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A GENERIC FRAMEWORK FOR CONTINUOUS ENERGY MANAGEMENT AT CRYOGENIC AIR SEPARATION PLANTS

by

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To thank all the people who gave me their continuous support throughout, will not be possible in the available space and, to them, I would like to express my deepest gratitude in making this study possible.

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To Marilene

SUMMARY

Steel, petrochemicals, metallurgy, explosives, food and many other industries require large amounts of air products such as oxygen and nitrogen. Cryogenic air separation technology is, unlike other air separation technologies, in a mature stage of its life cycle and currently the only practical means available for mass-production of these air products. Inherent to its operation, cryogenic air separation plants are generally energy intensive and power input is considered the main factor on which the ultimate production cost will depend. Experience has shown that relatively small improvements in energy efficiency on these plants generally result in significant reduction of production cost.

This dissertation discusses the means for effective energy management at these plants, aimed at ultimately reducing the electrical cost per quantity of air product produced. It introduces a model, aimed at the manager responsible for energy management at plants of this nature.

At the core of the model is the definition of the energy management structure, which consists out of the following main managerial functions: organizing, planning, leading, and controlling.

Organization implies a formalized intentional structure of roles and positions whereas the planning process entails setting up the energy policy and defining the energy strategy. The managerial function of leading involves leadership, motivation and communication and in controlling, the energy manager sets energy standards, measures performance and initiate appropriate corrective actions.

KEYWORDS

Cryogenic Air Separation plant, Energy Management Model, Energy Policy, Energy Strategy

OPSOMMING

Die staal industrie, petrochemiese maatskappye, metallurgie, plofstofvervaardigers en die voedselbedryf benodig groot hoeveelhede gasprodukte soos suurstof en stikstof. Kriogeniese lugskeiding tegnologie is, anders as ander lugskeidingstegnologieë, in 'n volwasse stadium van sy lewenssiklus en is huidiglik ook die enigste praktiese manier beskikbaar vir massa produksie van die laasgenoemde gasprodukte. Inherent tot sy prosses, is kriogeniese lugskeidingsaanlegte normaalweg energie intensief en energie-inset word normaalweg beskou as die hoof faktor waarop die uiteindelike produksie koste sal afhang. Ondervinding het bewys dat relatiewe klein verbeterings in die energie effektiwiteit van hierdie aanlegte normaalweg lei tot beduidende verlagings in produksiekoste.

Hierdie verhandeling bespreek 'n metode waarop effektiewe energiebestuur by hierdie aanlegte toegepas kan word en is daarop gemik om die uiteindelike energie koste per uitsetprodukhoeveelheid te reduseer. Dit stel 'n model bekend wat gemik is op die bestuurder wat verantwoordelik is vir energiebestuur by hierdie aanlegte.

Die definisie van die energiebestuurstruktuur vorm die kern van die model, en bestaan uit die volgende hoof bestuursfunksies: organisering, beplanning, leiding en beheer.

Organisering impliseer 'n geformaliseerde en beplande struktuur van take en funksies, terwyl die beplanningsprosses die bepalling van die energiebeleid en formuleering van die energiestrategie insluit. Die bestuursfunksie van leiding sluit in leierskap, motivering en kommunikasie en in die beheer funksie stel die energiebestuurder energiestandaarde vas, meet prestasie en inisieër relevante korrektiewe aksies.

SLEUTELWOORDE

Kriogeniese lugskeiding, Energiebestuurmodel, Energiebeleid, Energiestrategie

LIST OF ABBREVIATIONS

Abbreviation		Meaning
AC	-	Air Compressor
Ar	-	Argon
AR	-	Average Recovery
ASU	-	Air Separation Unit
CB	-	Coldbox
CBM	-	Condition-based maintenance
CO_2	-	Carbon Dioxide
CT	-	Current Transformer
FTM	-	Fixed-Time maintenance
GAN	-	Gaseous Nitrogen
GOX	-	Gaseous Oxygen
He	-	Helium
HP	-	High Pressure
IA	-	Instrument Air
Kr	-	Kripton
LOX	-	Liquid Oxygen
LP	-	Low Pressure
MG-set	-	Motor-Generator set
MP	-	Medium Pressure
N_2	-	Nitrogen

Nm^3/h OR nm^3/h	-	Normal Cubic Meters per hour. This is the flow of a commodity (gas or liquid) at normal conditions (0°*C* and 1.013 *absolute bar*).
O_2	-	Oxygen
OC	-	Oxygen Compressor
OEM	-	Original Equipment Manufacturer
PM	-	Preventive Maintenance
PT	-	Potential Transformer
tpd	-	Tons per Day
WN_2	-	Waste Nitrogen
Xe	-	Xenon

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CHAPTER 1 PROBLEM IDENTIFICATION AND BACKGROUND

1.1. INTRODUCTION

Steel, metal and petrochemical industries all require large amounts of air products such as oxygen and nitrogen. Kotz *et al.* [1] states that oxygen and nitrogen are annually among the top five chemicals produced in the United States. Cryogenic air separation plants are, currently, the only efficient and economically viable method of producing air products on large scale (Smith *et al.* [2]). Because transportation adds considerably to the cost, plants are usually constructed on-site and located close to the point of consumption.

It is also a fact that plants of this nature are generally energy intensive, especially the large tonnage plants, and it has been found that relatively small improvements in plant energy efficiency may lead to significant energy cost savings.

1.2. ENERGY MANAGEMENT AT CRYOGENIC AIR SEPARATION PLANTS

The energy crises of the early 1970's necessitated significant improvement of energy management efforts at these energy intensive plants and initial efforts were mostly aimed at energy conservation through introduction of better technology available for that time (Birmingham *et al.* [3]).

As a consequence of this, intentional consideration to improved plant energy efficiency has been given during its design phase ([4], [5], [6]); this is manifested by the fact that energy efficiency increased by approximately 9.1% from 1980 to the late 80's, [4], and from 1997 to 2001 Air Liquide reports a 10% decrease in power consumption of its cryogenic air separation plants. [7].

Since the 1970's, energy optimization techniques have been given elevated importance in the design phase of cryogenic air separation plants and numerous studies addressing the issues surrounding improved energy optimization have been widely publicized (refer to Birmingham *et al.* [3], Biddulph [8], Gupta *et al.* [9] and Sarkar [6]). It is also a fact that all these studies are almost solely aimed at improving the energy efficiency of the plant through intervention at the design phase of the cryogenic air separation plant. Although there have certainly been significant improvements in plant energy efficiency during the past years, as stated earlier, not much have been written on how proper maintenance of this energy efficiency should be conducted and needles to say, proper energy management.

The aim of energy management is defined by Thuman *et al.* [10] as the reduction of energy expenditure for the purpose of reducing product cost; this would ultimately lead to an increase in competitive performance and it becomes clear that, by employing effective energy management, much more benefit can be drawn by the relevant stakeholders and consequently also makes business sense.

This energy management effort should not only be confined to the design phase of the plant, but should be a continuous action, applying it throughout the whole productive part of the plant's life-cycle.

With today's relatively high, and continuously increasing, energy prices it not only becomes a necessity but also makes business sense to maintain and continuously improve the plant's energy efficiency. Managing the plant's energy expenditure and efficiency would be the correct response to the already high and ever-increasing energy cost and may reduce overall input cost dramatically.

To make this managerial action value-adding, there needs to be an effective and continuous energy management program in place that aims to reduce the plant's energy expenditure so as to ultimately reduce product cost.

1.3. DISSERTATION OBJECTIVES

The dissertation objectives are as listed under the main and specific objectives in the sub-sections that follow.

1.3.1. Main objective

The main objective of this dissertation is to present a structured framework which would enable effective management of energy cost and efficiency on cryogenic air separation plants.

1.3.2. Specific objectives

The main objective is accomplished by addressing several key specific objectives:

- Present a model for energy management at cryogenic air separation plants.
- Introduce the theory behind an energy policy.
- Introduce an energy management strategy.
- Present an efficient energy audit process.
- Derivation of a mathematical model for the cryogenic air separation plant.
- Defining performance indicators, which would assess the success of the energy management program.
- Present the means for conducting energy systems maintenance on relevant equipment on the plant.

1.4. DISSERTATION STRUCTURE

This dissertation is structured in accordance with the energy management model.

Chapter 2 introduces the reader to some of the various technologies available today for producing air products and also elaborates on the basic theory behind cryogenic air separation.

The main processes within the air separation plant are described as well as the equipment used in realizing these processes.

Chapter 3 introduces the energy management model and, more specifically, the energy management system. This chapter sets the scope for the chapters that follow and gives a brief introduction of what each one entails.

Chapter 4 describes the organizational structure of the energy management program as well as the components it's comprised of. It also elaborates on energy management planning and introduces the concept behind the energy policy and strategy. In this chapter, components of the energy policy strategy are described in detail and selected concepts are explained by means of case studies.

In chapter 5, the managerial function of leading is described as well as a few issues surrounding employee motivation. Also included in chapter 5 is the theory behind energy management controlling where concepts surrounding energy standards, detection of deviations and correction of deviations are elaborated on.

The last chapter, chapter 6, concludes the dissertation objectives and ends with recommendations with regard to selected topics.

Lastly, the case studies presented in this study are with reference to the oxygen plant at Sasol Secunda in South Africa, unless otherwise stated.

CHAPTER 2 CRYOGENIC AIR SEPARATION

2.1. INTRODUCTION

Air is a composition of various gasses, of which nitrogen (N_2) and oxygen (O_2) collectively account for approximately 99.03% of the total sample volume (Table 2.1.). Various needs have been developed for application of these gasses, especially in the steel, petrochemical and metal industries where large amounts of oxygen and nitrogen are required. According to Kotz *et al.* [1], oxygen and nitrogen are used the most extensively by industry and they are annually among the top five chemicals produced in the United States.

Table 2.1: Components of air and their properties (Sources: Austin [11], Kotz *et al.* [1]).

Gas	**Molar Mass (mole)**	**Volume (%)**	**Boiling Point (K)**
Nitrogen	28.01	78.084	77.35
Oxygen	32.00	20.946	90.19
Argon	39.95	0.934	87.27
Hydrogen	1.01	0.00005	20.27
Neon	20.18	0.001921	27.09
Helium	4.00	0.0005239	4.22
Krypton	83.80	0.0001139	119.81
Xenon	131.29	0.0000087	165.04
Carbon dioxide	44.01	0.02-0.04	194.68

- Average molar mass of dry air = 28.96 g/mol

Oxygen and nitrogen are produced by means of an air separation process, which entails the separation of air into its constituents. The rare gasses like, for example, Argon, Krypton and Xenon are normally obtained as byproducts of the air separation process.

Realization of the air separation process is done through the implementation of a specific air separation technology. There exist different air separation technologies today, each one aimed at exploiting different attributes with regard to the difference in physical properties between the constituent air gasses. In other words, an air separation technology is based on the fact that the fundamental components of air all have different physical properties and air separation is therefore realized through, for example, distinguishing between molecule sizes, distinguishing between difference in diffusion rates through certain materials, adsorption preference special materials have towards certain gasses of the atmosphere and difference in boiling temperatures.

Some of the technologies being used today include adsorption, chemical processes, polymeric membranes, ion transport membrane (ITM) and cryogenic. Table 2.2 compares the different air separation technologies to each other in terms of technology status, byproduct capability, product purity limit and plant startup time. As can be seen from the table, cryogenic air separation technology is in a mature stage of its life cycle, consequently making it the only feasible means currently available for mass production of air products such as oxygen and nitrogen.

Table 2.2: Comparison of air separation technologies (Smith *et al.* [2]).

Process	**Status**	**Byproduct capability**	**Purity limit (vol. %)**	**Start-up time**
Adsorption	Semi-mature	Poor	93-95	minutes
Chemical	developing	Poor	>99	hours
Cryogenic	mature	Excellent	>99	hours
Membrane	Semi-mature	Poor	40	minutes
ITM	developing	Poor	>99	hours

The sections that follow will be dedicated to cryogenic air separation technology.

2.2. PROCESS DESCRIPTION

Cryogenic air separation technology is based on the fact that the different constituent gasses of air all have different boiling points and by manipulating the immediate environment in terms of temperature and pressure, the air can be separated into its components.

Various processes are needed in a cryogenic air separation plant, of which the fundamental ones are: air compression, air purification, heat exchanging, distillation and product compression (figure 2.1).

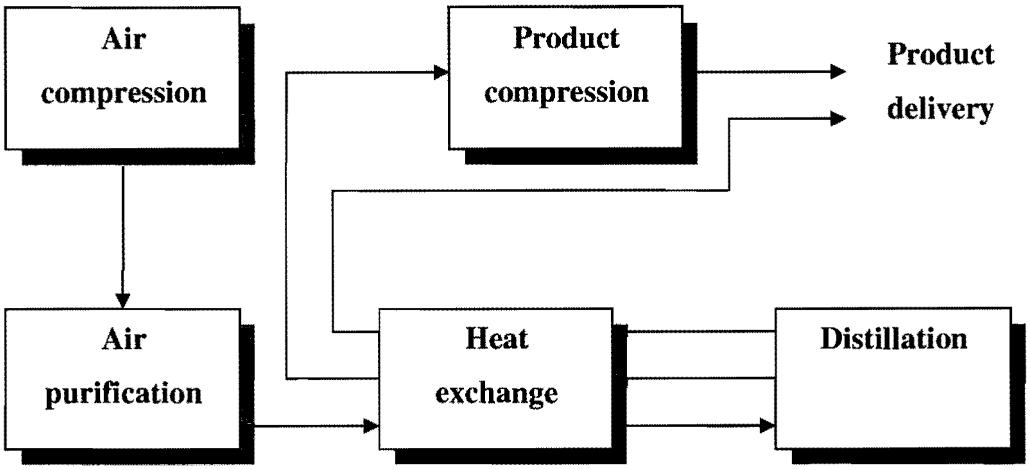

Figure 2.1: Processes involved in cryogenic air separation.

Each process of figure 2.1 has a certain function and this function is performed by means of relevant equipment; Table 2.3 lists the equipment type utilized in each of the required processes as well as their respective main functions.

Table 2.3: A description on the function of each process and the equipment used for the implementation thereof.

Process	Function	Equipment type
Air compression	Pressurize air feed lines in order to achieve required production	Compressor
Air purification	Purifying the air by removing water and CO_2	Reversible exchangers/sieve adsorbers
Heat exchanging	Cooling of incoming air feed by means of cold recovery from exiting products	Heat exchanger
Distillation	Partial separation of air into its constituents	Distillation columns
Product compression	Pressurize outgoing product feed in to meet user requirement	Compressor

In figure 2.1, incoming air is pressurized by the air compressors and enters the process with a certain flow-rate, as determined by the demand of air product at the output of the plant.

The air pre-treatment section removes impurities like water, carbon dioxide and hydrocarbons and is necessary because it prohibits vapour condensation, liquid water solidification and gaseous CO_2 condensation from occurring within the heat-exchanger, thus ensuring continuous operation of a train.

In order to obtain the required conditions for air distillation, the air first needs to be cooled down and this is done by means of heat exchanging between the air and outgoing product streams.

The distillation process is at the heart of the overall process; this process performs the actual separation of air into its constituents. These air products are produced with a certain purity, which is defined as the ratio of the quantity of 100% pure air product to the quantity of total of air product at the output.

The outputs from the distillation process are fed back through the heat exchanger in order to realize the cold recovery process that is needed for the cooling of the incoming air feed lines. The main air product is at low pressure when exiting the distillation process and is, for this reason, usually compressed to the client's pressure specification prior to delivery.

The system, incorporating these processes, is referred to as an oxygen or nitrogen train, whatever the main product may be. A number of such trains are usually cascaded in order to produce a high-tonnage air product output and is then collectively referred to as an oxygen or nitrogen plant.

The capacity, of cryogenic air separation trains, is expressed in tons per day (*tpd*) of main product output. The flow of air products is usually quantified in terms of normal-cubic meter per hour (Nm^3/h), which is defined as the flow at 1.013 *absolute bar* and $0°C$. This is in actuality a mass flow and not a volume flow and conversion between Nm^3/h and *tpd* may be done by using the ideal gas law as stated in Perry *et al.* [12] and Fishbane *et al.*[13].

$$pV = nRT \tag{1}$$

where:

- p is the gas pressure (kPa)
- V is the volume (m^3)
- T is the gas temperature (K)
- R is the gas constant ($8.31451 J.mol^{-1}.K^{-1}$)

Rearranging equation (1) and substituting the normal conditions stated earlier, gives equation (2).

$$V = 22.414 \times n \tag{2}$$

Thus, the volume occupied by one mole of gas is $22.414m^3$ at normal conditions, whatever the gas may be. The periodic table (Kotz *et al.* [1]) states the molar mass of elements and this is $32 g/mol$ for oxygen (O_2) and $28 g/mol$ for nitrogen (N_2) and, knowing that $1 tpd$ is equivalent to$10^6/24$ *g/hour*, one may evaluate the ton per day rating for oxygen and nitrogen from the mass flow specification, or vice versa.

$$1 tpd\ O_2 = 29.18\ Nm^3/h \tag{3}$$

$$1 tpd\ N_2 = 33.35\ Nm^3/h \tag{4}$$

2.3. DISTILLATION

As stated earlier, the distillation process is at the heart of the overall process and, for the purpose of this dissertation, this section will be dedicated to a basic explanation on its operation. The working of this process will be explained by means of an example, highlighting the critical elements of distillation, and later on applying these principles to the distillation of air.

2.3.1. Example: Distillation of an alcohol and water mixture

Consider a distillation flask in which there is a mixture of water and alcohol, as depicted in figure 2.2.

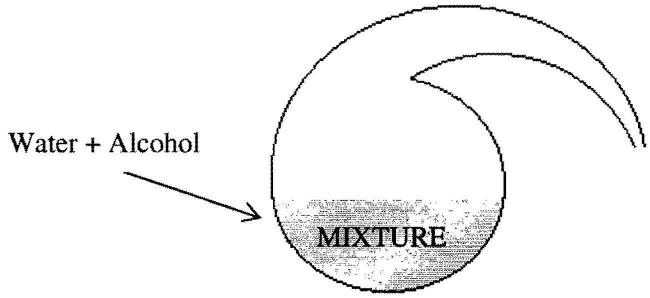

Figure 2.2: Distillation flask with water and alcohol mixture.

In figure 2.3, the mixture is brought to boiling point with a boiler and a gaseous phase, richer in the most volatile component, is obtained. The gas is condensed and, as alcohol vaporizes at a lower temperature than water (we say that alcohol is more volatile than water) a distillate richer in volatile elements is obtained.

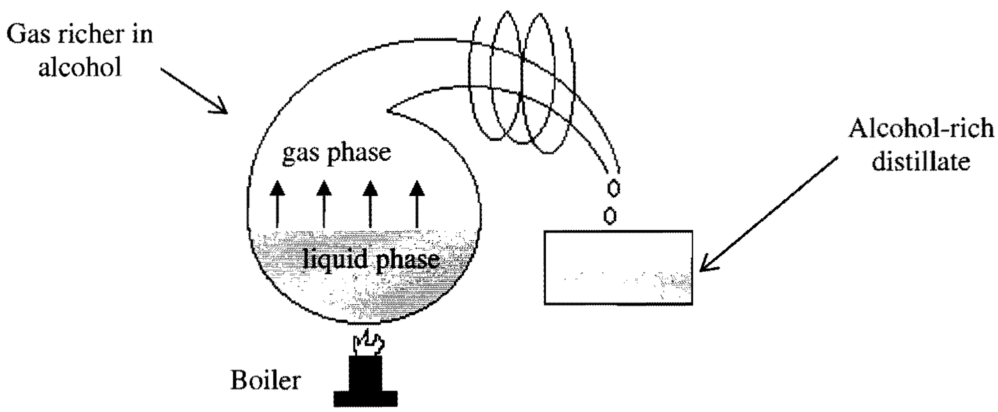

Figure 2.3: Water and alcohol mixture at boiling point, producing a gas, and consequent distillate, richer in alcohol.

By simply cascading a number of such systems as in figure 2.3, it is possible to make the distillate richer and richer in volatile elements and thus effectively increasing the volatile element purity of the distillate. This arrangement is depicted in figure 2.4 and shows the location of where the respective volumes of the volatile rich element and the less volatile rich element may be obtained.

This arrangement, however, has the disadvantage that it needs as many boilers and condensers as distillation flasks, but this can be overcome by making the liquid-gas contact more efficient as is also being done in practice.

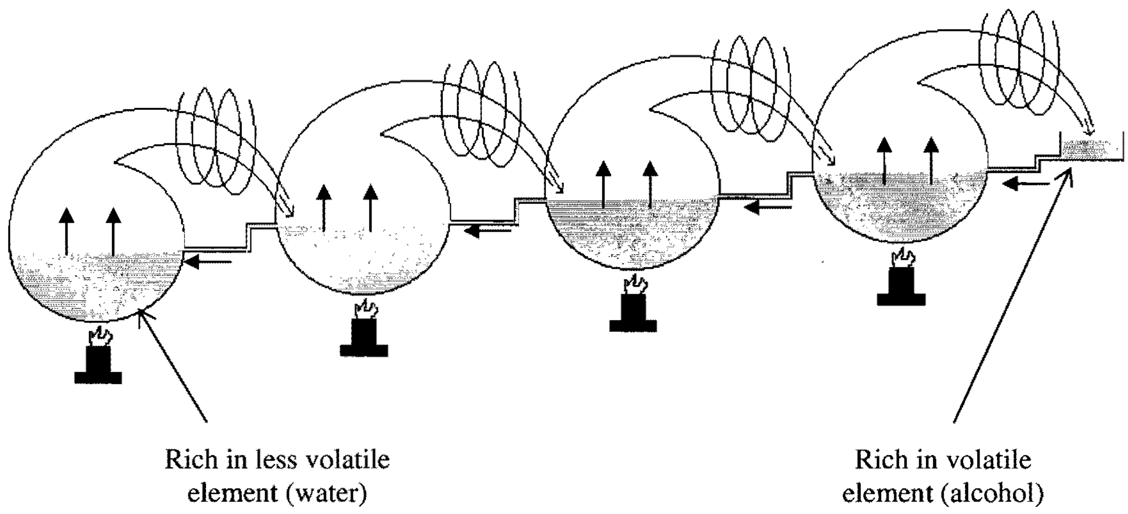

Figure 2.4: Cascaded distillation flasks, producing a substance rich in volatile element at the top and a substance rich in less volatile element at the bottom.

By improving liquid-gas contact, as shown in figure 2.5, better heat exchanging between the liquid and the gas may be realized, causing the gas to be cooled down partially and the liquid to be heated up partially. Cooling down the gas leads to its partial condensation and heating up the liquid is accompanied by partial boiling, thus, distillation with only one boiler, may still be realized given that liquid gas contact is improved.

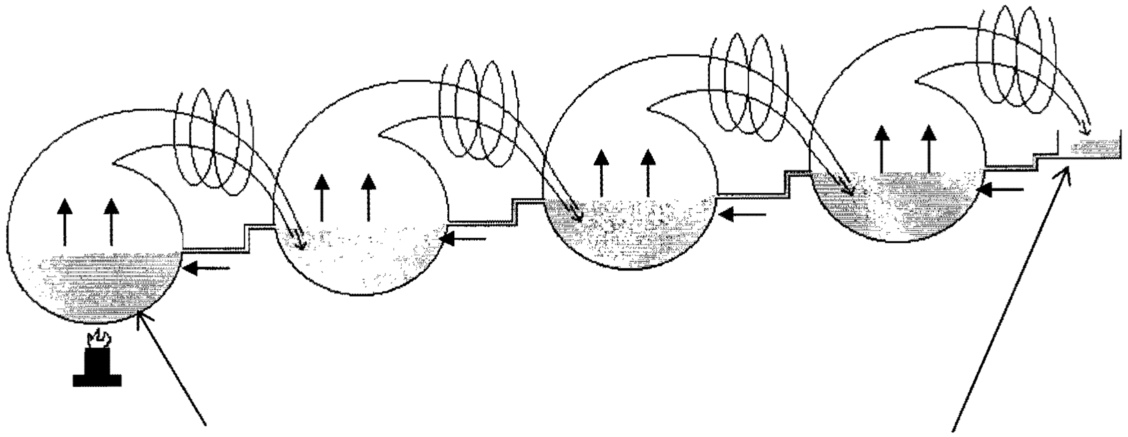

Figure 2.5: Distillation by means of improved liquid-gas contact between cascaded distillation flasks.

This concludes the water and alcohol example and the basic theory explained here will now be made applicable to air distillation.

2.3.2. Distillation of air

In practice, distillation trays instead of flasks are used and the basic function of the tray is to enable efficient contact of the descending liquid and the rising gas. Thus, the tray sets the stage for following:

- Cooling and partial condensation of the rising gas.
- Heating and partial vaporization of the descending liquid.

Figure 2.6 depicts a distillation column with only one vaporizer and one condenser. Distillation is made possible by efficient liquid-gas contact and this is enabled through proper contact between the descending liquid and the rising gas. The respective purities of the most volatile and less volatile elements differ at each tray, with the lower and upper sides of the distillation column being the two extremes, which is also where the pure elements are obtained.

Suppose that the mixture is no longer water and alcohol but, oxygen and nitrogen (i.e. air), then oxygen (less volatile element) would be produced at the bottom and nitrogen (most volatile element) at the top.

In figure 2.6 it is clear that the tray provides the rising gas with a certain resistance, and thus creating a pressure drop; this pressure drop must be as small as possible for it has a significant impact on the energy consumption of the air compressor and is also an important parameter in development of a tray's technology. Distillation packing is another technology that is being used and, as opposed to fractional distillation trays, ensures a much smaller total pressure drop as well as improved liquid-gas contact.

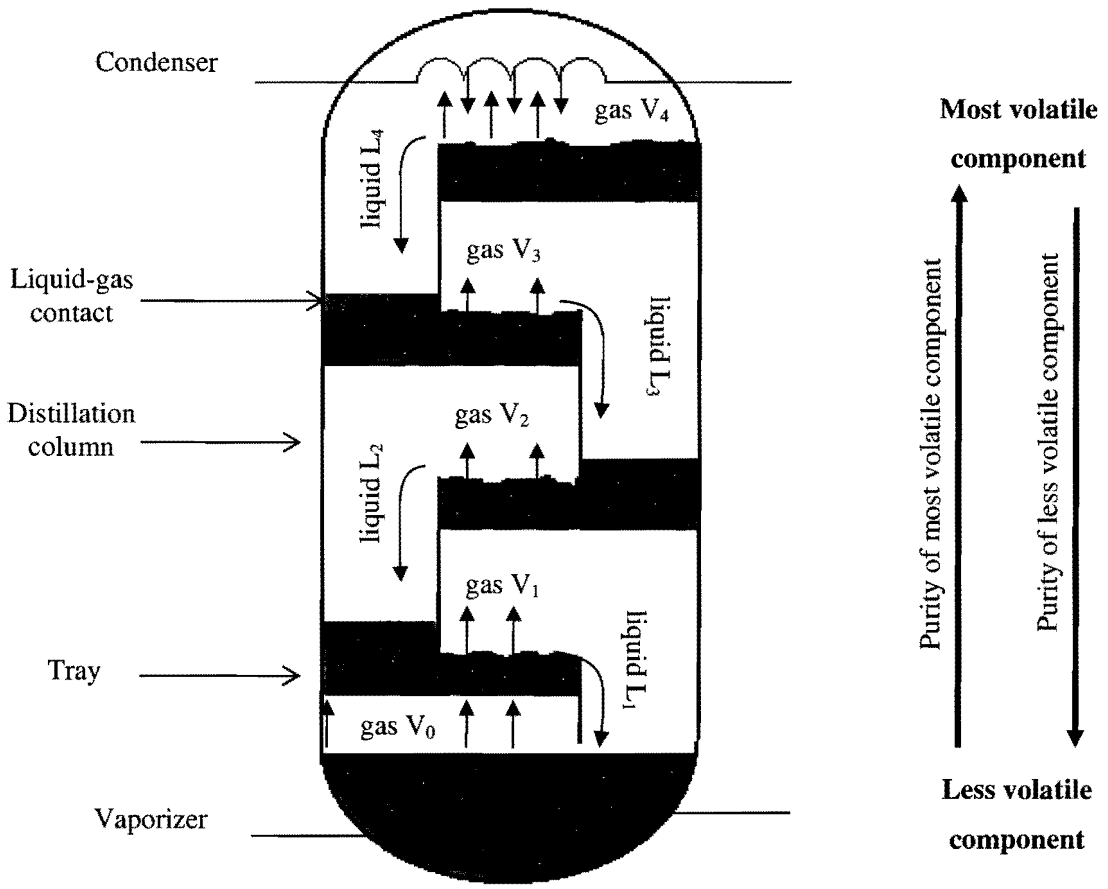

Figure 2.6: Distillation column producing oxygen and nitrogen by means of fractional distillation trays [5].

In practice, the model presented in figure 2.6 would be uneconomical since it needs both a vaporizer and condenser. It is possible to remove either one, but then the column would be limited to either producing oxygen or nitrogen and not both at the same time.

When removing the condenser, it is still possible to produce oxygen, however, a liquid mixture of nitrogen and oxygen is needed and this must be injected at the top of the column, as shown in figure 2.7.

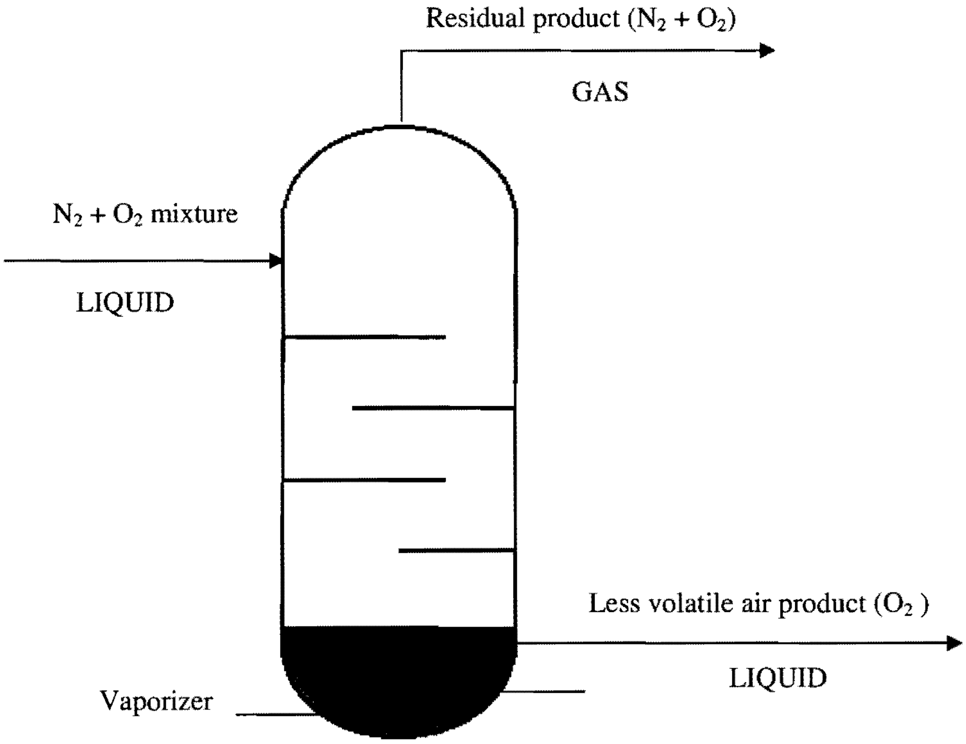

Figure 2.7: Producing oxygen by utilizing a distillation column with no condenser [5].

It is important that the mixture entering the column must be in the liquid phase, otherwise there will only be one phase (gas phase) in the column, which means that distillation would not be possible as it requires both a gas phase and a liquid phase.

Thus, with the model presented in figure 2.7, liquid oxygen is produced at the bottom and a residual gas, consisting of nitrogen and oxygen, at the top.

Figure 2.8 shows a model for producing nitrogen. The distillation column utilizes only a condenser and it is required that a nitrogen and oxygen gas mixture be injected at the bottom of the column.

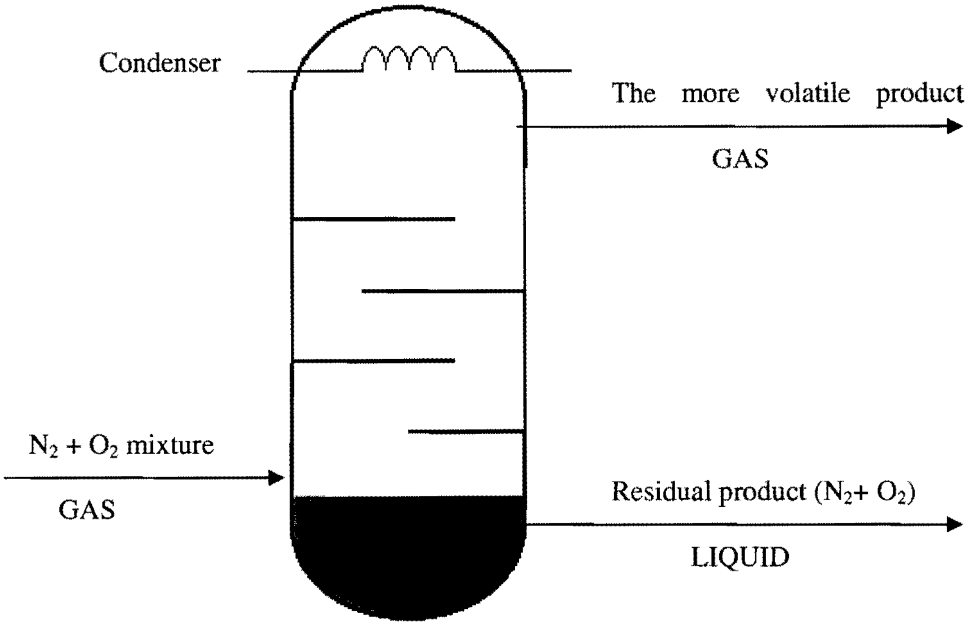

Figure 2.8: Producing nitrogen by utilizing a distillation column with no vaporizer [5].

Gaseous nitrogen is obtained at the top of the column whereas a residual liquid mixture, rich in oxygen, is obtained as a byproduct at the bottom of the column.

By injecting a liquid oxygen and nitrogen mixture instead of a gaseous mixture at the bottom of the column would make distillation impossible because there will again be only be one phase (liquid phase) present.

Thus, to summarize, when producing oxygen a liquid mixture of oxygen and nitrogen and a column, equipped with a vaporizer at the bottom, is required. To produce nitrogen a gaseous mixture of oxygen and nitrogen as well as a column, equipped with a condenser at the top, is needed; a byproduct, rich in oxygen, will also be produced in this instance.

By stacking the columns, presented in figures 2.7 and 2.8, on top of one another and by routing the oxygen rich liquid, which is obtained at the bottom of the nitrogen column, to the top of the oxygen column it is possible to produce oxygen and nitrogen by using only a condenser, as shown in figure 2.9.

An oxygen rich liquid enters the top of the upper distillation column, and through distillation, results in liquid oxygen (LOX) at the bottom of the same column. Vaporization of the LOX into gaseous oxygen (GOX) is realized by means of the heat exchanging that occurs between the gaseous nitrogen (GAN) at the top of the lower column and the LOX at the bottom of the upper column. At the top of the upper column a waste product, consisting of a nitrogen and oxygen gas mixture, is also produced.

In practice, the function of the condenser is fulfilled by a heat exchanger that ensures that proper heat is carried over from the GAN to the LOX and vice versa, in order to enable vaporization of the LOX and condensation of the GAN, which is required for the continuous operation of the distillation columns.

In this model the columns are stacked on top of each other, but it is also possible to place them alongside one another, as occasionally being done in practice.

This concludes the discussion on distillation, further explanation on this subject is beyond the scope of this dissertation and the basic theory presented here should be sufficient and relevant to understanding the selected material presented in this study.

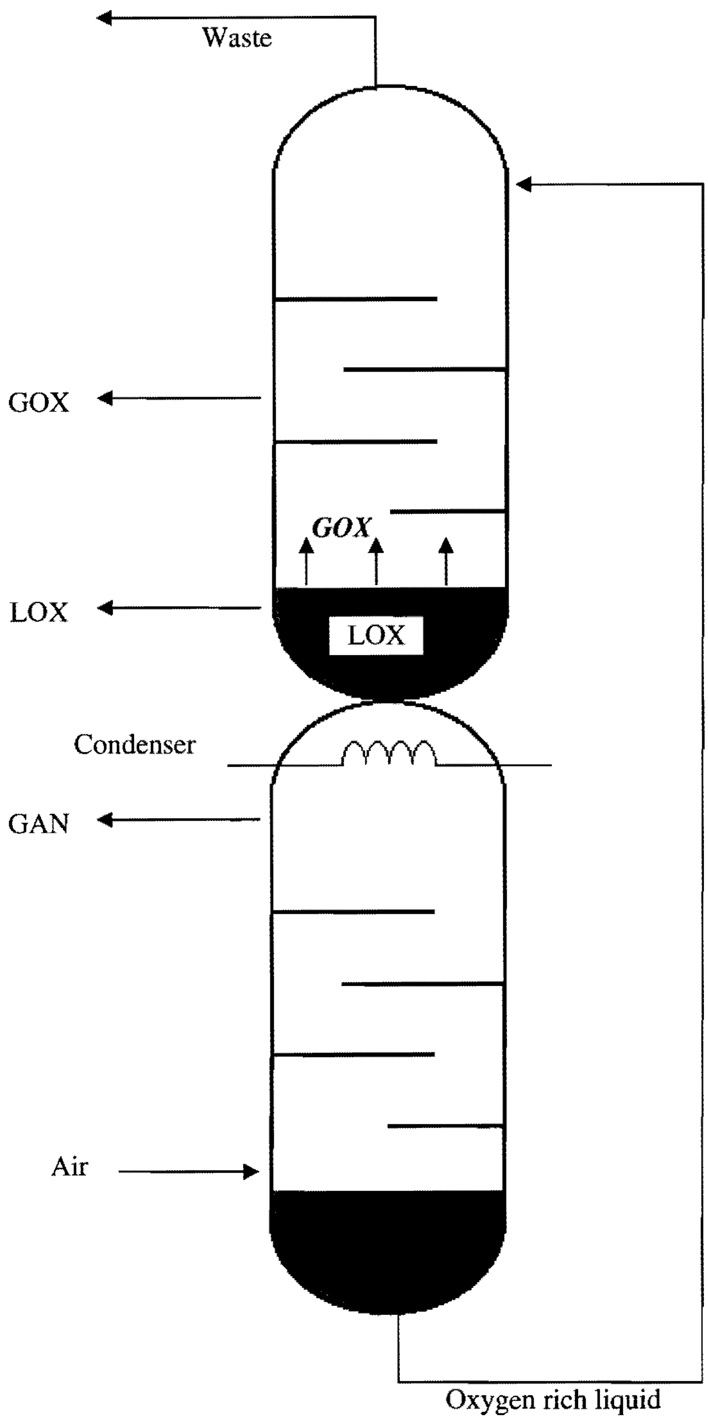

Figure 2.9: Stacked column model that enables the production of oxygen and nitrogen.

2.4. CONCLUSION

This chapter has explained the basic theory behind cryogenic air separation. It details the properties of air and compares the various technologies for producing certain air products.

This chapter states the main processes of cryogenic air separation and they are: air compression, air purification, heat exchanging, distillation and product compression. These processes as well as the interaction between them have been described.

Distillation is the key process in cryogenic air separation and has consequently been given special consideration to in this chapter. The basic theory behind distillation as well as how this applies to the separation of air have been elaborated on, which should serve as a sufficient reference for the remainder of this dissertation.

CHAPTER 3 ENERGY MANAGEMENT

3.1. INTRODUCTION

Management is essential in any organized collaboration and should be implemented at all levels of an enterprise (Koontz [14] *et al.*). An organization has certain inputs to its disposal, be it human resources, funds, technology, skills etc. and it is the basic function of the manager in charge to efficiently manage these valuable inputs in pursuit of achieving predefined objectives in an optimum manner. In an industrial plant, like the cryogenic air separation plant, typical inputs are production personnel, the various maintenance departments (electrical, mechanical, instrument, turbo etc.), engineering, financial and information technology, among others and all these resources are normally subjected to some form of management. Energy is another important input to the plant; the plant needs energy to produce its products to the client's specification and given that cryogenic air separation plants are energy intensive by nature, efficient energy management will have a definite impact in the cost per product produced.

For instance, the oxygen plant at Sasol Secunda in South Africa is composed out of several trains, which collectively account for approximately 35% of the factory's total power consumption. In terms of the total operating cost of the oxygen plant itself, the energy cost constitutes 72% thereof compared to the 2% of labor costs and 8% of maintenance related costs [15]. This relatively large electricity cost is typical of cryogenic air separation plants (also refer to Sarkar [6] and Gupta *et al.* [9]) and it is quite possible to manage the usage of energy in such a way as to ultimately reduce the cost per product produced.

3.2. ENERGY MANAGEMENT AT CRYOGENIC AIR SEPARATION PLANTS

Turner [16] defines energy management as the control of energy consuming devices for the purpose of minimizing energy demand and consumption. Energy management is defined by Janse van Rensburg [17] to be the perspicacious and efficient usage of energy. Another definition is that from Ottaviano [18] where energy management is defined as the reduction of demand through conservation.

The aim of energy management is defined by Thuman *et al.* [10] as the reduction of energy expenditure for the purpose of reducing the cost of a product so as to increase competitive performance.

With the various energy management definitions in mind, one can come to the conclusion that energy management is some sort of process, ultimately resulting in reduced energy expenditure. How, then, would one go about describing this process which energy management is? In terms of energy management applied to cryogenic air separation plants, energy management may sufficiently be described as a transformation process and this will be the topic of the next section.

3.2. MODEL FOR ENERGY MANAGEMENT AT CRYOGENIC AIR SEPARATION PLANTS

The Oxford dictionary [19] defines a model as a representation of reality, a simplified description of a complex system. The model developed here serves as a generic framework for energy management at cryogenic air separation plants and provides insight and understanding of the energy management process as well as giving structure to this understanding; it is a product of systems thinking and takes on a holistic approach towards energy management. A basic outline of the model is presented in figure 3.1.

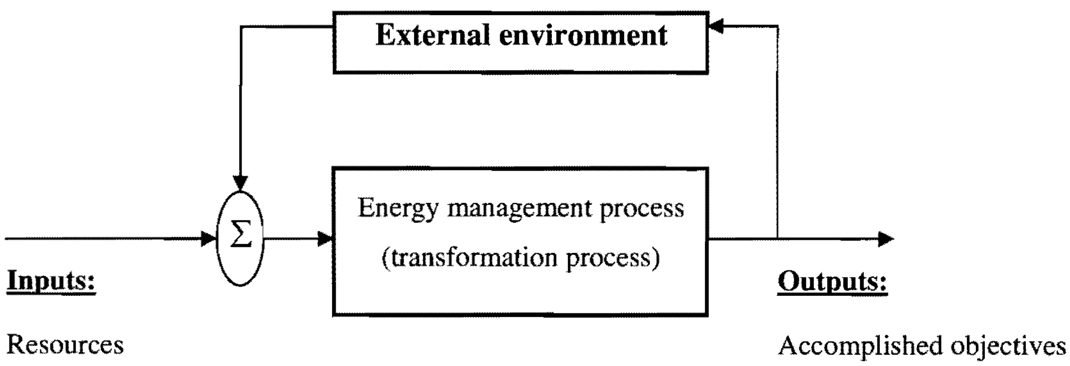

Figure 3.1: Basic outline of the energy management model.

The basic function of the energy manager is to transform the inputs (resources), in an effective and efficient manner, into outputs of higher value. With the available resources as levers and with the expected objectives in mind, the energy manager has to convert the resources into the pre-defined objectives by means of a transformation process. This transformation process is the organizational structure of the energy management program for which the management thereof is the responsibility of the energy manager.

The organizational structure of the energy management program is part of larger systems such as the industry to which it belongs, social systems, economic systems and even the natural environment and this is accounted for by the inclusion of the external environment. Typical inputs from the external environment are resources like capital, skills, facilities and people and, as shown in the figure, the external environment is ultimately affected by the outcomes of the energy management program.

3.3. ENERGY MANAGEMENT SYSTEM: THE TRANSFORMATION PROCESS

It is generally accepted that the fundamental components of management are planning, organizing, staffing, leading and controlling (Koontz *et al.* [14]). Energy management is a managerial action and most of these functions also apply to the energy management system. Figure 3.2 depicts the energy management model and states the components of the transformation process.

Through organizing the energy management program the energy manager gives it definition and structure. It mainly involves identification and classification of required activities and the grouping of these activities in a structured and meaningful way.

Planning involves the decision-making process. This is where policies are set, objectives are determined and the strategies in attaining these objectives are established.

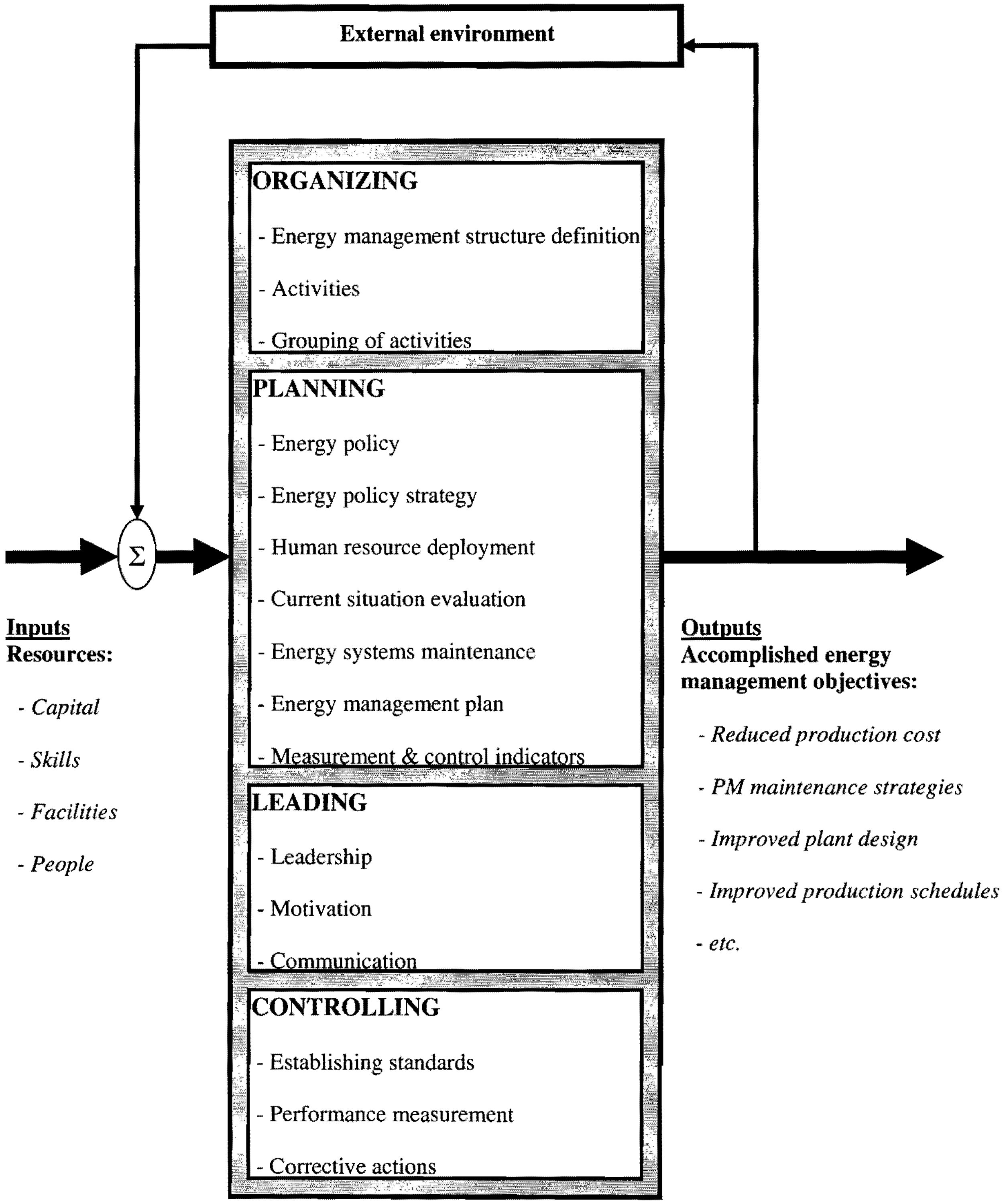

Figure 3.2: The energy management model.

Leading refers to the process of influencing people so that they will strive willingly and enthusiastically toward the achievement of energy management goals.

Controlling is the measurement and correction of performance in order to ensure that objectives and the plans devised in attaining them are being accomplished.

These managerial functions make up the transformation process and in performing these functions, the energy manager enables an efficient and effective process for achieving energy management objectives. Analysis of each of these functions will be given in the chapters that follow.

3.4. CONCLUSION

In this chapter a model for energy management is given; the energy management process is modeled as a transformation process, in which resource inputs are converted into outputs of higher value.

The model entails the transformation process, its inputs and outputs and the external environment as well as the interaction between all of these. Inputs are resources like people, skills and facilities; outputs are the accomplished energy management objectives like improved preventive maintenance schedules, optimized production schedules and reduced energy cost.

The external environment accounts for the higher-order systems to which the energy management system belongs. The transformation process involves the managerial functions of organizing, planning, leading and controlling, which are the core managerial functions the energy manager has to perform. Each function entails various activities and will be explained in more detail in the chapters that follow.

CHAPTER 4 ORGANIZING AND PLANNING

4.1. ORGANIZING

With reference to general management, Koontz *et al.* [14] states that organization implies a formalized intentional structure of roles and positions. Generally, organization involves 1) the identification and classification of required activities, 2) the grouping of activities necessary to obtain objectives and 3) the delegation of authority for the means of managing these groupings.

With reference to energy management, there should be an intentional and formal structure in place for conducting a continuous and efficient energy management program. The structure presented in this study defines three groups of activities: energy management planning, leading and controlling. The activities under each grouping will be explained in the sections and chapters that follow.

4.2. PLANNING

Planning involves decision-making. This is where courses of action are selected, objectives are set and strategies in attaining these objectives are determined. The starting block of the energy management program is the energy policy. The energy policy is a statement or understanding that guides or channels thinking, it is an expression of the commitment plant management has towards a continuous and effective energy management and sets the scope for energy management strategies at plant level.

4.3. THE ENERGY POLICY

Plant management should establish an energy policy that is in line with major policies in order to ultimately add value to overall company objectives. The energy policy at plant level may be derived from a major policy and is therefore called a derivative or minor policy (Koontz *et al.* [14]). Figure 4.1 shows the energy policy at various levels of the organization, as well as the scope of the policy at each of these levels.

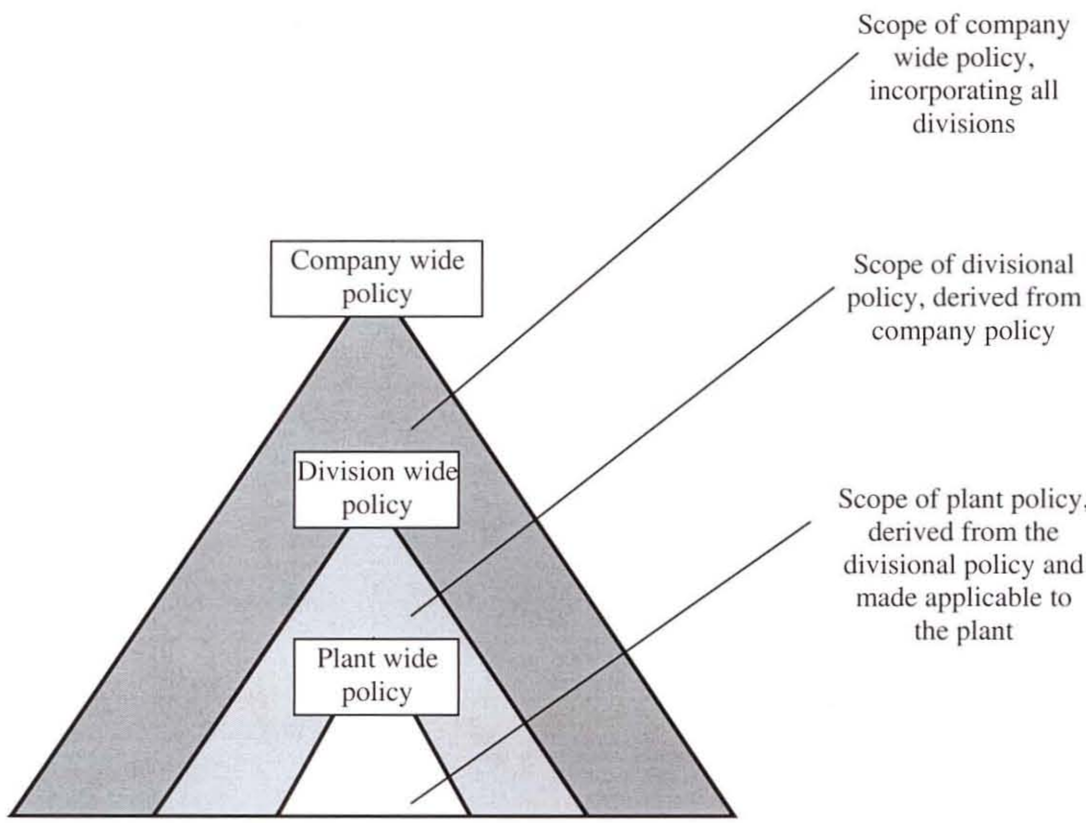

Figure 4.1: Energy policy at different levels of the organization and the scope of the policy at each level.

Thus, the energy policy at plant level is typically a derivation of higher-order policies; these policies may be higher-level energy or environmental policies and has a much larger scope than the plant-level energy policy.

As an example, the safety, health and environmental policy of Sasol Secunda is a company-wide policy:

- *Company-wide policy (Safety, Health and Environmental Policy):*

"We are committed to responsible utilization of natural resources and we will manage our company, wherever we do business, in an ethical way that strikes an appropriate and well reasoned balance between economic, social and environmental needs." [20].

From this policy it can be seen that Sasol recognizes it's responsibility towards the environment and also states that intentional effort concerning the balance between economic and environmental issues will be instated by means of managerial actions, which is also where the high-level energy policy may stem from:

- *Division-wide policy:*

"To manage the Sasol/Electricity Supply Industry interface, so as to minimize the total cost of energy for the Sasol group of companies. Further to this, to promote energy efficiency and reward energy management success by decentralizing accountability for electricity costs and by aligning internal electricity tariff structures with the Eskom marginal rate." [21].

From the above, an energy policy at plant-level may now be derived:

- *Plant-wide energy policy:*

We at oxygen plant are committed to responsible energy usage and endorse efficient energy management practices in order to optimize our energy consumption.

The energy policy normally consists out of three components: the declaration of commitment, mission statement and specific objectives. To illustrate the difference between these, the division-wide policy, [21], will be taken as an example. The mission statement defines the scope of the energy management program and, as can be seen in this case, it has been included in the declaration of commitment.

The specific objectives are the means for achieving that stated in the mission statement and, from the same example, some objectives are:

- Develop ways of getting all stakeholders involved in energy management.
- Implement and continuously improve world-class best practice energy management within our operations.
- Pioneer cross-functional and cross-divisional collaboration within the group of companies.
- Facilitate the creation of an enabling environment, which leads all key role players agreeing to and achieving stretched targets.
- Develop and maintain the electricity measurement system within the group of companies.

4.4. THE ENERGY POLICY STRATEGY

With the energy policy in place, the logical next step would be to formulate a strategy in order to realize the vision as expressed by the policy. The energy policy strategy effectively encapsulates the plan for changing current reality into future vision and, in doing so, the following activities need to be addressed:

- deployment of human resources,
- current situation evaluation,
- energy systems maintenance,
- energy management planning,
- establishment of measurement and control indicators.

These are the constituents of the energy policy strategy and each will be elaborated on in the sections that follow.

4.4.1. Deployment of human resources

Plant management should appoint a dedicated person for taking the responsibility of driving the energy management program. This person should be knowledgeable of the technology used in cryogenics and be experienced in energy auditing and management. This person should also assist plant management in adjusting/refining the current energy policy in order to make sure that it adds value and makes allowance for the holistic approach of energy management.

Koontz *et al.* [14] defines two types of policies namely, intended policy and actual policy. Initially, plant management may have had no intended energy policy but by agreeing upon the appointment of a dedicated energy manager to drive an energy management program, they have in actuality instated an ill-defined energy policy and it is the task of the energy manager to now properly structure and formalize the energy policy in conjunction with management.

4.4.2. Current situation evaluation

The current situation of the plant is assessed by means of an energy audit process. Energy auditing is an important phase of the energy management program and the success of such a program, to a large extent, depends on how well and to what extent the energy audit was done (Thuman [22] and Ottaviano [18]). After all, the plant first has to know itself before it can correct itself. The aim of the auditing process is to establish the relative position of the plant from an energy management point of view.

Auditing is not a once-off process; instead it should be done on a regular basis so that the energy manager can make the value-adding decisions regarding corrective measures. The outcomes of the auditing process are the following (refer also to Ottaviano [18]):

- assessment of energy consumption and energy usage patterns,
- identification of potential improvement opportunities,
- assessment of energy norms,

- employee awareness,
- feasibility of potential energy projects.

4.4.2.1. The energy audit process

The audit process consists out of the energy audit policy and the energy audit strategy. The energy audit policy sets the scope for what to audit whereas the energy audit policy strategy states how this would be done.

The audit strategies are the means for conducting the energy audit and the relative position of the plant with regard to energy management is determined through the evaluation of certain plant efficiencies as listed by Senekal [23]:

- Management efficiency
- Maintenance efficiency
- Operating efficiency
- Design efficiency
- Storage efficiency
- Information efficiency

These efficiencies are determined from an energy management perspective and a holistic approach to energy management lies in managing available resources in such a manner as to optimize all these efficiencies.

4.4.2.2. The plant efficiencies

The cryogenic air separation plant, like any other enterprise, aims to convert resource inputs, into outputs of higher value. For the cryogenic air separation plant typical inputs are capital, employees, skills and technology and the common goal is to convert these inputs into products like oxygen, nitrogen and/or rare gases, to customer satisfaction. This conversion is done with some amount of efficiency loss and in optimizing the overall efficiency necessarily means a higher level of output with the same amount of input.

Each department within the plant contributes to the overall efficiency loss and the contribution energy management has is assessed in terms of the efficiencies already listed.

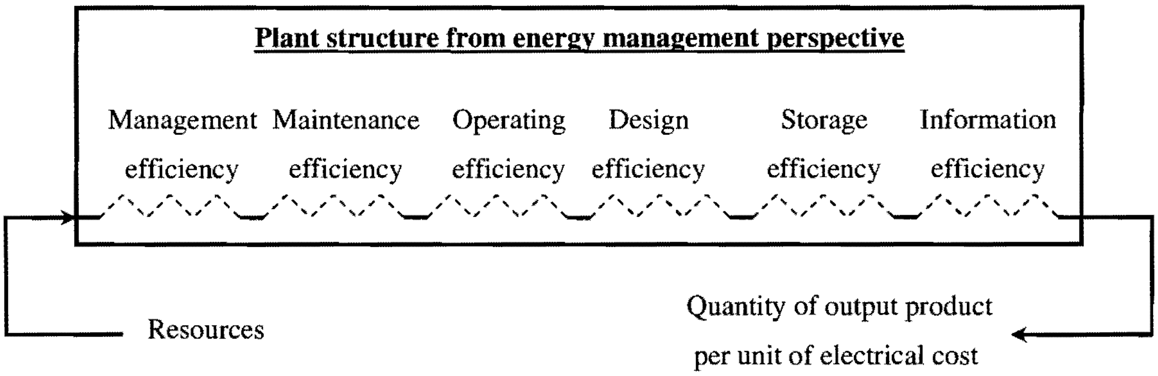

Figure 4.2: An illustration of efficiency losses, inherent to the plant's structure, from an energy manager's perspective and how they collectively contribute to the ultimate quantity of output product per Rand of electrical cost.

In order to assess these plant efficiencies, certain strategies should be employed, but first an explanation, on what each efficiency entail, will be presented.

- **Management efficiency**

Management efficiency is determined in terms of the commitment plant management has toward energy management. The level of this commitment should be determined and is a function of the following:

- The existing energy policy,
- Amount of resources allocated for energy management.

The energy manager should determine whether there is an existing energy policy in place and also establish on which level this policy originates from. Next, it should be determined whether this policy has been derived to plant level and also whether it has been applied at this level. The extent of this application should also be determined; i.e. are there any strategies outflowing from this policy? Have any resources been committed? Have they been implemented? Are they relevant and in scope?

- **Maintenance efficiency**

The maintenance efficiency is determined by the extent of intentional consideration given to the optimization of energy efficiency of relevant equipment in existing maintenance life plans. Maintenance efficiency goes hand in hand with energy systems maintenance, which will be dealt with in more detail later on in this chapter.

- **Operating efficiency**

By taking the system just as it is and not altering any design features, try to obtain the most efficient system operation. This could mean changing process schedules or consolidating plant activities.

As mentioned by Senekal [23], the operating, design and storage efficiencies are very closely related and in most of the cases by changing one it would have an influence on the other two. These three efficiencies may be determined by means of utilizing a mathematical model, which is a specific audit strategy and will be discussed later on.

As an example of operating efficiency, consider an oxygen plant that has electric motor driven compressors as well as steam turbine driven compressors. During peak hours, steam is cheaper than electricity, which means that just by changing production schedules of the electric and steam trains during these times (increasing production of the steam trains and lowering that of the electric trains), significant energy cost savings may be realized.

- **Design efficiency**

Design efficiency entails the evaluation of the plant's efficiency by taking into account the system's design. Restraining factors in the design are identified and by altering design parameters, the auditor can determine possible ways of optimization. These design deficiencies are normally the cause of:

- Inadequate design – from an energy manager's point of view.
- Inefficient equipment – a cause of equipment deterioration and/or the availability of improved and more energy efficient technology.

For example, at one plant, motor-generator sets are used for bringing the large air compressor motors up to speed. The MG sets were installed twenty years ago and, compared to soft starter technologies available today, are much more unreliable. The unreliability of the MG set caused numerous startup delays in the past, resulting in significant production losses, with the implication that production department insisted that the air compressors be kept online even when product demand is low. This decision acts as a barrier to potential energy savings that lies in taking an air compressor off-line when demand is low. Thus, by changing the original design through introducing better technology (implementing better soft starter technology), may lead to potential energy cost savings.

- **Storage efficiency**

Often there are cost saving opportunities by using storage facilities more efficiently. This can be seen in the case were the plant has a LOX tank facility to its disposal. Excess LOX can be pumped to the tank during off-peak times and can then be used later on to supplement the demand during peak times. Because there is now an extra supply channel, it leads to the air compressors having to produce less compressed air and ultimately results in energy cost savings.

- **Information efficiency**

Information efficiency refers to the availability and nature of the relevant information necessary for conducting the energy management program. Correct and accurate information is vital to the energy management program and the energy manager must make sure that relevant information is easily accessible.

For instance, data concerning the state (flows, pressures, temperatures, purities etc.) of air commodities within the plant and each of the respective trains, is crucial performing certain energy management activities and barriers restricting the accessibility and availability of this information should be addressed and overcome, if the energy management effort is, by any means, going to be successful.

4.4.2.3. Energy audit policy

The audit policy scopes the auditing work to be done and basically serves as a guideline in the auditing process. It is advisable to establish a formal energy audit policy, because it gives direction to the audit process and for the holistic approach, this policy should enable the assessment of all the relevant plant efficiencies, mentioned earlier.

4.4.2.4. Energy audit strategy

In order to determine the plant efficiencies, as stated in the audit policy, audit strategies are utilized and those that are most relevant are (also refer to Turner [16]):

- Familiarization with plant characteristics and operation.
    - The questionnaire.
    - The walk audit.
    - The measurement audit.
    - Database building.
    - Mathematical model.
    - Financial analysis and feasibility studies.

Each strategy will now be looked at in more detail in the sections that follow.

- **Familiarization with plant characteristics and operation**

For the audit to bear meaningful results, the energy manager should first attain a relatively thorough understanding of the characteristics of the plant as well as its production policy. This entails the following:

- Understanding of operating characteristics and production policy – This also includes identifying the input and output streams to and from the plant.
- Construct relevant process flow diagrams – This includes process models of the plant and relevant sub-systems. Also, identify and make a list of all the energy consuming components; include attributes such as equipment ratings, purpose of equipment and quantity of each.
- Establish the user requirements for the plant and critical sub-sections.

The key principles in plant familiarization will now be applied by taking the oxygen plant at Sasol Secunda, as an example.

- *Understanding of operating characteristics and production policy*

The oxygen plant is part of a process chain and to have an idea of where it fits into the overall system, the following two tables shows the inputs of and outputs to and from the oxygen plant.

Table 4.1: Details surrounding commodity inputs to the oxygen plant at Sasol Secunda.

Inputs	From plants	Commodity usage
Cooling water	Water works	Cooling of electrical motors
Electrical power	Distribution	To drive electric motors
Instrument and Plant air	Air utilities	Instrumentation and sealing gas for expansion turbines and oxygen compressors

Table 4.2: Details surrounding commodity outputs from the oxygen plant at Sasol Secunda.

Outputs	To plant
Oxygen	Gasification and Gas-reforming
Nitrogen	Synthol, Rectisol, Poliprop and Polifin
LOX	Kripton/Xenon plant
Instrument air	Supplying various factory loads

The plant is running at full load twenty-four hours per day seven days a week. All the outputs must be produced with minimal stoppage. The plant also incorporates a very useful buffer system: a LOX tank which is supplemented with excess LOX at times when oxygen demand is relatively low or whenever there is spare capacity available. The LOX tank serves the purpose of supplementing oxygen demand at peak times when the available capacity isn't able to match the demand. Because atmospheric temperature plays such an important role in producing excess LOX, this commodity is usually fed to the LOX tank overnight when temperatures are relatively low.

There is a balance to be maintained in producing the various products, which means that a change in major output streams has a definite influence on the other output products. There is, however, priority assigned to the production of each commodity, detailed in table 4.3.

Table 4.3: Prioritization of output products of the oxygen plant.

Priority	Product	Implication of production loss
1 (highest)	Oxygen & Nitrogen	Substantial production loss
2	Nitrogen	Substantial production loss
3	Instrument air	Non-critical plants trip
4 (lowest)	LOX	Production loss at Krypton/Xenon plant

- *Construct relevant process flow diagrams*

The oxygen plant comprises of seven oxygen trains as well as a spare oxygen compressor and the outline of the plant is shown in figure 4.3.

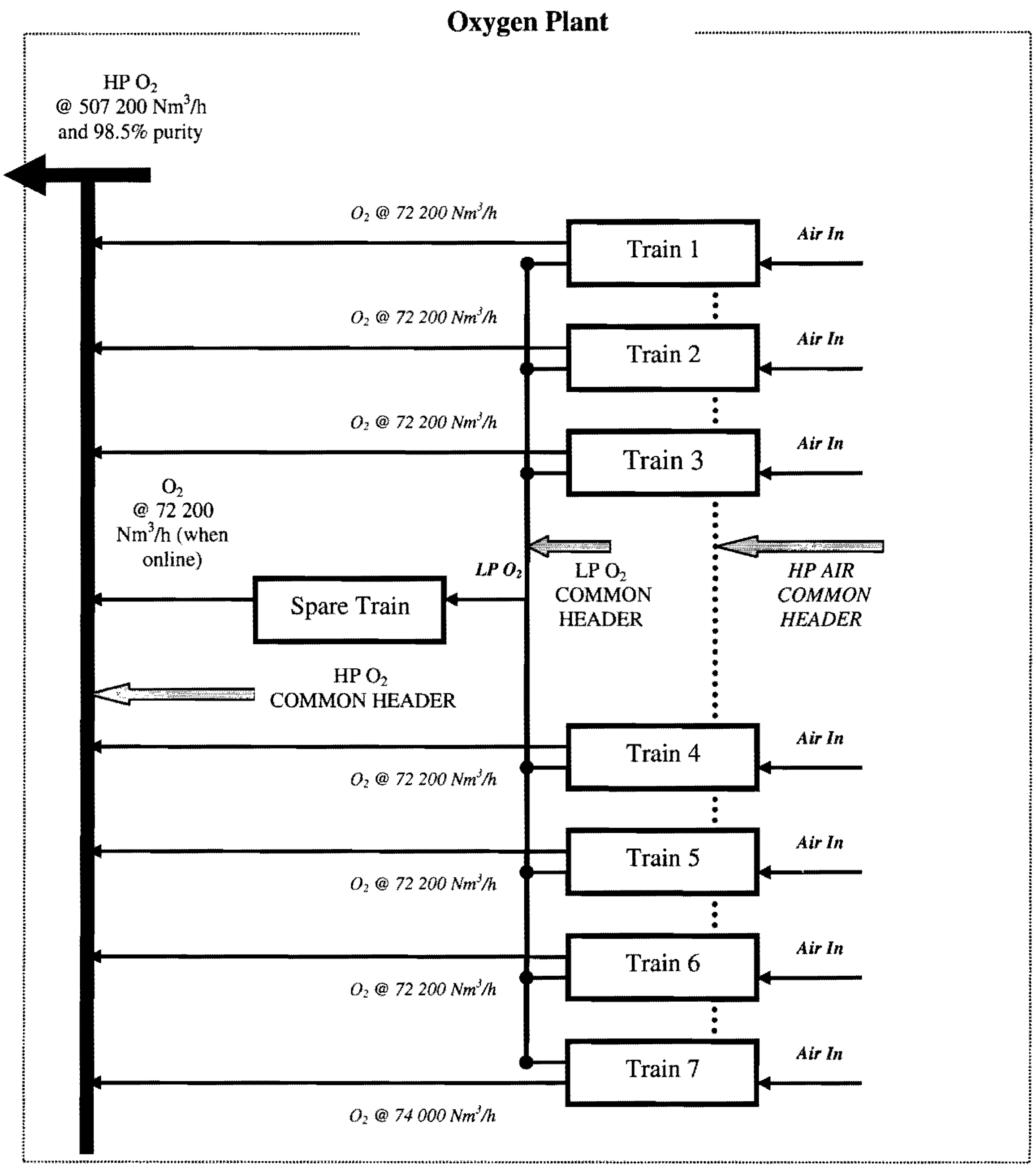

Figure 4.3: Basic outline of the oxygen plant at Sasol Secunda. The flows presented here are the steady state maximum amounts of oxygen that each train is able to produce.

The trains are linked by means of three common headers: the air, LP oxygen and HP oxygen common headers. Each train can sustain a continuous production of up to 72 200Nm^3/h of oxygen, except for train 7, which has a slightly higher capacity (74 000Nm^3/h), resulting in a collective maximum production capacity of 507 200Nm^3/h for the plant.

The main product, high purity gaseous oxygen, is produced at 98.5% purity (minimum), which is pumped into a common header and distributed to the various loads within each factory (gasification and gas-reforming).

The main purpose of the air common header is to minimize losses whenever an air compressor goes offline. In normal operation however, there is little or no air exchange between trains but as soon as one air compressor goes offline, the air present in the common header supplies that train's air demand. Trains 1-6 are connected to the air common header with train seven working in isolation. Usually the air valve of train seven remains closed; it is only in abnormal circumstances that it is opened, but then only by a relatively small amount.

A control system monitors and controls the production of compressed air and it does this by monitoring the compressed air demand and then opening or closing the guide vanes of all six compressors by an equal amount, thus effectively sharing the load equally between the six air compressors.

The spare train consists *only* of an oxygen compressor and is put online whenever one of the other oxygen compressors is taken out of operation (e.g. due to breakdown or for routine maintenance). Each train has two oxygen outlets, namely: the high-pressure (HP) outlet and the low-pressure (LP) outlet. In normal operation the train's LP oxygen output is isolated from the LP common header via a valve, but as soon as that train's oxygen compressor is out of operation the valve opens, enabling the LP oxygen to enter the common header and the spare oxygen compressor goes online.

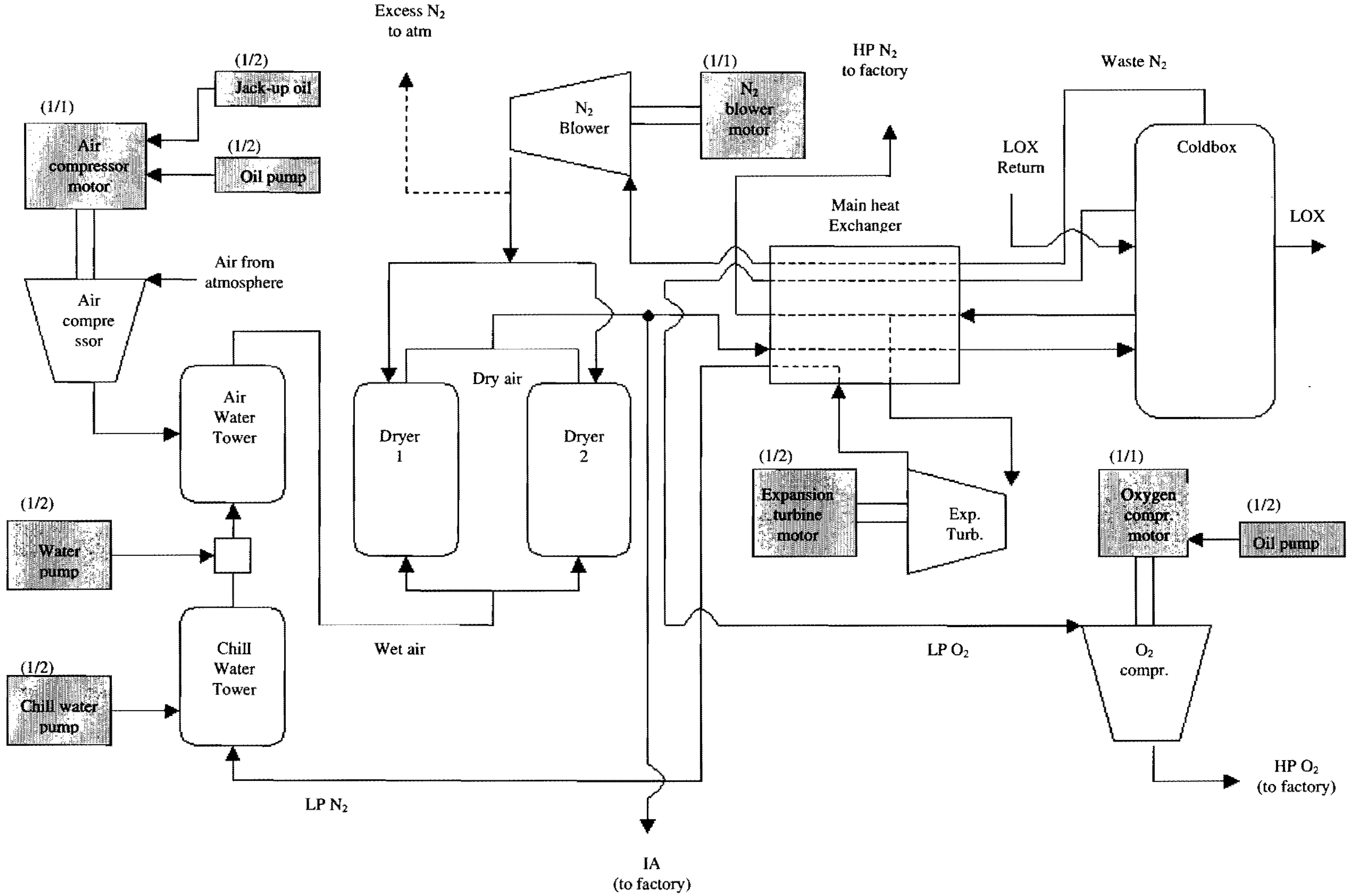

Figure 4.4: Process flow of a single oxygen train.

Figure 4.4 shows the process flow of a single train. All the electric utilizing equipment are highlighted. Note the quantity and process requirements are also brought onto this process flow diagram, for example, (1/2) means that process requirements need one of the two installed equipment types during normal operation.

Table 4.4: Summary of electrical machinery ratings and capacity requirements for production means.

Motor description	**Rating**	**Quantity/O2 train**	**Production requirement: QTY online**	**Operating time/day**
Expansion turbine motor	525 kW	2	1	24 h
Nitrogen blower motor	300 kW	2	1	24 h
Oxygen compressor motor	13.7 MW	1	1	24 h
Air compressor motor	37 MW	1	1	24 h
Chill water pump motor	75 kW	2	1	24 h
Water pump motor	132 kW	2	1	24 h
Jack-up oil pump motor	36 kW	2	1	24 h
Installed capacity				*52.836 MW*
Utilized capacity				*51.678MW*
% Utilization				*98. 0%*

- *Establish the user requirements*

Table 4.5 lists the user requirements for the oxygen plant's output products.

Table 4.5: Summary of the user requirements for each product.

Product	**Quantity** *(kNm^3/h)*	**Purity (min)**	**Delivery *p* (min)** *kPa*	**Delivery *p* (max)** *kPa*
Oxygen	72000	98.5%	3440	3480
Nitrogen	22000	99.9%	420	430
LOX	3500	-	100	120
IA	8000	-	420	450

- **The questionnaire**

In conducting the energy audit, the energy manager would undoubtedly find it necessary to conduct interviews with key personnel. The questionnaire is a structured and well-planned approach in acquiring important information from personnel and it is imperative to identify the appropriate personnel when conducting the audit. For example, determining maintenance practices by interviewing production personnel would, in most cases, give a distorted picture of the actual situation or, in other instances, not bear any meaningful results at all.

It is very important that the questionnaire is planned thoroughly in advance. The energy manager should aim to attain as much information as possible with the least amount of questions since personnel do not always have adequate time available.

- **The walk audit**

The walk audit goes hand-in-hand with plant familiarization and it enables the energy manager to view the plant first hand. It entails determining the state of the plant, and in order for the energy manager to make this audit value adding, it would be a good idea to also take a guide along, one who is experienced with the equipment and the operation of the plant.

- **The measurement audit**

Relevant measurements of energy consumption, flows, pressures and temperatures can be taken whenever there is no automatic measurement system in place, but at most of these plants real-time data collection is in place and data may simply be downloaded from were it is stored.

- **Database building**

Because the audit process is such an important phase in the energy management program all the data collected should be stored for easy reference. The database is a collection of various pieces of information in different formats and it is thus important to have a structure in place in which the information is organized in a meaningful manner. The database should compose of the following:

- Results from other audits conducted
- Specifications of machine ratings
- Process & equipment limitations and constraints
- Operating schedules of plant
- Maintenance strategies and schedules

- **Financial analysis and feasibility studies**

One output of the energy audit process is the identification of potential improvement opportunities and in response to this, the energy manager is now concerned with identifying alternatives as the means for realizing the different improvements.

Normally, most of the options would require capital investment to realize and the problem is that the benefits resulting from an investment option is stretched over a period of time whereas the investment is required now. Thus, feasibility studies are conducted with the aid of financial analysis tools, and only the most feasible option for each alternative should be considered.

- **Energy conversion model**

The energy model is an important auditing tool and adds great value to the energy management program. The basic idea behind the energy conversion model is to express the plant's power consumption as a function of main air product output, under certain conditions. From the cryogenic air separation plant's point of view a fairly accurate model may be very complicated, but it will be the aim of this section to present model building blocks that are relatively simple whilst still providing adequate accuracy.

As Delport [24] mentions, there are basically two levels within process modeling. The first level is the physical model, which is the energy manager's understanding of the real world system in conjunction with the following restraining factors:

- assumptions and simplifications that are in line with the model accuracy and requirements,
- level of detail that has been decided upon,
- system and subsystem boundaries,
- data requirements and availability.

The second level in process modeling is the energy conversion model, which is the mathematical representation of the physical model. The difference between the physical model and energy conversion model should be noted: the physical model is an abstraction of the real world system and the energy conversion model is an abstraction of the physical model.

In order to derive an energy model for the plant, the plant first needs to broken down into its various levels of subsystems as shown in figure 4.5. It should be noted that the air purification system and all other auxiliary equipment have been omitted from this system breakdown, this is because it is assumed that the energy loss through the purification system is negligible and the energy consumption of all other auxiliary equipment is insignificant compared to that of the compressor motors. It may be that in certain plants the auxiliary equipment may not be insignificant at all, in these situations the energy manager is urged to derive models for these subsystems as well.

Whole Industry	**CRYOGENIC AIR SEPARATION PLANT**							
End-User Groups	**Trains 1 to n**							
Processes	***Air Compression System***		***Air Separation Process***			***Product Compression System***		
Machinery	Air Compressor	Motor	Air purification system	Main Heat Exchanger	Distillation Columns	Product Compressor	Motor	

Figure 4.5: Simplified system breakdown structure of the cryogenic air separation plant.

From figure 4.5 the following is clear:

$$P_{plant} = \sum_{m=1}^{n} P_{train\ m} \tag{1}$$

where:

- n is the number of trains
- P_{plant} is the power consumption of the cryogenic air separation plant *(MW)*
- $P_{train\ m}$ is the power consumption of train m *(MW)*

Neglecting power consumption of auxiliary machinery, the power consumption for each end-user group will be as stated in equation (2).

$$P_{train\ m} = P_{AC,m} + P_{PC,m} \tag{2}$$

where:

- $P_{AC,m}$ is the input power of air compressor motor of train m *(MW)*
- $P_{PC,m}$ is the input power of product compressor motor from train m *(MW)*

The input power for a compressor motor is:

$$P_{x,m} = \frac{P_{x,m}^{shaft}}{\eta_{x,m}} \tag{3}$$

where:

- x refers to the motor of a compressor type x, i.e. the motor driving the air or product compressor.
- m is the train number.
- $P_{x,m}$ is the input power of type x compressor motor of train m *(MW)*

- $P_{x,m}^{shaft}$ is the shaft power (output power) of type x compressor motor of train m *(MW)*
- $\eta_{x,m}$ is the electromechanical efficiency of type x compressor motor of train m.

It is a fact that when a gas is compressed its temperature rises significantly and if this increase in temperature is too much, it would cause the oil to ignite and deteriorate mechanical parts. This places a restriction on the compression ratio (ratio of absolute outlet pressure to absolute inlet pressure) of the compressor and hence, this ratio is rarely greater than three (Air Liquide [5]).

Because of this constraint, multi-stage compression with inter-cooling is implemented to achieve the required output pressure. Inter-cooling is normally realized through either air- or water-cooling, however air-cooling is normally limited to smaller size compressors. Water-cooling is the more effective of the two, because of its ease of control and greater heat absorption capability (Talbott [25]).

Another reason for employing multi-staging in compressors is because of its energy saving attribute; the energy saving is achieved because cooling the air down between stages reduces the inlet air volume of the next compression stage and hence the work required to complete the compression (Salisbury [26] and Talbott [25]).

The operation of the multi-stage compressor can be followed by referring to the pressure-volume diagram in figure 4.6. The area enclosed by 1-2-3-4 represents the adiabatic work to be done by the compressor to compress a gas from a pressure of p_1 to p_2. The area demarcated by 1-2-5-4 represents the necessary work for isothermal compression.

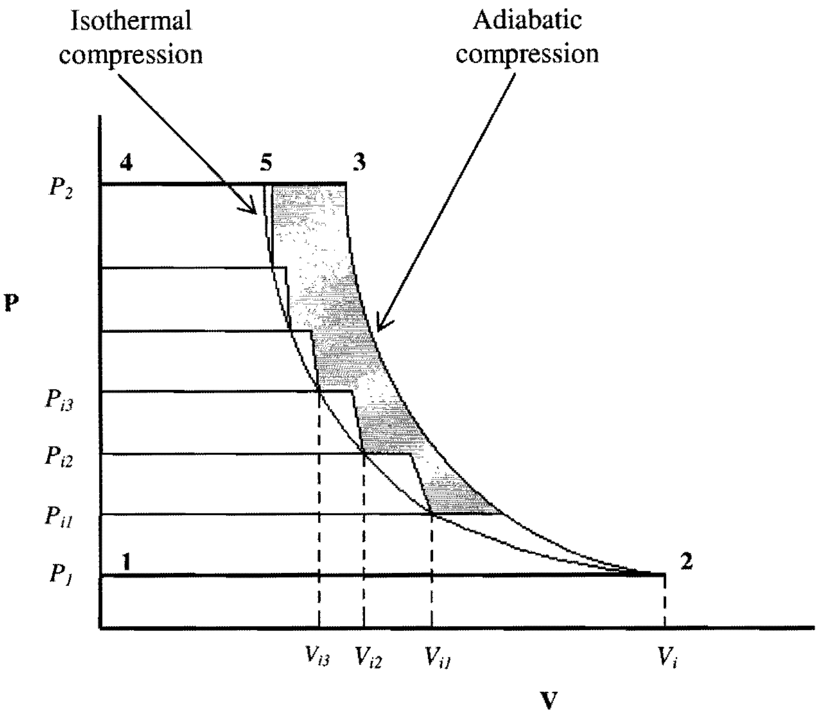

Figure 4.6: Multi-stage compression cycle with interstage cooling (Coulson *et al.* [27]).

Because the gas inlet temperature at each stage stays constant, one can see that actual compression takes place near the isothermal curve. Thus, a simplifying assumption would be to approximate the compressor characteristic by assuming isothermal compression.

Thus, the shaft power required by the compressor will be as expressed by equation (4).

$$P_{x,m}^{shaft} = \frac{P_{x,m}^{out}}{\eta_{I_{x,m}}} \tag{4}$$

where:

- $P_{x,m}^{out}$ = output power of type x compressor of train m *(MW)*
- $\eta_{I_{x,m}}$ = isothermal efficiency of type x compressor of train m

The output power of the compressor is a function of the intercooler temperature, the air flow and the pressure ratio and for isothermal compression, this relationship is expressed as in equation (5) (refer to Baumeister *et al.* [28] & Salisbury [26]):

$$P_{x,m}^{out} = k \times Q_{x,m} \times T_{IC} \times \ln\left(\frac{p_{x,m}^{out}}{p_{x,m}^{in}}\right) \tag{5}$$

where:

- $k = 1.03 \times 10^{-4}$
- $Q_{x,m}$ is the gas flow from compressor of type x of train m *(kNm³/h)*
- T_{IC} is the intercooler temperature *(K)*
- $p_{x,m}^{out}$ is the gas absolute output pressure of type x compressor of train m *(kPa)*
- $p_{x,m}^{in}$ is the absolute inlet pressure of type x compressor of train m *(kPa)*

In cryogenic air separation, air is separated into its constituents and only by knowing the constituent ratio of the main air product in a sample of air, it is possible to determine the airflow at the input of the train.

$$Q_{AC,m} = \frac{Q_m^{pure}}{r_{main\ product}} \tag{6a}$$

where:

- $Q_{AC,m}$ is the air flow from air compressor of train m *(kNm³/h)*
- Q_m^{pure} is the total flow of (pure) main air product that originally entered the air compressor of train m *(kNm³/h)*
- $r_{main\ product}$ is the constituent ratio of the air product in a sample of air. For oxygen this ratio is 20.9% and for nitrogen this is 78.0%; refer to table 2.1.

If there exists an air common header connecting all the trains, the main output product may not necessarily be a result of solely the airflow at that particular train's input since air exchange between trains does occur, and even more so in the case of an air compressor being out of operation. A good approximation would be to average out the total airflow over all the trains. In this case, equation (6a) takes on the form of equation (6b).

$$Q_{AC,m} = \left(\frac{1}{nr_{main\ product}} \right) \sum_{m=1}^{n} Q_m^{pure} \tag{6b}$$

The main product is rarely 100% pure, there is, to some acceptable extent, impurities present in the substance as well. Secondly, this product is produced with some amount of loss within the air separation process; this loss is quantified in terms the recovery efficiency. Thus, to obtain the total flow of the pure product that originally entered at the air compressor side:

$$Q_m^{pure} = Q_{PC,m} \times \frac{Purity_{main\ product,m}}{\eta_{rec,m}} \tag{7}$$

where:

- $Q_{PC,m}$ is the flow rate of the main product from product compressor of train m (kNm^3/h).
- $Purity_{main\ product,m}$ is the purity of the primary output product of train m
- $\eta_{rec,m}$ is the recovery efficiency of which the air separation process recovers the primary constituent of air that originally entered the process.

It is now possible to compute the air flow, however, the air discharge pressure is still needed for computation of the compressor power consumption. There is a definite relationship between the air discharge pressure and air flow, and this relationship is defined by the system characteristic. The system needs a specific discharge pressure at a certain flow rate from the air compressor and the relationship between these two parameters in the normal operating region of the compressor, may be approximated, quite accurately, by a linear model as shown in figure 4.7.

Thus, discharge pressure as a function of air flow will be as shown in equation (8).

$$p_{AC,m}^{out} = h_m + g_m Q_{AC,m} \tag{8}$$

where h_m and g_m are the constants for train m and may be determined by means of linear regression.

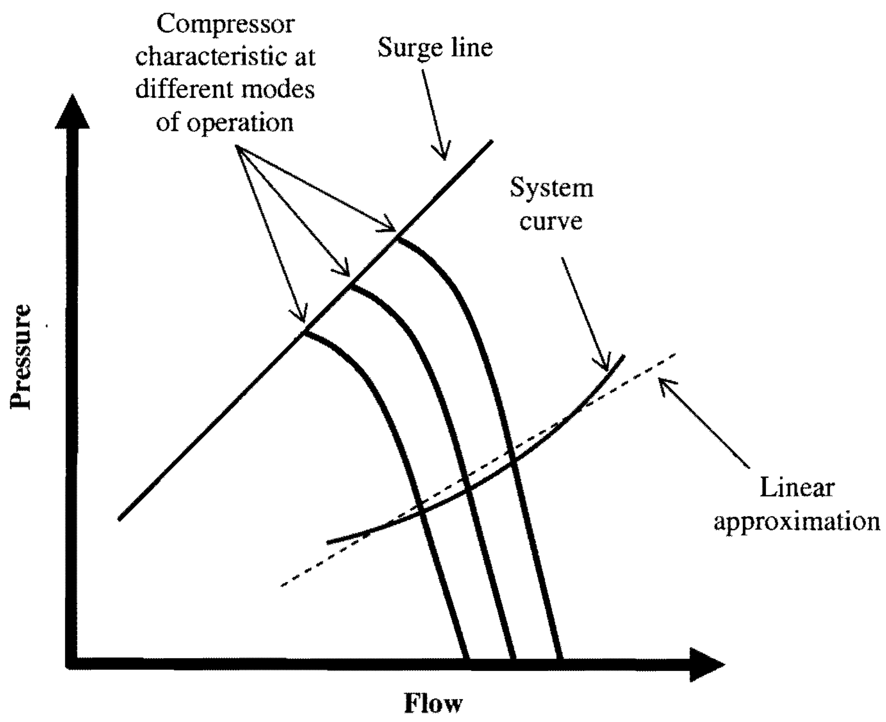

Figure 4.7: Linear approximation of system curve.

Although cryogenic air separation trains may have been designed in exactly the same manner, it is a fact that over time they drift in their parameter commonalities and by applying modeling parameters in one train to other trains as well would ultimately result in high inaccuracy of the overall plant model. Thus, certain parameters of the model should be done empirically train by train. Empirical modeling should be sufficient only for all the critical elements of each train which include:

- electromechanical efficiency of each compressor motor,
- isothermal efficiency of the air and product compressor,
- recovery efficiency of the air separation process.

Determination of the electromechanical efficiencies should be enabled through employment of the correct maintenance strategy, as will be discussed in the next chapter. If there is no initial data available concerning the current state of the motor, an assumption should be made at first.

The recovery, $\eta_{rec,m}$, is a symptom of the current state the ASU, thus essentially modeling this system; it is determined by taking the average over a sufficient sample period.

The isothermal efficiency of the compressor is a function of the gas flow, pressure and intercooler temperature. The pressure range in which these compressors are suppose to operate in is usually relatively small and the empiric modeling of the isothermal efficiency may be approximated, quite accurately, by a linear model.

$$\eta_{I_{x,m}} = a_{x,m} \times Q_{x,m} + b_{x,m} \times \frac{p_{x,m}^{out}}{p_{in,x}} + c_{x,m} \times T_{IC} + d_{x,m} \tag{9}$$

where $a_{x,m}$, $b_{x,m}$, $c_{x,m}$ and $d_{x,m}$ are constants of compressor type x of train m and are determined by means of linear regression. Multiple variable linear regression techniques like, for example, that described by Makridakis *et al.* [29] should be utilized in determining the constants. If there is no empirical data available for the compressor motors as yet, the motor efficiency and the isothermal efficiency of the compressor may be lumped together (i.e. making it one system) and this overall efficiency is then empirically modeled as in equation (9); this means that the model then (equation 9) encapsulates the compressor efficiency as well as the motor efficiency.

Substitution of these equations leads to the final energy conversion model, stated in equation (10). For a discussion on the application and verification of the abovementioned energy conversion model, the reader is encouraged to refer to the case study presented in the appendix.

$$P_{plant} = \sum_{m=1}^{n} \left(\frac{\frac{k}{nr_{main\ product}} \left(\sum_{m=1}^{n} Q_{PC,m} \times \frac{Purity_{main\ product,m}}{\eta_{rec,m}} \right) \times T_{IC} \times \ln \left(\frac{h_m + \frac{g_m}{nr_{main\ product}} \left(\sum_{m=1}^{n} Q_{PC,m} \times \frac{Purity_{main\ product,m}}{\eta_{rec,m}} \right)}{p_{AC,m}^{in}} \right)}{\eta_{AC,m} \times \left(a_{AC,m} \times Q_{AC,m} + b_{AC,m} \times \frac{p_{AC,m}^{out}}{p_{in,AC}} + c_{AC,m} \times T_{IC} + d_{AC,m} \right)} + \frac{k \times Q_{PC,m} \times T_{IC} \times \ln \left(\frac{p_{PC,m}^{out}}{p_{PC,m}^{in}} \right)}{\eta_{PC,m} \times \left(a_{PC,m} \times Q_{PC,m} + b_{PC,m} \times \frac{p_{PC,m}^{out}}{p_{in,PC}} + c_{PC,m} \times T_{IC} + d_{PC,m} \right)} \right) \quad (10)$$

4.4.3. Energy systems maintenance

There is a definite relationship between maintenance management and energy management and in most cases one would find that by initiating an action in one would have a definite effect on the other. In fact, Turner [16] has gone one step further and expressed the need for energy systems maintenance. Energy systems maintenance is defined as the maintenance of all systems that use or affect the use of energy.

Formulation of an energy systems maintenance life-plan, as well as the management thereof, is the responsibility of the energy manager and later on it will be explained on how to assemble such a plan. The output of this maintenance effort is a recommendation and it is up to the energy manager to assist maintenance managers in adopting an energy systems maintenance component into their life pans, which would enable them to consider such a recommendation.

In formulating an energy systems maintenance strategy, the energy manager first has to consider and understand at which point it is appropriate to initiate a suitable maintenance action on relevant equipment. To aid explanation to this question, refer to figure 4.8; from an energy management point of view, this system experiences a functional failure. A functional failure is defined by Campbell [30] as the inability of a physical asset to deliver its expected level of performance. In terms of energy management, this expected level of performance is given in the form of an energy norm or standard. The expected level of performance thus defines what can be considered a failure.

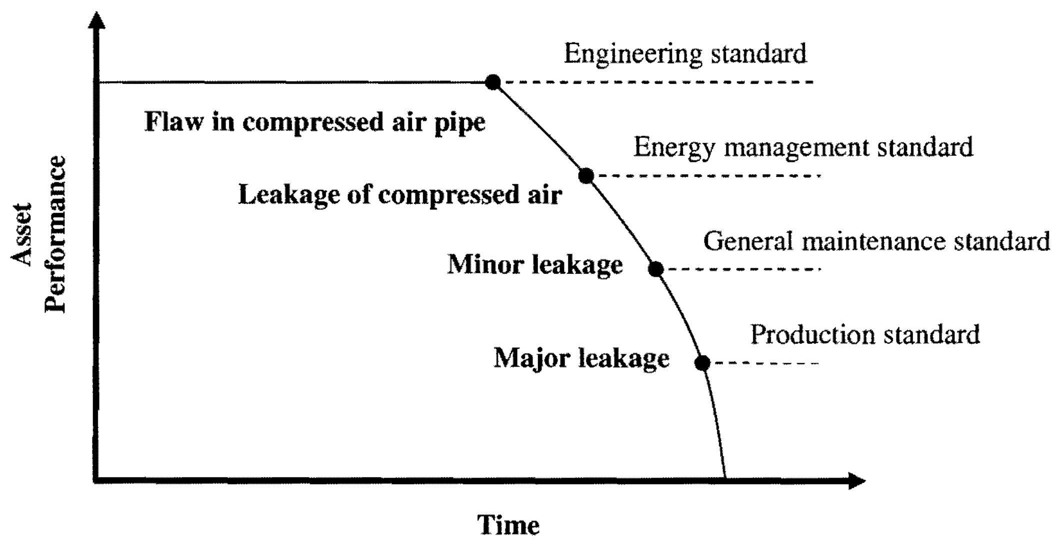

Figure 4.8: Functional failures and performance standards.

Different departments within the plant (engineering, maintenance, production) may differ in asset performance requirements and thus giving rise to the different standards. In this example, the flaw in the compressed air pipe causes a leakage of compressed air leading to a decrease in energy efficiency and money could be saved by initiating a maintenance action sooner than as scheduled by maintenance department.

The energy norm or standard thus defines the not only what should be considered a failure but also the amount of maintenance needed to preserve this level of performance.

The difference in standards frequently creates conflict between various departments and when initiating an energy cost saving maintenance action, the energy manager should first reach a compromise with the different departments. For example, the electrical maintenance department of one plant reported high maintenance costs on the oxygen compressor motors. Maintenance department reported that the motors were at the end of their life-cycle and blamed the more frequent maintenance intervals as the main cause of the rising cost. An energy audit also revealed that the motors lost an average of 9% electromechanical efficiency from their initial value, which gave rise to increased energy cost as well.

Considering these two factors, an oxygen replacement project was proposed with immediate commencement. Production department, however, rejected the proposal because the plant, which already operated at full capacity, would suffer significant production losses during the replacement action and proposed that the project should be postponed to a year from then when an extra oxygen train, currently being constructed at that time, is in full operation, to which the parties agreed upon and thus effectively reaching a compromise.

4.4.3.1. Establishing an energy systems maintenance life plan

Because plant maintenance has such a significant effect on energy efficiency, the energy manager has to establish an energy systems maintenance life plan, aimed at managing electricity cost, that would supplement existing maintenance efforts on the plant.

Energy systems maintenance on only those systems that normally have a major impact on the energy consumption of the train will now be discussed; they are the air and product compressors, the air and product compressor motors, and the ASU.

4.4.3.2. Energy systems maintenance on compressors

Some of the major aspects influencing the energy efficiency of a compressor are the following (Talbott [25]):

- Wear of mechanical parts.
- Component fouling.
- Contamination with impure substances.
- Inadequate or dirty lubricants.

Wear of mechanical parts changes the characteristics of the compressor and ultimately leads to decreased efficiency. Mechanical wear also result from destructive effects dirt particles have, and it is crucial that filtration be kept effective and all inlet piping be kept clean.

Fouling changes the flow and pressure relationship of the compressor and thus changing the characteristic of the original design. Even if a good filter is provided, fouling is inevitable and an obvious effect is the restriction of intercooler passages; this not only causes poor heat transfer between the coolant and gas but also leads to an increased pressure drop over the intercooler resulting in reduced performance (lower efficiency).

Lubricated compressors depend upon oil for both friction reduction and sealing. It is obvious then, that if the oil has to be contaminated or corrosive it would be destructive of both efficiency and valuable capital equipment.

4.4.3.3. Energy systems maintenance on motors

The aim of energy systems maintenance on motors is to improve and preserve the motor's energy efficiency.

The great majority of induction motors are used to drive pumps, fans, blowers and compressors; attempting to increase the efficiency of these motors may well result in reduced motor internal losses but this doesn't necessarily mean reduced input power, unlike the case for synchronous motors, as also motivated by Htsui *et al* [31]. Induction motors with a higher efficiency normally run at a higher speed (lower slip), which ultimately leads to increased compressor load (also refer to Sen [32]). Figure 4.9 shows a graphical representation of this situation.

- **The fan laws**

Suppose that the existing motor (motor 1) is substituted by a new motor (motor 2) of higher efficiency, which inherently has a smaller full load slip; motor 1 operated at operating point 1 (OP 1) and motor 2 now has another operating point (OP 2). The power curve of the new motor intersects the system curve (compressor load) at a higher load speed, resulting in the compressor requiring more shaft power.

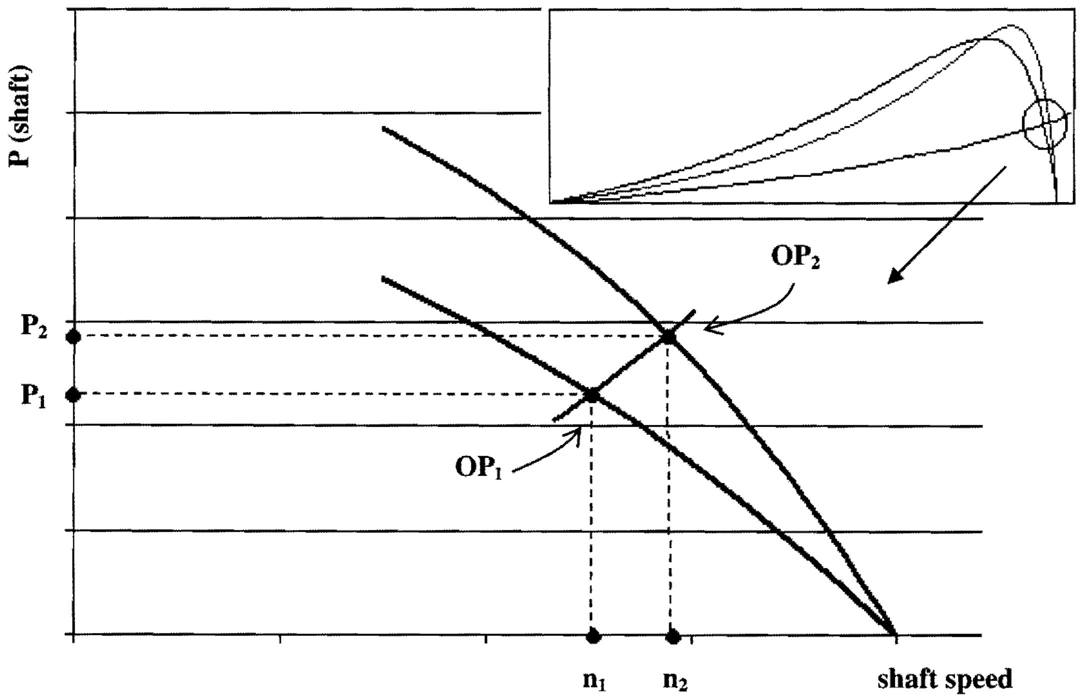

Figure 4.9: Partial power curves of the existing motor (motor 1) and the new motor (motor 2) as well as that of the compressor load, illustrating the implication of installing a higher efficiency motor than is currently in operation.

The reason for the load increasing with increased shaft speed is because of the compressor conforming to the relationships expressed by the fan laws. The following relationships are a statement of the fan laws and are listed by Brown [33]. The fan laws also apply to blowers, fans and pumps and the theory developed here may also be applied to induction motors driving either one of these mechanical devices.

$$Q \, \alpha \, n \quad (11)$$

$$p \, \alpha \, n^2 \quad (12)$$

$$P \, \alpha \, n^3 \quad (13)$$

where:

- n is the shaft rotational speed *(rpm)*
- Q is the gas flow *(kNm³/h)*
- p is the discharge pressure of the gas *(kPa)*
- P is the power requirement of the compressor *(MW)*

Thus, the gas flow is proportional to the shaft speed, the discharge pressure is proportional to the square of the shaft speed and lastly the compressor power requirement is proportional to the cube of the shaft speed. Equating the above relationships, gives the following, as stated by Salisbury [26] and Baumeister *et al.* [28].

$$Q_2 = Q_1 \left(\frac{n_2}{n_1} \right) \quad (14)$$

$$p_2 = p_1 \left(\frac{n_2}{n_1} \right)^2 \quad (15)$$

$$P_2 = P_1 \left(\frac{n_2}{n_1} \right)^3 \quad (16)$$

Were the *1* and *2* subscripts refer to the initial and new conditions, respectively. Thus, by knowing the compressor performance at one speed, one may predict its performance at another speed.

Figure 4.10 shows a typical compressor characteristic curve as well as the characteristic at other speeds, other than the nominal.

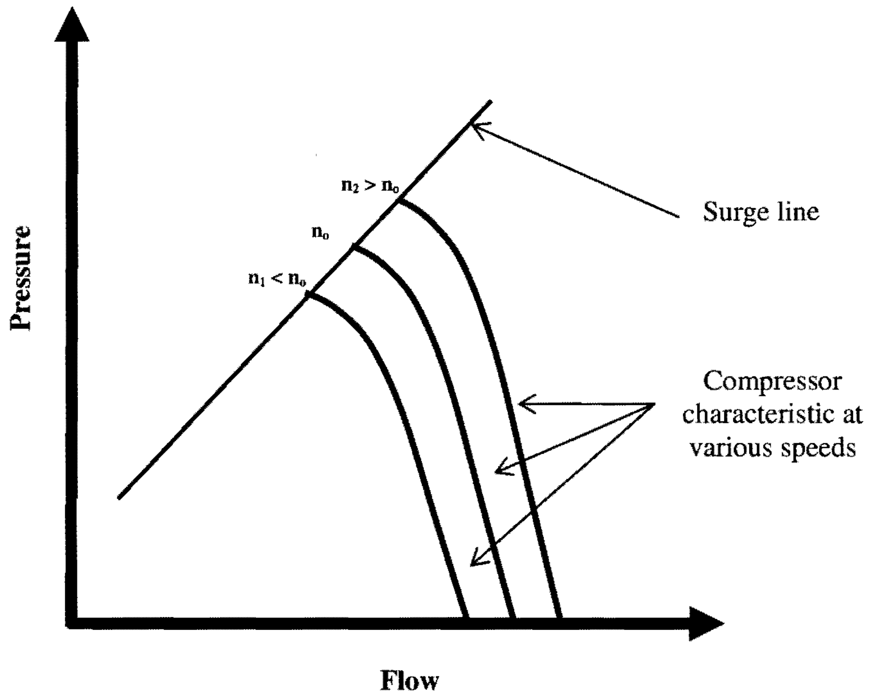

Figure 4.10: Compressor characteristic curve at various shaft speeds.

- **Energy efficiency analysis**

At this stage it becomes quite obvious that there are two contradicting factors presenting themselves: if a higher efficiency motor is installed the motor internal losses have been reduced, but at the same time, the motor is most likely to run at a lower slip, leading to increased shaft power demand.

Thus, it becomes clear that an action aimed at reducing electricity cost by improving the motor efficiency may not be as simple and the energy manager or person in charge should have a means for quantifying the actual feasibility such an action would have.

Installing a new motor for the aim of reducing electricity cost should only become an option when, at least, the following statement is true:

$$P_{in2} < P_{in1} \tag{17}$$

were P_{in1} and P_{in2} are the input power to motor 1 (current motor) and motor 2 (new motor), respectively. After substitution, equation, (17) becomes:

$$\frac{P_{out2}}{\eta_{m2} \times \eta_{D2}} < \frac{P_{out1}}{\eta_{m1} \times \eta_{D1}} \tag{18}$$

where:

- P_{out1} and P_{out2} are respectively the output power of the current and the new motor at normal operating conditions.
- η_{m1} and η_{m2} are respectively, the electromechanical efficiency of each motor.
- η_{D1} and η_{D2} are respectively, the efficiency of the device (compressor, blower, fan etc.) at the operating point of motor 1 and that of motor 2.

What is now needed is an indicator, which would inform the energy manager on whether a new high efficiency motor would consume less power than the existing one. This indicator is defined here as the threshold efficiency, which is the efficiency the new motor should at least have to be the more feasible option. The inequality expressed in (18) can be rearranged to give the following:

$$\eta_{m2} > \eta_{m1}\left(\frac{P_{out2}}{P_{out1}}\right) \times \left(\frac{\eta_{D1}}{\eta_{D2}}\right) \tag{19}$$

The fan law implies that in changing the shaft speed of the compressor, its efficiency stays constant, i.e. $\eta_{D2} = \eta_{D1}$ and by inserting equation (16) in (19), equation (20) is obtained.

$$\eta_{m2} > \eta_{m1}\left(\frac{n_2}{n_1}\right)^3 \tag{20}$$

The operating speed of each motor is where the compressor load curve intersects each motor's power curve, thus n_1 and n_2 may only be determined by actually plotting the motor curves with that of the compressor load. For the energy engineer to make a clear decision on whether to upgrade motor efficiency, it becomes clear that there should be a maintenance strategy in place that result in the assessment of the motor's current condition. And as stated earlier, this assessment is made in terms of the motor efficiency as well as the power or toque curve of the motor. This assessment is the responsibility of the rewinder or the person responsible for the refurbishment of the motor.

The operating speed of the new proposed motor can be expressed in terms of its full load speed and other known variables. For low slip values, the power curve may be approximated by a linear relationship as shown in figure 4.11, which leads to equation (21).

$$P_2 = \left(\frac{P_{FL2}}{n_s - n_{FL2}}\right)(n_s - n_2) \tag{21}$$

where:

- subscript *2* refers to the new proposed motor.
- P_2 is the output power *(MW)*
- P_{FL2} is the rated full load shaft power *(MW)*
- n_s is the synchronous speed *(rpm)*
- n_{FL2} is the rated full load speed *(rpm)*

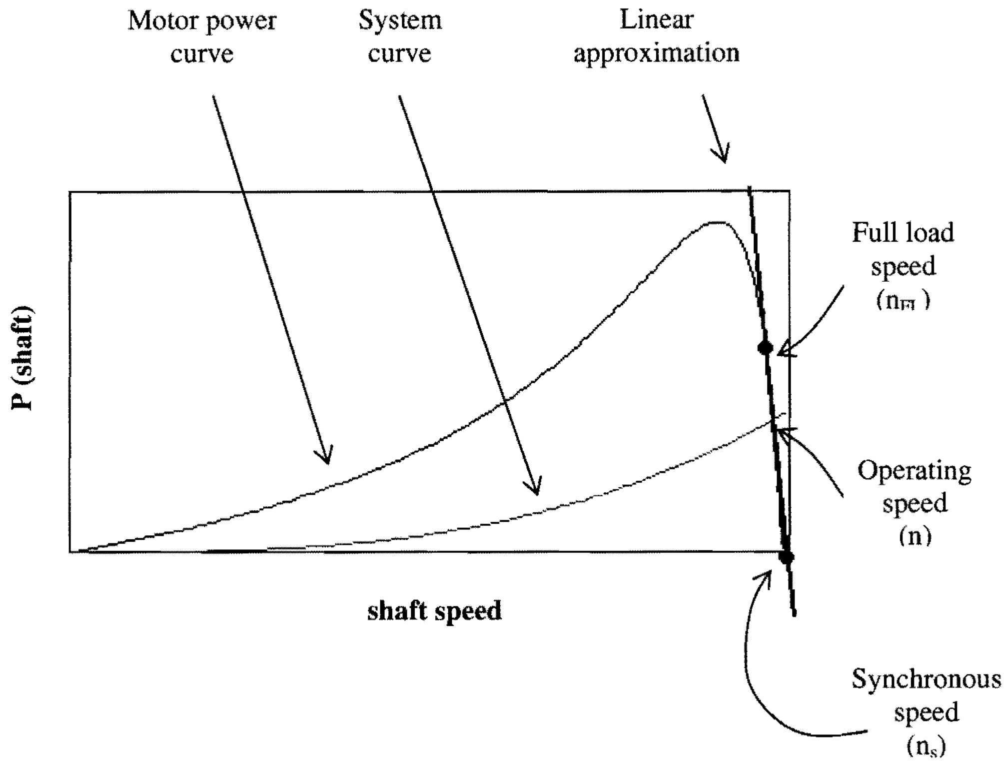

Figure 4.11: Approximating the power curve with a linear model at low slip values.

Applying the fan law by substituting equation (16) into (21) and rearranging to solve for n_2,, gives the following:

$$\frac{\eta_{m1}P_{in1}(n_s - n_{FL2})}{n_1^3 P_{FL2}} n_2^3 + n_2 - n_s = 0 \tag{22}$$

This is a cubic equation and can be solved by applying Cardan's solution [34]. From Cardan's solution the equation has one real root and gives the approximate load speed the proposed new motor will operate at.

$$n_2 = n_1 \left[\frac{P_{FL2}}{\eta_{m1}P_{in1}(n_s - n_{FL2})} \right]^{\frac{1}{3}} \times \left[\left(0.5n_s + \sqrt{\frac{n_1^3 P_{FL2}}{27\eta_{m1}P_{in1}(n_s - n_{FL2})} + \frac{n_s^2}{4}} \right)^{\frac{1}{3}} + \left(0.5n_s - \sqrt{\frac{n_1^3 P_{FL2}}{27\eta_{m1}P_{in1}(n_s - n_{FL2})} + \frac{n_s^2}{4}} \right)^{\frac{1}{3}} \right] \tag{23}$$

Substituting (23) into inequality (20) gives the requirement, in terms of its full load speed and efficiency, the new motor should conform to for it to be a more energy efficient option.

$$\eta_{m2} > \left[\frac{P_{FL2}}{P_{in1}(n_s - n_{FL2})}\right] \times \left[\left(0.5n_s + \sqrt{\frac{n_1^3 P_{FL2}}{27\eta_{m1}P_{in1}(n_s - n_{FL2})} + \frac{n_s^2}{4}}\right)^{\frac{1}{3}} + \left(0.5n_s - \sqrt{\frac{n_1^3 P_{FL2}}{27\eta_{m1}P_{in1}(n_s - n_{FL2})} + \frac{n_s^2}{4}}\right)^{\frac{1}{3}}\right]^3 \quad (24)$$

- **Case study**

Suppose the existing motor of figure 4.9 is considered for replacement. This is a four-pole, 13.7MW machine, it is fifteen years old and have been rewound three times during its productive life. The decision to do a feasibility study comes after assessment of its current condition, which is detailed in table 4.6.

Table 4.6: Current motor parameter values.

Parameter	Value
P_{in1}	13.2 MW
η_{m1}	93%
n_1	1487 rpm

Substituting these parameter values into (24) results in the graph depicted in figure 4.12. This curve is basically a motor selection curve for selecting a new 4 pole, 13.7MW induction motor, as it houses the criteria for the proposed new compressor motor being more energy efficient than the existing one. Now, suppose there are three suppliers of these motors as detailed in table 4.7.

Table 4.7: Three suppliers of a 4-pole, 13.7MW induction motor with their respective ratings.

Supplier	Motor efficiency	Motor rated full load speed
1	97.0%	1492
2	96.0%	1490
3	97.5%	1496

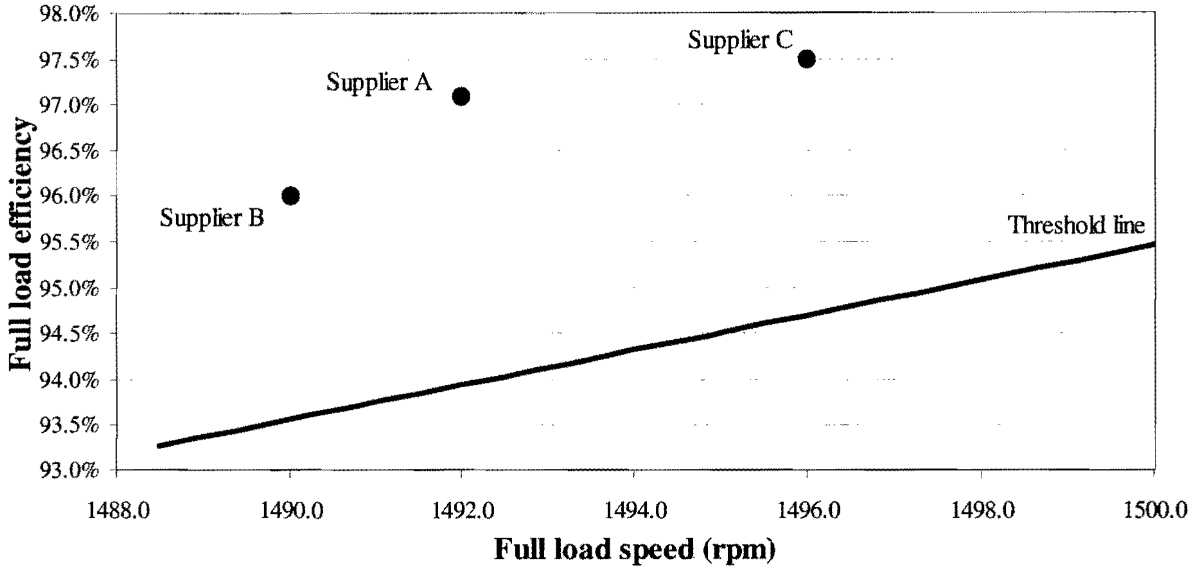

Figure 4.12: Threshold efficiency, proposed new motor should adhere to, as a function of its full load speed.

As can be seen from the graph, all three motors will in each case improve the energy efficiency of the current compression system, for they have ratings that enable them to be above the threshold line.

Now that we know that energy efficiency will be improved regardless of what motor is selected, the next step would be to quantify the energy saving in each case and, obviously, the motor with the largest energy saving would ultimately be the most feasible option from an energy manager's point of view.

P_{in1} and P_{in2} have been defined in (8), and taking the ratio of these gives:

$$\frac{P_{in2}}{P_{in1}} = \left(\frac{\eta_{m1}}{\eta_{m2}}\right)\left(\frac{n_2}{n_1}\right)^3$$

or,

$$P_{in2} = P_{in1}\left(\frac{\eta_{m1}}{\eta_{m2}}\right)\left(\frac{n_2}{n_1}\right)^3 \tag{25}$$

thus,

$$Power\ saving = P_{in1} - P_{in2} = P_{in1}\left[1-\left(\frac{\eta_{m1}}{\eta_{m2}}\right)\left(\frac{n_2}{n_1}\right)^3\right] \tag{26}$$

Substituting n_2 of equation (23) into (26) gives the approximate power saving in terms of the known quantities.

$Power\ saving =$

$$P_{in1}\left[1-\left(\frac{P_{FL2}}{\eta_{m2}P_{in1}(n_s-n_{FL2})}\right)\times\left[\left(0.5n_s+\sqrt{\frac{n_1^3P_{FL2}}{27\eta_{m1}P_{in1}(n_s-n_{FL2})}+\frac{n_s^2}{4}}\right)^{\frac{1}{3}}+\left(0.5n_s-\sqrt{\frac{n_1^3P_{FL2}}{27\eta_{m1}P_{in1}(n_s-n_{FL2})}+\frac{n_s^2}{4}}\right)^{\frac{1}{3}}\right]^3\right] \tag{27}$$

The results of each option's power saving are listed in table 4.8.

Table 4.8: Power saving for the different motors from the three suppliers.

Supplier	**Power saving**
A	410 *kW*
B	260 *kW*
C	370 *kW*

The motor from supplier A will be the most feasible option, in terms of energy efficiency, although it doesn't have the highest efficiency.

A condition-based maintenance strategy for the induction motors should be employed, in which the condition of the current motor is assessed either on an appropriate time base or when an opportunity arises to permit this. The end-result of the motor assessment is the threshold line, which will be used as a reference for comparing the feasibilities of different energy efficiency improvement alternatives.

It is recommended that condition-based maintenance of this type only be done on the larger motors where significant power savings are attainable, which could justify the effort, time and cost involved in realizing this maintenance effort.

- **An energy management tool for induction motor renewal/replacement**

If an induction motor fails or experiences a functional failure, is it better to refurbish it or replace it with a high efficiency motor? In most of the immediate circumstances, refurbishment is the more feasible option, driven by the fact that it is approximately one fifth the cost of buying a new motor. On the other hand, refurbishment in most cases, refers to rewinding and motors that have been rewound tend to be less efficient as also expressed by Campbell [35].

By utilizing the maintenance strategy as presented in the foregoing section, the energy manager is in a position to make a fairly good decision between replacement and renewal. Suppose that the, previously referred to, 13.7 *MW* induction motor's condition has been assessed after each rewind, and the threshold line after each assessment have been determined as shown in figure 4.13.

From the graph it can be seen that the threshold line changed with time and after each assessment, replacement seems to become a more and more attractive option.

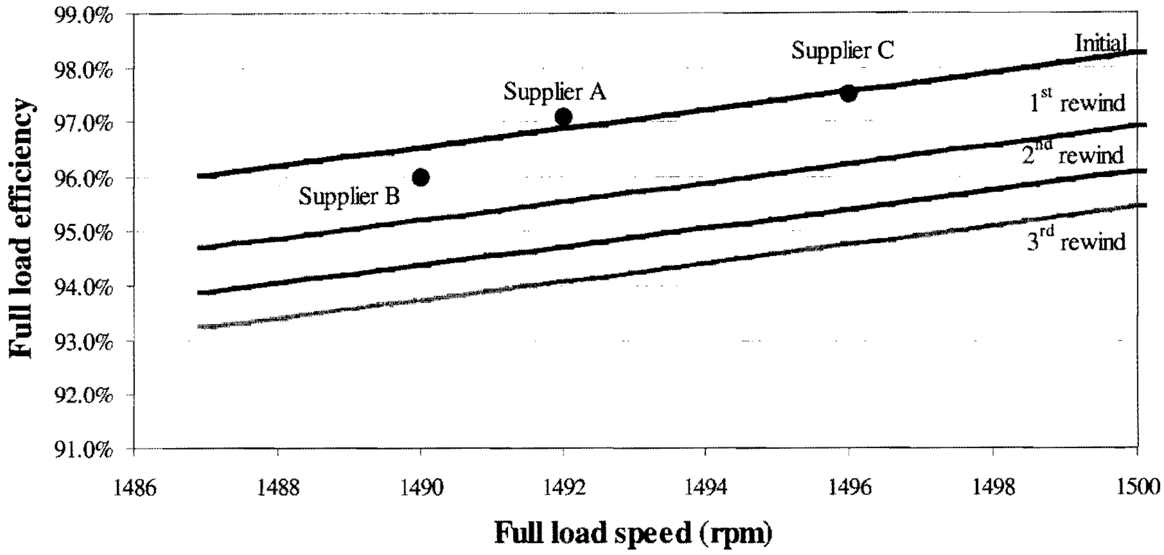

Figure 4.13: Threshold lines of motor after every rewind.

In conclusion, the energy manager may recommend rewinding if the threshold line is near (just above or below) that of the full load specifications of available motors, and should recommend replacement when the latter is sufficiently above the threshold line. Lastly, justifying motor replacement will be a function of reduced energy costs as well as the projected maintenance cost reduction.

4.4.3.4. Energy systems maintenance on distillation columns

The distillation column is made up out of distillation trays. The basic function of these trays is to enable contact of the descending liquid and the rising gas under the most favorable conditions. The mere presence of the trays provides the rising gas with a certain resistance, resulting in a pressure drop. This pressure drop must be as small as possible for it has a significant impact on the energy efficiency of the train. Needless to say, distillation trays have a major impact on the energy consumption of the train, as also pointed out by Biddulph [8].

Various technologies have been developed for reducing this pressure drop to the minimum of which distillation packing is the more recent, and compared to the conventional sieve trays, are the more efficient as well (refer to chapter 2).

Deterioration of distillation trays are inevitable and possible damage may cause a decrease in main product recovery efficiency and sometimes also increased pressure drop, which ultimately results in the train being less energy efficient.

Maintenance on distillation trays are sometimes limited because of the large production losses the plant would suffer during replacement, but it is up to the energy manager to assess the loss in energy expenditure and do feasibility studies on the relevant alternatives that would enable upgrading of the column's energy efficiency.

4.4.3.5. Energy systems maintenance life plan

Table 4.9 shows an energy systems maintenance life plan based on the foregoing information. The condition of each major system is assessed in the control phase of the energy management program and based on this assessment, the energy manager is able to inform and/or make informed recommendations to the relevant maintenance department in case of the occurrence of deviations.

Table 4.9: Energy systems life plan for the critical systems on the cryogenic air separation plant.

Item/Component	Maint. Type	on/off line	Frequency of maintenance task	Labour time	Type of labour or specialization	Initial maintenance on condition	Action
Compressor Motors	CBM	off	opportunity based	-	Contractor (most likely)	Make recommendation on whether to Repair/replace motor	Repair/Replace and assessment of motor condition
Compressor	CBM	on	monthly	minutes	Energy manager	Inform relevant maintenance dept. on deviation and impact it has	Corrective action will be enabled by relevant maintenance dept.
Distillation columns	CBM	on	monthly	minutes	Energy manager	Inform relevant maintenance dept. on deviation and impact it has	Corrective action will be enabled by relevant maintenance dept.

4.4.4. The energy management plan

The energy management plan basically consists out of the long-range plan and the building blocks that make up this plan, which are the following:

- Primary objective
- Specific objectives
- Short term plan
- Decisions surrounding project prioritization
- Short term tactics

Primary objectives are stated in the energy policy. Long-range plans are the means for achieving these objectives. Thus, long-range plans are the stepping-stones towards fulfilling the vision posed by the energy policy. A primary objective, on its turn, is a composition of specific objectives and in achieving these objectives, energy projects need to identified and implemented. Potential energy projects were already identified in the audit process and these projects now need to be allocated to the relevant specific objectives and also prioritized. Normally, multiple projects are required in fulfillment of a specific objective and consequently, there may be numerous projects listed under the short-term plan. The energy manager needs to assign priority to each project in order to ensure that the planned sequence of events are structured in an optimally efficient manner.

The short-term plan entails the decision-making with regard to which projects to implement when for the next financial year. The end result of the long-term plan ultimately depends on the implementation of the short-term plans. The short-term plan requires short-term tactics in order to realize. These short-term tactics are the actions and their timing that is needed to carry out the short term plan.

As an illustrative example, consider the division-wide energy policy of Sasol presented in section 4.3 [21].

- *Primary objective of the division-wide energy policy of Sasol*

  "To manage the Sasol/Electricity Supply Industry interface, so as to minimize the total cost of energy for the Sasol group of companies. Further to this, to promote energy efficiency and reward energy management success by decentralizing accountability for electricity costs and by aligning internal electricity tariff structures with the Eskom marginal rate." [21].

The underlined phrase is a primary objective of the energy policy, and in order to realize the "decentralization of electricity cost accountability" a few specific objectives first need to be realized; one such objective is stated in the list of specific objectives in the energy policy.

- *A specific objective of the energy policy*

  "Develop and maintain the electricity measurement system within the group of companies."

A specific objective is realized through the implementation of a short term plan or combination of short-term plans and, for above mentioned specific objective, a short term plan is given in the next paragraph.

- *Short term plan*
  - Upgrade existing measurement system on those plants that already have this system in place.
  - <u>Install measurement system on all energy intensive plants.</u>
  - Establish a maintenance strategy for measurement system.
  - Make data freely accessible and ....

Actions and their timing are the tactics needed to carry out the short term plan and for the underlined short term plan the short term tactics are as stated in the following paragraph.

- *Short term tactics*
  - Finalize decisions surrounding data logger selection – January 2000
  - Order PT's and CT's for the measurement system – January 2000
  - Install network connection in substations – March 2000
  - Install and commission data logger – May 2000

4.4.5. Measurement and control indicators

Now that there is an energy management program in place, the energy manager has to decide on how the progress and results of this program will be assessed. Key performance indicators have to be defined and energy standards need to be determined. In the control function of this model, the energy engineer will assess these KPI's and decide upon appropriate corrective actions.

There is one KPI that encapsulates the outcome of the whole energy management effort and that is the energy cost per primary product output *(R/kNm³)*. This is an important KPI as it is a global indicator and by trending it over time, the energy engineer is in a position to quantify the impact of his energy management program, however, this doesn't mean that it is the only one that should be monitored, there need to be other indicators defined as well; lower level indicators that are more specific and are able to identify critical component inefficiencies. Critical system components are defined here as only that system components that have a major impact on the energy consumption of the plant. These system components include the compressors, the compressor motors and the air separation unit.

The lower level KPI's should 1) indicate whether there has been a drift in system characteristics and also 2) whether the system operated above or below expectation during the past month. It should be noted that only the means for determining the KPI's are presented here, and they will only be applied in the control function the energy manager has to fulfill, as detailed later on.

Thus, the following parameters are the important ones and need to be monitored:

- Electromechanical efficiency of the air and product compressor motors
- Isothermal efficiency of each compressor
- Recovery efficiency of each train
- Specific energy of the plant *(kW/kNm³* of main product)

With these parameters as the basis, a key performance indicator will now be derived for each.

4.4.5.1. KPI for determining the state of the compressor motor

The compressor motor efficiency has a significant influence on the overall efficiency of the train, therefore a key process indicator need to be defined for the compressor motors and this KPI should comment on the degradation in motor electromechanical efficiency.

Obviously, it wouldn't make sense assessing this KPI each month, and should therefore only be assessed after each time the current condition of the motor has been evaluated.

$$KPI_{AC,motor} = \frac{\eta^{c}_{AC,m}}{\eta^{i}_{AC,m}} \quad (28)$$

where:

- m is the train number
- $\eta^{i}_{AC,m}$ is the design efficiency of the motor, i.e. the efficiency at the time when it was initially installed.
- $\eta^{c}_{AC,m}$ is the current efficiency of the air compressor motor.

The KPI of the product compressor motor takes on a similar form.

$$KPI_{PC,motor} = \frac{\eta^{c}_{PC,m}}{\eta^{i}_{PC,m}} \quad (29)$$

where:

- $KPI_{PC,motor}$ refers to the extent of deterioration within the air compressor motor.
- $\eta^{i}_{PC,m}$ is the design efficiency of the motor of train m, i.e. the efficiency at the time when it was originally installed.
- $\eta^{c}_{PC,m}$ is the current efficiency of the product compressor motor of train m.

4.4.5.2. KPI for determining the state of the air and product compressor

$$KPI_{x,m} = \frac{\eta_{I_{x,m}}^{actual}}{\eta_{I_{x,m}}^{theoretical}} \tag{30}$$

where:

- $KPI_{x,m}$ is an indicator that refers to how well compressor type x of train m performed.
- $\eta_{I_{x,m}}^{theoretical}$ is the theoretical isothermal efficiency of compressor type x of train m.
- $\eta_{I_{x,m}}^{actual}$ is the actual isothermal efficiency of compressor type x of train m.

Equation (30) then takes on the form of equation (31)

$$\therefore KPI_{x,m} = \frac{\dfrac{1.03\times10^{-4}\times Q_{x,m}\times T_{IC}\times\ln\left(\dfrac{p_{x,m}^{out}}{p_{x,m}^{in}}\right)}{P_{actual}\times\eta_{x,m}}}{a_{x,m}\times Q_{x,m}+b_{x,m}\times\dfrac{p_{x,m}^{out}}{p_{x,m}^{in}}+c_{x,m}\times T_{IC}+d_{x,m}} \tag{31}$$

where P_{actual} is the actual measured MW power consumption at that specific flow and pressure. Again, if the motor efficiency has not been determined yet it should be lumped with the isothermal efficiency of the relevant compressor; in this case equation (4) should be modified by simply removing the electromechanical efficiency ($\eta_{x,m}$) of the motor.

4.4.5.3. KPI for determining the state of the air separation unit

$$KPI_{ASU,m} = \frac{\eta_{rec,m}^{actual}}{\eta_{rec,m}^{emperical}} \tag{32}$$

where:

- $KPI_{ASU,m}$ is the indicator for how well the ASU operated during the sample time
- $\eta_{rec,m}^{emperical}$ is the empirical recovery efficiency that has been determined for the ASU of train *m*
- $\eta_{rec,m}^{actual}$ is the actual recovery efficiency of the ASU of train *m*

4.4.5.4. KPI for determining the overall efficiency of the plant

Except for the global energy cost KPI there should also be a KPI that measures the overall energy efficiency of the plant. This indicator should assist the energy manager in determining the following:

- If there were any deviations in any system component of any train and also quantify the impact of this on the overall efficiency of the plant.
- The impact of abnormal plant operation, for example due to routine maintenance on some trains or unexpected breakdown, on the overall plant energy efficiency.
- Whether the plant operated above or below expectation.

$$KPI_{eff} = \left(\frac{\sum_{m=1}^{n} P_{actual,m}}{\sum_{m=1}^{n} Q_m} \right) \Bigg/ \left(\frac{\sum_{m=1}^{n} P_{theoretical,m}}{\sum_{m=1}^{n} Q_m} \right) \tag{33}$$

where:

- KPI_{eff} is the in indicator that measures the total plant energy efficiency *(kWh/Nm^3 of main product)*
- $P_{actual,m}$ is the total power consumption of train *m (MW)*
- Q_m is the total main product flow at the output of train *m (kNm^3/h)*

This indicator provides the energy manager with a summary with reference to the state of energy efficiency of the whole plant. Caution should be taken that this is an overall indicator and may not be as sensitive to an inefficiency in a specific system component within a train and by only looking at this indicator may give the energy manager a false idea of the actual state of the plant. Thus, this indicator should be viewed in conjunction with the lower level indicators.

4.5. CONCLUSION

In this chapter, energy management organizing and planning was discussed. Through organizing, the energy management program is given definition and structure. It mainly involves identification and classification of required activities and the grouping of these activities in a structured and meaningful way.

Planning involves the setting up the energy policy and installing the energy policy strategy. The energy policy strategy has five components: human resource deployment, current situation evaluation, energy systems maintenance, the energy management plan as well as establishment of measurement and control indicators.

Human resource deployment involves appointing a dedicated person charged with driving the energy management program as well as giving this person access to other human resources, like administrative, technical etc.

Current situation evaluation is a critical step in the energy management program, and the outcome of the program, to a large extent depends on how well and thorough the energy audit was done.

Plant maintenance has a definite and significant impact on energy efficiency and in this chapter the need for an energy systems maintenance life plan was expressed. This life plan is effectively the energy manager's contribution to the overall maintenance effort on the plant and aims to improve energy efficiency.

The energy management plan is a structured and well-formulated set of plans and tactics that should be followed in order to ultimately achieve the primary objectives as stipulated in the energy policy. It involves long-term and short-term planning as well as setting up tactics for the means of achieving the short-term objectives.

Key performance indicators (KPI's) were defined for the means of quantifying plant performance in terms in energy efficiency, and these find their application in the managerial function of controlling, which will be discussed in chapter 5.

CHAPTER 5 LEADING AND CONTROLLING

5.1. LEADING

The main purpose of leading is to harmonize individual and organizational objectives. People do not work in isolation, rather they work in groups toward the achievement of personal and enterprise objectives; these objectives are not always in harmony and in fulfilling the function of leading the manager aims to align objectives of the individual with that of the enterprise.

Koontz *et al.* [14] defines the managerial function of leading as the process of influencing people so that they will strive willingly and enthusiastically toward the achievement of organizational goals. In order for people to willingly strive for such a goal they would need some form of motivation to do so. There exists various means for stimulating motivation in people (refer to Fukuda [36] and Jordaan *et al.* [37]) and one way of doing so is through awareness.

This awareness is encouraged by doing the following:

- Disclosing energy KPI's and also explaining possible abnormal deviations to employees.
- The impact certain practices of relevant departments within the plant's organization have on the plant's energy efficiency and ultimately energy cost. For example, this may include energy inefficient maintenance strategies, faulty equipment or even inefficient production schedules.

Turner [16] also lists the following relevant strategies for improved awareness:

- Providing relevant employees with energy management best practices, which are practical and relevant to their working environment within the plant's organization.
- Providing energy conservation opportunity checklists to plant operators, maintenance personnel, supervisors and engineers.

Another motivational tool is recognition. The energy manager should recognize the energy management efforts of employees and also show them the impact their efforts had during the past month.

Lastly, Turner [16] also states that competition may lead to improved performance. Fostering reasonable competition between relevant departments in the plant's organization may inspire employees to work harder in achieving their goals.

5.2. CONTROLING

Controlling is the measurement and correction of performance in order to ensure that objectives and the plans devised in attaining them are being accomplished. Koontz [14] defines three basic steps for control: 1) establishing standards, 2) measuring performance against these standards, and 3) correcting undesired deviations from standards and plans. These steps will now each be defined from an energy management perspective.

5.3. ESTABLISHING ENERGY STANDARDS/NORMS

Previously, energy management key process indicators were defined for the cryogenic air separation plant; those indicators are now utilized in the control function. The standard for each KPI is the theoretical quantity of the measured parameter, i.e. the denominator of each KPI as defined in equations (31), (32) and (33) of chapter 4, is the theoretical system performance and also the standard to which actual system performance is compared. KPI's for the compressor motors are the exception (equations (28) and (29) of chapter 4), in that the denominator in each is based on the original electromechanical efficiency specification.

5.4. PERFORMANCE MEASUREMENT

The KPI's should be trended over time and significant deviations from expected performance must be noted. This must be done on a monthly basis, except for the motor deterioration indicators, which may be assessed according that as stipulated by the maintenance strategy.

To illustrate performance measurement with a practical example, consider the month-end evaluation of one train of the seven-train oxygen plant at Sasol Secunda. This specific train boasts the characteristics listed in table 5.1.

Table 5.1: Characteristic parameters of a train used in its performance measurements.

Parameter	Value	KPI equation (Ch. 4)
1. Motors:		
1.1. Air compressor motor		28
$\eta^{i}_{AC,m}$	98.2%	
$\eta^{c}_{AC,m}$	93.0%	
1.2. Product compressor motor		29
$\eta^{i}_{PC,m}$	97.1%	
$\eta^{c}_{PC,m}$	91.0%	
2. Compressors:		
2.1. Air compressor		31
a	0.0009366	
b	-0.0574043	
c	0.0021501	
d	0.7272151	
2.2. Oxygen compressor		31
a	0.0044099	
b	0.0090275	
c	0.0030923	
d	-0.9017176	
3. ASU:		32
$\eta^{emperical}_{rec,m}$	95.41%	

What follows, will be performance measurement by means of KPI trending after which analysis of each will continue in the next section.

Results for the train's global efficiency indicator is shown in figure 5.1.

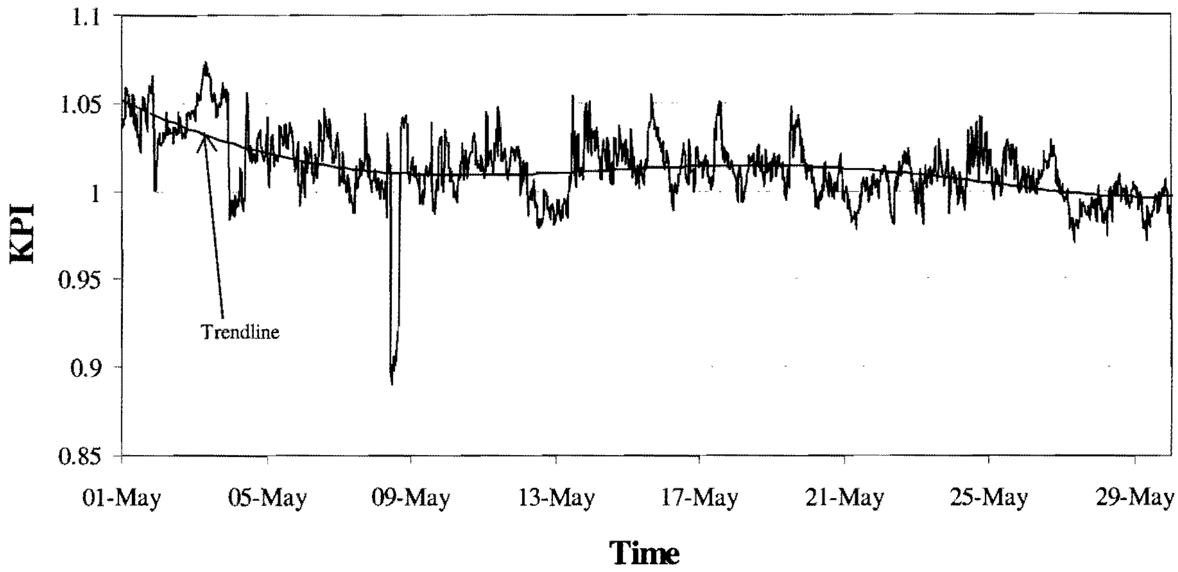

Figure 5.1: KPI trend for the global efficiency indicator.

As implied earlier, the KPI's characterizing each motor's state are not trended over time, instead its given as a single value and are listed in table 5.2.

Table 5.2: KPI values for the air and oxygen compressor motors.

Compressor motor type	KPI value
Air	0.949
Oxygen	0.937

Figure 5.2 shows KPI trending for the air compressor.

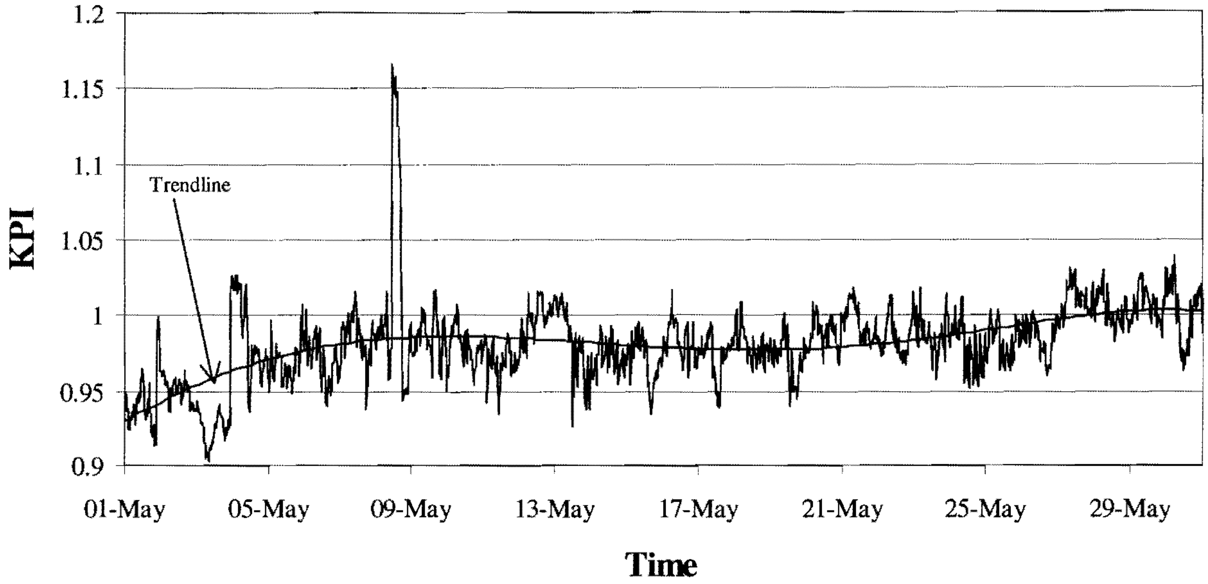

Figure 5.2: KPI trending for the air compressor

The KPI trend for the oxygen compressor is shown in figure 5.3.

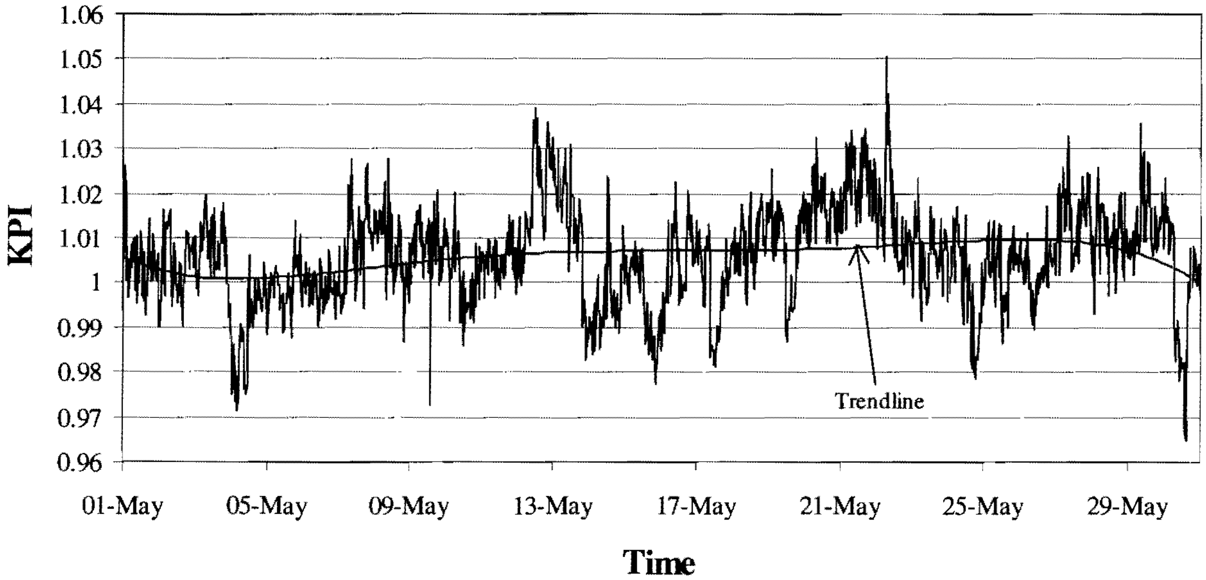

Figure 5.3: KPI trend for the oxygen compressor.

The KPI trend for the air separation unit (ASU) is shown in figure 5.4.

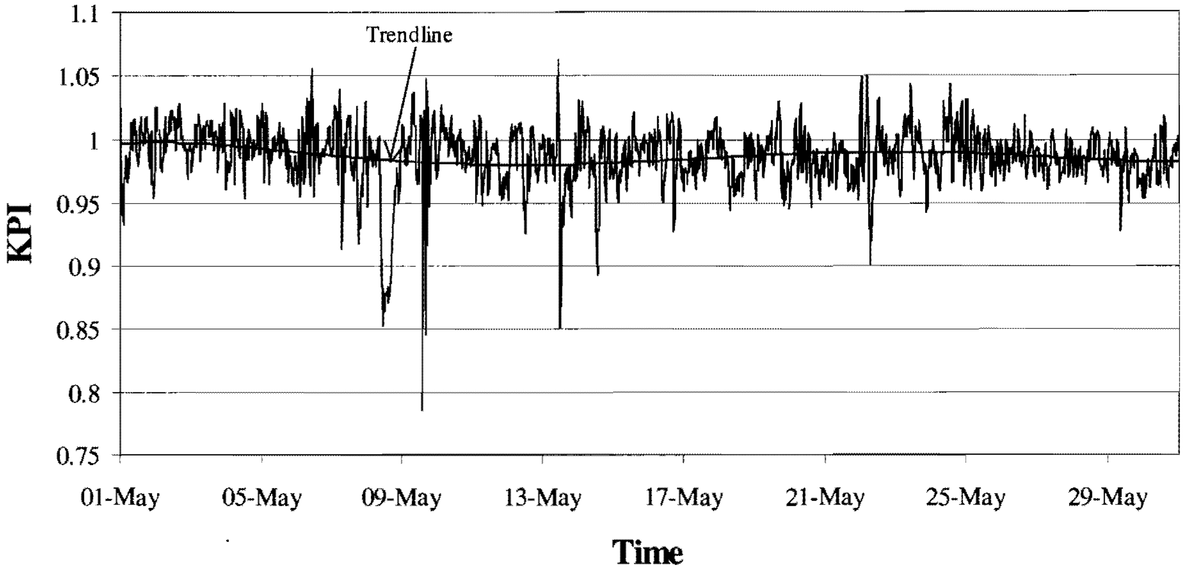

Figure 5.4: KPI trend for the ASU.

Table 5.3 shows the average power loss contribution from each of the major systems. These results were obtained by calculating the average power loss, defined as the difference between actual performance and expected performance (i.e. at KPI equal to unity), during that particular month.

Table 5.3: System inefficiencies quantified in terms of average power loss.

System	Average power loss
Air compressor motor	660 *kW*
Oxygen compressor motor	400 *kW*
Total	***1060 kW***
Air compressor	630 *kW*
Oxygen compressor	-70 *kW*
Air separation unit (ASU)	430 *kW*
Total	***990 kW***
Grand total	**2050 kW**

5.5. CORRECTIVE ACTION

Now that system performance have assessed, the energy manager is now in a position to manage equipment inefficiencies and determine whether there has been improvement in those that have been addressed on previous occasions.

5.5.1. Global efficiency indicator

This KPI should be below one, in case of energy efficient train operation, but as can be seen from figure 5.1, it is mostly above unity, implying some form of efficiency loss within the oxygen train.

On 8th May, there was a sudden improvement in the global efficiency indicator and the reason for this will become apparent in the discussion regarding the KPI trend for the air compressor.

It is worth noting from the graph that there seem to be a slight trend downwards up to around 27th May were it stayed on or below unity for the rest of the remaining time; the reason for this is that average ambient temperature decreased as the year approached June, ultimately leading to increased train efficiency. This trend can also be seen in the air compressor graph of figure 5.2 and the fact that the ambient temperature has such a favorable effect on train energy efficiency, its actual performance is disguised somewhat and one can expect that the losses listed in table 5.3 may even be slightly higher during the summer months.

5.4.2. Compressor motors

The fact that these two values are below one (refer to table 5.2), implies that there has been some degradation in motor efficiencies; the air compressor motor is currently about 95% of its original efficiency and that of the oxygen compressor motor is around 94%. Based on this assessment the energy manager may quantify the cost associated with the respective 5% and 6% degradation in motor efficiencies and is now in a position to manage this energy loss.

5.4.2.1. Air compressor motor

All air compressor motors on this plant are rated 37MW and are 2-pole synchronous motors. This air compressor motor's KPI is at 0.949 (table 5.2), which equates to an average power loss of 660 *kW*. The energy cost associated with this loss combined with current maintenance costs cannot, at this stage, justify buying a new high-efficiency synchronous motor; therefore other corrective actions should be employed in improving the motor's energy efficiency and in this particular case, the following steps will be taken:

- Assessment of partial discharge condition monitoring results, and scheduling an opportunity maintenance action if these results show a degree of partial discharge.
- Schedule an in-situ motor inspection, carried out by the OEM in which the state of the stator and rotor may be determined, minor servicing of the motor may be enabled and recommendations can be made by the OEM.

5.4.2.2. Oxygen compressor motor

All oxygen compressor motors on the plant are 13.7 MW, 4-pole induction machines and for this particular motor its KPI has been evaluated at 0.937, leading to an average power loss of 400 *kW* (this result takes into account the principles discussed in section 4.4.3.3 and is based on the power saving that would result in upgrading it to its original specifications).

For the oxygen compressor motor, there is much more potential for a replacement action, because of the relatively high energy loss and the fact that maintenance costs for this motor has risen quite dramatically over the past two years. Considering all the related variables, a payback period of 17 years has been calculated when replacing this motor with a new one. Management rules state that business-case approval will only be given to projects with a payback period of 15 years or less, however, KPI monitoring on the other trains revealed that the majority of oxygen compressor motors are in a worse state than the motor from this particular train and by consolidating the project (i.e. recommending replacement of all motors at once instead of just the one), the payback period was calculated at just below 15 years.

5.4.3. Air compressor

On 8th May the actual compressor performance was significantly above that expected (refer to figure 5.2.), the reason for this being that demand at that time required high product flow at high purity, and auxiliary air compressors were put online to supplement this demand; the auxiliary air compressors are unaccounted for in the model, which ultimately manifests in exceptional compressor performance.

Although air compressor performance did improve as the month progressed (gradual decrease in ambient temperature), for the majority of operational time it remained below expected performance. This under-performance resulted in an average power loss of 630 kW (table 5.3) and upon further investigation it was found that routine maintenance was done quite a long way back, and given the poor air quality at Sasol Secunda, a significant amount of compressor fouling was inevitable. Production requirements from production department and low priority assignment from maintenance department resulted in these irregular and, mostly, delayed maintenance intervals. A proper corrective action from the energy manager in this case would be to facilitate a compromise between these two departments by ensuring that consensus have been reached on the scheduling of this maintenance action, and also that this scheduling leads to increased energy efficiency.

5.4.4. Oxygen compressor

Figure 5.3 shows the KPI trend for the oxygen compressor and, as can been seen from this figure, the KPI stayed above unity for the majority of time which implies good compressor operation. This is also manifested in the average power loss for this compressor, which has been calculated at $-70kW$, as listed in table 5.3, implying that the oxygen compressor, overall, operated slightly above expectation.

In general, one can expect that the product compressor's performance, in terms of energy efficiency, should normally be above that of the air compressor because, as opposed to the air compressor, it handles a clean and pure gas and is therefore not as susceptible to compressor fouling, also, in some cases it is less prone to physical damage resulting from large solid particles.

5.4.5. Air separation unit

From figure 5.4 it can be seen that the ASU under-performed for the majority of time, resulting in an average power loss of 430 *kW* (table 5.3). Calculations showed that the average recovery efficiency for this time was 94.17%, which is slightly less than its empirical value (95.41%), meaning the air compressor has to make an added effort for compensating this drop in efficiency.

Production department acknowledged the decrease in recovery efficiency and the problem was identified as damaged distillation trays inside the distillation column. Initiating a maintenance action to repair defective trays in the near future will not be feasible because this would lead to significant production losses. Again, the energy manager has to manage this loss to the minimum. The following actions would do just this:

- Keep monitoring the recovery efficiency and initiate a maintenance action as soon as energy loss could justify this and/or determine the production loss when the air compressor has reached its full capacity and cannot compensate for the recovery efficiency loss anymore, which ever comes first or, should it be it the case, when both conditions have been reached.
- Minimize the loss by sharing a portion of this train's load equally between the more efficient trains at times of low oxygen demand or whenever there is more efficient spare capacity available.

5.5. CONCLUSION

In this chapter the managerial functions of leading and energy management controlling have been discussed.

The managerial function of leading involves, leadership, motivation and communication. Leadership refers to the ability to lead, which involves the process of influencing people so that they will strive willingly and enthusiastically toward the achievement of energy management goals. Motivation is vital in aligning objectives of the individual with that of the energy management program and it is important that the energy manager practice effective motivational techniques. Communication is the process by which information can be received or send. It is a vital skill and an essential activity in the energy management program.

Controlling is one of the functions the energy manager has to perform in order to ensure continuity of an effective energy management program.

Control is necessary in the energy management program, as it brings actual performance in line with desired performance, and based on the discrepancy between these two, the energy manager is in a position to strategize corrective measures. It is important for the energy manager to establish good communication links with the relevant departments within the plant's organization, as they are in a position to provide information relevant in the control phase and are also the stakeholders that need convincing before buying into corrective action strategies.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1. INTRODUCTION

In chapter 1, the main and specific objectives of this dissertation were listed; these objectives were addressed during the course of this dissertation and will now be properly concluded through referring to the relevant sections. Lastly, recommendations with regard to certain aspects of the energy management system presented in this dissertation will be made followed by a closing remark.

6.2. CONCLUSIONS ON THE OBJECTIVES

The main objective of this dissertation was to present a framework that would enable effective management of energy cost and efficiency in cryogenic air separation plants, as stated in section 1.2.

In this dissertation, a model has been defined which serves as the framework for the energy management program at cryogenic air separation plants. Within this framework, various functions have been defined and the energy management effort is realized through performing the activities surrounding each of the respective functions.

6.2.1. Conclusion on the energy management model

The energy management model was introduced in chapter 3. The model is depicted in figure 3.5 and entails the transformation process, its inputs and outputs and the external environment as well as the interaction between all of these. Inputs are resources like capital, skills, people and facilities; outputs are the accomplished energy management objectives like improved preventive maintenance strategies, optimized production schedules, reduced energy cost and improved plant design.

The external environment accounts for the higher order systems to which the energy management system belongs. The transformation process involves the managerial functions of organizing, planning, leading and controlling, which are the core managerial functions the energy manager has to perform.

6.2.2. Conclusion on the energy policy

Theory behind the energy policy was presented in section 4.3. The energy policy normally consists out of three components: the declaration of commitment, mission statement and specific objectives. The energy policy guides or channels thinking, it is an expression of the commitment plant management has towards a continuous and effective energy management program and sets the scope for energy management effort at plant level.

6.2.3. Conclusion on the energy policy strategy

The energy policy strategy is the means for accomplishing the vision expressed by the energy policy and was introduced in section 4.4. The energy policy strategy thus encapsulates the plan for changing current reality into future vision. This plan is composed of five activities, and they have been identified as the following:

- deployment of human resources,
- current situation evaluation,
- energy systems maintenance,
- energy management planning,
- establishment of measurement and control indicators.

Deployment of human resources entails the appointment of a dedicated person, in charge of the plant's energy management program, as well as enabling this person to utilize other relevant human resources.

Energy systems maintenance refers to maintenance actions regarding the energy efficiency of equipment that use or affect the use of energy.

The energy management plan is a structured and well-formulated set of plans and tactics that should be followed in order to ultimately achieve the primary objectives as stipulated in the energy policy.

Key performance indicators were presented in section 4.4.5 and these indicators enable the energy manager to assess the plant's energy efficiency and also to perform the control function of the energy management program.

6.2.4. Conclusion on the energy audit process

The energy audit process was discussed in section 4.4.2, and consists out of the energy audit policy and the energy audit strategy. The energy audit policy sets the scope for what to audit whereas the energy audit policy strategy states how this would be done.

Auditing is done through assessing relevant plant efficiencies, as listed in section 4.4.2.1 and, for the holistic approach to energy auditing, assessment of all these plant efficiencies should be enabled; this assessment is done by means of the audit strategy as detailed in section 4.4.2.4.

6.2.5. Conclusion on the mathematical model

Model building blocks, with regard to all the major systems, were derived in section 4.4.2.4. The energy conversion model is a very important auditing tool and most of the building blocks derived in this section also find their application in the control function of the energy management program (section 5.2).

Model accuracy is greatly enhanced through empirical modeling of critical plant elements, and as stated in chapter 4, it becomes obvious that availability of relevant data is critical in model building.

6.2.6. Conclusion on the performance indicators

KPI's (key performance indicators) were derived in section 4.4.5 and consist of global indicators as well as lower level indicators. Global indicators quantify the performance of the plant as a whole and include the energy cost per product produced (R/Nm^3) and energy consumption per cumulative product produced (kWh/Nm^3). The lower level indicators enable the energy manager to monitor the energy efficiency of critical components such as the compressor motors, compressors and the distillation columns and are also utilized in the control function of the energy management program.

Each KPI is defined as the ratio between actual and theoretical performance. The theoretical performance effectively defines the energy standard of a particular system, which enables the energy manager to identify system inefficiencies when comparing this to the actual system performance.

6.2.7. Conclusion on energy systems maintenance

Energy systems maintenance with regard to cryogenic air separation plants was introduced in section 4.4.3. Energy systems maintenance is the energy manager's contribution to the overall maintenance effort on the plant and is conducted by means of an energy maintenance life plan.

The state of each of the respective critical systems is monitored in terms of their energy efficiency and deviations are acted upon so as to minimize resulting energy losses. The critical systems are the compressors, distillation columns and compressor motors and a maintenance plan for these systems were presented in section 4.4.3.5.

A cryogenic air separation plant normally utilizes a large number of induction motors for driving loads such as blowers, pumps and compressors and these motors consequently have a significant impact on the energy efficiency of the plant. As stated in section 4.4.3.3 energy systems maintenance on large induction motors driving these loads may not be so simple and in this section a tool that facilitates decision-making between induction motor replacement and renewal was presented as well.

6.3. RECOMMENDATIONS

This section contains recommendations with regard to certain aspects of the energy management system at cryogenic air separation plants.

6.3.1. Recommendations on setting up the energy management program

First and foremost, it is the responsibility of the appointed energy manager to ensure that there is a formal and well-defined energy policy in place at plant level, for the whole energy management program will be as a direct consequence of this policy and is therefore the foundation from which all energy management efforts will outflow. This policy should be agreed upon by the relevant stakeholders and approved by top management.

For the energy management system to be fully integrated into the plant's organizational structure and to ensure that top management continually gives it the commitment it needs, it is recommended that the outcomes of this program be accounted for in the overall performance of the plant in order for it to ultimately have an impact on the merits of plant performance.

As a direct consequence of the energy policy, capital will be made available for the energy management program in the form of a financial budget. The energy manager is responsible for formulating the energy management budget for the next financial year and this budget should then serve as the cost goal for the energy management program. This is a critical resource input to the program and the energy manager should make sure that optimum use of this resource is exercised through proper planning and allocation (see section 4.4.4).

When implementing the energy management program it is important that the appointed person should first organize a workshop session in which all the relevant departments in the plant's organization are informed about what the proposed energy management effort entails, what is expected of them and how they can benefit from it. This is also a good opportunity for the energy manager to highlight the importance of effective energy management on these energy intensive plants and to aspire fellow personnel in contributing positively towards energy management objectives.

6.3.2. Recommendations regarding existing energy management programs

In the case where there already is an existing energy management program in place, the contents of this dissertation may be used to supplement or adjust current efforts. The model presented in this dissertation aims to foster an effective and value-adding energy management program without compromising production output streams and will add to the success of existing energy management efforts.

6.3.3. Recommendations regarding energy modeling

In section 4.4.2.4 it becomes obvious that in building the energy conversion model the energy manager requires a large amount of data of different types, ranging from process variables like temperature, pressure and flow to capacity limits on equipment. To avoid spending too much time in model building and ensuring good accuracy, the energy manager must enable easy access to relevant data.

Building the energy conversion model may take a relatively long time, especially in plants incorporating multiple trains, and most of the time will be consumed by processing relevant data, it is therefore recommended that appropriate computer software be used. Spreadsheets will undoubtedly proof to be most efficient in data processing and it is also recommended that software capable of multiple variable regression be utilized in modeling certain subsystems.

Lastly, some model building blocks are utilized in the control function of the energy management system, and it would be advisable to link the relevant model outputs to the respective KPI's in which they are utilized; in this manner, KPI's are automatically evaluated whenever plant performance needs to be determined.

6.3.4. Recommendations regarding the energy manager

Although it is recommended that the energy management system should form part of the plant's organization, it doesn't necessarily mean that the person appointed to drive this program should be stationed at the plant. This person may form part of an organization external to the plant's organization like for example an energy management task team that is charged with managing energy cost on a company-wide level, a technical hub or even an outside company (outsourcing).

It is required that the appointed person should be experienced in general management and competent in applying financial tools. This person should also be technically orientated, typically operating from the base of mechanical, electrical or process engineering.

6.3.5. Recommendations regarding energy management at Sasol Secunda

It is a fact that certain plants within the Sasol complex are generally energy intensive and, in optimizing the energy cost per output product more efficiently, it is recommended that intentional consideration should be given to energy management at plant level. Realizing this energy management effort lies in adopting an efficient managerial structure, such as the one presented in this dissertation, and allocating resources to fuel this energy management effort.

Driving this managerial effort would be the responsibility of a dedicated energy manager appointed by the company. Lastly, Janse van Rensburg [17], also suggested that an energy manager should be appointed by each of the major energy consumers within the factory and that a specific plant's performance, with regard to energy management, should have an impact on the overall performance merit of the plant, thereby motivating relevant personnel in achieving energy management objectives.

6.4. FUTURE WORK

Although there are key commonalities between various cryogenic air separation plants they may still be diverse in design and it is up to the energy manager to derive an energy model specific to his/her plant; this may be done by employing the basic modeling theory presented in chapter 4.

Another point worth mentioning is that of extending the application of the energy model. Utilization of the energy model is basically limited to that of the energy manager, but by modifying the model such that it is able to receive real-time data in order to produce specific predefined outputs in real-time, the proactive element of the energy management effort is greatly enhanced. The model may be added as an extension to the control operator's workstation. The control operator is directly responsible for the process control of the plant and is able to see (in real time) on how certain of his/her actions impact on the energy cost and efficiency of the plant.

Lastly, this study was aimed at presenting a generic framework for energy management at cryogenic air separation plants, however, it was also the intent of the author to introduce an energy management framework that may be applied to plants of any nature. In the quest for deriving an energy management program, future studies may thus apply the basic philosophy presented in this study to other types of plants as well.

6.5. CLOSING REMARKS

This dissertation presents a framework for energy management at cryogenic air separation plants. It addresses all the critical managerial aspects required in conducting a successful energy management program and may be used as a reference or tool in managing electrical cost and energy efficiency at these energy intensive plants.

Because these plants are so energy intensive, a relatively small improvement in energy efficiency may lead to significant energy cost savings. Cost savings are not the only benefits resulting from the energy management effort, indirect benefits resulting from this include reduced CO_2 emissions and conservation of the earth's energy resources.

From the above it can be seen that energy management at plant level not only makes business sense but is also the answer to environmental concerns and the ever-increasing energy price.

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APPENDIX A CASE STUDY: BASIC ENERGY CONVERSION MODEL FOR THE SASOL SECUNDA OXYGEN PLANT

A.1. MODEL INPUTS AND OUTPUTS

Table A.1 lists the empirical values for the oxygen compressor (refer to equation (9) of chapter 4). Factored into these constants are the respective electromechanical efficiencies of the oxygen compressor motors.

Table A.1: Oxygen compressor empirical values.

Train	a	b	c	d
1	0.004013	0.008215	0.002814	0.820563
2	0.004853	0.009605	0.002887	0.960213
3	0.005213	0.004361	0.003537	0.960292
4	0.001955	0.005158	0.001532	0.193396
5	0.004018	0.008176	0.002817	0.820563
6	0.005104	0.01082	0.002722	0.960236
7	0.003524	0.005223	0.003751	0.960292
AC's	0.000871	-0.853386	0.0019996	0.067631

With reference to equation (8) of chapter 4, the system constants from the air compressor side are the following: $h = 0.14$ and $g = 1.2$, which have been assumed the same for all trains.

The average recovery efficiencies for each train are as listed in table A.2.

Table A.2: Coldbox average recovery efficiencies.

Train	AR
1	94.67 %
2	90.55 %
3	95.18 %
4	96.13 %
5	95.28 %
6	91.52 %
7	95.09 %

Refer to figure A.1 for model input and output nametags.

Model inputs:

- *Management rules:* Specifies production constraints i.e. the minimum and maximum levels of the different commodities involved in the oxygen production process.
- *Oxygen demand:* This input is mainly determined by the gasification and gas-reforming processes, and will vary in response to their demand.
- *Oxygen supply pressure:* This is the pressure with which oxygen is supplied to the Gasification and Gas-Reforming plants. The supply pressure should be kept between the constraints as set forth by these two plants.
- *Minimum and maximum limits of process outputs and equipment:* Specifies the constraints in which the equipment should function in normal operation. This includes:
    - *Max. & Min. limits of air compressor:* 37*MW* & 28*MW* (when online), respectively.
    - *Max. & Min. limits of oxygen compressor:* 13.7*MW* & 10*MW* (when online), respectively.
    - *Max. & Min. limits of oxygen purity:* 99.4% & 98.5%, respectively
    - *Max. & Min. limits of Pressure in oxygen common header:* 3480kPa & 3350kPa, respectively
    - *Max. & Min. limits of* N_2/O_2 *ratio:* 30% & 20% respectively
- *HP* N_2*/LP* O_2 *ratio:* Defines the relationship between the HP nitrogen and LP Oxygen and is assumed a constant value.
- *Instrument Air flow:* The plant also produces instrument air and for the purpose of the model, a constant value is assumed.
- O_2 *purity:* The main product purity is assumed constant.
- *Other constants:* This includes the following:
    - Atmospheric pressure at Secunda (85kPa).

- O_2 pressure at cold box outlet (95kPa).
- Cooling water temperature (20°C):
- Average recovery efficiencies of each train (AR).

Model outputs:

- *Specific energy:* This is defined as the energy efficiency of the oxygen plant, i.e. the efficiency with which energy is utilized in producing oxygen. It has units of kWh/Nm^3, i.e. the amount of kilowatts that should constantly be applied for one hour in order to produce one normal cubic meter of oxygen.

- *New load profiles:* This includes:
  - Load profiles of all trains
  - Load profile of whole industry (train 1-7)

- *Cost of energy:* Gives the cost of energy based on the tariff structure.

For the model simulation, the following input values, listed in table A.3, were used.

Table A.3: Input values used for model simulation.

Parameter held constant	**Value**
Oxygen supply pressure	3440 kPa
N_2/O_2 ratio	25%
Average recovery (AR)	Refer to table C.2
Instrument air flow	3.5 kNm^3/h
Oxygen purity	98.6%
Electricity tariff structure	WEPS (2002 Sasol structure)

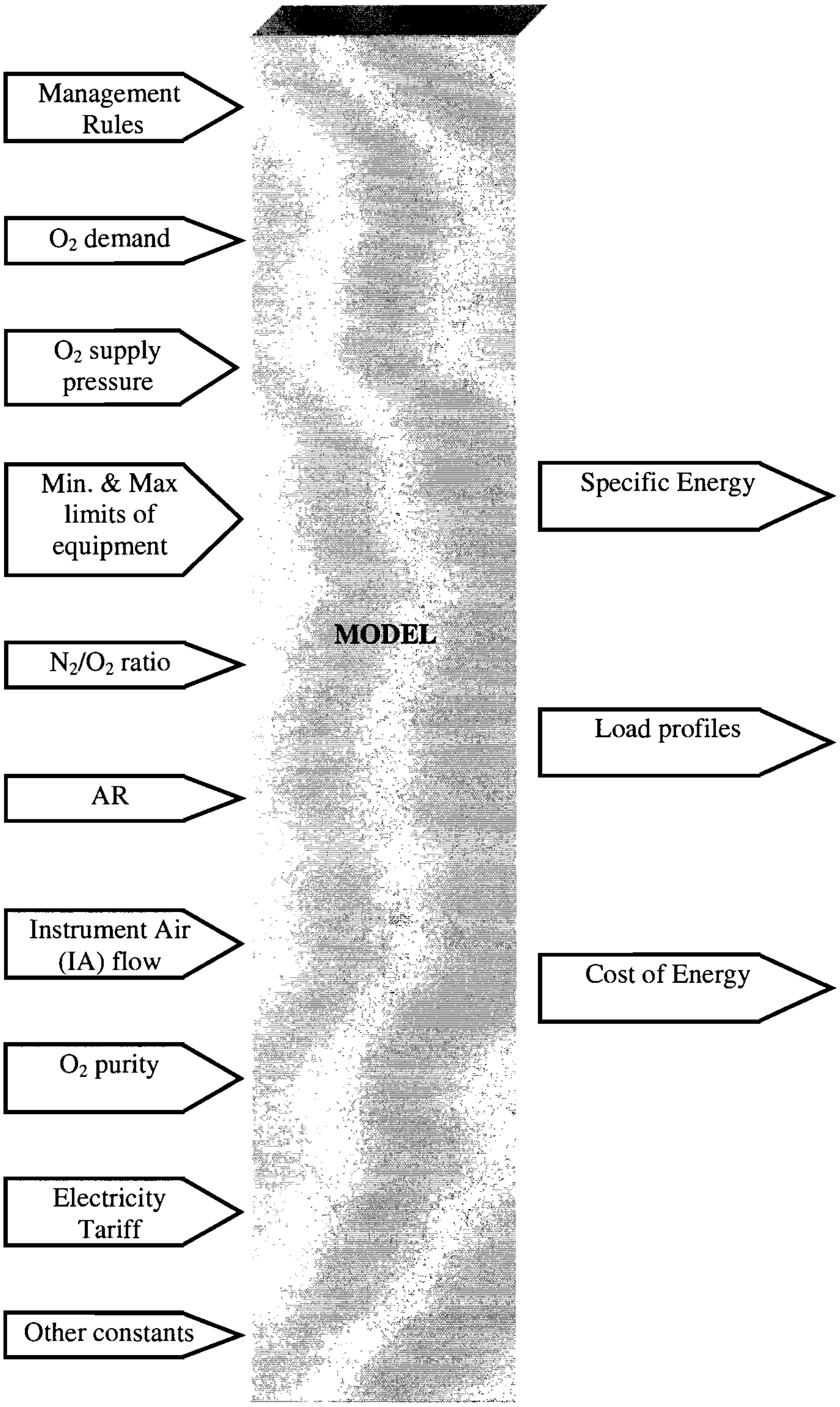

Figure A.1: Inputs and outputs for the basic energy conversion model.

Table A.4: Simulation results calculated over a period of one moth.

Parameter	Value
Specific energy	0.6589 kWh/Nm^3
Cumulative load profile	Refer to figure C.2
Cost of energy during sample month	R21 156 843

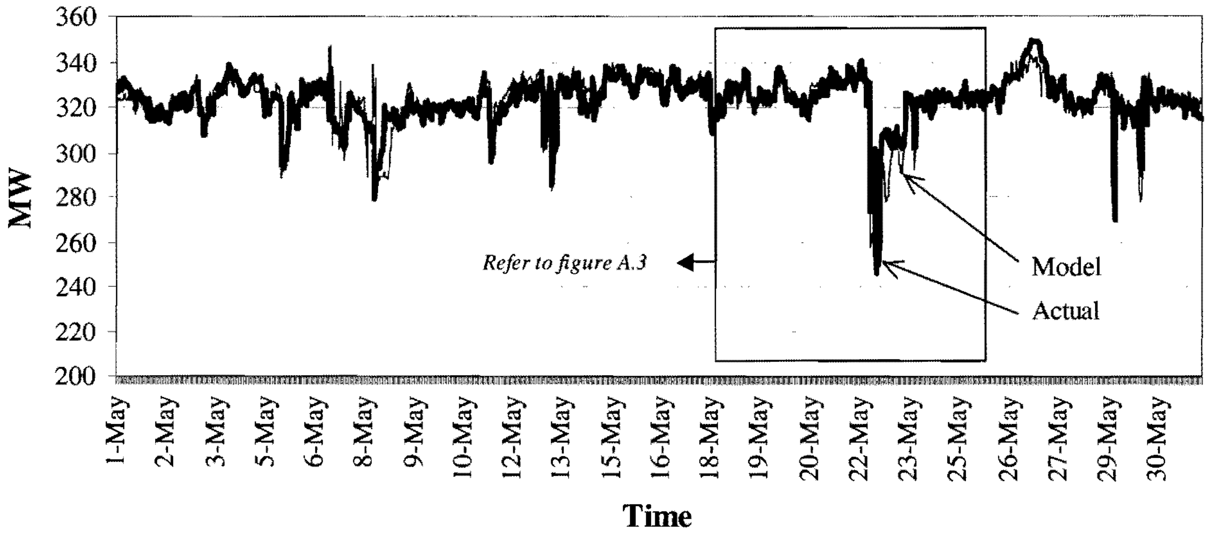

Figure A.2: Actual and simulated load profile for the oxygen plant at Sasol Secunda.

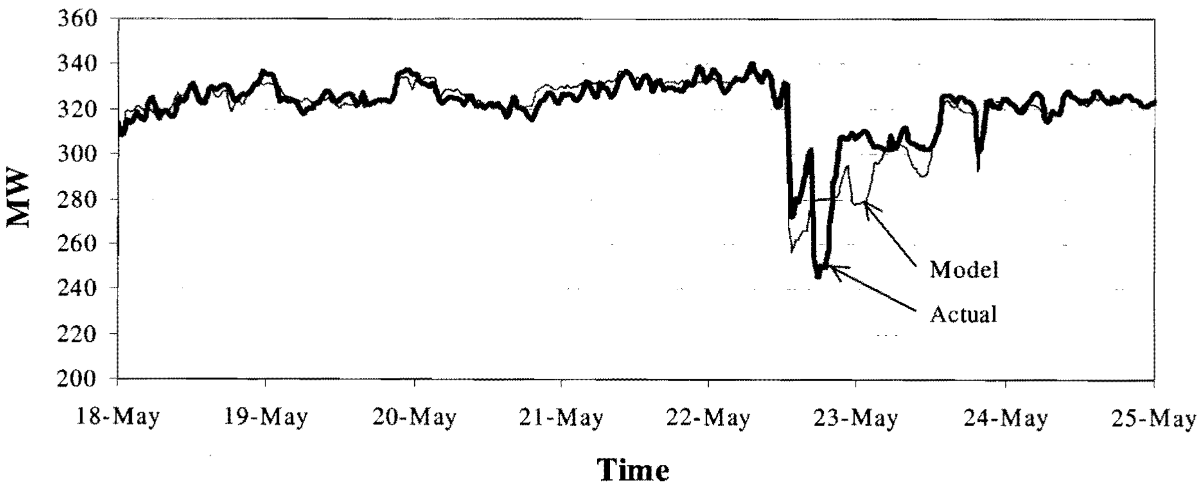

Figure A.3: Section of actual and simulated load profile of figure C.2

On 8th May the actual load profile plunges momentarily, while the model doesn't seem to be responding to this change in power consumption. This is due to the fact that the model assumes that only *one* oxygen compressor can be offline at any point in time, which is usually the case; on this particular day, however, between 07:30 and 9:30 train two's oxygen compressor tripped and was offline for approximately two hours, in addition to the oxygen compressor of train one. This has the implication that the spare oxygen compressor was summed twice for two hours. On 7th May the same incident happened for approximately one hour.

Two oxygen compressors are very rarely offline at the same time, and as these incidents happened only for a relatively small time the entire month (approximately three hours in total), it's impact is negligent and also for the sake of model simplicity, this aspect was neglected in modeling the oxygen plant.

As will be illustrated later in this section, an oxygen train's power consumption increases when a higher purity oxygen is produced. Between 1st and 2nd of May, the actual load profile seems to be slightly higher compared to that of the model. The model assumes that oxygen is produced at a constant purity (98.6%) however, in this case, oxygen was produced at a higher purity leading to an increased power consumption; this is also the case for the respective load profiles between 27th and 28th of May. The same reasoning can be applied to the results seen between 30th and 31st of May, except that in this case, lower purity oxygen (i.e. less than 98.6%) was produced.

When the power consumption of the oxygen plant drops, like for instance at 5, 7, 8, 9, 23 and 30th May, it seems that the model overshoots the minimum point at times; this is mainly due to the minimum permissible power consumption the compressors are allowed to have. The model assumes 28*MW* and 10*MW* for the air and oxygen compressor motors respectively, but these values vary from train to train (may be higher or lower than 28*MW*/10M*W*) and thus may overshoot at times or even undershoot the actual load profile at these conditions.

A.2. IMPACT OF KEY PARAMETERS ON ENERGY EFFICIENCY

The energy conversion model defined in the previous section will now be used to quantify the impact certain key process parameters have on the energy consumption, efficiency and cost of the plant. Normal operating conditions will be used as the baseline and are as listed in table A.5; at these conditions the model outputs are as listed in table A.6.

Table A.5: Normal operating conditions of the oxygen plant at Sasol Secunda.

O_2 Purity	98.6 %
HP N_2/LP O_2	25 %
IA flow	3.5 kNm^3/h
O_2 common header pressure	3440 kPa

Table A.6: Model results at normal operating conditions.

Specific energy	0.6589 kWh/Nm^3
Load profile of oxygen plant	Figure A.2
Average power consumed	323.44 MW
Total cost of energy	R 21,156,843

The effects of changing following parameters will be determined:

- Oxygen purity,
- Average recovery efficiency (AR),
- Instrument air flow (AI),
- Cold box availability.

Table A.7 lists the different simulation scenarios, with table A.8 displaying the respective model outputs in terms of specific energy, average power consumption and total cost of energy.

Table A.7: Model simulation scenarios.

Variables	O_2 purity	IA flow per train	O_2 CH pressure	Recovery efficiencies	CB offline
Oxygen purity					
- *Scenario 1*	98.5%	3.5kNm^3/h	3440kPa	Table A.2	None
- *Scenario 2*	98.7%	3.5kNm^3/h	3440kPa	Table A.2	None
AR efficiency					
- *Scenario*	98.6%	3.5kNm^3/h	3440kPa	Trains 2&6 changed to 95%.	None
IA flow					
- *Scenario*	98.6%	Load shifting IA of trains 2&6 to train 7	3440kPa	Table A.2	None
Cold box availability					
- *Scenario*	98.6%	3.5kNm^3/h	3440kPa	Table A.2	Train 1

Table A.8: Model outputs based on the scenarios listed in table A.7.

Variables	Specific energy *(KWh/Nm^3)*	Average power consumed *(MW)*	Total cost of energy *(R)*	Increase in specific energy	Increase in average power consumed	Increase in total cost of energy *(R)*
Oxygen purity						
- *Scenario 1*	0.6553	321.72	21,049,009	-0.55%	-0.53%	-107,834
- *Scenario 2*	0.6631	325.53	21,287,147	0.64%	0.65%	130,304
AR efficiency						
- *Scenario*	0.6524	320.29	20,960,289	-0.99%	-0.97%	-196,654
IA flow						
- *Scenario*	0.6578	322.91	21,123,850	-0.17%	-0.16%	-32,993
Cold box availability						
- *Scenario*	0.7360	311.89	20,401,463	12.35%	-3.57%	-755,380

APPENDIX B LIST OF TABLES

APPENDIX C LIST OF FIGURES