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.

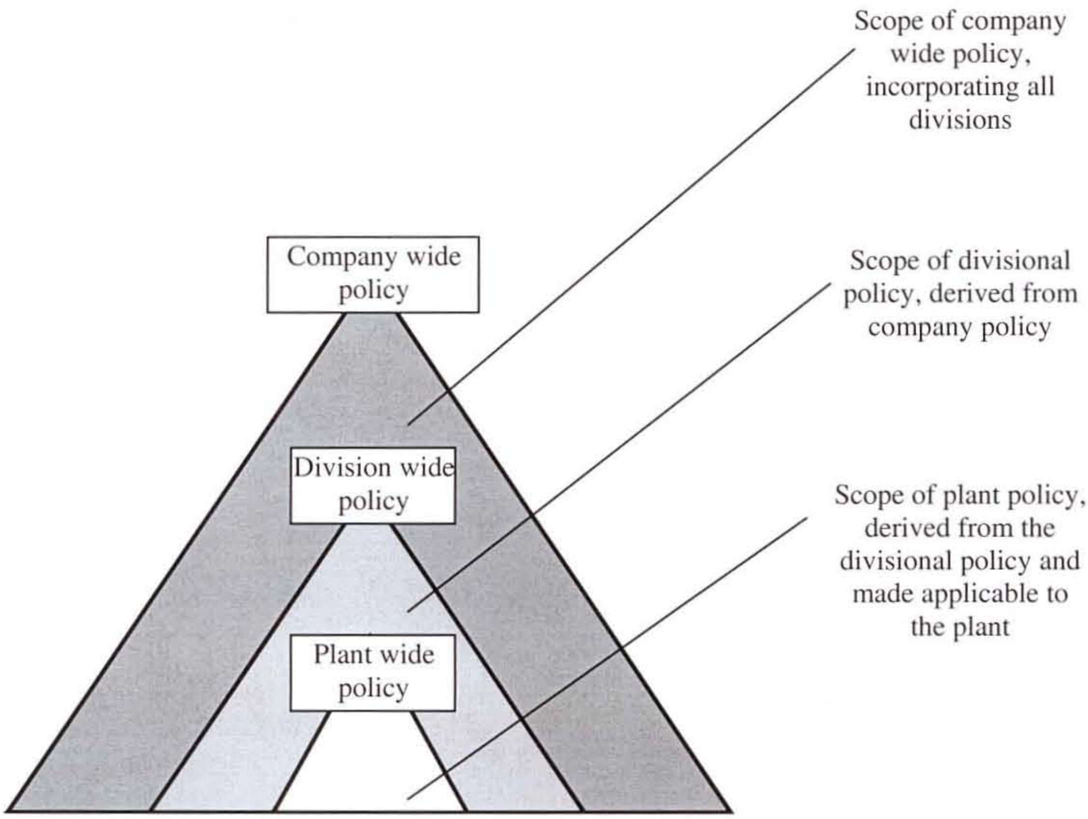

Figure 4.1: Energy policy at different levels of the organization and the scope of the policy at each level.

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.

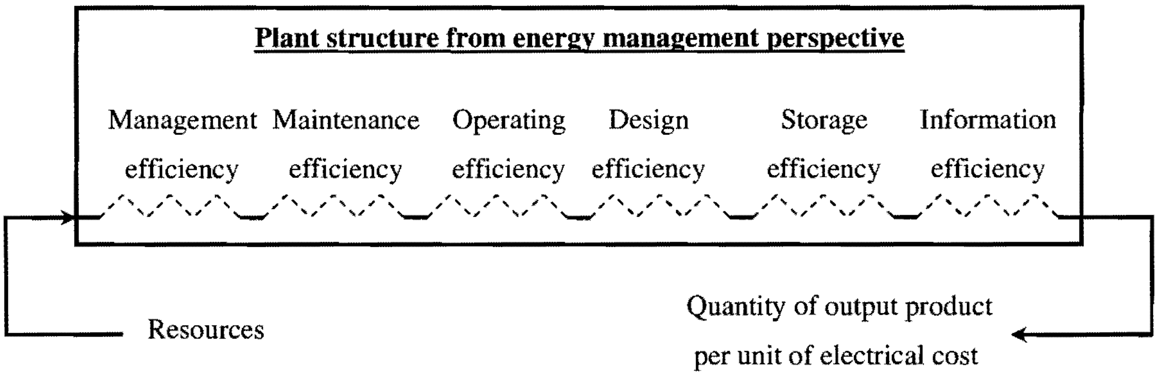

Figure 4.2: An illustration of efficiency losses, inherent to the plant's structure, from an energy manager's perspective and how they collectively contribute to the ultimate quantity of output product per Rand of electrical cost.

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.

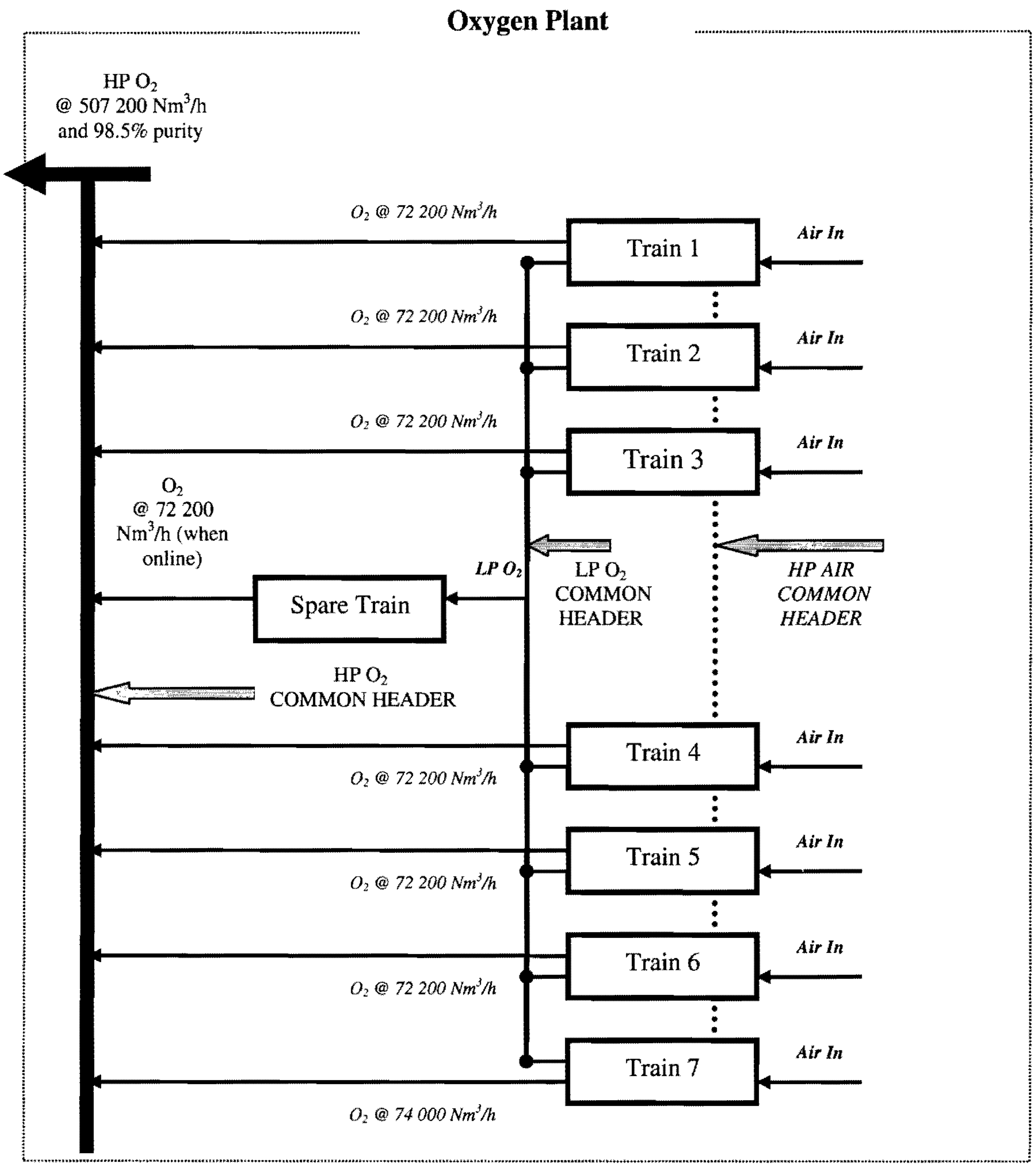

Figure 4.3: Basic outline of the oxygen plant at Sasol Secunda. The flows presented here are the steady state maximum amounts of oxygen that each train is able to produce.

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.

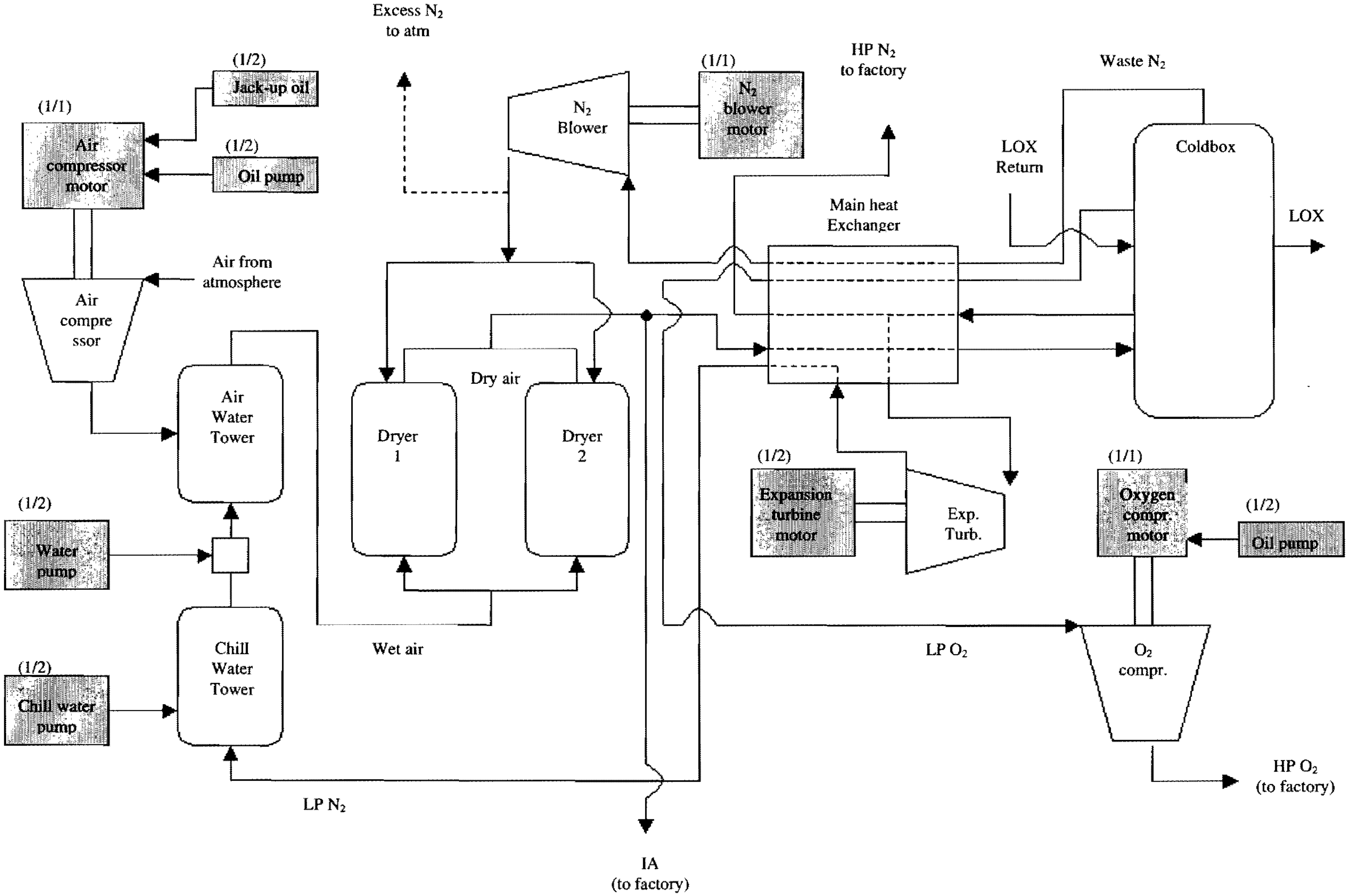

Figure 4.4: Process flow of a single oxygen train.

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.

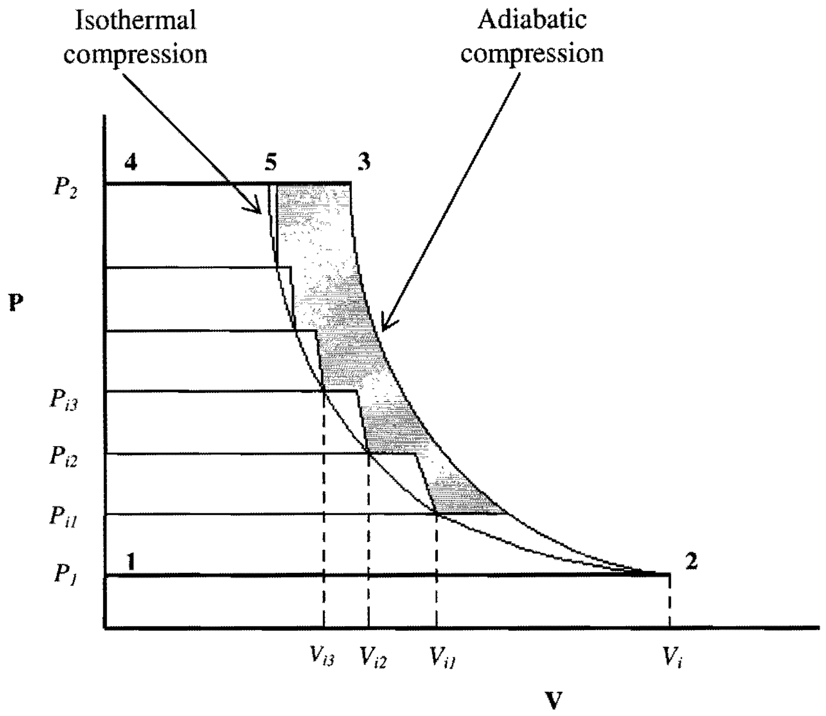

Figure 4.6: Multi-stage compression cycle with interstage cooling (Coulson *et al.* [27]).

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).

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

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 *(kNm^3/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 *(kNm^3/h)*
- Q_m^{pure} is the total flow of (pure) main air product that originally entered the air compressor of train m *(kNm^3/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).

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

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:

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

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).

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

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

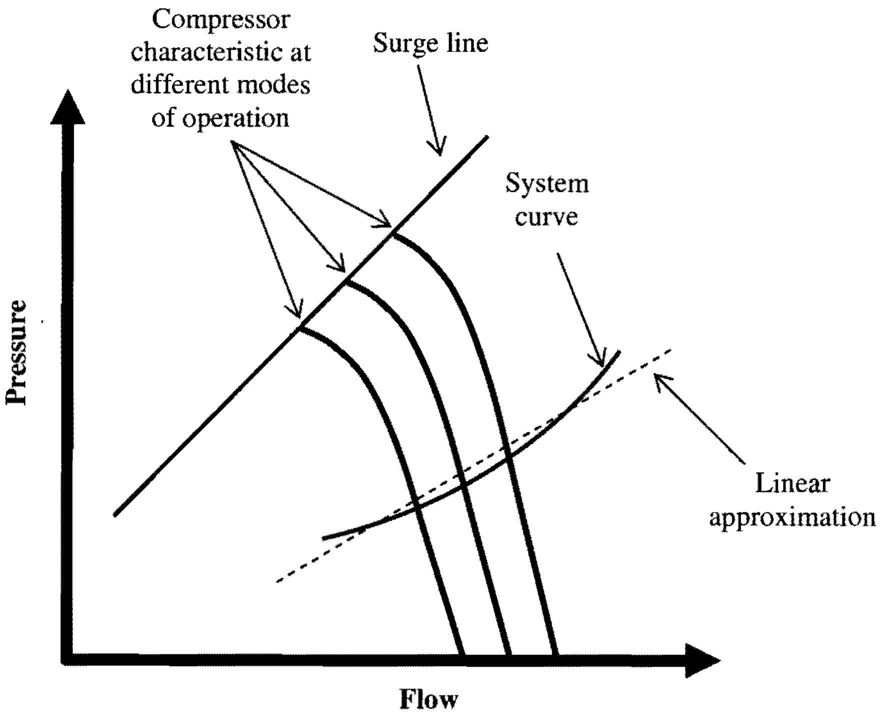

Figure 4.7: Linear approximation of system curve.

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.

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

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.

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

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.

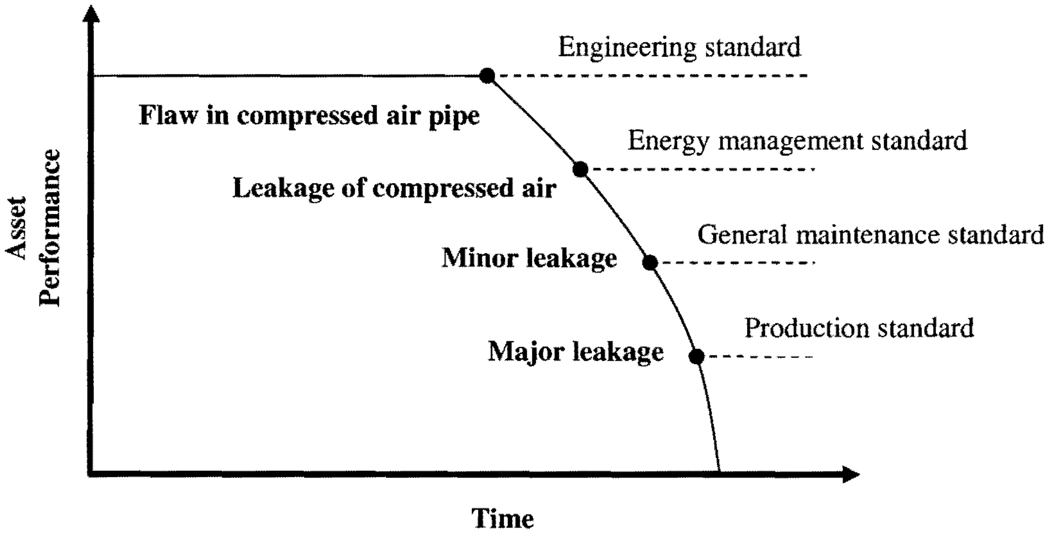

Figure 4.8: Functional failures and performance standards.

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.

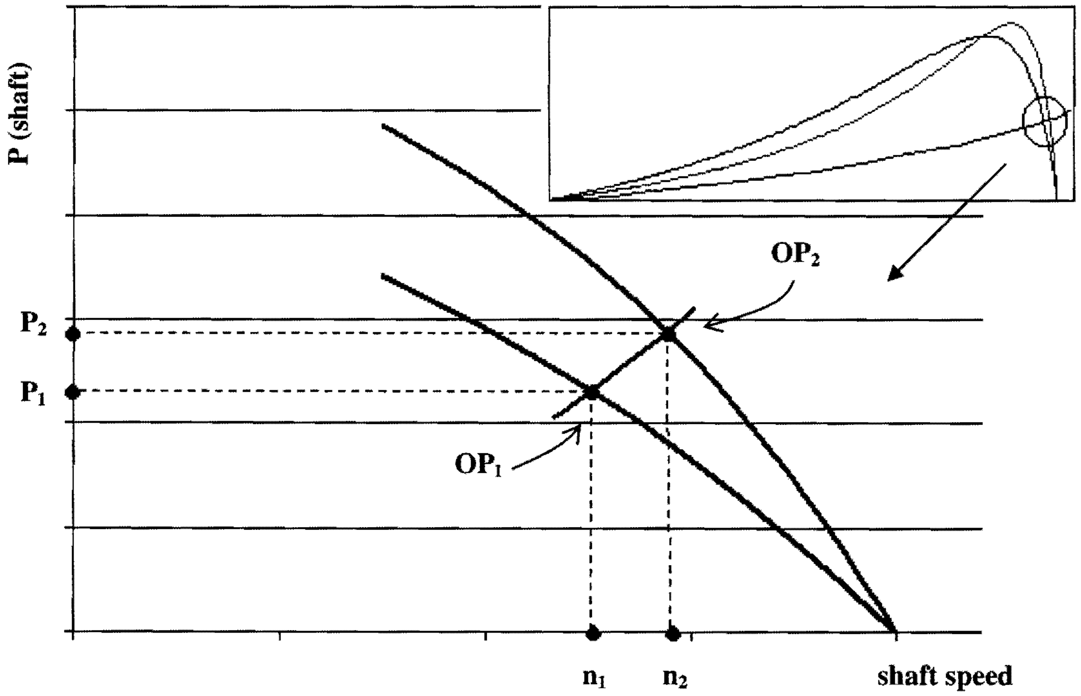

Figure 4.9: Partial power curves of the existing motor (motor 1) and the new motor (motor 2) as well as that of the compressor load, illustrating the implication of installing a higher efficiency motor than is currently in operation.

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.

$$Q \, \alpha \, n \tag{11}$$

$$p \, \alpha \, n^2 \tag{12}$$

$$P \, \alpha \, n^3 \tag{13}$$

where:

- n is the shaft rotational speed *(rpm)*
- Q is the gas flow *(kNm^3/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].

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

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

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

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.

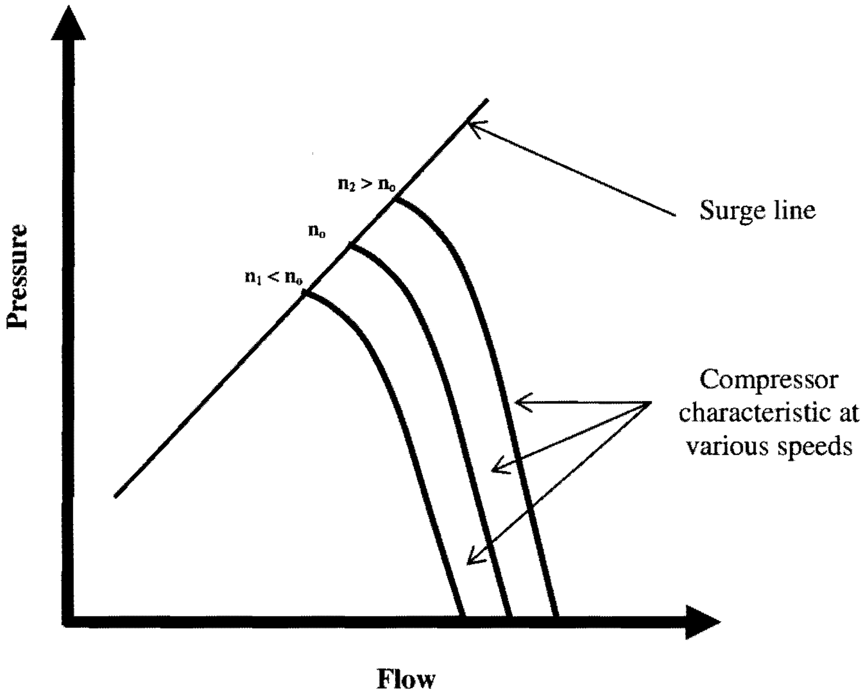

Figure 4.10: Compressor characteristic curve at various shaft speeds.

- **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)*

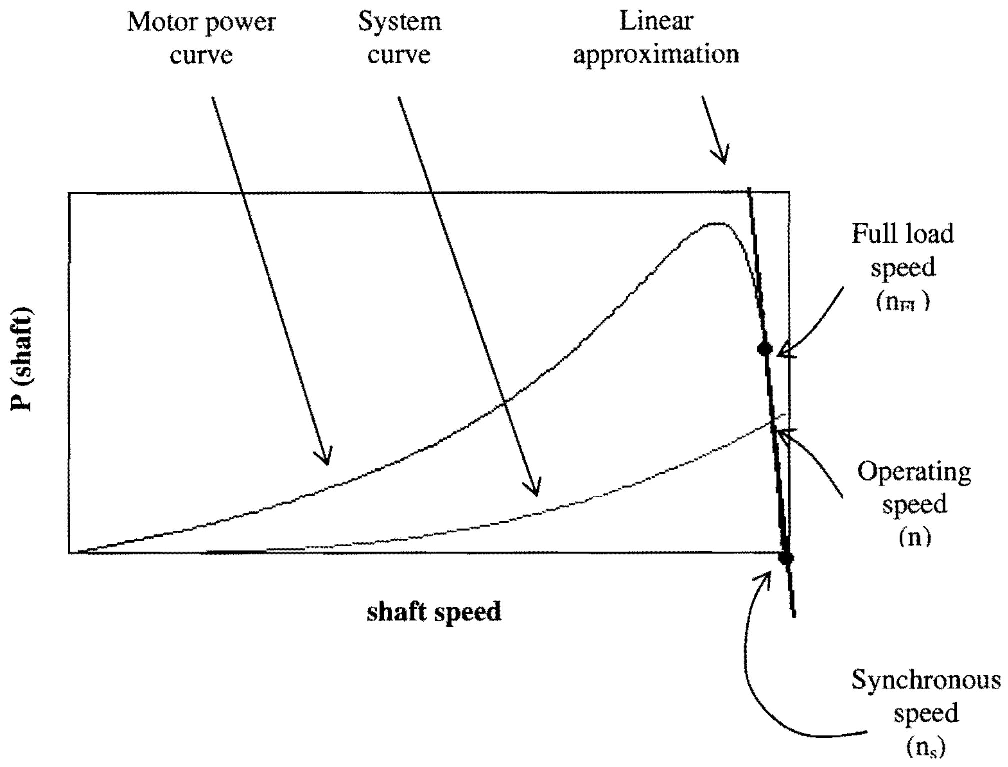

Figure 4.11: Approximating the power curve with a linear model at low slip values.

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.

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

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, 13.7*MW* 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, 13.7*MW* 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

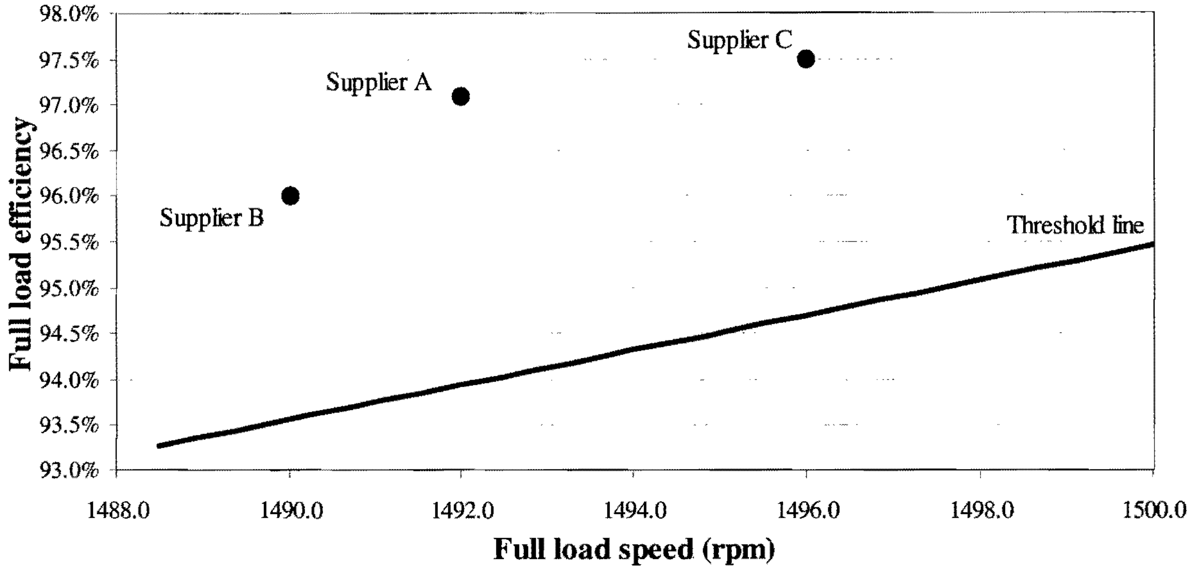

Figure 4.12: Threshold efficiency, proposed new motor should adhere to, as a function of its full load speed.

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.

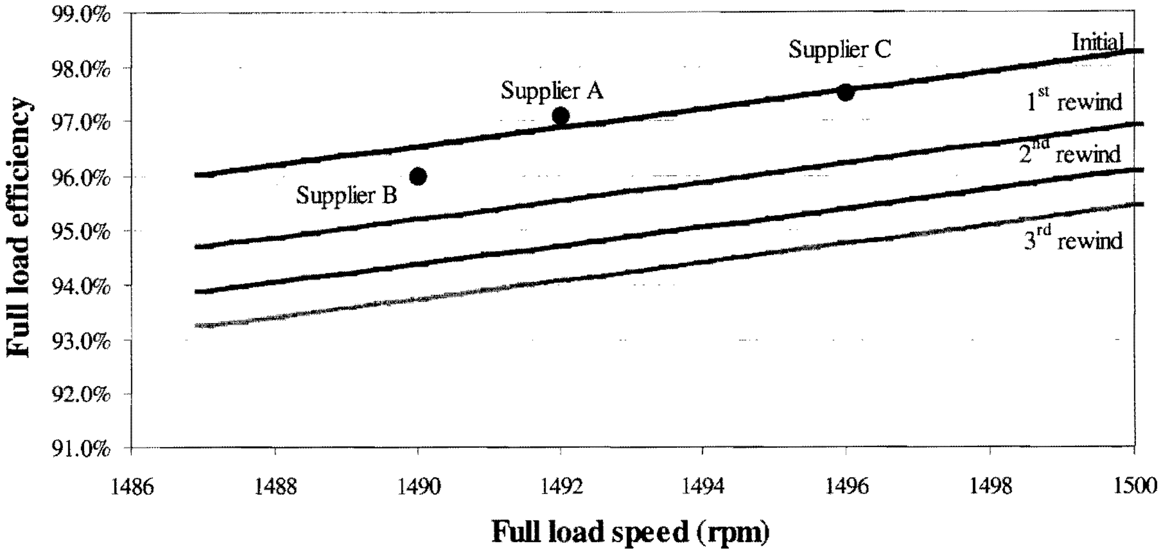

Figure 4.13: Threshold lines of motor after every rewind.

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/kNm^3)*. 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/kNm^3* 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.

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

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.

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

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.