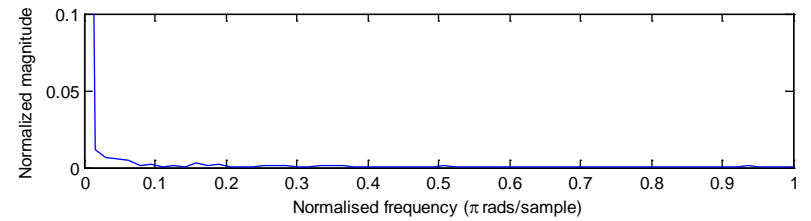
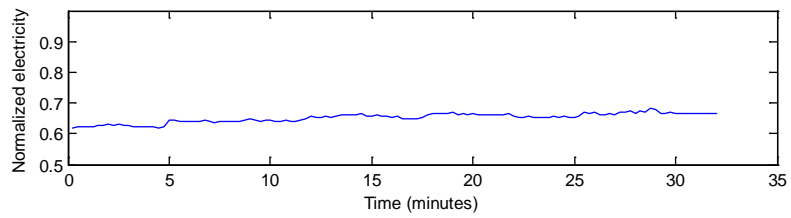
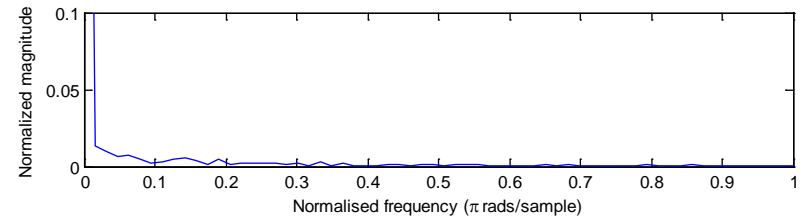
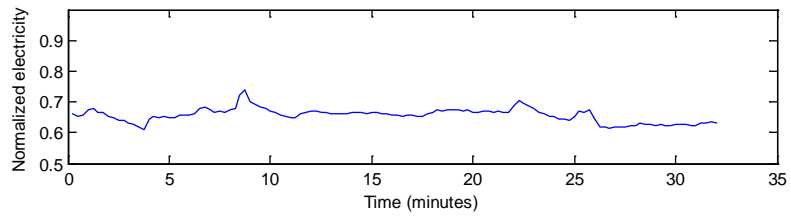
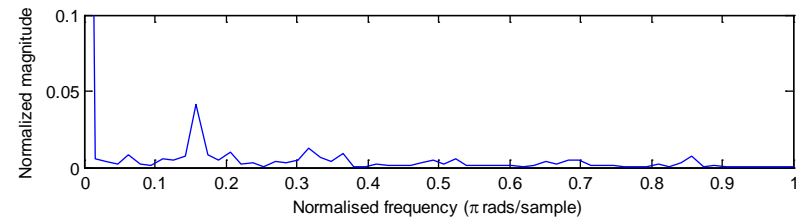
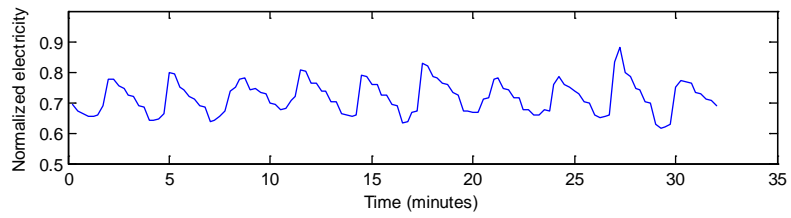
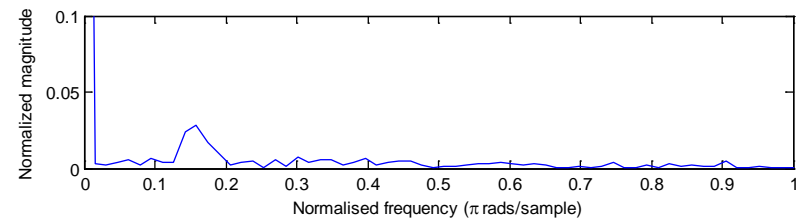
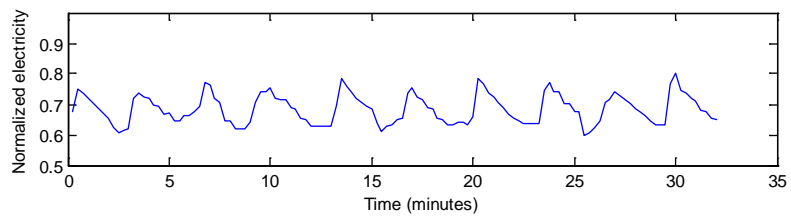
January



February

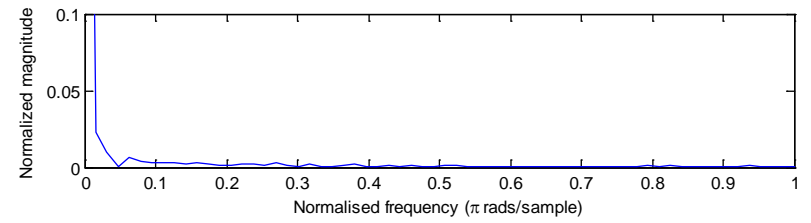
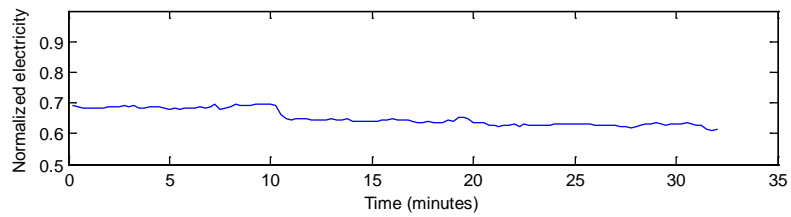
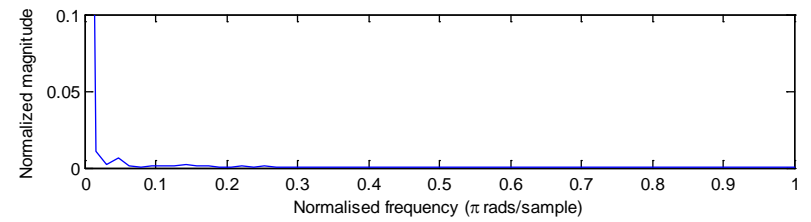
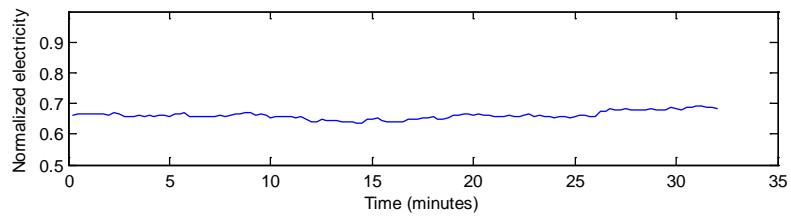
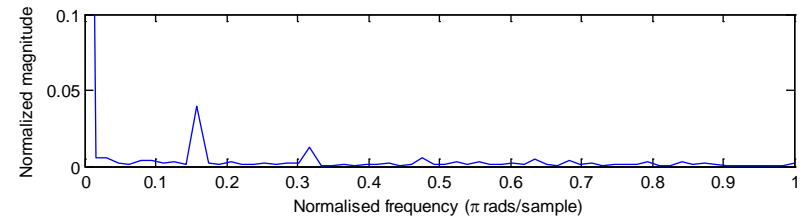
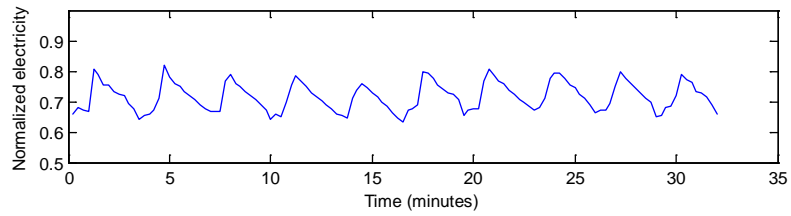
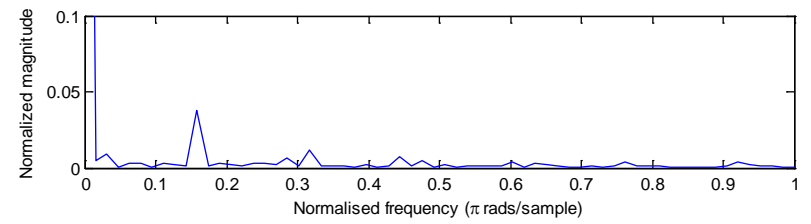
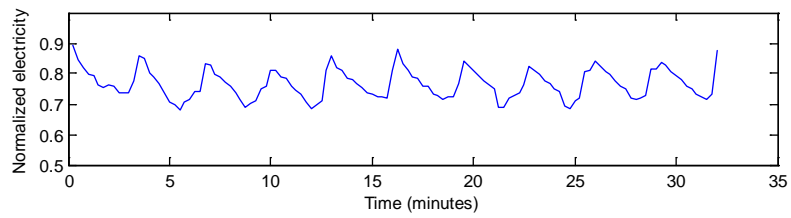


March

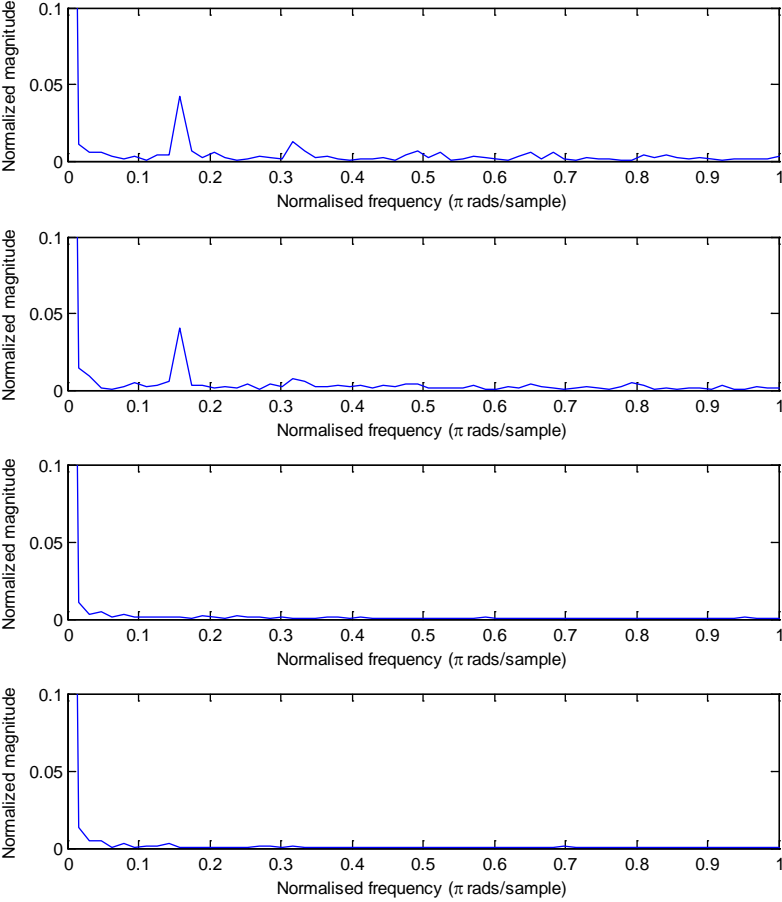
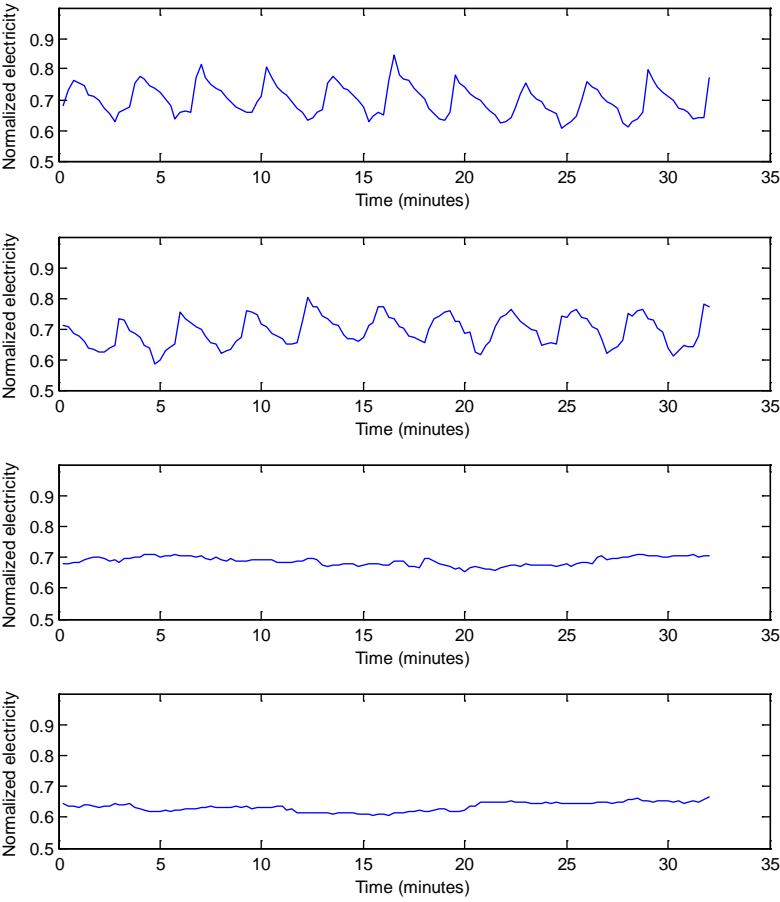


April

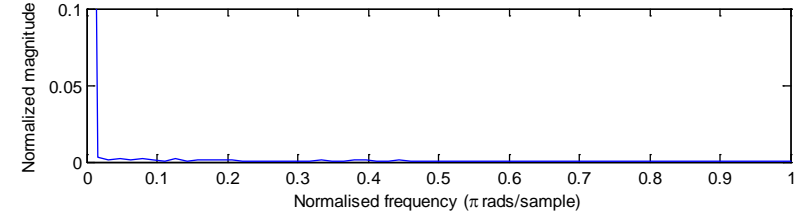
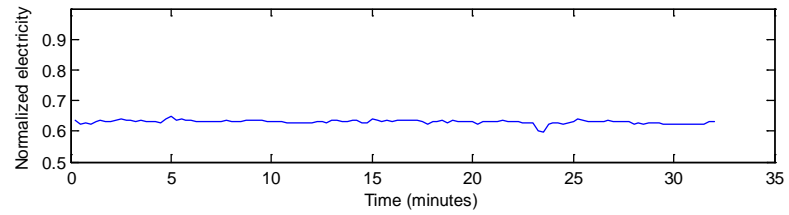
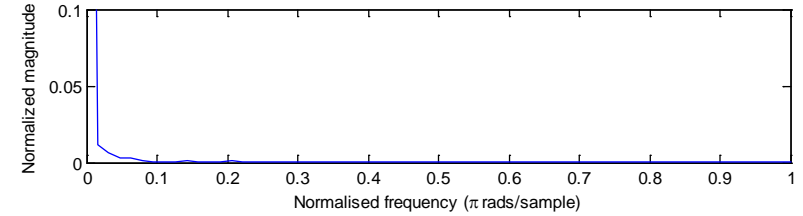
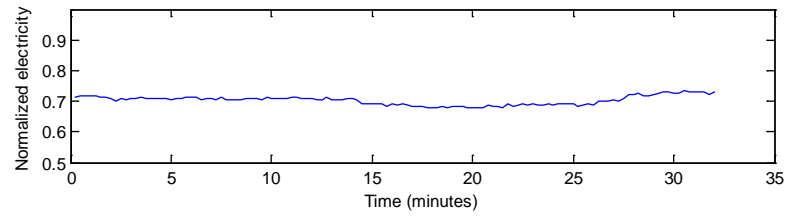
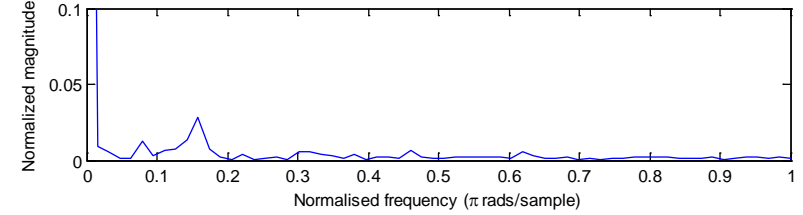
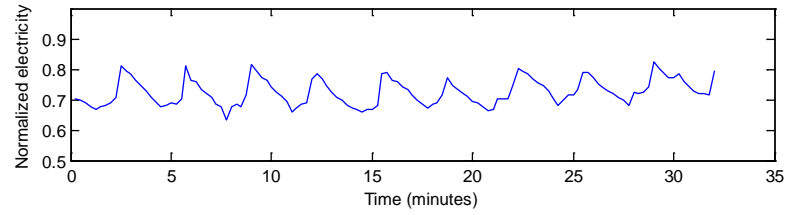
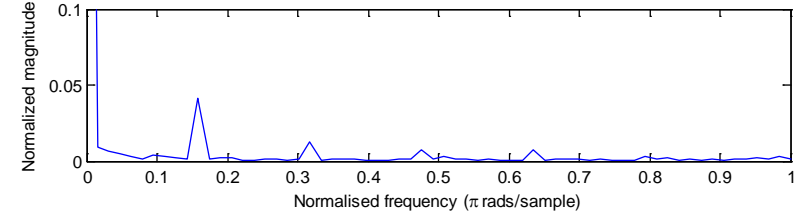
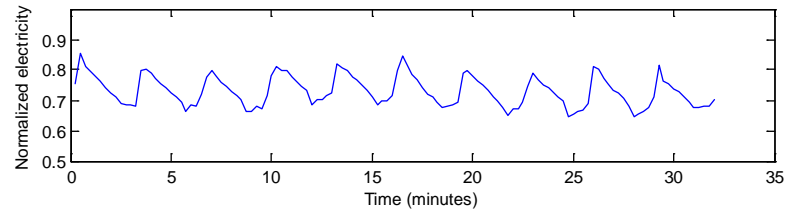




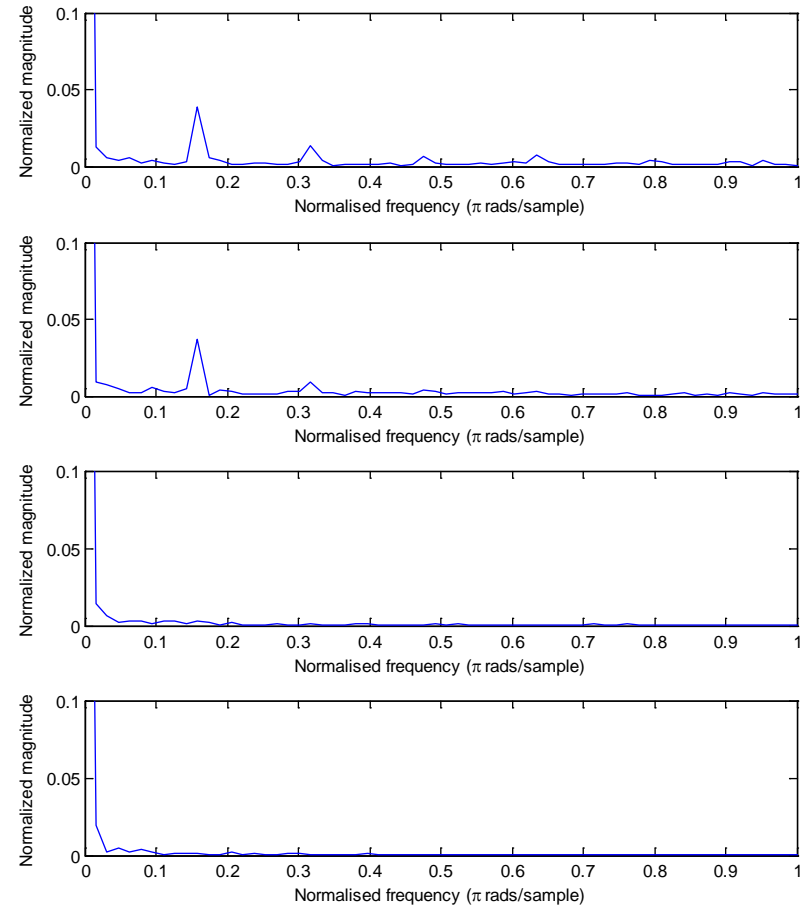
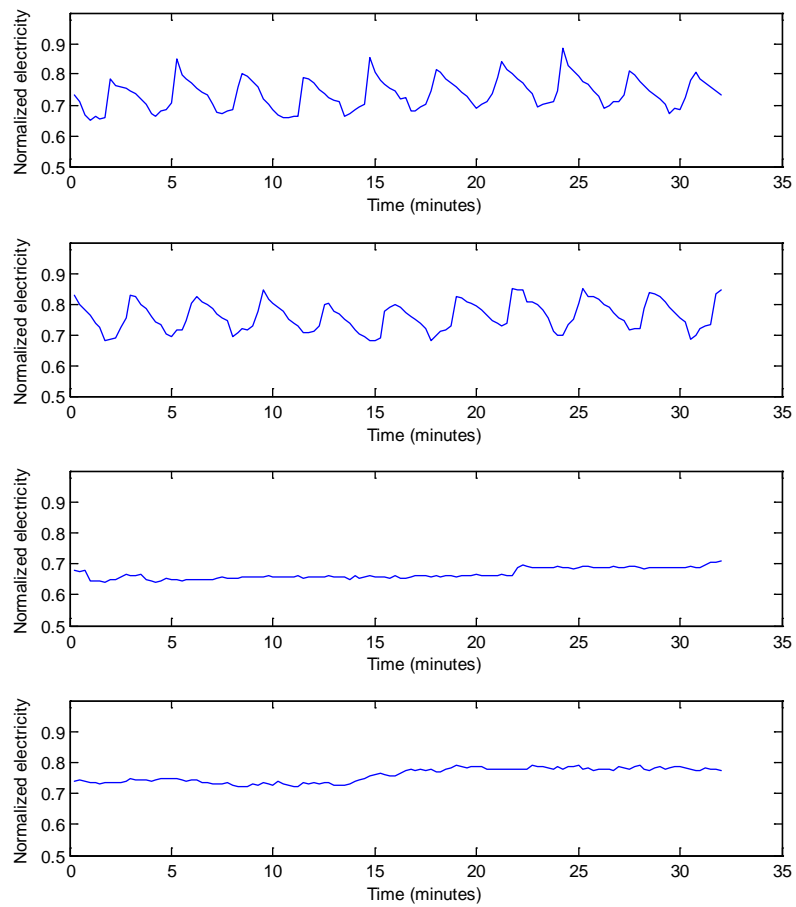
May



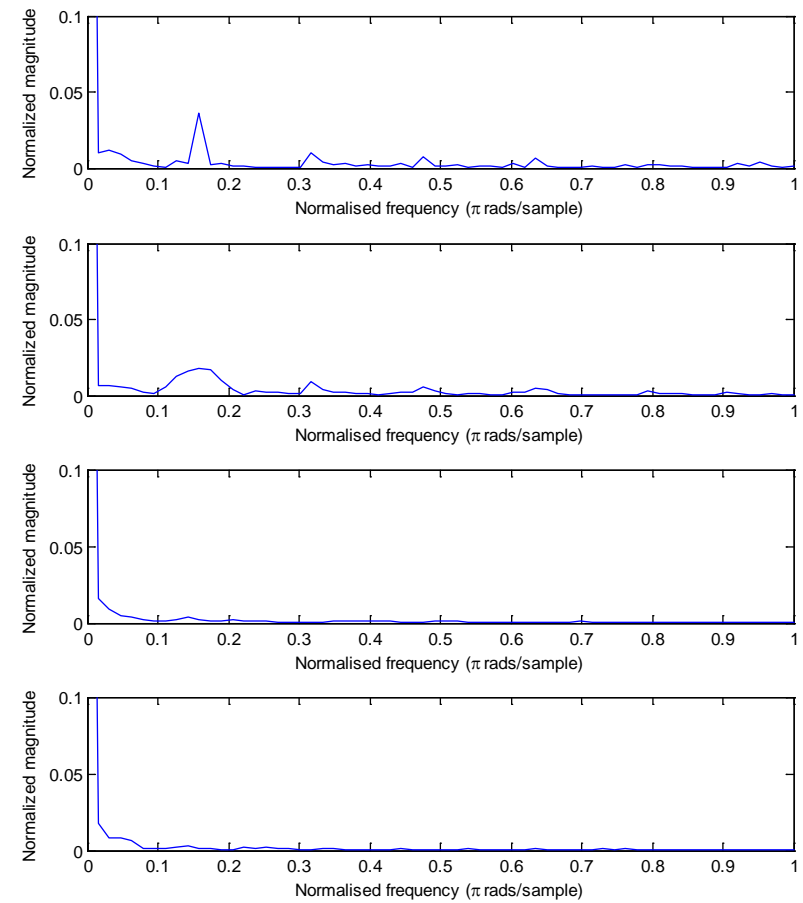
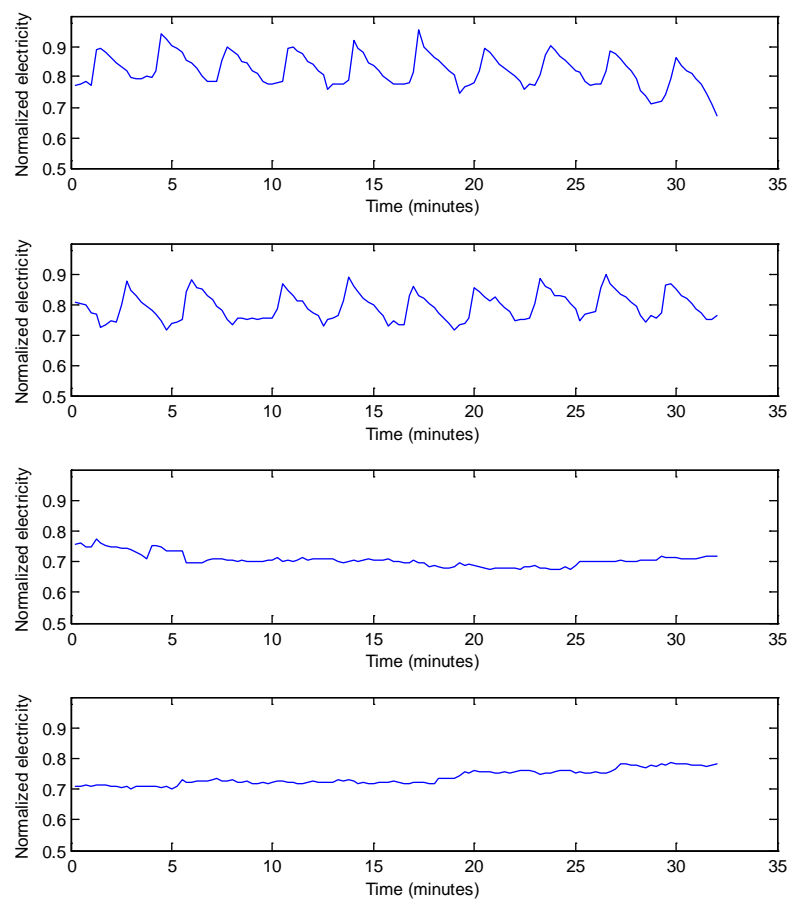
June



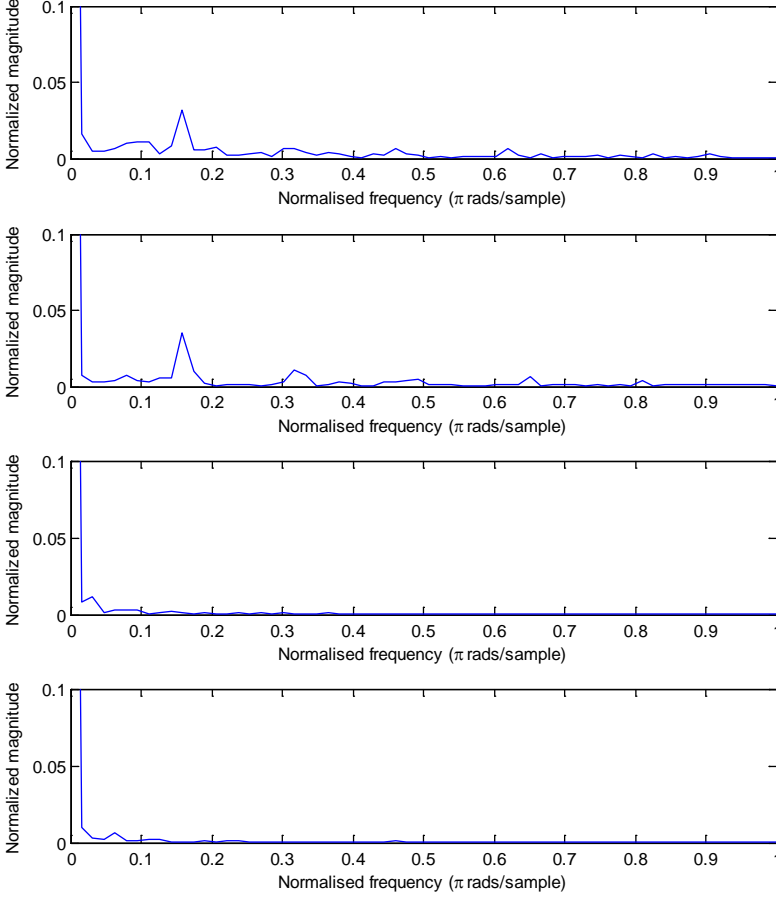
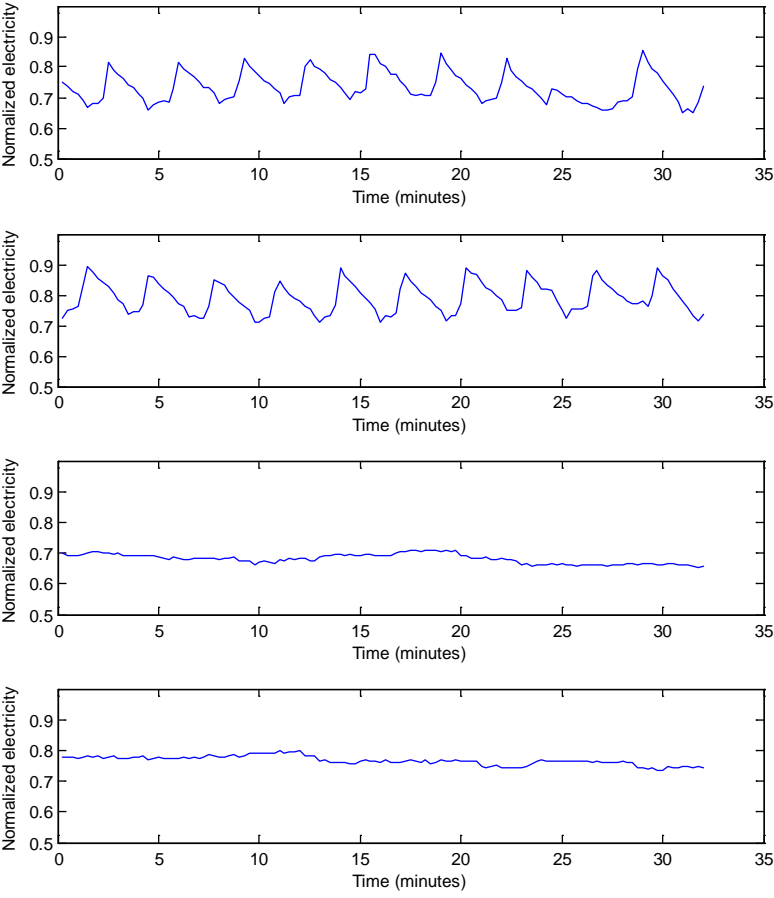
July



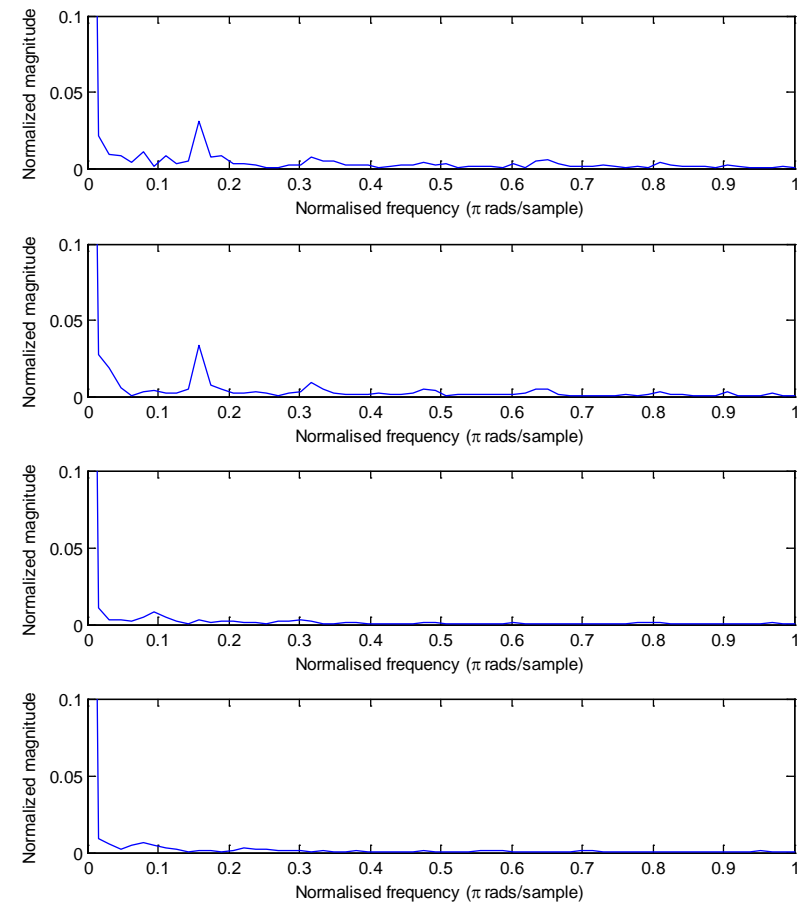
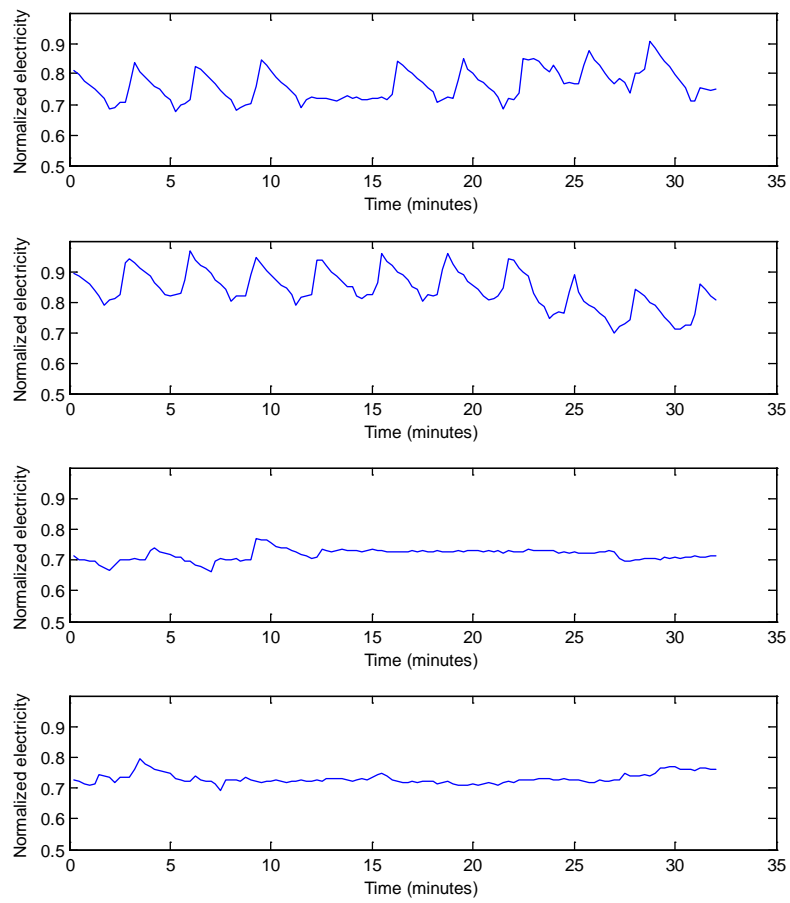
August



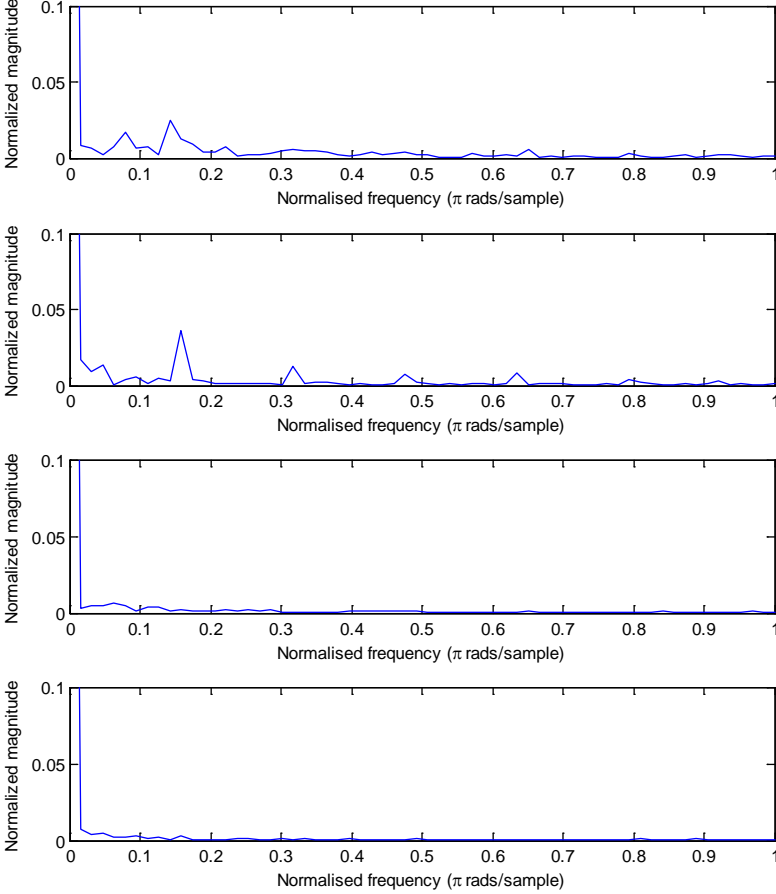
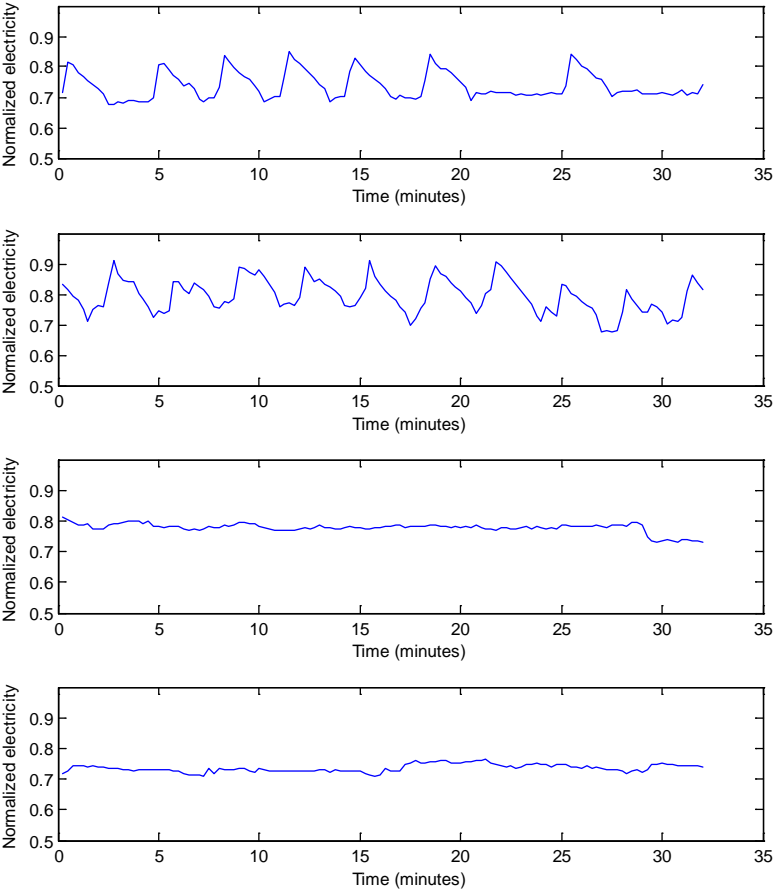
September



October



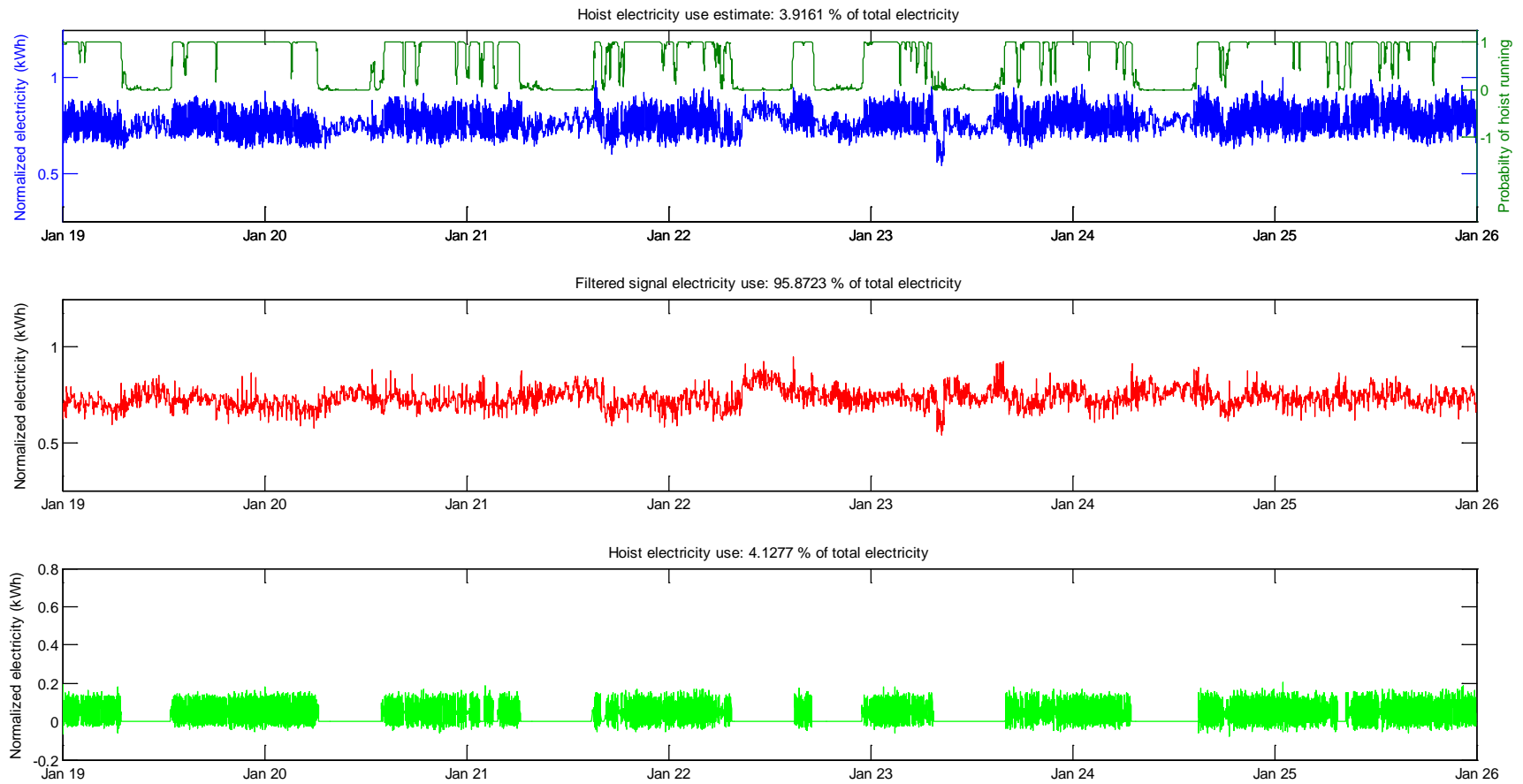
November



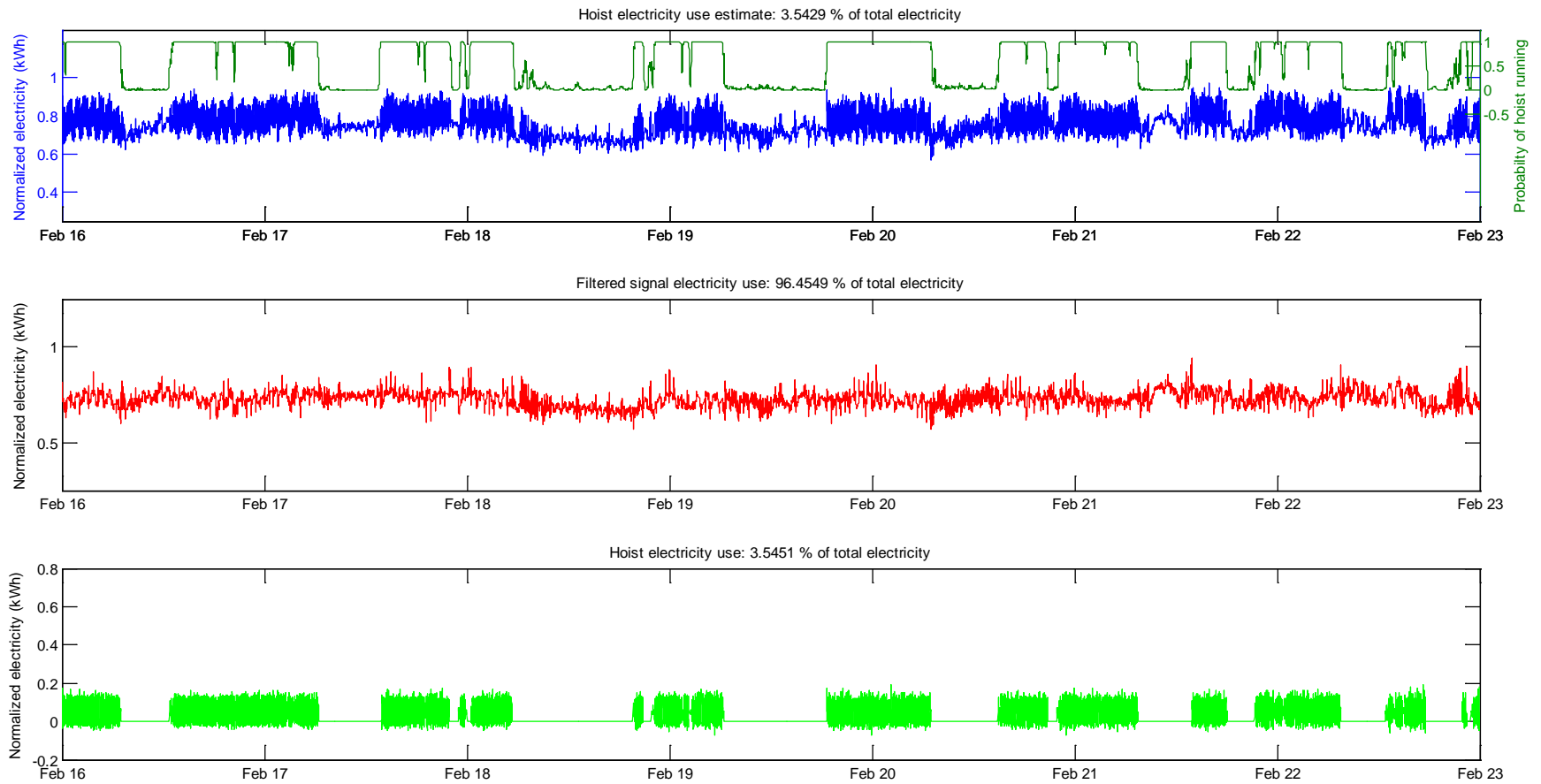
December



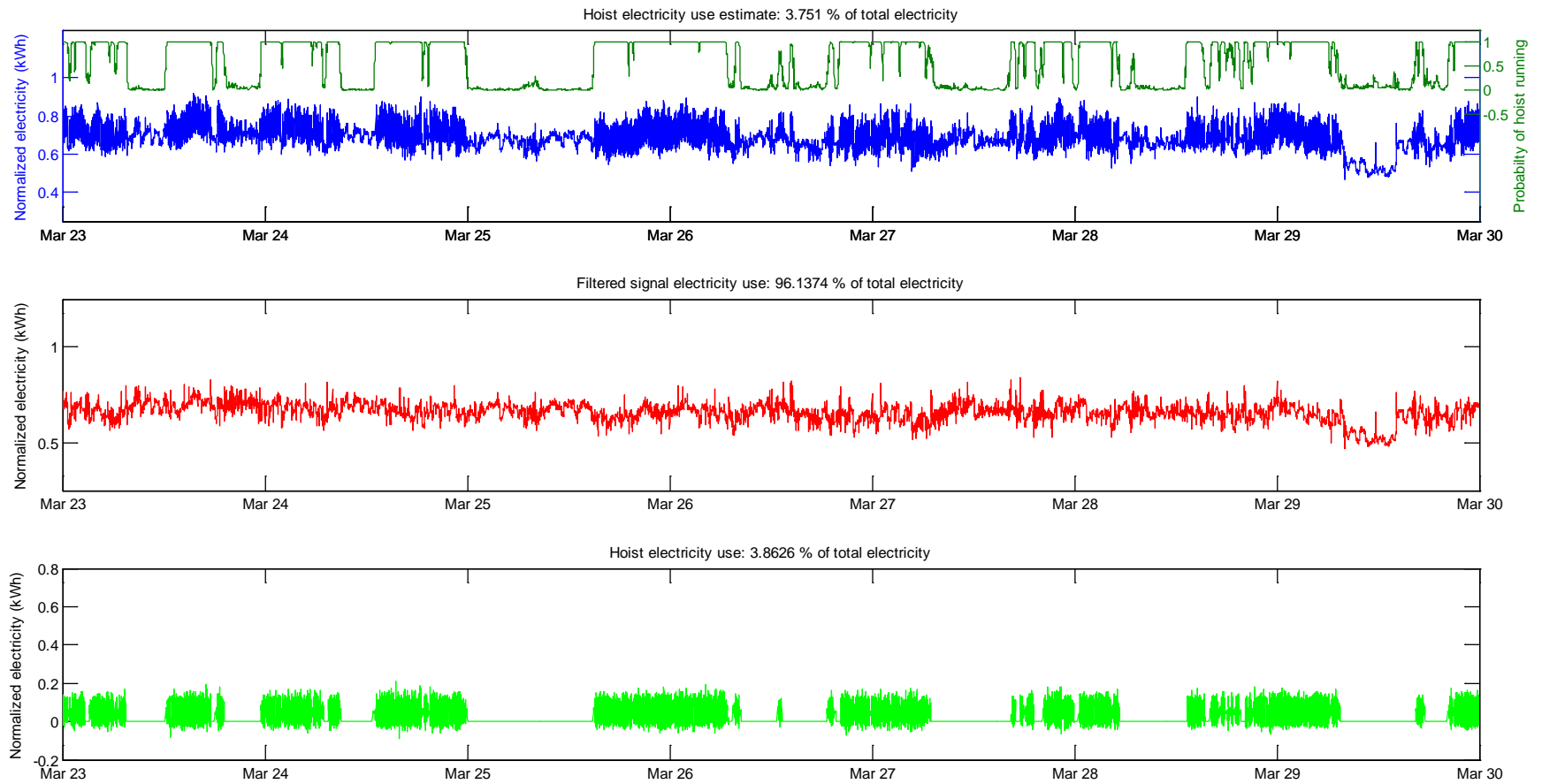
**Appendix B – Summary of results from weekly data analyzed from all months (aggregated electricity signal, probability of hoist operation, filtered signal after extracting hoist electricity use, and hoist electricity consumption)**



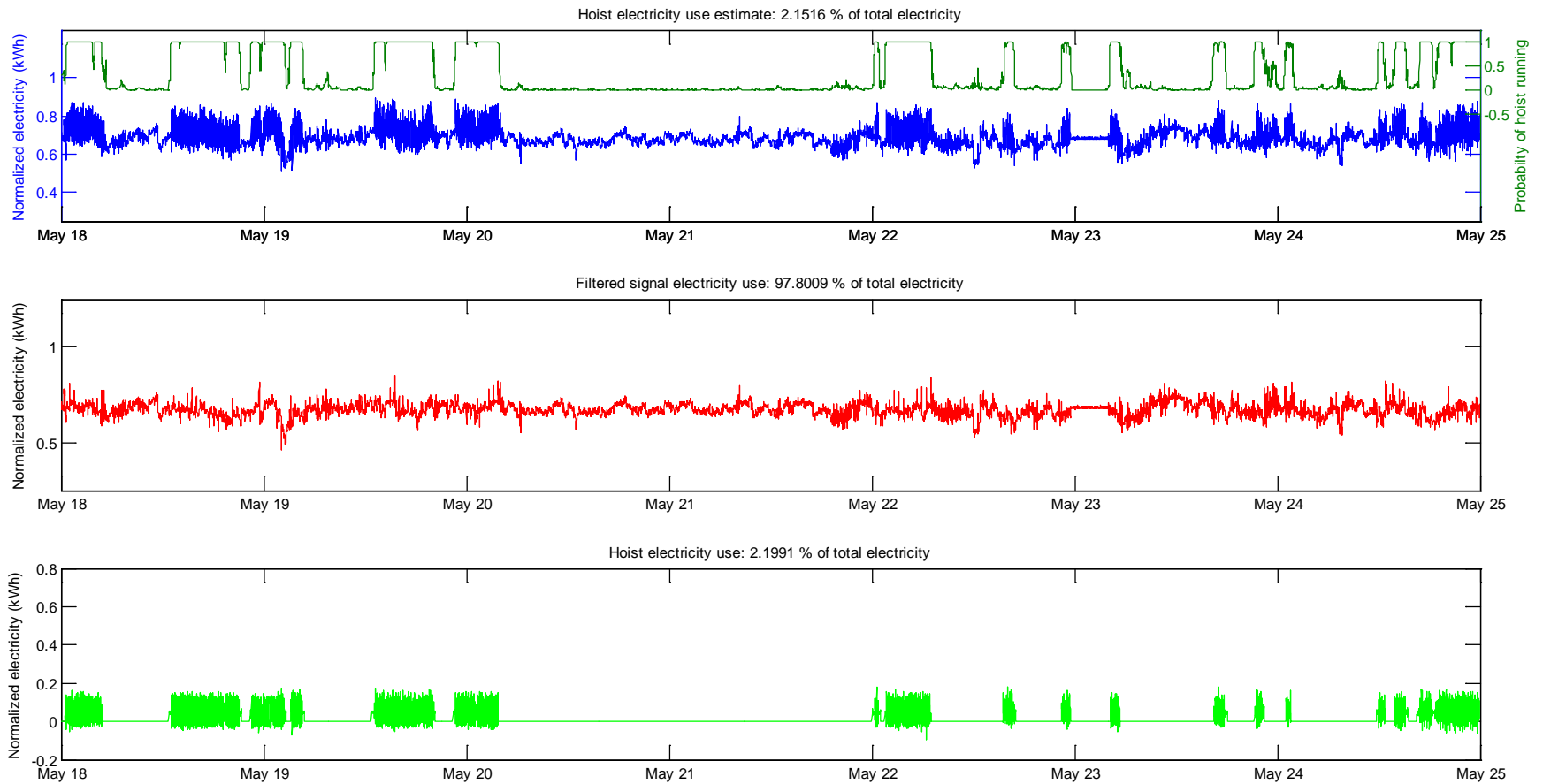
January



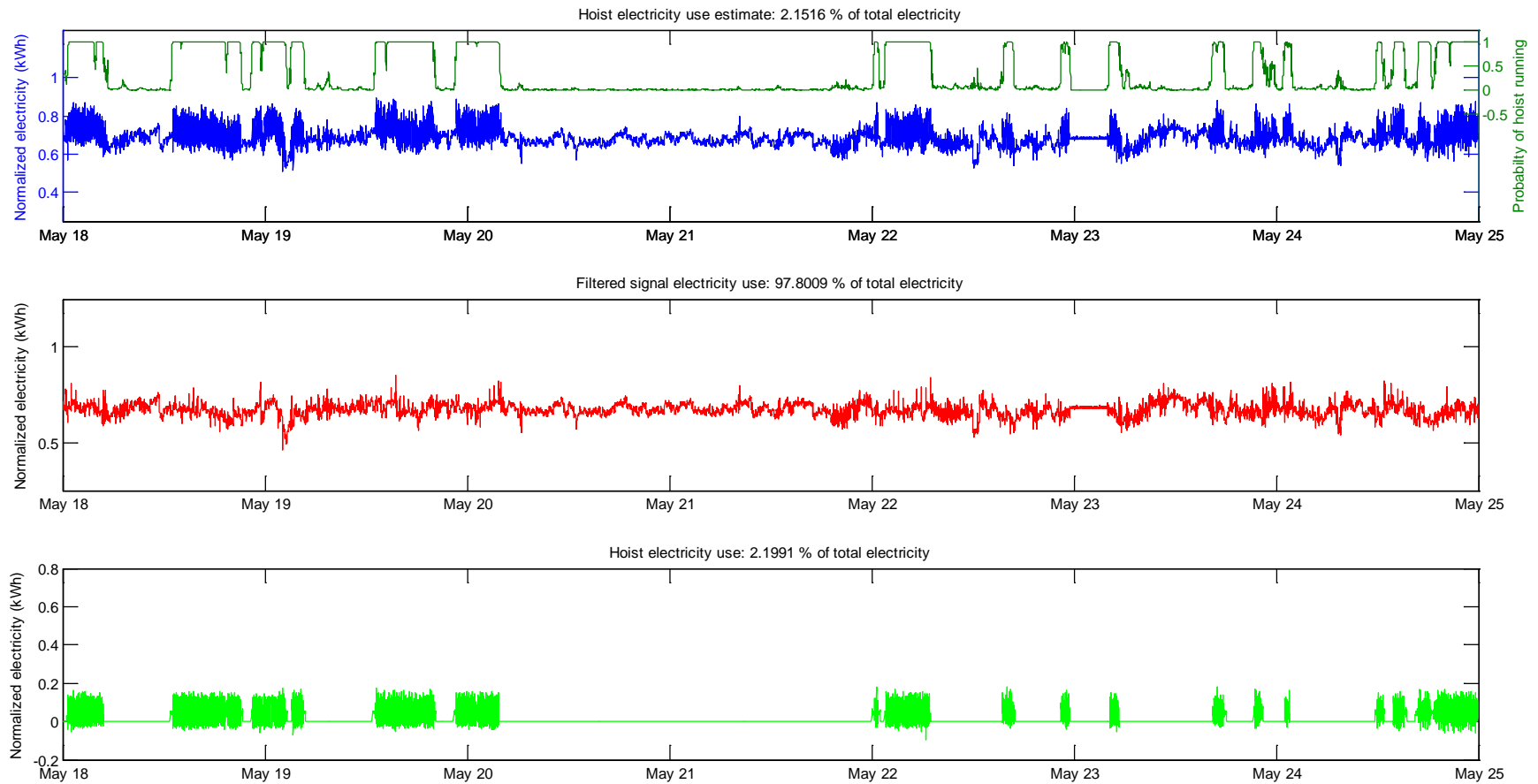
February



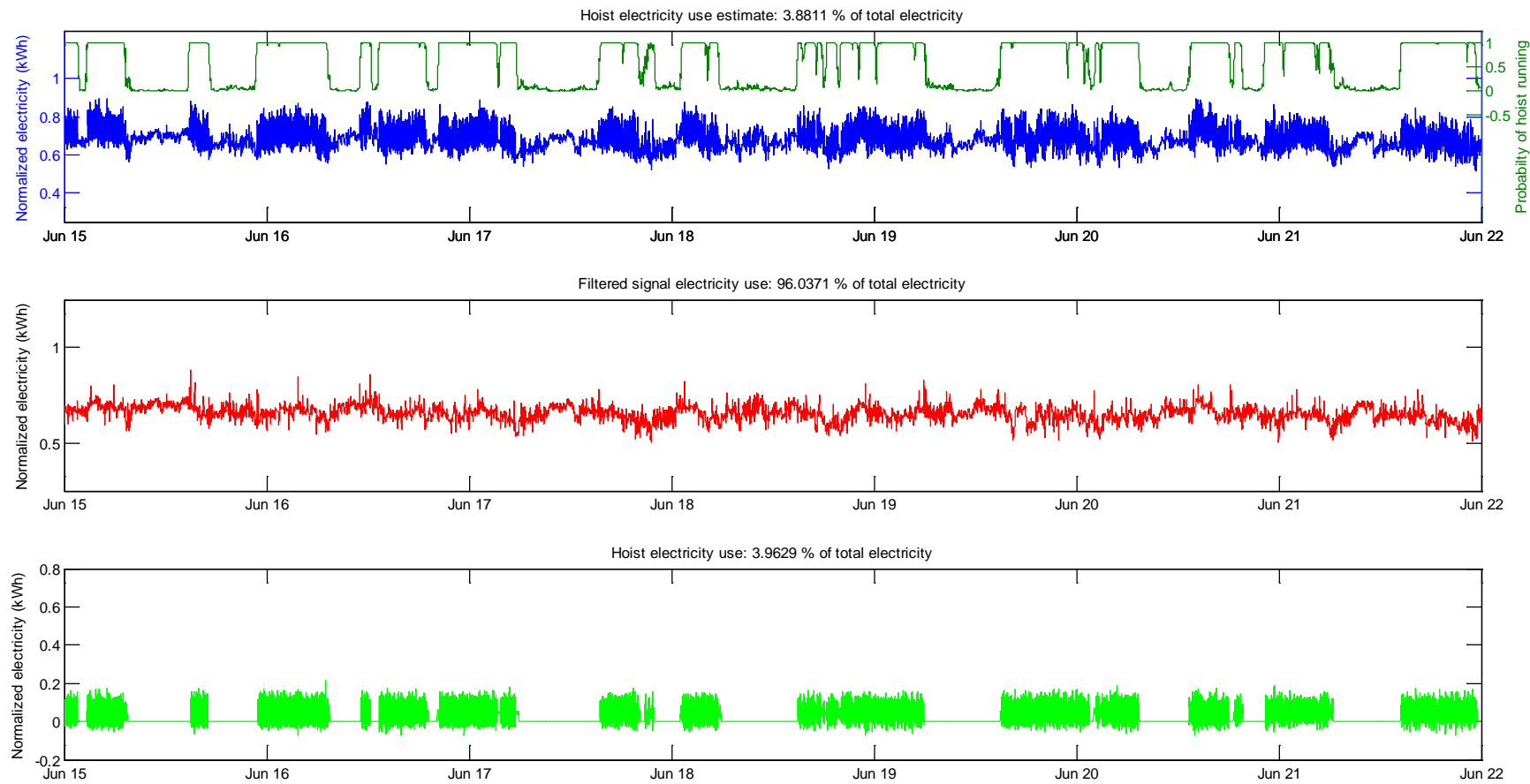
March



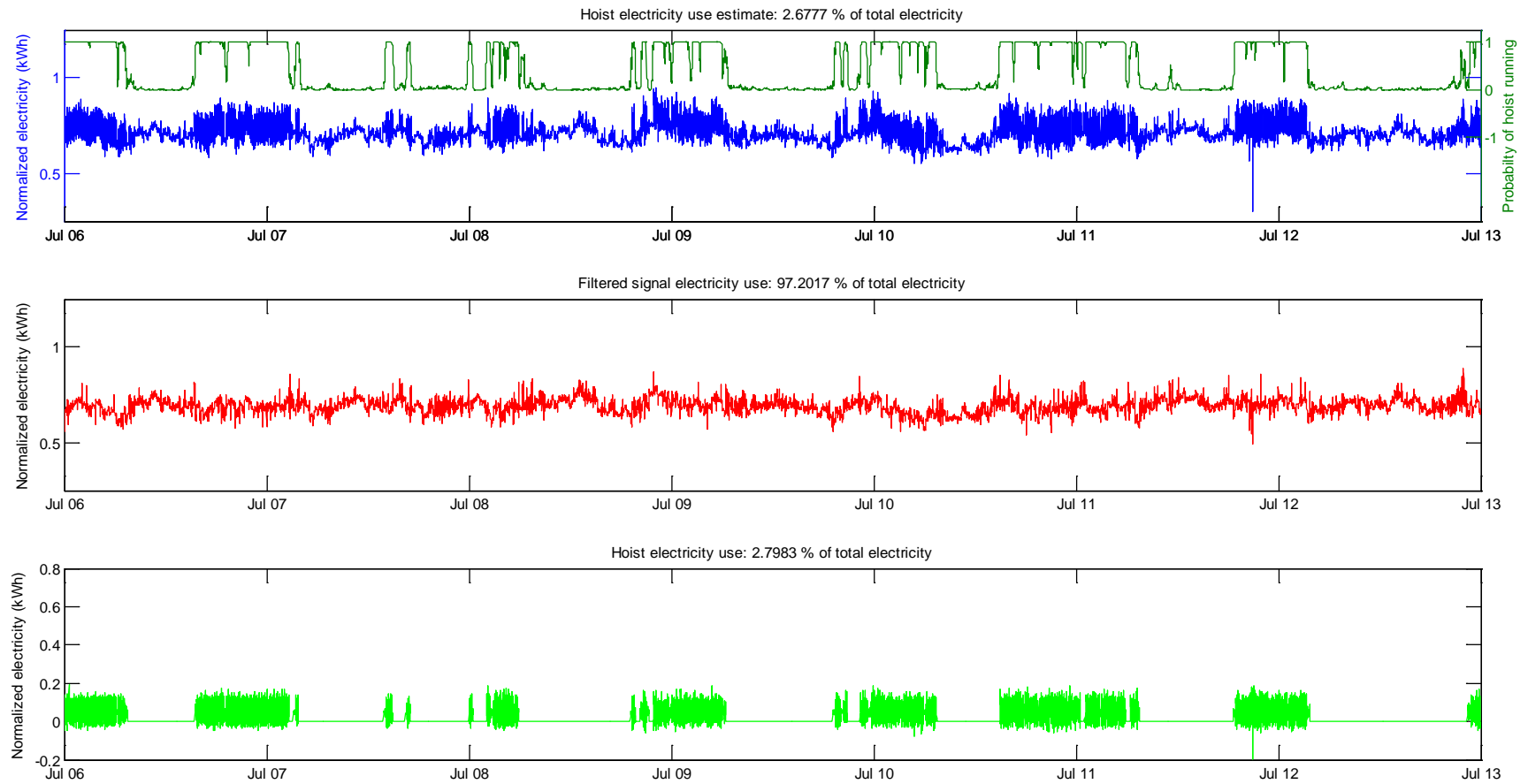
April



May

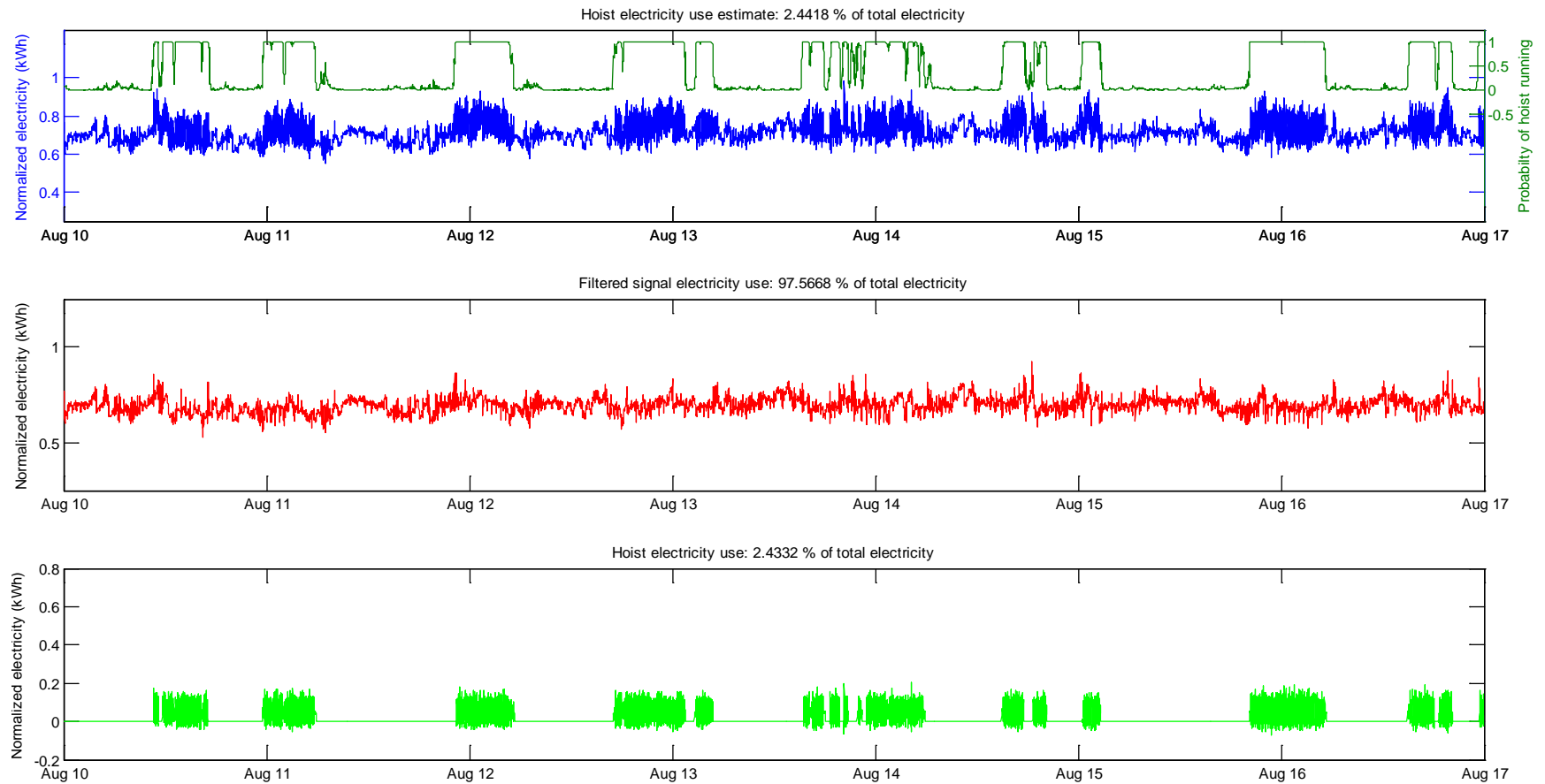


June

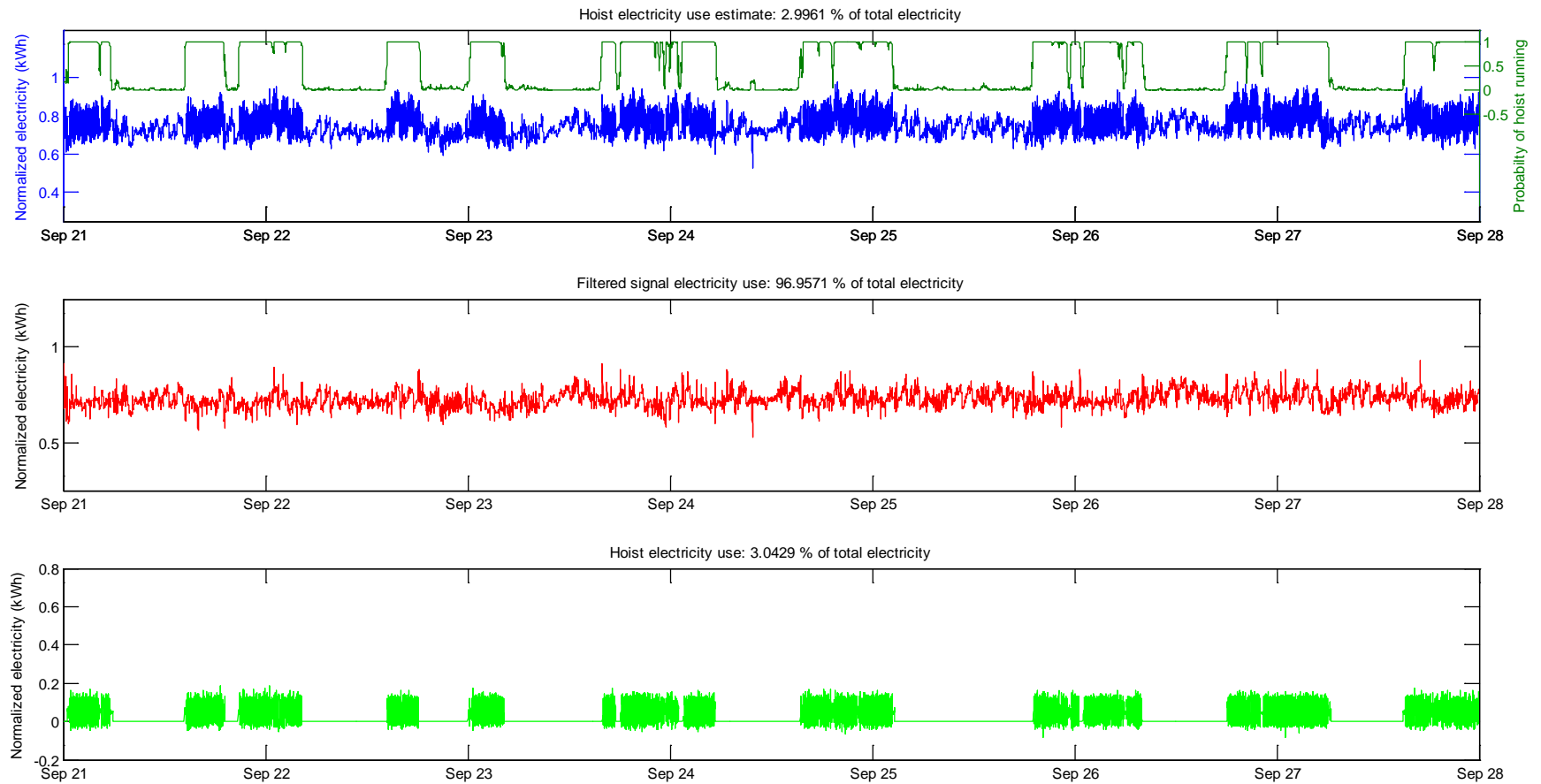


July

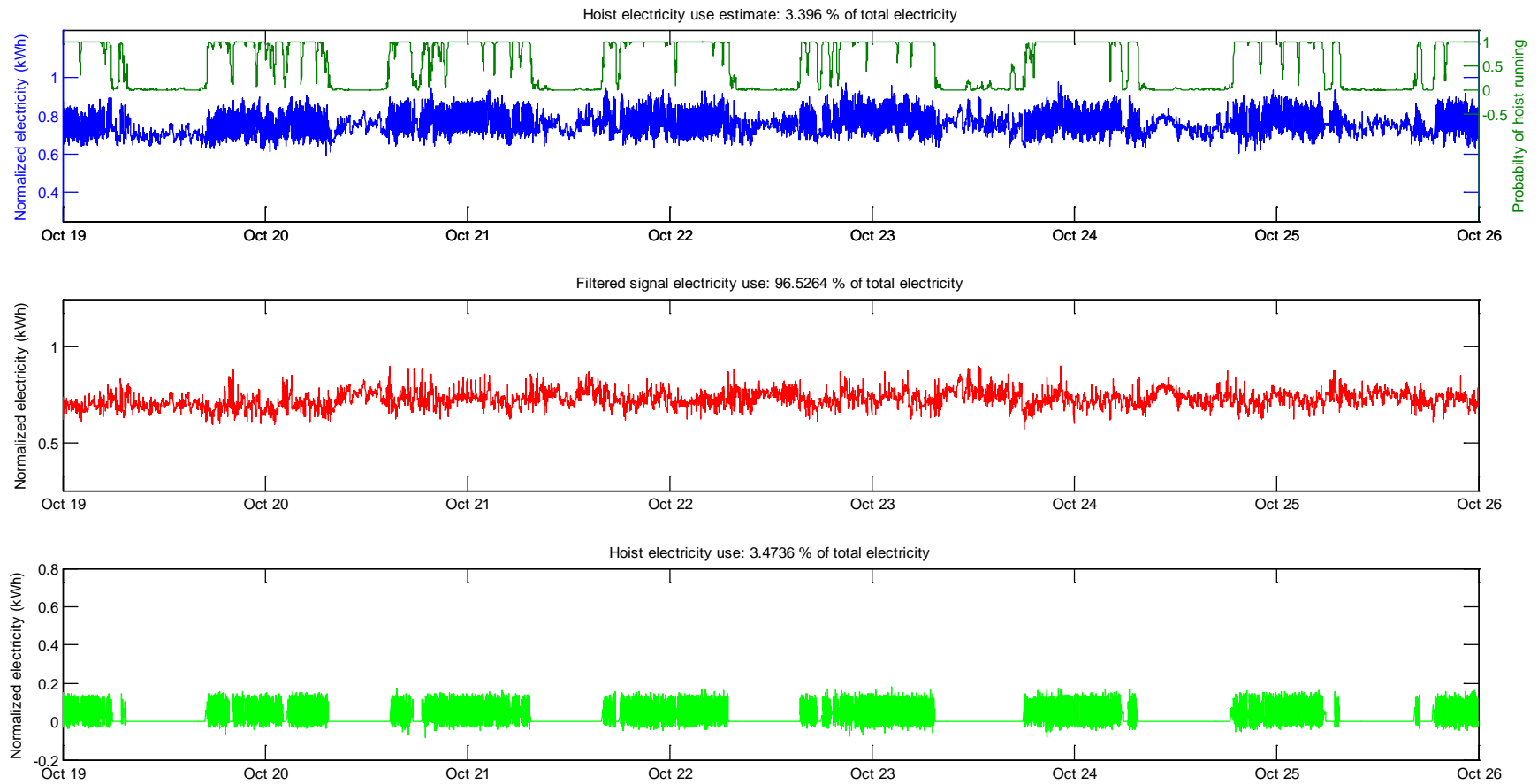




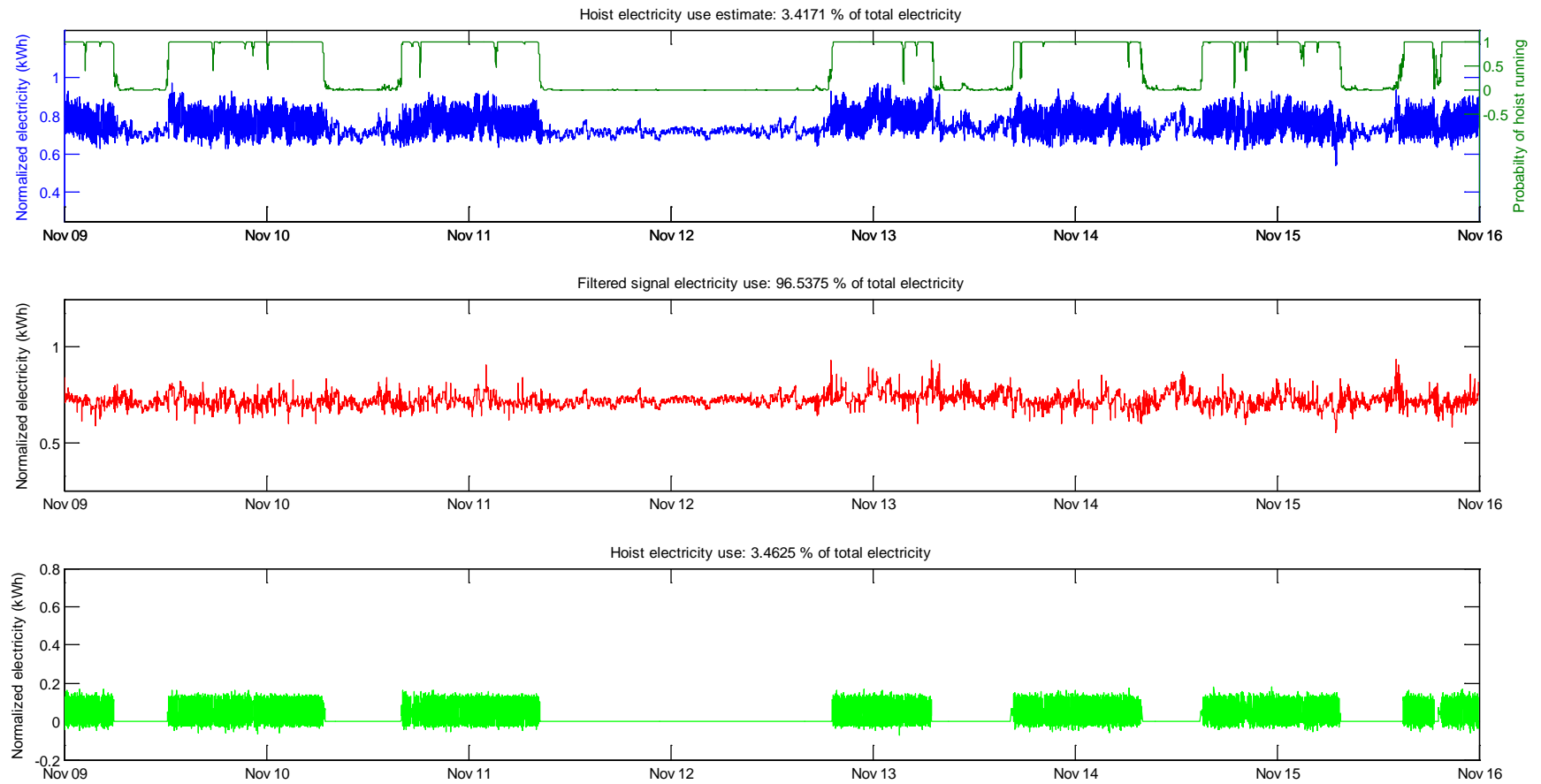
August



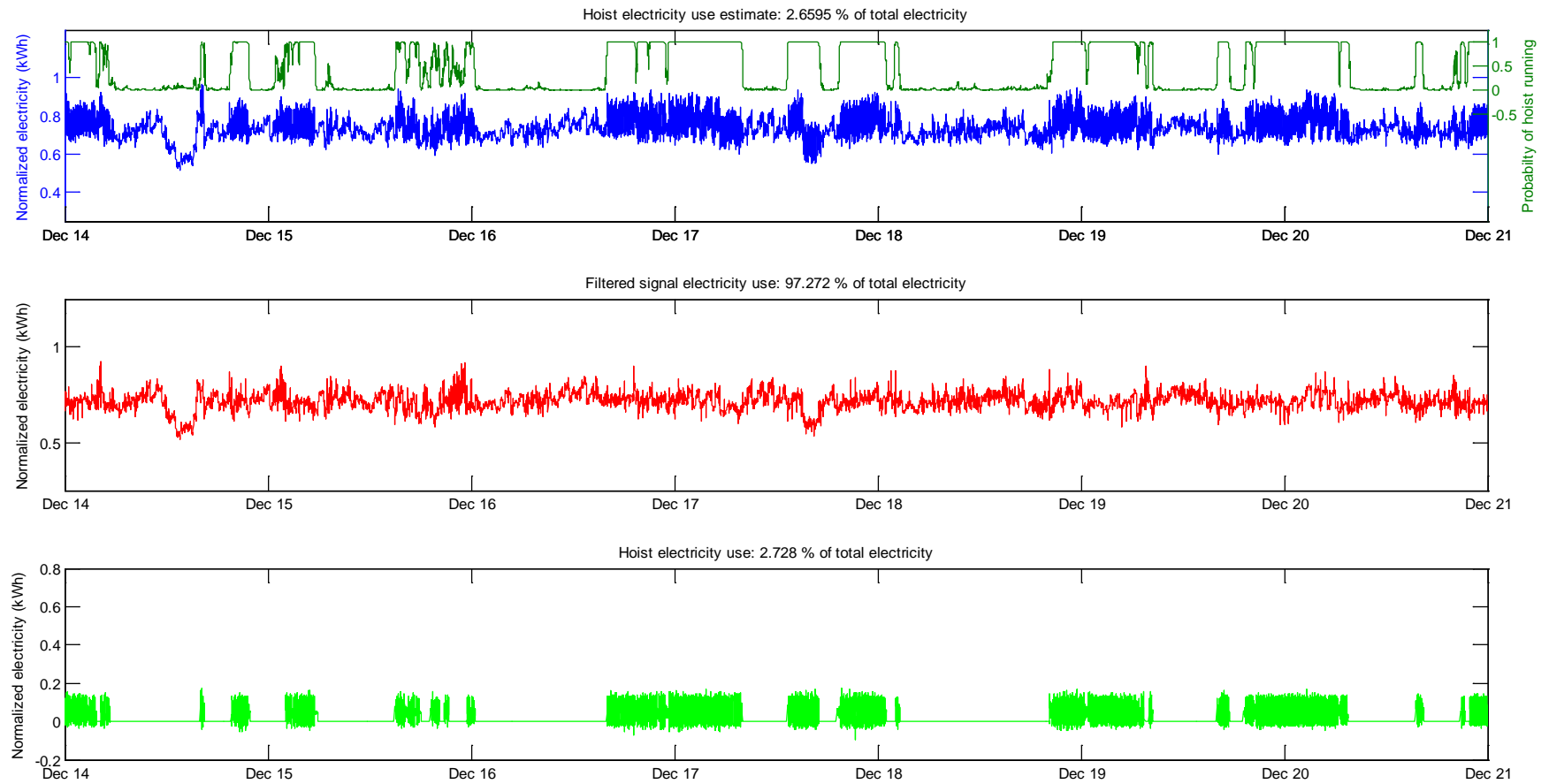
September



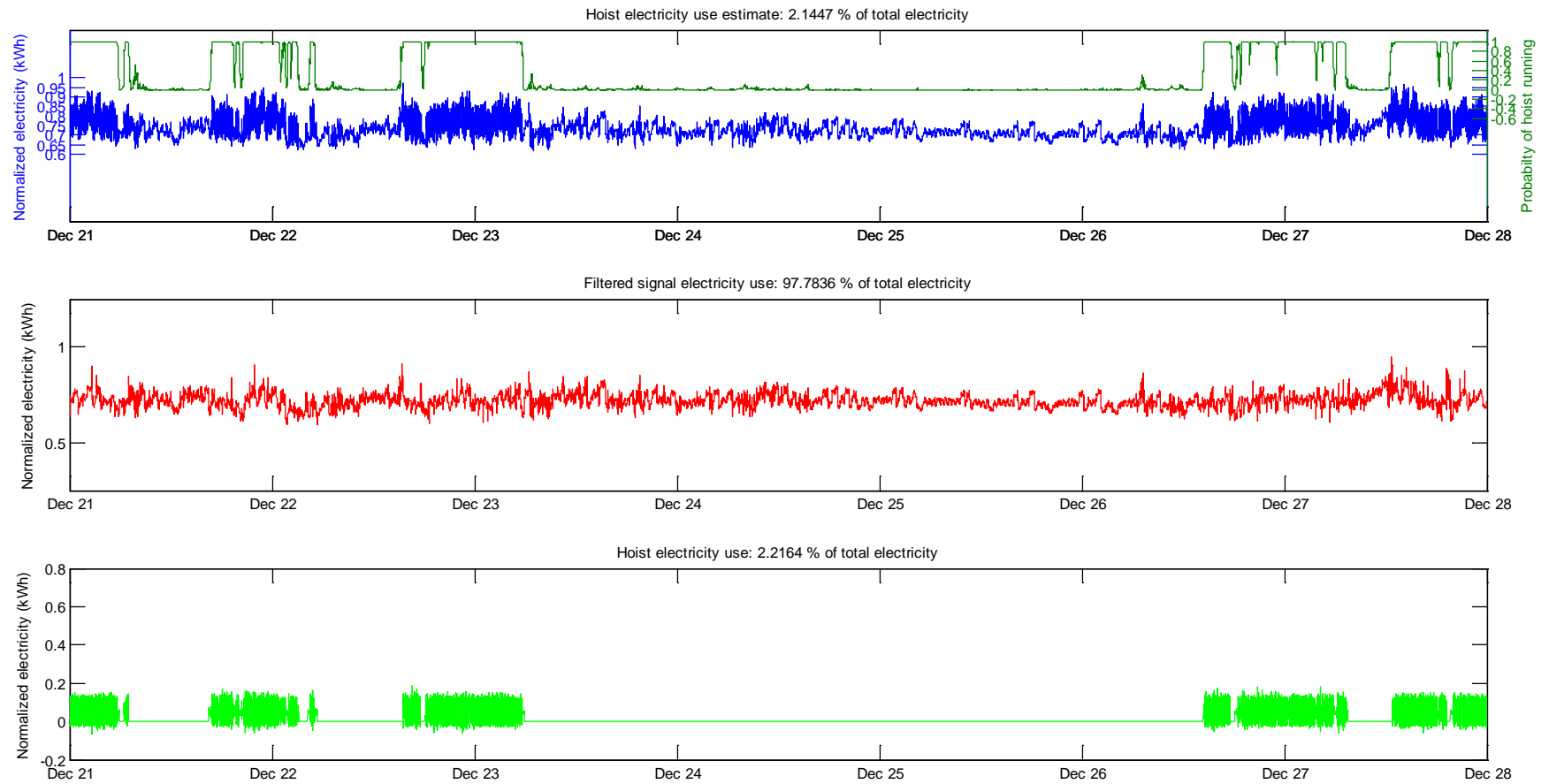
October



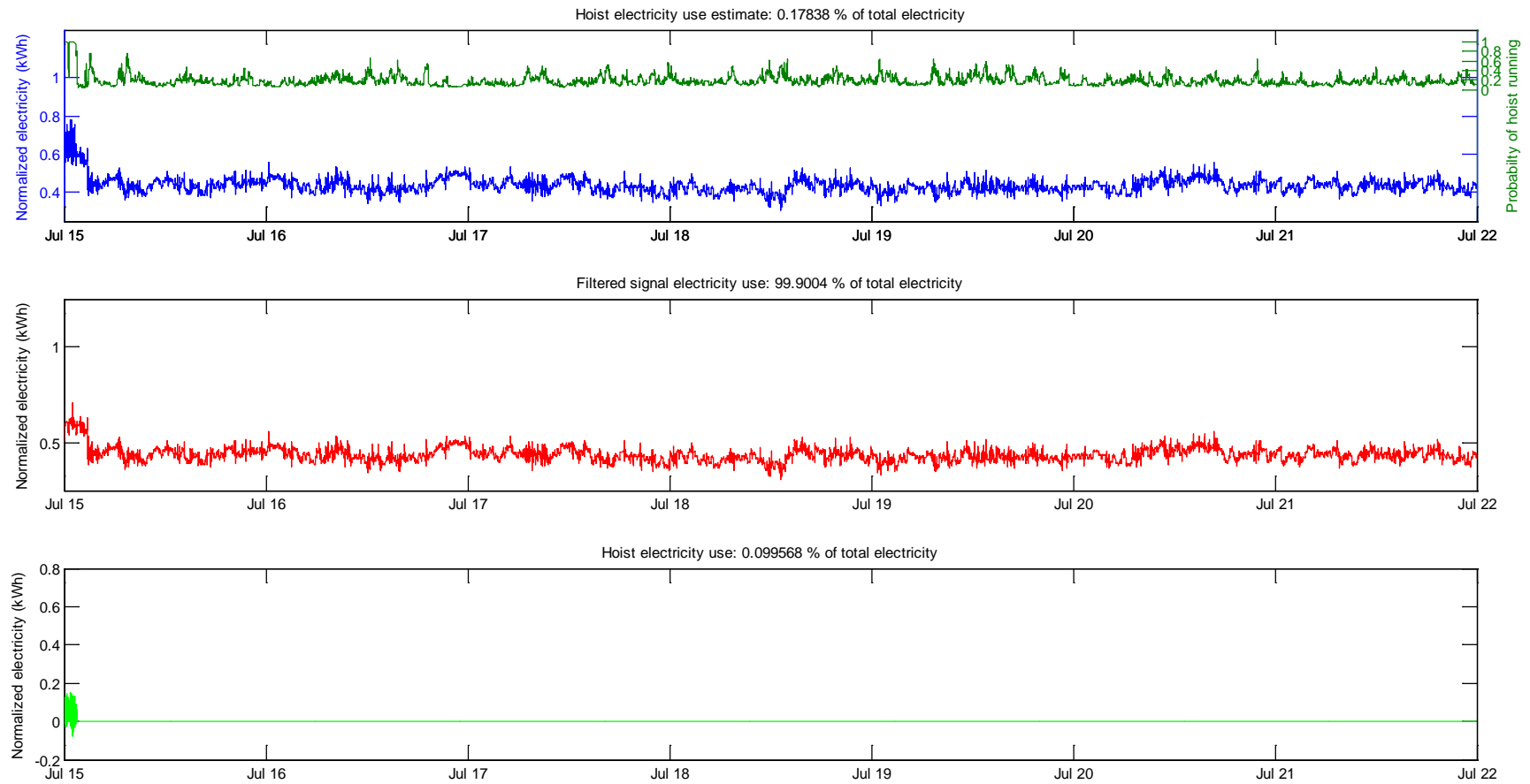
November



December



## Holidays



Shutdown