Energy Auditing and Reporting Guidelines for Industries

Department of Renewable Energy,
Ministry of Economic Affairs,
Royal Government of Bhutan

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DEPARTMENT OF RENEWABLE ENERGY
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Thimphu : Bhutan

Foreword

The Department has conducted numerous studies to scrutinize the energy consumption pattern of various energy intensive sectors in the Country. One such study was carried out in 2014 which revealed that the Buildings and the Industries are the major energy consuming sectors. The Building sector alone consumed around 42 % of the total energy followed by Industries at 37 %[1] The Department therefore sees potential for substantial energy savings through the implementation of energy efficiency interventions in these sectors.

The major energy losses in the Bhutanese Industries occur due to the inefficient technologies installed in the plant. Such inefficient technologies are known to be undermining the energy efficiency of the equipment. Only a portion of the consumed energy produces a meaningful output while rest is being wasted owing to its inefficiency. Thus, the energy consumption pattern has to be evaluated to identify major causes of energy losses in the Industries.

Therefore, the Department deems it necessary and timely to develop the Energy Auditing and Reporting Guideline for Industries to guide all the energy auditors and managers to conduct a well-structured and effective energy audit.

The Department aspires that this guideline will promote the practice of energy auditing in Bhutan and thus, contribute towards achieving optimum energy efficiency for the Industry sector in the country.

Tashi Delek

Phuntsho Namgyal
Director
Department of Renewable Energy
Ministry of Economic Affairs

[1] Energy Efficiency Roadmap 2019

Executive Summary

These Energy Auditing and Reporting Guidelines for industries are designed to serve as a practical guide for an energy professional to gain a strong background on energy auditing through the detailed explanations on the components of an energy audit, the general methods and procedures to be followed as well as the reporting practices of an effective energy audit.

A survey was conducted with several industries to determine their awareness level of energy conservation practices. This survey along with detailed interactions with local experts from industry and academia helped shape the structure of these guidelines. Chapter 2 of these guidelines helps the reader select the type of energy audit most suitable for the industry, and to prepare for the audit before commencing the audit.

These guidelines contain the information an energy auditor would need to assess and to identify energy conservation measures for key energy consuming equipment commonly found at the industries in Bhutan. For the benefit of the reader of these guidelines, this information is always presented under six distinct sections for each of the equipment covered. The six sections are: introduction to the equipment, data collection required for assessment of that equipment, instruments required, performance terms and definitions, performance assessment techniques and energy saving opportunities commonly associated with the specific equipment.

With this approach and the steps explained, an energy professional would be able to carry out energy performance assessment of a wide variety of equipment and to identify energy conservation measures best suited for the concerned industry.

The approach to conduct plant level energy use assessment is explained in Chapter 6, which is followed by guidance on developing and use of benchmarks for energy efficiency in Chapter 7. The reader is explained various ways to carry out economic evaluation of identified energy conservation measures in Chapter 8. These are particularly important for reporting to senior management of industries. Chapters 9 and 10 guide the energy professional on optimum reporting methods and on post audit evaluation and monitoring for effectiveness of the implemented measures. In the concluding chapters of these guidelines, data collection templates and energy saving calculation formulae and tips are provided to support the auditors.

The authors have practical experience of conducting over 700 energy audits in several countries in South Asia. They have leveraged this experience and conducted detailed primary and secondary research covering best energy management practices from seven countries, to optimally balance theoretical background with practical inputs on how to carry out effective energy audit at industries, especially for Bhutan.

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Acronyms

AC	Alternating Current
BEE	Bureau of Energy Efficiency
COP	Coefficient of Performance
DC	Direct Current
DRE	Department of Renewable Energy
EAF	Electric Arc Furnace
EER	Energy Efficiency Ratio
FAD	Free Air Delivery
HVAC	Heating, Ventilation, Air Conditioning
IE	International Efficiency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IR	Infra-Red
IRR	Internal Rate of Return
ISO	International Organisation for Standardisation
MD	Maximum Demand
PF	Power Factor
ROI	Return on Investment
SA	STENUM Asia Sustainable Development Society
SEC	Specific Energy Consumption
Solar PV	Solar Photo Voltaic
UNEP	United Nations Environment Programme
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

Units

°C	Degree Celsius
A	Ampere
hr	hours
kcal	kilo calorie
kg	kilogram
kJ	kilo Joules
kl	kilo litre
kVA	kilo Volt Ampere
kVAr	kilo Volt Ampere reactive
kWh	kilo Watt hour
l	litre
m	meter
t	ton
toe	tonne of oil equivalent
TR	Tonne of Refrigeration
V	Volt

1 Introduction to Energy Audit

1.1. Energy audit definition

There are several relatively similar definitions of an energy audit. As per ISO 50002, energy audit definition is:

"Systematic analysis of energy use and energy consumption of audited objects, in order to identify, quantify and report on the opportunities for improved energy performance".

As per Indian Energy Conservation Act 2001, an energy audit is defined as:

"Verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption".

1.2. Objective and benefits of energy audit

In simple terms, an energy audit is usually conducted to understand a given facility and then to find opportunities for improving overall energy savings. There are many reasons for undertaking an energy audit including:

- To improve energy performance and minimise the environmental impacts of the industry's operations.
- To identify behavioural change opportunities by evaluating current operations and maintenance practices.
- To identify technical opportunities by evaluating significant energy consumers equipment or utilities including motors, compressors, boilers, refrigeration plant, furnaces, and other energy users.
- To provide clear financial information regarding energy savings opportunities and to prioritise the energy savings opportunities in a way that would help top management for decision making.
- To gain a greater understanding of a part or all of the industry's energy usage patterns.
- To identify potential for using renewable energy supply technologies.
- To achieve compliance with legal requirements (if any) and comply with corporate social responsibility goals.
- To contribute to the process for certification to a formal energy management system in accordance with ISO 50001 guidelines.

1.3. Overview of energy audit procedures

An overview of the procedure for a detailed energy audit is shown in **Figure 1**. A walk-through audit contains some of the same steps of the procedure shown, but the depth of the data collection and analysis might be different depending on the scope and objectives of the audit. Overall, there are three main steps (excluding the post-audit activities) each of which has several sub-steps. These three main steps are energy audit planning, execution, and reporting.

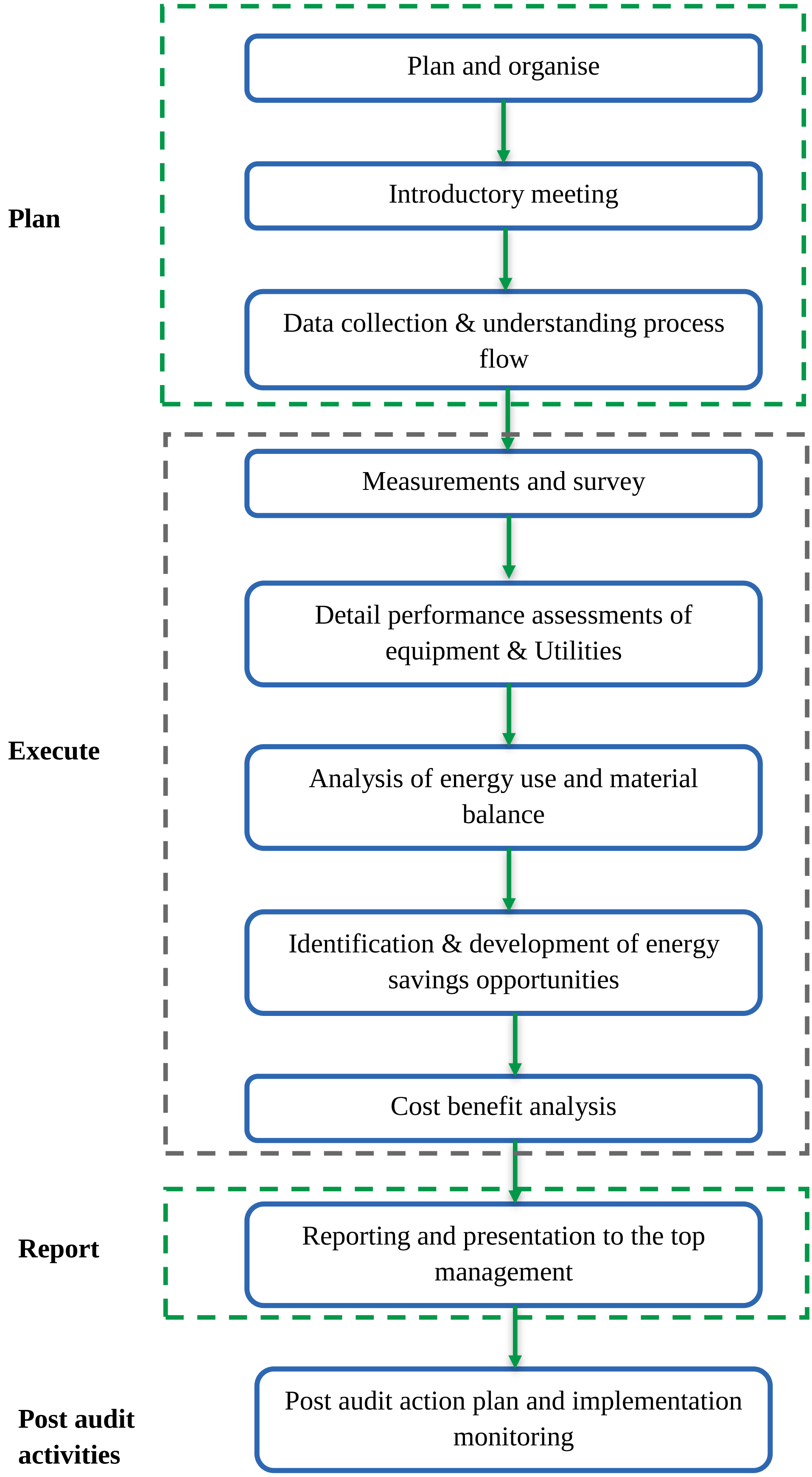


Figure 1: Overview of detail energy audit procedure

2 Types of Energy Audit and Approach

The type of energy audit to be performed depends on the type of industry, the depth to which final audit is needed, and the potential and magnitude of cost reduction desired. Thus, an energy audit can be classified into the following types: walk-through energy audit, targeted energy audit and detailed energy audit.

2.1. Walk-through energy audit

In a walk-through energy audit, readily available data are mostly used for a simple analysis of energy use and performance of the plant. This type of audit does not require a lot of measurement and data collection. These audits take a relatively short time and the results are more general, providing common opportunities for energy efficiency. The economic analysis is typically limited to calculation of the simple payback period.

2.1.1. Objectives of walk-through energy audit

- Identification and basic evaluation of low-cost opportunities that can be easily implemented.
- Understanding of energy consumption at an industry or equipment/utility level
- Improved awareness of energy costs and the potential benefits of managing energy
- Understanding of the extent of more capital-intensive opportunities.
- Indications of potential savings and benefits from undertaking more detailed investigations such as targeted or detailed energy audit.

The savings potential identified from conducting a walk-through audit can help the clients to determine whether they should proceed to undertake targeted audit or a detailed audit. Simultaneously, a walk-through audit helps the audit team to prepare a more effective audit plan (which includes composition of audit team and allocation of time or certain section of client facility, selection of instruments to carry) when proceeding with targeted or detailed audit.

2.1.2. Preparations for walk-through energy audit and resources required

Walk-through audit by itself can give significant benefits, provided it is carried out by an experienced energy audit team as limited time and resources are available and detailed measurements are not feasible.

Resources required

1. Team: 1 to 2 members
2. Basic instruments for quick assessments (if available) such as:
    - Non-contact type Infra-red thermometer,
    - Hand-held clamp meter
    - Pen-type thermometer
    - Sling Psychrometer
    - Anemometer
    - Measuring tape
    - Electric tester, etc.

Refer **Chapter 11** for list of instruments and their usage.

3. Others
    - Data collection format
    - Audit checklist,
    - Log sheet
    - Diary/notebook

2.1.3. Process of carrying out walk-through energy audit

1. Introductory meeting

The walk-through audit generally begins with an introductory meeting with industry management personnel. The purpose of the preparatory meeting is to understand the industry and major processes before actual visit to the shop floor or plant so that the audit goals reflect the operations of the industry. The energy auditor shall start the meeting with a short presentation apprising the management about the audit goals and possible benefits to the industry. The energy auditor shall take the management views on which aspects of operation should be the focussed area during the audit and shall identify the key issues of the clients. The energy auditor shall collect energy consumption (electricity and fuel bills for 12 months) and corresponding production data (for same 12 months). The energy auditor shall try to get a detailed description of industry process, significant energy consumers, type of products and other general information.

2. Walk-through

The next step is to walk-through the industry with appropriate plant personnel who is familiar with all the installed equipment and utilities related operation. During walk-through, the energy auditor then identifies key issues of the client and gather inputs on the areas of concern, record observations, note the nameplate and meter readings, identify low cost and easily implementable energy savings measures. The energy auditor shall ensure covering all functional areas while conducting a walk-through.

The reader may refer audit checklist given in **Annexure-13.1** to select appropriate and relevant energy savings opportunities that may be applicable.

3. Closing meeting

The energy auditor shall hold a short wrap-up meeting to review main points observed during the walk-through, highlight any observation or finding which needs immediate attention by industry management. Fix the date for walk-through audit report presentation and submission with industry management.

4. Analysis & report preparation

Start analysing the collected data, reviewing the notes taken during the walk-through, and start preparing the energy savings recommendations. Recommendations to industry should be specific and supported by data to the extent possible and presented in order of monetary savings (highest savings on top or shortest return on investment on top). These should contain estimated costs (checked from local market), estimated savings and simple payback calculations. Consider the priority set by industry while preparing the walk-through audit report.

5. Report presentation and action plan

The energy auditor shall personally hand over the walk-through audit report to the industry on the agreed date, explaining the recommendations made to the top management. The energy auditor shall help the industry management to prepare an action plan with selection of recommendations along with timeline for implementation.

Typical content of Walk-through energy audit report

1. Executive Summary
    - Summary of energy savings potential
    - Recommendations breakup in payback and savings categories
2. Current Industry Situation
    - Industry processes
    - General information on energy consumption
    - Energy and production data analysis
3. Energy Savings recommendations in format as shown in **Table 1**
4. Annexure

Table 1: Energy savings recommendation table format for walk-through energy audit

Sl. No.	Description of the present situation and the problem observed	Description of recommended actions	Amount of the annual savings		Estimated Investment Costs (Nu.)	Simple payback period (months)
			Energy savings (kWh/year or kl/year) (as appropriate)	Amount (Nu. /year)		

2.2. Targeted energy audit

The need for targeted energy audits often identified pursuant to a detailed analysis of the results of a walk-through audit with client / management. The targeted audits provide data and detailed analysis on specified target projects. For example, an organization may target its lighting system or boiler system or steam system or compressed air system with a view of effecting energy savings.

Targeted audits therefore involve detailed surveys of the target subjects and analysis of the energy flows and cost associated with the targets. Final outcome is the recommendations regarding actions to be taken for energy conservation. Detail on how to carry out targeted audit on certain utilities or equipment are provided in respective sections under **Chapter 5**

2.3. Detailed energy audit

Detailed energy audit is a comprehensive audit and results in a detailed energy project implementation plan for a facility since it accounts for the energy use of all major equipment. It considers the interactive effects of various projects and offers the most accurate estimate of energy savings and cost. It includes detailed energy cost saving calculations and project implementation costs. One of the key elements in a detailed energy audit is the energy balance. This is based on an inventory of energy-using systems, assumptions of current operating conditions, measurements, and calculations of energy use. Detailed energy auditing is carried out in three phases as shown in **Figure 1.**

3 Preparation for Detailed Energy Audit

3.1. Audit scope

As per ISO 50002, definition of scope is “activities the energy auditor and the organisation agree are necessary for the energy audit”.

The audit scope needs to consider the available resources such as staff, time, audit boundaries, level of analysis, expected results, the degree of detailing, and the budget for conducting the energy audit. The audit scope will depend on the purpose of the specific audit and may be defined by an overall government or company audit program. It should also define the share of processes included in the audit of the industry’s total energy use as well as comprehensiveness and the level of detail for the final recommendations. Therefore, the scope of the audit may be defined in terms of the processes to be covered or the areas or sections of the industry that need to be covered, from within the entire industry. In many cases the entire industry would be the scope of the audit.

It is responsibility of the energy auditor to clarify and define the scope of the energy audit before starting the audit, by considering all the points mentioned in previous paragraph.

3.2. Preliminary data collection

Energy bills along with other current and historical energy and production related data and information should be collected at the beginning of the audit process to analyse power consumption pattern and anomalies therein. The more historical data available, the better the auditor can understand the performance of the plant at differing times of day, in various seasons, and under diverse production conditions. The suitable time to conduct energy audit in an industry is over the period when the industry is running at its highest production output or close to highest production capacity. The collected preliminary data will give some indication of appropriate time duration for completing an effective energy audit.

The data that can be collected at the beginning of an energy audit may include the following:

- Month wise electricity bills and fuel bills for the last 1 to 2 years
- Monthly production data for the same period
- List of major energy consuming equipment with their nameplate ratings.
- Status of energy management and any energy-saving measures implemented in the recent past (by the industry on their own or as part of external consultancy or agency driven improvement programme).
- General information about the plant (year of construction, ownership status, renovations, types of products, operation schedule particularly for certain equipment that does not operate throughout the operating shifts, operating hours, scheduled shutdowns, etc.)

The energy auditor shall study and analyse the collected preliminary data from audit planning point of view.

3.3. Audit plan

An audit plan outlines the audit strategy and procedure. The plan helps the auditors to check the consistency and completeness of the audit process and ensure that nothing important is neglected or overlooked. The audit plan, after taking into consideration the preliminary data collected, should provide the following

- Scope of the audit
- Time of the audit and its duration as well as the timeline for each step of the audit process
- Elements of the audit that have a high priority
- Responsibilities and tasks of each audit team member
- Format of the audit report and its outline

3.3.1. Selection of energy audit team

Upon reviewing the collected preliminary data and defining the audit scope, a competent team for energy audit shall be constituted. The team competence can be shown by:

- Appropriate education and/or training for energy audit
- Relevant technical, managerial, and professional experiences and skills
- Familiarity with appropriate local regulations, and energy auditing & reporting guidelines
- Familiarity with the energy equipment, utilities and process being audited
- Familiarity with energy audit instruments and competent enough to operate and handle the energy audit instruments safely.

In case, any of above-mentioned criteria are not met within the available team, an external professional may be hired/consulted to be part of the audit team.

It is a good practice to prepare a documented audit plan and to share it with the industry client upfront. To the extent possible the audit team should follow the audit plan, however, in view of new observations / issues notice or ground situation changes, the audit plan may be modified during the audit. In such cases, the updated audit plan may be shared with the client subsequently.

3.3.2. Safety considerations

Ensure that relevant personal protective equipment (PPE) is available to all team members. Commonly relevant PPEs are: Electrical safety gloves, industrial safety boots, heat resistant furnace gloves, face masks, protective eyewear, safety helmet (hard hat). Loose clothing (such a necktie or shawl) is to be strictly avoided to safely operate plant(s) and machineries to prevent accidents at site.

It is strongly recommended to comply with the health and safety guideline and procedures as defined by the relevant local authorities.

Energy auditors must ensure their own safety by following safe practices while carrying out energy audits. Following safe pathways, not touching objects that may be hot, keep safely away from any live wires, cables and other conductive surfaces are a few basic safety considerations that must be followed at all times by the auditors. Moreover, the auditors need to study and put into practice all the relevant safety considerations on their own at each site and in each audit depending upon the nature of activities undertaken by the clients.

3.4. Introductory meeting

The purpose of the introductory meeting is to set the context for the energy audit, confirm its scope, engage all relevant industry personnel in the audit process and request specific additional energy information from the industry. This information should enable appraisal of the client organisation's current energy use and energy management system.

In the introductory meeting, the energy auditor shall request the industry to:

- Identify a person to liaise with the energy auditor, where necessary supported by other appropriate individuals constituted as a team for the purpose.
- Inform all the divisional engineering heads and other interested parties about the energy audit and any requirements placed on them in connection with it.
- Disclose any unusual conditions, maintenance work or other activities that will occur during the energy audit.
- Ensure cooperation of the engineering team and other interested parties.
- Nominate a management representative to take responsibility for evaluation and implementation of energy performance improvement measures identified during the audit.

The energy auditor shall agree with the organization on:

- Arrangements for access to the audited objects for the energy auditor.
- Health, safety, security and emergency rules and procedures.
- Resources and data to be provided
- Proposed visit and other schedules
- Requirements for special measurements, if needed
- Procedures to be followed for installation of measuring equipment, if needed
- Aspects of data confidentiality (pertaining to the data already provided or yet to be collected), if required.

The energy auditor shall share the audit plan, describe the processes, means and schedule of the energy audit and the possible need for additional metering equipment.

3.5. Initial walk-through visit

The purpose of the initial walk-through visit is for the energy audit team to become familiar with the industry to be audited. The auditors shall go through the processes and utilities that they will audit in detail later.

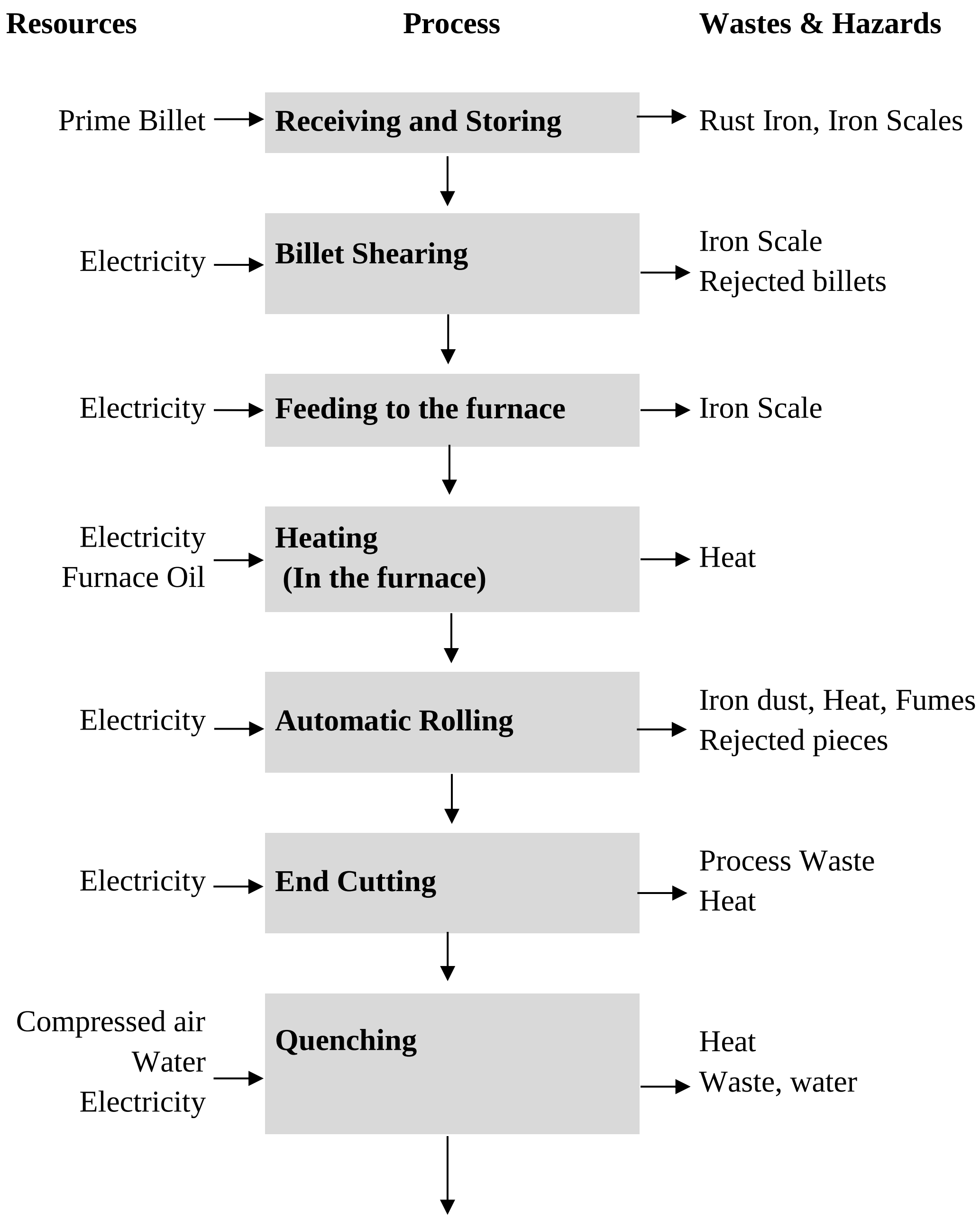
The audit team shall also meet with the managers of the areas to be audited to provide an introduction and establish a common understanding of the audit process. The auditors can solicit comments from the facility staff and can collect readily available data during the walk-through visit. The outcome of this visit should be:

1. To finalise the energy audit team
2. To identify the main energy consuming areas/plant items to be surveyed in detail during the audit.
3. To identify and prepare list of specific instruments required for energy audit
4. To collect macro data on plant energy resources, major energy consuming equipment.
5. To build up awareness and support for detailed energy audit.
6. To update the audit plan, if necessary.

4 Conducting Detailed Energy Audit

4.1. Process flow diagram

An overview of unit operations, important process steps, material and energy use and waste generation should be assembled in the form of process flow diagram. This visualisation of the process flow, along with identification of energy input and output flows, helps the energy auditor to identify energy saving potential to focus on during the detailed audit. Information from existing drawings, records and shop floor surveys will help in preparing the flow chart. Simultaneously the team should identify the various inputs and outputs streams at each process step. An example of process flow chart of re-rolling mill (highlighting input resources and outputs) is shown below:



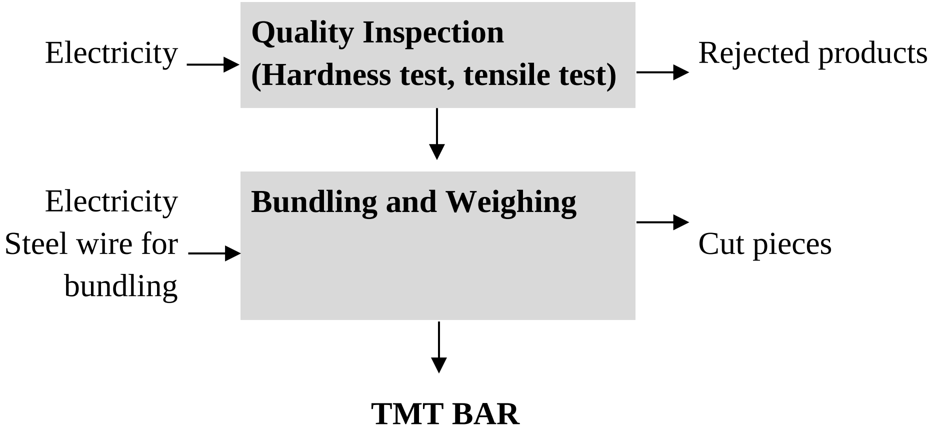


Figure 2: An example of process flow chart

It may be noted that waste heat and rejection (rejection is not directly related to energy consumption, but it is leading to rework and increased energy consumption of mill) has been identified at various stages in this flow chart. The audit focus will depend upon consumption of input resources, energy efficiency potential, impact of process step on entire process or intensity of waste generation/energy consumption.

4.2. Comprehensive data collection

Based on the preliminary data collection, the energy auditor shall prepare a customised data collection spread sheet to suit the industry type. The data collection spread sheet shall have clear and descriptive headings with appropriate rows and columns for different energy consumers. A general data collection sheet shall be avoided as it will not serve meaningful purpose.

In addition to data collected at preliminary data collection stage, the energy auditor shall also collate the following information during energy audit:

- List of energy consuming systems, processes, and equipment
- Detailed characteristics of the audited object(s) including known relevant variables and how the organization believes they influence energy consumption
- Current and historical data of:
    - energy consumption
    - relevant variables
    - relevant related measurements
- Monitoring equipment configuration, and analysis information such as local gauges, distributed control systems, instrumentation types.
- Future plans that affect energy use such as planned expansions, contractions or changes in production volume or planned changes in replacement of equipment or systems that have significant energy implications.
- Design, operation and maintenance documents
- Energy audits or previous studies related to energy and energy performance
- Current or a reference tariff of electricity and fuel to be used for financial analysis and other relevant economic data

- Knowledge on how the organization manages its energy and relative configuration of the energy distribution system and the management structure

The data collected should be comprehensive enough to determine the energy baseline period. **Energy baseline period** is a suitable period in which the organisation account for operating cycles, regulatory requirements or variables that affect the energy consumption and energy efficiency, so that the data period adequately demonstrates a full range of performance. Data that the industry has, can be data what it has internally generated (e.g. through measurements, log sheets) or data which it has access to electricity bills, fuel bill and annual reports).

Energy reduction target year: The industry management may have established quantifiable objectives of energy performance improvement. If so, there would be some data analysis done by the industry to develop, track the energy reduction over a period. Review of this data would help the energy auditor determine further opportunities for energy saving as well as to obtain insights into the industry's focus and approach to energy conservation.

4.2.1. Difference between sales figures and production figures

While analysing the energy consumption of an industry over a period of time, it is important to relate energy consumption to production output. It is understandable that in period of high production output, higher energy consumption may be needed. However, it is the energy auditor's task to analyse the relationship between production figures and energy consumption. Sometimes the industry may provide their monthly sales or despatch figures rather than the actual month by month production figures, since the latter are not maintained well.

Sales figures may be significantly different from production figures due to storage or carrying inventories. Hence energy audits prefer to use actual production figures to compare energy consumption. In case the inventory levels are small or are nearly constant over the months under study, sales figures may be treated as a proxy for production figures.

4.3. Energy bills analysis

4.3.1. Understanding energy costs

Contrary to common belief, energy costs are not a fixed overhead, there is often a huge potential for cost savings, understanding energy cost is a vital factor for awareness creation and savings calculation. In some industries, sufficient meters may not be available to measure all the energy used. In such cases, bills for fuels and electricity will be useful. The annual company balance sheet is the other sources where fuel cost and power are given with production related information.

Energy bills shall be analysed by auditor since they:

- Provide a record of energy purchased in a given year which gives a baseline for future reference
- Indicate the potential for savings when related to production requirements.
- Provide the basis of maximum demand tariff.
- Allow comparison of energy cost (and changes in energy consumption) over time.

4.3.2. Fuel costs

Following are the most common types of fuels used in Bhutan for thermal energy supply are

- Diesel
- Coal
- Furnace oil

Understanding fuel cost is simple and it is purchased in tons (t) or kilolitres (kl) and generally defined in Tonnes of Oil Equivalent (TOE). The three main factors that affect the fuel costs are:

- Price at source, transport charge, type of transport
- Quality of fuel (contaminations, moisture, etc.)
- Energy content of fuel (calorific value)

The main components of fuel bills are:

1. Quantity (kl or kg)
2. Price (Nu.) including transportation cost
3. Calorific value of fuel

The calorific value of the fuel is the key parameters while analysing actual energy consumption, rather than simply considering the procurement quantity (e.g. 1 t of low calorific value coal may have less embodied energy than 0.8 t of high calorific value coal).

4.3.3. Electricity bill analysis

The electricity billing by utilities for medium and large industries is often done on two-part tariff structure, i.e. one part for capacity (power or demand) drawn and the second part for actual energy drawn during the billing cycle. Capacity or demand is in kVA (apparent power) or kW terms. The reactive energy, i.e. kVAr drawn by the service is also recorded and billed for in some utilities, because this would affect the load on the utility. Accordingly, utility charges for maximum demand, active energy, and reactive power drawn (as reflected by the power factor) in its billing structure. In addition, other fixed and variable expenses are also levied.

The tariff structure generally includes the following components:

- **Maximum demand Charges** also called as normative availability of a power plant, relates to the maximum demand registered during month/billing period and corresponding rate of utility.
- **Energy Charges** relate to energy (kilowatt hours) consumed during month or billing period and corresponding rates, often levied in slabs of use rates.
- **Power factor** penalty or bonus rates, as levied by most utilities, and includes cost of reactive power drawn from the grid.
- **Time of day (TOD)** rates like peak and non-peak hours are also prevalent in tariff structure provisions of some utilities.

- Penalty for exceeding **contract demand**. Contract demand means the maximum amount of apparent power (kVA) demand that the customer expects to use and for which the customer has contracted the utility.
- Any other charges, taxes, or subsidy as applicable.

Analysis of utility bill data and monitoring its trends helps energy auditors to identify ways for electricity bill reduction through available provisions in the tariff framework.

The utility employs an electromagnetic or electronic tri-vector meter, for billing purposes. The minimum outputs from the meters are:

- Maximum demand registered during the month, which is measured in pre-set time intervals (15- or 30-minute duration) and this is reset at the end of every billing cycle.
- Active energy in kWh during billing cycle
- Reactive energy in kVArh during billing cycle
- Apparent energy in kVAh during billing cycle

It is important to note that while maximum demand is recorded, it is not the instantaneous demand drawn, as is often misunderstood but the time integrated demand exceeding the predefined cycle, that in fact gets recorded.

As an example, in an industry if the drawl over a recording cycle of 30 minutes is:

1. 2500 kVA for 4 minutes
2. 3600 kVA for 12 minutes
3. 4100 kVA for 6 minutes
4. 3800 kVA for 8 minutes

The energy meter will be computing maximum demand as:

$$\frac{(2500\ X\ 4) + (3600\ X\ 12) + (4100\ X\ 6) + (3800 X\ 8)}{30} = 3603.7\ kVA$$

The month's maximum demand will be the highest among such demand values recorded over the month. The energy meter registers only if the value exceeds the previous maximum demand value and thus, even if, average maximum demand is low, the industry has to pay for the maximum demand charges for the highest value registered during the month, even if it occurs for just one recording cycle duration i.e. 30 minutes during whole of the month.

Electricity Bill data collection: An energy auditor shall try to collect electricity bill data in a prescribed spread sheet format for analysis as shown in below example **Table 2**

Table 2: An example of data collection sheet for electricity bill

Month & Year	Maximum Demand (kVA)	Energy consumption (kWh)	Power Factor (PF)	Maximum Demand charges (Nu.)	Energy charges (Nu.)	Total bill (Nu.)	Effective rate[2] (Nu. per kWh)
Jan-XX							
Feb-XX							
……							
……							
Dec-XX							

Based on the components in electricity bill for the industry being audited, more columns can be added or removed from the above table.

4.4. Analysis of historical energy use and SEC

Graphical analysis of historical energy use in a plant can help to better understand the energy use pattern in the plant. Sometimes the patterns are unexpected and can lead to opportunities to modify the way energy is used and thereby save energy. For example, one might not normally expect a heavy process industry like cement industry to exhibit a seasonal variation in energy use because of weather changes. Despite this, if a seasonal pattern shows up in the graphical analysis, this may suggest the need to investigate for the possible sources of energy losses. It is common for a plant's operating conditions or capacities to vary over the year. Therefore, the variation of energy use alone may not truly reflect the condition of energy efficiency in a plant. Thus, it is much better and more accurate to conduct this type of graphical analysis of a plant's specific energy consumption (SEC), which is the energy use per unit of output or production. SEC can be calculated by using monthly energy consumption data obtained from energy bills and the monthly production data (using the appropriate unit of production measurement). For example:

SEC = Energy consumption (kWh) / Production (t)

[2] Total electricity bill amount for the month divided by total energy consumed in the month (Nu./kWh)

A hypothetical example of specific electrical consumption for electricity and specific fuel consumption in a textile spinning plant in a four-season country is provided in **Figure 3** As can be seen, the electricity intensity pattern over one year does not vary much, whereas the fuel intensity pattern **Figure 4** varies by the change in seasons. The reason is that in a spinning plant, fuel is used just for heating during the cold months, as the temperature and moisture of the ambient air of spinning plants needs to be kept constant all over the year.

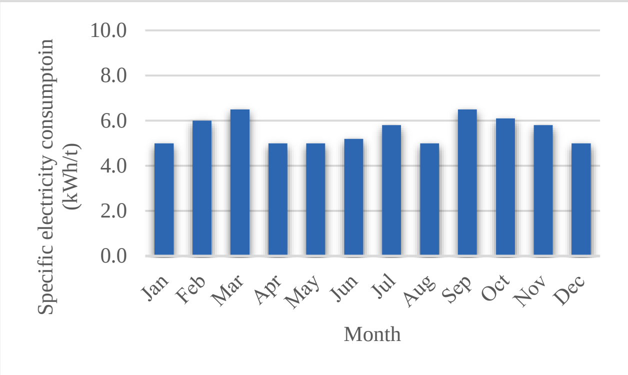


Figure 3: Historical electricity intensity patterns for a spinning mill

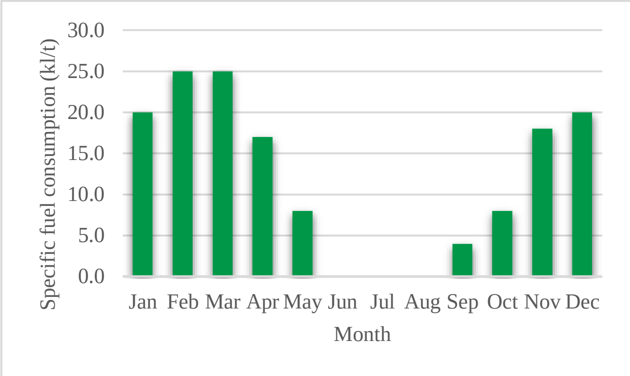


Figure 4: Historical fuel intensity pattern for a spinning mill

A pie chart is another type of chart that can be used for graphical analysis of historical energy use and cost data. A pie chart can be used to show the share of various types of energy use and their costs graphically. Both monthly and annual data can be used for plotting such graph. **Figure 5** shows a hypothetical example of the share of each type of final energy use of one year

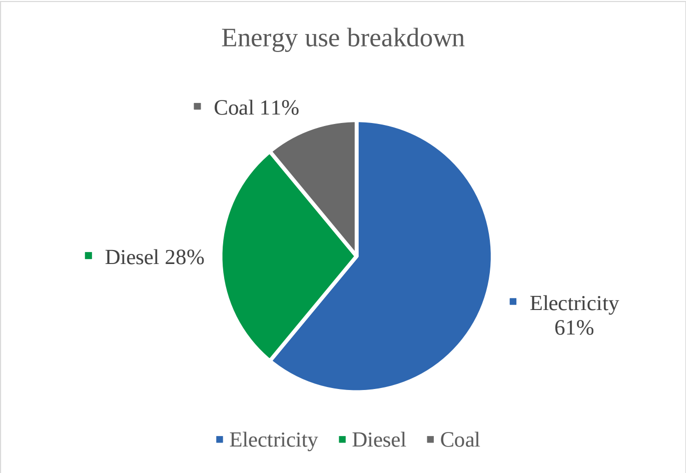


Figure 5: Visualisation of type of energy use in pie chart

Line graphs can be used to depict tends over time. A useful line graph can be one depicting SEC over period of time. Using a two-axis line graph is a good way to compare two parameters over same time period. As the example in **Figure 6** shows, the left side y-axis (green line) depicts SEC while the right-side y-axis (blue line) depict total production over the Jan to Dec time period. Here one can see that in months with high production, the SEC is low, and that SEC varies in range of ~20 kWh/t over the period. Indicating that perhaps the industry is not normally running at optimum production levels. By observing the trend line of the SEC, one notices that SEC has a rising trend even when production shows an increasing trend, which is not desirable.

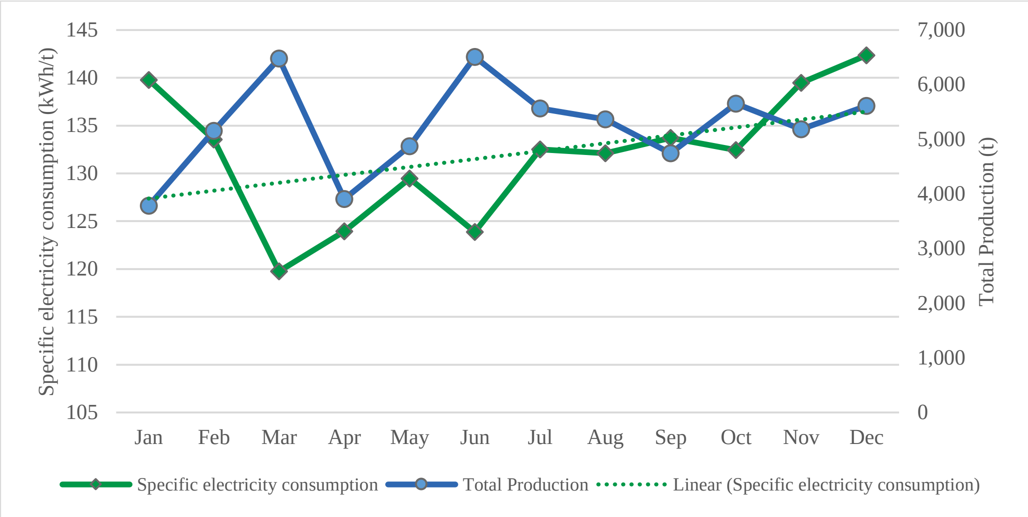


Figure 6: An example of line graph depicting specific electricity consumption (SEC) over time and increasing trend of SEC

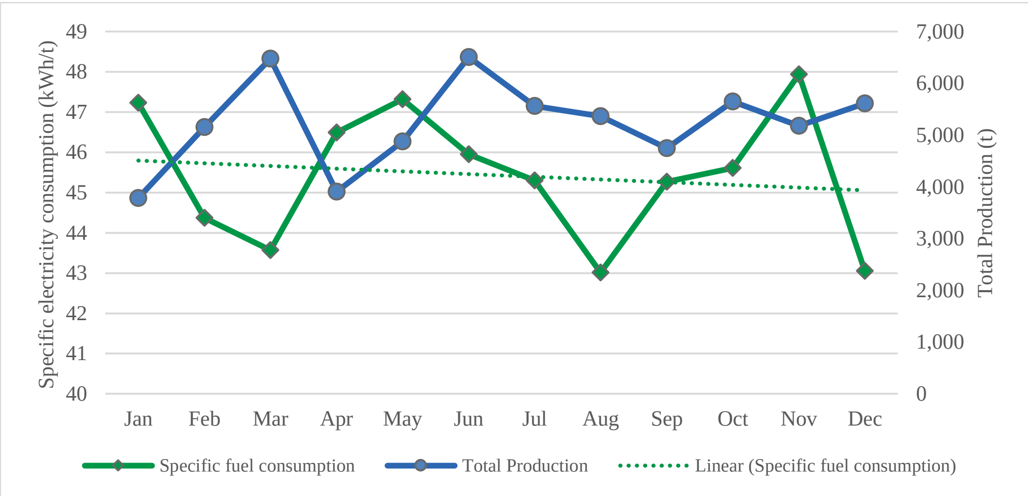


Figure 7: An example of line graph depicting specific fuel consumption (SFC) over time and decreasing trend of SFC

In another similar example of a two-axis line graph shown in **Figure 7**, the SEC trend line shows a small positive (lower SEC) trend, even with stable production over the period. This may indicate some small improvement measures or good practices being implemented by the industry over the period.

4.5. Measurements, survey, and verification of measured data

Gathering data through measurement and survey is one of the main activities of energy auditing. Without adequate and accurate data, an energy audit cannot be successfully accomplished. Some data are readily available and can be collected from different divisions of the plant being audited. Some other data can be collected through measurement and recording.

4.5.1. Electrical load inventory

Making an inventory of all electrical loads in a plant aims to answer two important questions:

- where the electricity is used?
- How much and how fast is electricity used in each category of load?

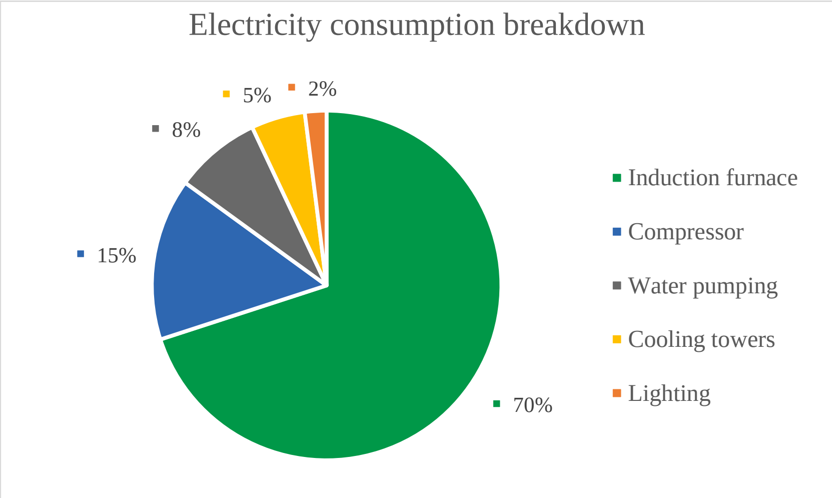


Figure 8: An example of electricity consumption breakdown

One way to prioritize the search for electricity-saving opportunities is by the magnitude of the loads (kW). Therefore, identifying and categorizing different loads in a plant can be useful. Often, the process of identifying categories of use allows energy waste to be easily identified, and this frequently leads to low-cost savings opportunities. Identifying high-consumption loads lets the auditor consider the best savings opportunities first. Because the inventory also quantifies the demand (i.e. how fast electricity is used) associated with each load or group of loads, it is invaluable for further interpretation of the demand profile. An example of electricity consumption breakdown is shown in **Figure 8**

4.5.2. Verification of the measured data

Verify the measured values of the equipment and utilities with rated parameters of the respective equipment and utilities and if a very wide variation observed between measured values and rated parameters, this is an indication of following:

- The equipment or utility under observation is faulty and immediate attention is needed by the facility engineering team.
- The equipment or utility under observation is partially loaded or not fully utilised, the energy auditor shall investigate further to find energy saving opportunities.

- The method of measurement used by energy auditor may be wrong. Energy auditor shall check whether their instruments are functioning well and shall take the measurements again to verify.

4.5.3. Portable measuring instruments for energy audit

The energy audit team should be well-equipped with all the necessary measurement instruments. The instruments used for measurements shall be well calibrated with valid calibration certificate and functioning properly. Modern portable meters can store data collected for a longer duration (24 hours or more) and can then be uploaded either directly or remotely for analyses off site.

The energy auditor shall ensure:

- The instruments are well calibrated, and their calibration certificates are valid.
- The instruments calibration certificates are attached/pasted on the instruments
- The instruments are functioning well and safe to operate.

Refer **Chapter-11** for detailed list of instruments required for energy audit.

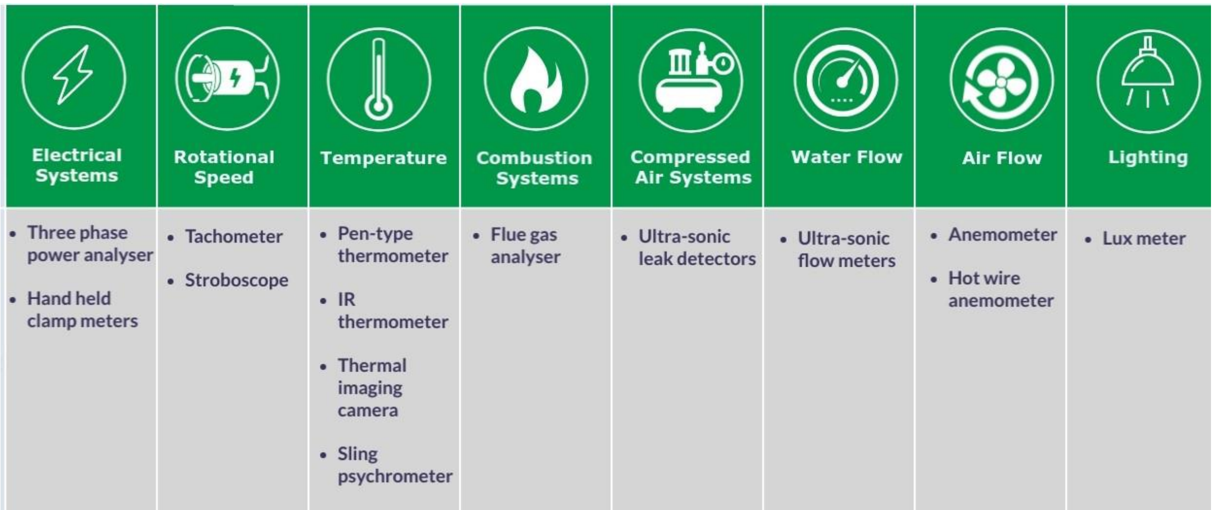


Figure 9: Appropriate portable measuring instruments for various systems

5 Detailed Energy Performance Assessment

5.1. Electrical systems & Power Factor

5.1.1. Introduction

The network through which the consumers get electricity from the source is called electrical supply system. An electrical supply system consists of generating units that produce electricity, high voltage transmission lines that transport electricity over long distances, and distribution lines that deliver electricity to consumer.

Figure 10 is an illustration of electricity transmission and distribution system, and linkages from electricity sources to end user.

The power generation units typically produce 50 Hertz alternating current (AC) electricity with voltages between 11 kV and 33 kV. At the power generation units, the three-phase voltage is stepped up to a higher voltage for transmission on cables strung on cross country towers. Extra high voltages (EHV) like 265 kV to 275 kV and high voltages (HV) like 110 kV, and above transmission is the next stage from power generation units to transport A.C. power over long distances. Sub-transmission network at 132 kV, 110 kV, 66 kV or 33 kV constitutes the next link towards the end user. Distribution at 11 kV/6.6kV/3.3 kV constitute the last link to the consumer, who is connected directly or through transformers depending upon the drawn level of service.

The transmission and distribution network include sub-stations, lines and distribution transformers. High voltage transmission is used so that smaller, more economical wire sizes can be employed to carry the lower current and to reduce losses. Sub-stations, containing step-down transformers, reduce the voltage for distribution to industrial users.

There is no difference between a transmission line and a distribution line except for the voltage level and power handling capability. Transmission lines are usually capable of transmitting large quantities of electric energy over great distances. They operate at high voltages. Distribution lines carry limited quantities of power over shorter distances.

Voltage drops in line are in relation to the resistance and reactance of line, length and the current drawn. For the same quantity of power handled, lower the voltage, higher the current drawn and higher the voltage drop. The current drawn is inversely proportional to the voltage level for the same quantity of power handled.

The power loss in line is proportional to resistance and square of current. (i.e. $P = I^2R$). Higher voltage transmission and distribution thus would help to minimize line voltage drop in the ratio of voltages, and the line power loss in the ratio of square of voltages. For instance, if distribution of power is raised from 11 kV to 33 kV, the voltage drop would be lower by a factor 1/3 and the line loss would be lower by a factor $(1/3)^2$ i.e., (1/9). Lower voltage transmission and distribution also calls for bigger size conductor on account of current handling capacity needed.

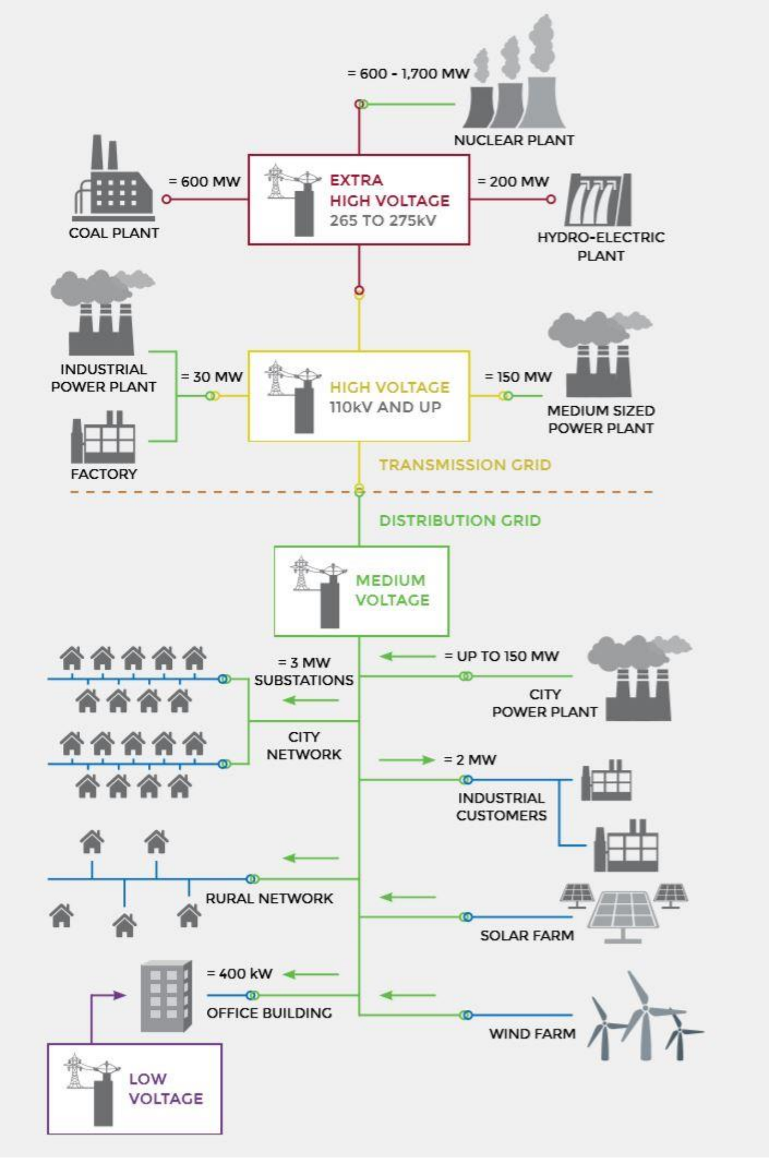


Figure 10: Illustration of electricity transmission and distribution system (Source: UNEP)

5.1.2. Data collection

Following data shall be collected during audit with support from plant supervisor:

- Electricity Bill for preceding 12 months (minimum)
- Log sheet related to electrical fault caused by overheating or overvoltage
- Any recurring electrical faults recorded by plant supervisor

In addition to above, the following data shall be collected through measurements

- Power logging at mains panel up to 24 hours (duration of logging should be decided mutually with plant supervisor)
- Power measurements at sub-panels
- Thermal images of inside electrical panels (to check overheating)

5.1.3. Instruments required

- Three-phase power analyser
- Hand-held clamp meter
- Thermal imaging camera (to check overheating inside electrical panels)

5.1.4. Observation parameters

- Maximum demand or Peak demand
- Power factor

5.1.5. Measurements

The following electrical parameters can be measured using hand-held clamp meter or three-phase power analyser.

- Voltage (V)
- Current (A)
- Power (kW)
- Power factor (PF)
- Apparent power (kVA)
- Reactive power (kVAr)
- Harmonics
- All other electrical parameters

5.1.6. Electrical load management and maximum demand control

Need for Electrical Load Management: In a macro perspective, the growth in the electricity use and diversity of end use segments in time of use has led to shortfalls in capacity to meet demand. As capacity addition is costly and only a long-time prospect, better load management at user end helps to minimize peak demands on the utility infrastructure as well as better utilization of power plant capacities. The utilities (Distribution companies) use power tariff structure to influence end user in better load management through measures like time of use tariffs, penalties on exceeding allowed maximum demand, night tariff concessions etc. Load management is a powerful means of efficiency improvement both for end user as well as utility. As the demand charges constitute a considerable portion of the electricity bill, from user angle too there is a need for integrated load management to effectively control the maximum demand.

Step by Step Approach for Maximum Demand Control

1. Load Curve Generation

Presenting the load demand of a consumer against time of the day is known as a 'load curve'. If it is plotted for the 24 hours of a single day with the help of a **three-phase power analyser**, it is known as 'hourly load curve' and if daily demands plotted over a month, it is called 'daily load curve'. A typical hourly load curve for an engineering industry is shown **Figure 11.**

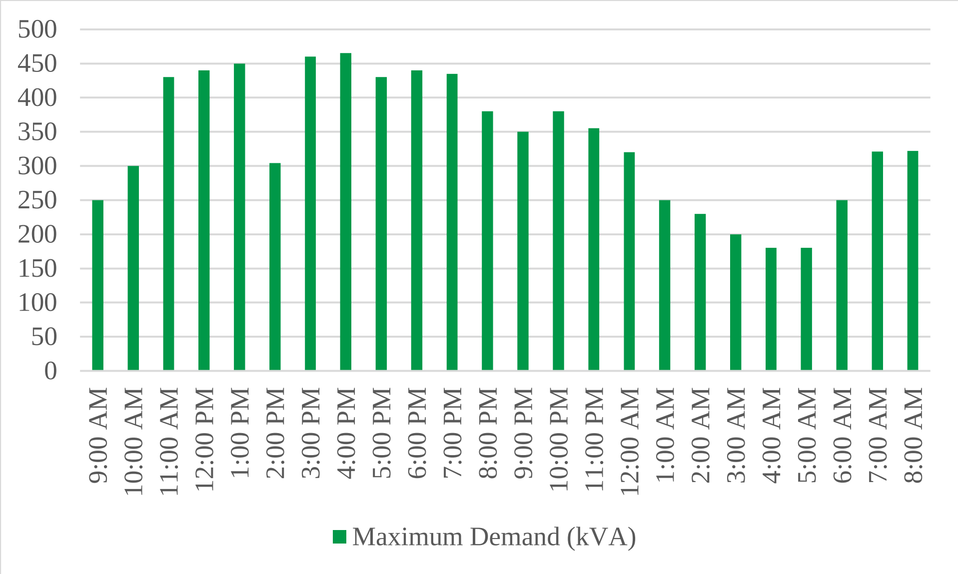


Figure 11: Hourly load curve

These types of curves are useful in predicting patterns of drawl, peaks and valleys and energy use trend in a section or in an industry or in a distribution network as the case may be.

2. Rescheduling of loads

Rescheduling of large electric loads and equipment operations, in different shifts can be planned and implemented to minimize the simultaneous maximum demand. For this purpose, it is advisable to prepare an operation flow chart and a process chart. Analysing these charts and with an integrated approach, it would be possible to reschedule the operations and running equipment in such a way as to improve the load factor which in turn reduces the maximum demand.

3. Storage of products/in process material/ process utilities like refrigeration

It is possible to reduce the maximum demand by building up storage capacity of products/ materials, water, chilled water *I* hot water, using electricity during off peak periods. Off peak hour operations also help to save energy due to favourable conditions such as lower ambient temperature etc. Example: Ice bank system is used in milk & dairy industry. Ice is made in lean period and used in peak load period and thus maximum demand is reduced.

4. Shedding of non-essential loads

When the maximum demand tends to reach pre-set limit, shedding some of non-essential loads temporarily can help to reduce recorded peak demand. It is possible to install direct demand monitoring and control systems which will switch off non-essential loads when a pre-set demand is reached. Simple systems give an alarm, and the loads are shed manually. Sophisticated microprocessor-controlled systems are also available, which provide a wide variety of control options like:

- Accurate prediction of demand
- Graphical display of present load, available load, demand limit
- Visual and audible alarm

- Automatic load shedding in a predetermined sequence
- Automatic restoration of load
- Recording and metering

5. Operation of captive generation and Diesel Generation (DG) sets

When diesel generation sets are used to supplement the power supplied by the electric utilities, it is advisable to connect the D.G. sets for durations when demand reaches the peak value. This would reduce the load demand from the utility to a considerable extent and minimize the demand charges.

6. Reactive power compensation

The maximum demand can also be reduced at the plant level by using capacitor banks and maintaining the optimum power factor. Capacitor banks are available with microprocessor-based control systems. These systems switch on and off the capacitor banks to maintain the desired Power factor of system and optimize maximum demand thereby.

5.1.7. Power factor

Power factor Basics

All AC electrical networks consume two types of power: active power (kW) and reactive power (kVAr):

Active power P (in kW) is the real power transmitted to loads such as motors, lamps, heaters, electrical appliances, etc. The electrical active power is transformed into mechanical power, heat, or light. Active power is measured in kW.

Reactive power Q (in kVAr) is used only to supply the magnetic circuits of machines, motors, and transformers. Reactive power is measured in kVAr

Apparent power S (in kVA) the vector sum of the active power and reactive power make up the total apparent power used. Total apparent power measured in kVA. This is the power generated by the power generation units for the user to perform a given amount of work.

The power generation units supply both active power and reactive power as shown in below **Figure 12**

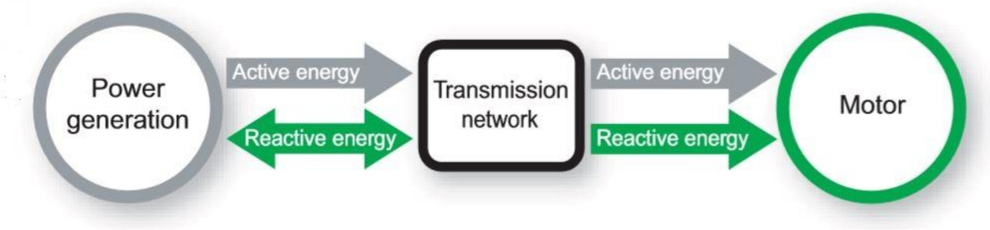
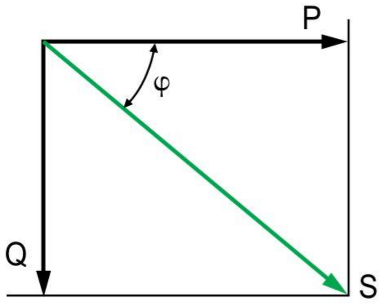


Figure 12: Reactive energy supplied and billed by the energy supplier or utility

Power triangle

The active power in kW and the reactive power in kVAr required are 90° apart vectorially in a pure inductive circuit i.e., reactive power in kVAr lagging the active power kW. The vector sum of the active power, P in kW and reactive power, Q in kVAr is called apparent power, S in kVA. The ratio of active power to apparent power is called the Power Factor (P/S), which is always less than or equal to unity and also represented by cosφ. **Ideally power factor of a facility should be 1 (unity) or near to unity.**



$$\cos \Phi = \frac{P\ (kW)}{S\ (kVA)}$$

Figure 13: Power triangle

5.1.8. Improving power factor

The circulation of reactive power in the electrical network has major technical and economic consequences. For the same active power P, a higher reactive power means a higher apparent power and thus, a higher current must be supplied. Due to this higher supplied current, circulation of reactive energy on distribution networks results in:

- Overload of transformers
- Higher temperature rise of the supply cables
- Additional losses
- Large voltage drops
- Higher energy consumption and cost
- Less distributed active power

For these reasons, there is a great advantage to generate reactive energy at the load level in order to prevent the unnecessary circulation of current in the network. This is what known as "Power Factor Correction". This is obtained by the connection of capacitors, which produce reactive energy in opposition to the energy absorbed by loads such as motors. The result is a reduced apparent power, and an improved power factor.

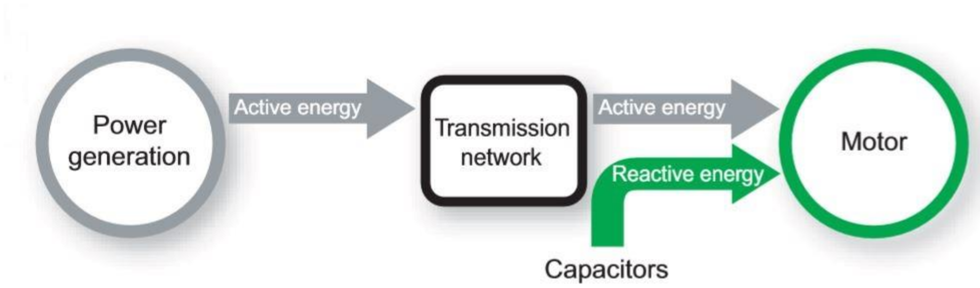


Figure 14: Connection of capacitors at load level

The power generation and transmission networks are partially relieved, reducing power losses and making additional transmission capability available. Since the reactive power is supplied by capacitors there is no billing of reactive power by the utility (energy supplier).

5.1.9. Advantages of power factor improvement

- Reduction of I^2R losses in cables, thus reduced distribution losses (kWh) within the facility's electrical network system, which results in energy savings
- Reduction of voltage drop at motor terminals and improved performance of motors.
- Increase in available power by improving the power factor of a load supplied from a transformer, the current through the transformer will be reduced, thereby allowing more load to be added. In practice, it may be less expensive to improve the power factor to unity, than to replace the transformer by a larger unit.
- Reduced maximum demand (kVA) charges in electricity bill.

5.1.10. Power factor correction guidelines

The selection of the Power Factor correction equipment can follow a 4-step process:

1. Calculation of the required reactive energy
2. Selection of the compensation mode:
   - Central compensation, for the complete installation
   - Group compensation at section feeders
   - Individual compensation such as at large motors
3. Selection of the compensation type:
   - Fixed, by connection of a fixed-value capacitor bank,
   - Automatic, by connection of different number of steps, allowing the adjustment of the reactive energy to the requested value,
   - Dynamic, for compensation of highly fluctuating loads.
4. Taking account of operating conditions and effects of harmonics

1. Calculation of the required reactive energy

a) Power factor correction for transformer no-load compensation

The transformer works on the principle of Mutual Induction. The transformer will consume reactive power for magnetizing purpose. Following equivalent circuit of transformer provides the details of reactive power demand inside the transformer.

kVA rating of the Transformer	kVAr required for No-load compensation
Up to and including 2000 kVA	2% of the kVA rating

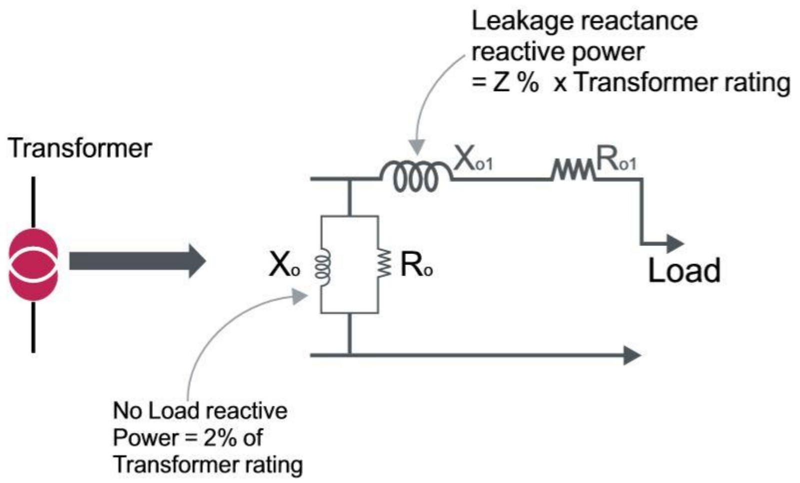


Figure 15: No-load compensation for transformer

b) Power factor correction where load and present power factor is Known

The objective is to determine the required reactive power Q_C (kVAr) to be installed, in order to improve the power factor cosφ and reduce the apparent power S. For φ' < φ, we will get: cosφ' > cosφ and tanφ' < tanφ, this is illustrated in the below **Figure 16**

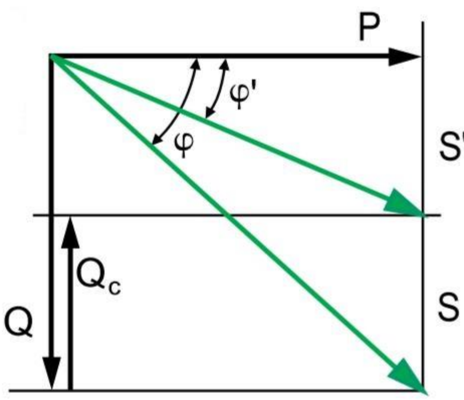


Figure 16: Power factor correction triangle

$Q_{C,}$ required capacitor rating in kVAr can be determined from the formula:

Q_C = Active power (kW) X (tanφ - tanφ')

Where,
tanφ: tangent of the phase angle - before compensation,
tanφ': tangent of the phase angle - after compensation
The parameters φ and tanφ can be obtained from the billing data, or from direct measurement in the installation.

Alternatively, the following **Table 3** can be used for direct determination.
The figures given in the **Table 3** are multiplication factors which are to be multiplied with the active power (kW) to obtain the required capacitor rating in kVAr to improve the present power factor to a new desired power factor.

Table 3: Multipliers to determine capacitor kVAr requirements for power factor correction (Source: adapted from Schneider Electric)

Before compensation		Reactive power (kvar) to be installed per kW of load, in order to get the requested tanφ' or cosφ'							
tanφ	cosφ	tanφ'	0.75	0.62	0.48	0.41	0.33	0.23	0.00
		cosφ'	0.8	0.85	0.9	0.925	0.95	0.975	1.00
1.73	0.5		0.98	1.11	1.25	1.32	1.40	1.50	1.73
1.02	0.7		0.27	0.40	0.54	0.61	0.69	0.79	1.02
0.96	0.72		0.21	0.34	0.48	0.55	0.64	0.74	0.96
0.91	0.74		0.16	0.29	0.42	0.50	0.58	0.68	0.91
0.86	0.76		0.11	0.24	0.37	0.44	0.53	0.63	0.86
0.80	0.78		0.05	0.18	0.32	0.39	0.47	0.57	0.80
0.75	0.8			0.13	0.27	0.34	0.42	0.52	0.75
0.70	0.82			0.08	0.21	0.29	0.37	0.47	0.70
0.65	0.84			0.03	0.16	0.24	0.32	0.42	0.65
0.59	0.86				0.11	0.18	0.26	0.37	0.59
0.54	0.88				0.06	0.13	0.21	0.31	0.54
0.48	0.9					0.07	0.16	0.26	0.48

Example: The electricity bill shows an average power factor of 0.8 (cosφ = 0.8) with an average active power of 1000 kW. How much kVAr is required to improve the power factor to 0.95?

Solution:
Using Formula:

1. Q_C = Active power (kW) X (tanφ - tanφ‘)
2. Existing power factor cosφ = 0.8, tanΦ = 0.75
3. Desired power factor cosφ`= 0.95, tanΦ` = 0.329
4. Required capacitor rating Q_c = 1000 (0.75- 0.329) = 420 kVAr

Using **Table 3:**

1. Locate existing power factor 0.8 in column 2
2. Read across desired power factor to 0.95 column, we find multiplier 0.42
3. Multiply 1000 kW by 0.42 = 420 kVAr
4. Install 420 kVAr to improve power factor to 0.95.

2. Selection of compensation mode for PF improvement

The location of low-voltage capacitors in an installation constitutes the mode of compensation, which may be central (one location for the entire installation), by group (section-by section), at load level, or some combination of the latter two. In principle, the ideal compensation is applied at a point of consumption and at the level required at any instant. In practice, technical and economic factors govern the choice.

The place for connection of capacitor banks in the electrical network is determined by:

- Global objective (avoid penalties on reactive energy, relieve of transformer or cables, avoid voltage drops and sags),
- Operating mode (stable or fluctuating loads),
- Foreseeable influence of capacitors on the network characteristics,
- Installation cost.

Central compensation
The capacitor bank is connected at the head of the installation to be compensated in order to provide reactive energy for the whole installation. This configuration is convenient for stable and continuous load factor.

Group compensation
The capacitor bank is connected at the head of the feeders supplying one particular sector to be compensated. This configuration is convenient for a wide installation, with workshops having different load factors.

Compensation of individual loads
The capacitor bank is connected right at the inductive load terminals (especially large motors). This configuration is well adapted when the load power is significant compared to the subscribed power. This is the technical ideal configuration, as the reactive energy is produced exactly where it is needed and adjusted to the demand.

3. Selection of the compensation type
Different types of compensation shall be adopted depending on the performance requirements and complexity of control:

- Fixed, by connection of a fixed-value capacitor bank
- Automatic, by connection of different number of steps, allowing the adjustment of the reactive energy to the requested value
- Dynamic, for compensation of highly fluctuating loads.

Fixed compensation
This arrangement uses one or more capacitor(s) to provide a constant level of compensation. Control may be:

- Manual: by circuit-breaker or load-break switch
- Semi-automatic: by contactor
- Direct connection to an appliance and switched with it.
- These capacitors are applied:
- At the terminals of inductive loads (mainly motors),
- At bus bars supplying numerous small motors and inductive appliances for which individual compensation would be too costly
- In cases where the load factor is reasonably constant.

Automatic compensation

This kind of compensation provides automatic control and adapts the quantity of reactive power to the variations of the installation in order to maintain the targeted cos φ. The equipment is applied at points in an installation where the active-power and/or reactive-power variations are relatively large, for example:

- At the busbars of a main distribution switchboard
- At the terminals of a heavily loaded feeder cable.

Where the kVAr rating of the capacitors is less than, or equal to 15% of the supply transformer rating, a fixed value of compensation is appropriate. Above the 15% level, it is advisable to install an automatically controlled bank of capacitors. Control is usually provided by contactors. For compensation of highly fluctuating loads, fast and highly repetitive connection of capacitors is necessary, then static switches must be used.

Dynamic compensation

This kind of compensation is requested when fluctuating loads are present, and voltage fluctuations should be avoided. The principle of dynamic compensation is to associate a fixed capacitor bank and an electronic var compensator, providing either leading or lagging reactive currents. The result is a continuously varying and fast compensation, perfectly suitable for loads such as lifts, crushers, spot welding

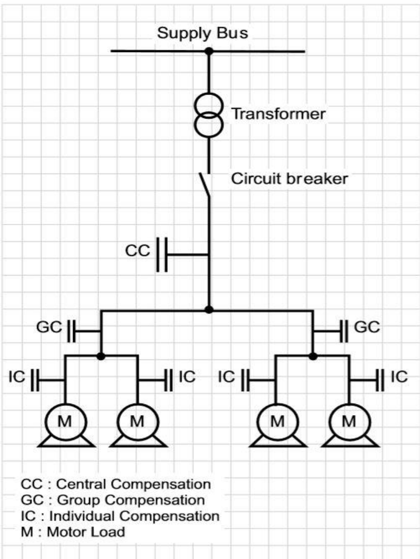


Figure 17: Different compensation modes for power factor improvement

4. Effects of harmonics

Harmonics in electrical installations

The presence of harmonics in electrical systems means that current and voltage are distorted and deviate from sinusoidal waveforms.

Harmonic currents are currents circulating in the networks and which frequency is an integer multiple of the supply frequency. Harmonic currents are caused by non-linear loads connected to the distribution system. A load is said to be non-linear when the current it draws does not have the same waveform as the supply voltage. The flow of harmonic currents through system impedances in turn creates voltage harmonics, which distort the supply voltage.

The most common non-linear loads generating harmonic currents are using power electronics, such as variable speed drives, rectifiers, inverters, etc. Loads such as saturable reactors, welding equipment, arc furnaces, also generate harmonics.

Influence of harmonics in capacitors
Capacitors are particularly sensitive to harmonic currents since their impedance decreases proportionally to the order of the harmonics present. This can result in a capacitor overload, shortening steadily its operating life. In some extreme situations, resonance can occur, resulting in an amplification of harmonic currents and a very high voltage distortion.

Amplification of Harmonic currents is very high when the natural resonance frequency of the capacitor and the network combined happens to be close to any of the harmonic frequencies present. This situation could result in severe over voltages and overloads which will lead to premature failure of capacitors.

To ensure a good and proper operation of the electrical installation, the harmonic level must be taken into account in the selection of the power factor correction equipment. A significant parameter is the cumulated power of the non-linear loads generating harmonic currents.

5.1.11. Capacitor selection based on operating conditions

The operating conditions have a great influence on the life expectancy of capacitors. For this reason, different categories of capacitors, with different withstand levels, must be selected according to operating conditions.

Capacitors must be selected in function of the following parameters:

- Ambient Temperature (°C),
- Expected over-current, related to voltage disturbances, including maximum sustained over voltage,
- Maximum number of switching operations/year,
- Requested life expectancy.
- Capacitors are particularly sensitive to harmonics. Depending on the magnitude of harmonics in the network, different configurations shall be adopted.

5.1.12. Troubleshooting of electrical power systems

System problem	Common cause	Possible effects	Solutions
Poor connections in distribution or at connected loads	Loose bus bar connections, loose cable connections, lose or worn contactors	Produces heat, causes failure at connection site, leads to voltage drops and voltage imbalances	Use Thermal imaging camera to locate hot-spots and correct.
Undersized conductors	Facilities expanding beyond original design, poor power factors	Reduces current-carrying capacity of wiring, voltage regulation effectiveness, and equipment life	Add capacitors to counter reactive loads
Cable Insulation leakage	Degradation over time due to extreme temperatures, abrasion, moisture, chemicals	Variable energy waste	Replace cables
Low power factor	Inductive loads such as motors, transformers, and lighting ballasts non-linear loads, such as electronic loads	Reduces current-carrying capacity of wiring, voltage regulation effectiveness, and equipment life.	Add capacitors to counter reactive loads

5.2. Transformers

5.2.1. Introduction

Transformers are electrical devices consisting of two or more coils of wire used to transfer electrical energy by means of a changing magnetic field. A transformer can accept energy at one voltage and deliver it at another voltage. This permits electrical energy to be generated at relatively low voltages and transmitted at high voltages and low currents, thus reducing line losses and voltage drop.

Types of transformer

Transformers are classified as two categories: power transformer and distribution transformers. Power transformers are used in transmission network of higher voltages, deployed for step-up and step-down transformer application, usual voltage ratings are 440 kV, 200 kV, 110 kV, 66 kV, 33kV.

Distribution transformers are used for lower voltage distribution networks as a means to end user connectivity, usual voltage ratings are 11 kV, 6.6 kV, 3.3 kV, 440 V, 230 V.

Rating of transformer

Rating of the transformer is calculated based on the connected load and applying the diversity factor on the connected load, applicable to the particular industry and arrive at the kVA rating of the Transformer.

Diversity factor is defined as the ratio of overall maximum demand of the plant to the sum of individual maximum demand of various equipment. Diversity factor varies from industry to industry and depends on various factors such as individual loads, load factor and future expansion needs of the plant. Diversity factor will always be less than one.

Location of Transformer

Location of the transformer is very important as far as distribution loss is concerned. Transformer receives HT voltage from the grid and steps it down to the required voltage. Transformers should be placed close to the load centre, considering other features like optimization needs for centralized control, operational flexibility etc. This will bring down the distribution loss in cables.

5.2.2. Data collection

Following data shall be collected during audit of transformer from transformer manufacturer's test report and by interviewing the operator or plant supervisor:

- Transformer rating
- Type of transformer
- Age of transformer
- Rated transformer efficiency
- Rated No-load loss
- Rated load loss
- All other rated parameters

5.2.3. Instruments required

- Three-phase power analyser (2-sets, if applying method-2 to determine transformer efficiency)
- Thermal imaging camera

5.2.4. Performance terms and definitions

The transformer efficiency varies between 96 to 99%. The efficiency of the transformer depends on the design of the transformer and the effective operating load.

$$Transformer\ efficiency\ (\eta) = \frac{Output\ power}{Output\ power + total\ loss}\ X\ 100$$

Transformer losses consist of two parts: No-load loss and Load loss

No-load loss also called core loss is the power consumed to sustain the magnetic field in the transformer's steel core. Core loss occurs whenever the transformer is energized, core loss does not vary with load. Core losses are caused by two factors: hysteresis and eddy current losses. Hysteresis loss is that energy lost by reversing the magnetic field in the core as the magnetizing AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core.

Load loss (also called copper loss) is associated with full-load current flow in the transformer windings. Copper loss is power lost in the primary and secondary windings of a transformer due to the ohmic resistance of the windings. Copper loss varies with the square of the load current. ($P=I^2R$).

For a given transformer, the manufacturer can supply values for no-load loss and load loss. The total transformer loss, at any load level can be calculated from below formula:

Total transformer loss = No load loss + [(Loading (%) of transformer)^2 X full load loss]

Transformer losses as a percentage of load is given in **Figure 18**

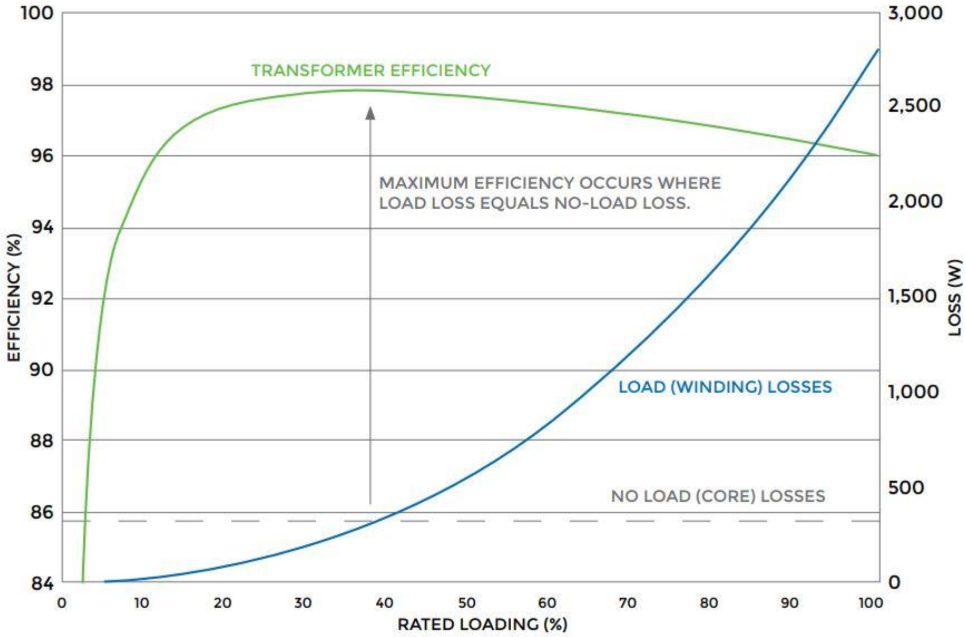


Figure 18: Transformer losses as a percentage (%) of load (Source: UNEP)

5.2.5. Performance assessment of transformer

Determine transformer efficiency

Method-1

Follow the below steps to determine transformer efficiency:

1. Using a three-phase analyser, measure the average apparent power (kVA) at the primary side of transformer by CT (current transformer), PT (potential transformer) ratio conversion method. **Caution:** Never attach voltage clips directly to primary side of transformer, it may lead to injury and sudden death.

2. Note the transformer No load loss and load loss from the transformer's manufacturer test report which is generally available with facility manager.
3. Also, note the transformer rating from manufacturer test report.
4. Using the below formula, calculate the transformer total loss (kW)

$$Total\ loss\ (kW) = \ No\ load\ loss + \left(\left(\frac{Measured\ apparent\ power\ (kVA)}{Rated\ apparent\ power\ \ (kVA)}\right)^2\ X\ full\ load\ loss\right)$$

5. Using a three-phase power, measure the output power (kW) (at secondary side) of the transformer.
6. Using the below formula, calculate transformer efficiency

$$Transfomer\ efficiency\ (\eta) = \frac{Output\ power}{Output\ power + total\ loss}\ X\ 100$$

Method-2

1. By using 2 sets of three-phase power analyser, measure simultaneously primary side input power (kW) and secondary side output power (kW) of transformer.
2. Using the below formula, calculate transformer efficiency

$$Transformer\ efficiency\ (\eta) = \frac{output\ power}{input\ power}\ X\ 100$$

Compare the obtained transformer efficiency with rated efficiency of existing transformer or new energy efficient transformer. If there is wide variation in efficiencies, use the below formula to calculate power loss.

Power (kW) loss = Average load (kW) X [(1/$\eta_{measured}$ – 1/$\eta_{rated\ or\ new}$)]

5.2.6. Energy saving opportunity

Replace old (20 years and above) transformers with energy efficient transformers

Most energy loss in dry-type transformers occurs through heat or vibration from the core. The new high-efficiency transformers minimize these losses. The conventional transformer is made up of a silicon alloyed iron (grain oriented) core. The iron loss of any transformer depends on the type of core used in the transformer. However, the latest technology is to use amorphous material-a metallic glass alloy for the core. The expected reduction in core loss over conventional (Si Fe core) transformers is roughly around 70%, which is quite significant. By using an amorphous core- with unique physical and magnetic properties- these new types of transformers have increased efficiency even at low loads which is **98.5%** efficiency at 35% load. Electrical distribution transformers made with amorphous metal cores provide excellent opportunity to conserve energy right from the installation.

On a life-cycle cost basis, an energy-efficient transformer is very appealing given its non-stop operation and 25-year service life. These savings translate into reductions in peak loading, lower electricity bills and greater reliability of supply. These points should be kept in mind by the auditor while recommending replacement of inefficient transformers with more efficient ones. Payback periods vary with the equipment and electricity costs and can be as short as one year or as long as six years or more. For transformers, a six-year payback on a product that typically lasts more than 25 years is considered attractive (Source: UNEP)

5.3. Motors and application of Variable Frequency Drive (VFD)

5.3.1. Introduction

An electric motor is a device that converts electrical energy into mechanical energy by the interaction between the magnetic fields set up in the stator and rotor windings. Electric motors are used in driving a broad range of industrial applications such as pumps, compressors, fans, blowers, conveyors, and other machines. Motor systems have been identified as being the major electricity consumer in the industrial sector and the poor efficiency of the substandard motors leads to more energy consumption and energy cost. Therefore, improvement in efficiency of the motor must be a part of any comprehensive energy savings effort.

5.3.2. Data collection

Following data shall be collected during audit of motor from motor name plate and by interviewing the motor operator or plant supervisor:

- Motor manufacturer/make
- Model and type
- Rated motor power (kW)
- Rated motor efficiency and efficiency class
- Rated speed
- All other motor nameplate details
- Motor rewound status (if yes, no. of times rewound)
- Motor operating hours (daily & annual)
- Whether equipped with VFD or not (if yes, note operating frequency and signal feedback to VFD is manual or automatic)

In addition to above, following data shall be collected through measurements:

- Voltage (V)
- Current (A)
- Power Factor
- Power (kW)
- Motor operating speed (RPM)
- Motor surface temperature

5.3.3. Instruments required

- Hand-held clamp meter
- Three-phase power analyser
- Non-contact type thermometer or thermal imaging camera
- Stroboscope or non-contact type tachometer
- Resistance meter or multi-meter

5.3.4. Motor performance terms

Motor efficiency: The efficiency of the motor is given by following relation:

$$\eta = \frac{\text{Output power of the motor}}{\text{Input power of the motor}}$$

Motor Loading: The motor loading in percentage (%) is given by following relation:

$$\text{Motor loading (\%)} = \frac{\text{Input power drawn by the motor (kW)at existing load}}{\frac{\text{Name plate full load (kW)rating}}{\text{Name plate full load motor efficiency}}} X\ 100$$

5.3.5. Motor load survey methodology

Large industries have huge numbers of low tension (LT) motors ranging from low rated power (<1 kW) to high rated power (>200 kW). To identify improvements options a load survey methodology shall be established as per following factors:

Prioritising motors for audit

The objective of prioritising motor for audit is to select those motors first which are major energy consumers and representative of all the motors installed in a facility, following criteria shall be considered for prioritisation:

- Regardless of the motor rated power, preference shall be given to those motors with continuous running operation or high utilisation factor for example, 18 to 24 hours per day.
- Motors with high rating power (kW) among the all installed motors shall be given preference.
- Motors which has been identified as running with inefficient capacity controls on the machine side or with fluctuating load systems shall be given preference.
- In case, there is a large quantity (>10) of small sized motors in a system (<5 kW) with same rated power (kW) and due to some constraints measurements on each motor is not feasible, sample representative method shall be used where measurements and analysis of one or two motors can be reasoned as representative for all same size motors in the rest of the system.

Measurements

Studies on motors involves measurement of electrical parameters namely voltage (V), current (A), power factor (PF), and power drawn (kW) with hand-held clamp meter or three-phase power analyser without affecting the motor routine operation. Motors running with fluctuating load shall be chosen for recording the various electrical parameters using three-phase power analyser over a period as suitable.

Using a non-contact type infra-red thermometer or thermal imaging camera, measure the motor surface temperature to check motor overheating.

Observations

Following parameters shall be observed while conducting motor audit:

- Motor loading (%)
- Voltage unbalance & Motor overheating
- Motor efficiency
- Motor load (kW)
- Motor power factor
- Motor rewound status
- Motor idle, load and unload running conditions

5.3.6. Determine motor loading

The simplest method to determine motor loading is by input power measurements, as per following steps:

- Measure motor input power with a hand-held clamp meter or three-phase power analyser.
- Note the full load rated power (kW) and efficiency (η) from the motor nameplate. The rated power mentioned on the motor nameplate by manufacturer is motor output i.e. mechanical power output delivered at shaft in kW.
- To obtain rated input power, divide motor nameplate rated power at full load by rated efficiency (η)

$$Motor\ rated\ input\ power\ = \frac{Motor\ nameplate\ full\ load\ rated\ power\ (kW)}{Motor\ nameplate\ full\ load\ rated\ efficiency(\eta)}$$

- The motor loading percentage loading can now be calculated as follows

$$Motor\ loading\ (\%) = \frac{Motor\ measured\ input\ power\ (kW)}{Motor\ rated\ input\ power\ (kW)} X\ 100$$

To illustrate the above steps an example has shown below:

Example: The nameplate details of a motor are noted as, full load rated power = 11 kW, full load rated efficiency = 0.88. Using a three-phase power analyser the measured input power drawn found to be 7 kW. Determine the loading of the motor?

Solution:

$$Motor\ rated\ input\ power\ = \frac{11}{0.88} = 12.5\ kW$$

$$Motor\ loading\ (\%) = \frac{7}{12.5} X\ 100 =\ 56\%$$

Hence, the motor loading is 56%

5.3.7. Determine voltage unbalance in motors

Voltage unbalance in a three-phase motor is a condition, where the voltages in the three phases of motor are not equal. Voltage unbalance typically occurs because of supplying single-phase load disproportionately from one of the phases. It can also result from the use of different sizes of cables in the distribution system. Voltage unbalance is detrimental to motor performance and motor life. The effect of voltage unbalance on motor performance is shown below **Table 4**

Table 4: Effect of voltage unbalance on motor performance (source: BEE)

Effect of voltage unbalance on motor performance			
Impact on below parameters due to voltage unbalance	Voltage unbalance in percentage (%)		
	0.30	**2.30**	**5.40**
Unbalance in current (%)	0.4	17.7	40
Increased temperature rise (°C)	0.18	10.6	58

The NEMA (National Electrical Manufacturers Association of USA) standard definition of voltage unbalance is given by the following equation:

$$Voltage\ unbalance\ (\%) = \frac{Maximum\ deviation\ from\ mean\ of\ v_{Ry}, v_{yB}, v_{BR}}{Mean\ of\ v_{Ry}, v_{yB}, v_{BR}} X\ 100$$

Where,
V_{RY} is voltage measured between R & Y phases
V_{YB} is voltage measured between Y & B phases
V_{BR} is voltage measured between B & R phases
To illustrate the above steps an example has shown below:

Example: The line voltages measured in three phases of motor are V_{RY} = 415, V_{YB} = 426, V_{BR} = 418. Determine the voltage unbalance in motor?

Solution: Mean of $V_{RY,}$ $V_{YB,}$ V_{BR} = (415 + 426 + 418) / 3 = 419.6

Maximum voltage among $V_{RY,}$ $V_{YB,}$ V_{BR} = 426

$$Voltage\ unbalance\ (\%) = \frac{426 - 419.6}{419.6} X\ 100 = 1.52\%$$

Hence, the voltage unbalance is **1.52%**

It is recommended that voltage unbalance at the motor terminal shall not **exceed 1%,** anything above this will lead to de-rating of the motor. The common causes of voltage unbalance are:

- Unbalanced incoming supply from energy supplier
- Unequal tap settings of transformers

- Large single-phase distribution transformer on the system
- Open phase on the primary of a three-phase transformer on the distribution system
- Faults or ground in the power transformer
- Open delta connected transformer banks
- A blown fuse on a three-phase bank of power factor improvement capacitors
- Unequal impedance in conductors of power supply wiring
- Unbalanced distribution of single-phase loads such as lighting
- Heavy reactive single-phase loads such as welders

Voltage unbalance causes overheating of the motor and leading cause of premature failure of motors. Voltage unbalance causes extremely high current imbalance. The magnitude of current imbalance may be 6 to 10 times higher as the voltage imbalance. The additional temperature rise in motors or motor overheating due to voltage unbalance is estimated by following equation:

Additional temperature rise = 2 X (Voltage unbalance in %)^2

For example, *if the voltage unbalance is 2% for a motor operating at 100°C, the additional temperature rise will be 8°C.*

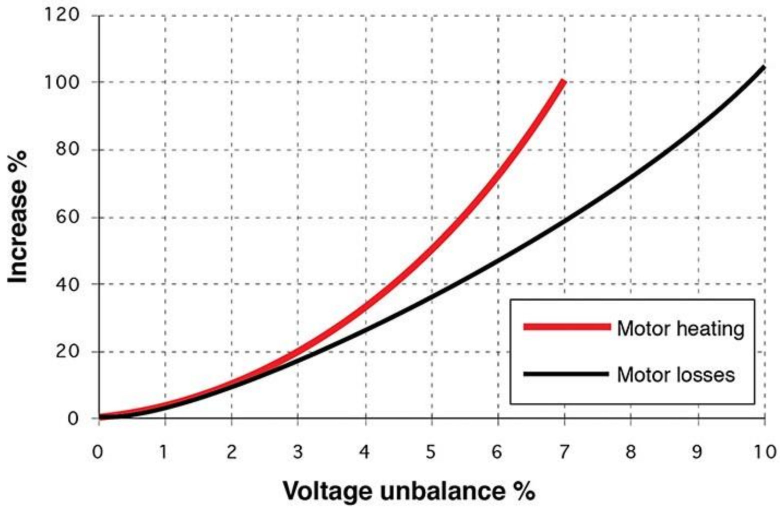


Figure 19: Voltage unbalance (%) versus motor losses & motor heating (Source: BEE)

The winding insulation life is reduced by one half for each 10°C increase in operating temperature. The motor losses also increase due to voltage unbalance as shown in **Figure 19**

5.3.8. Motor Efficiency

Two important attributes relating to efficiency of electricity use by A.C. induction motors are efficiency (η), defined as the ratio of the mechanical energy delivered at the rotating shaft to the electrical energy input at its terminals, and power factor (PF). Motors, like other inductive loads, are characterized by power factors less than one. As a result, the total current draw needed to deliver the same real power is higher than for a load characterized by a higher PF. An important effect of operating with a PF less than one is that resistance losses in wiring upstream of the motor will be higher since these are proportional to the square of the current. Thus, both a high value for η and a PF close to unity are desired for efficient overall operation in a plant.

Squirrel cage motors are normally more efficient than slip-ring motors, and higher-speed motors are normally more efficient than lower-speed motors. Efficiency is also a function of motor temperature. Totally enclosed fan-cooled (TEFC) motors are more efficient than screen-protected, drip-proof (SPDP) motors. Also, as with most equipment, motor efficiency increases with the rated capacity.

The efficiency of a motor is determined by intrinsic losses that can be reduced only by changes in motor design. Intrinsic losses are of two types: fixed losses- independent of motor load, and variable losses – dependent on load.

Fixed losses consist of magnetic core losses and friction and windage losses. Magnetic core losses (sometimes called iron losses) consist of eddy current and hysteresis losses in the stator. They vary with the core material and geometry and with input voltage. Friction and windage losses are caused by friction in the bearings of the motor and aerodynamic losses associated with the ventilation fan and other rotating parts.

Variable losses consist of resistance losses in the stator and in the rotor and miscellaneous stray losses. Resistance to current flow in the stator and rotor result in heat generation, that is proportional to the resistance of the material and the square of the current (I^2R). Stray losses arise from a variety of sources and are difficult to either measure directly or to calculate but are generally proportional to the square of the rotor current. Part load performance characteristics of a motor also depend on its design. Both the η and PF fall to very low levels at low load. **Figure 20** shows the effect of load on power factor and efficiency. Power factor drops sharply at part loads. **Figure 21** shows the effect of speed on power factor.

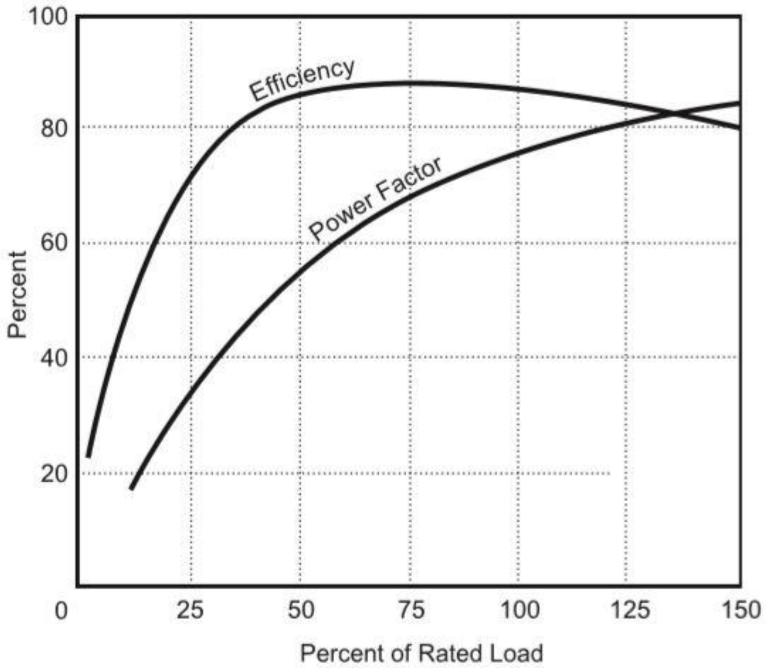


Figure 20: Effect of motor loading on efficiency & power factor (Source: BEE)

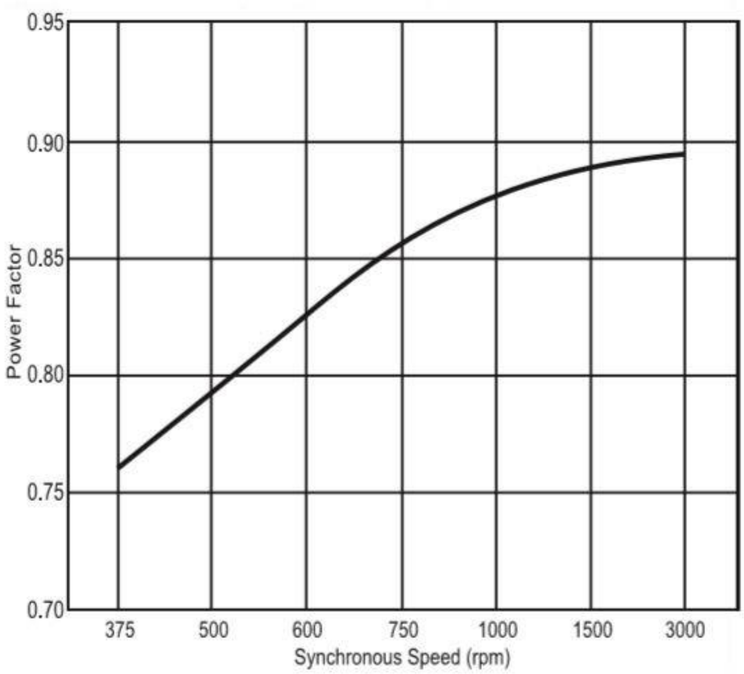


Figure 21: Effect of motor speed on power factor (Source: BEE)

5.3.9. Determine motor efficiency

The efficiency of induction motors remains almost constant between 50% to 100% loading (refer, **Figure 22**) hence for simplicity motor nameplate efficiency rating may be used for calculations if the motor is operating in the range of 50 to 100% loading.

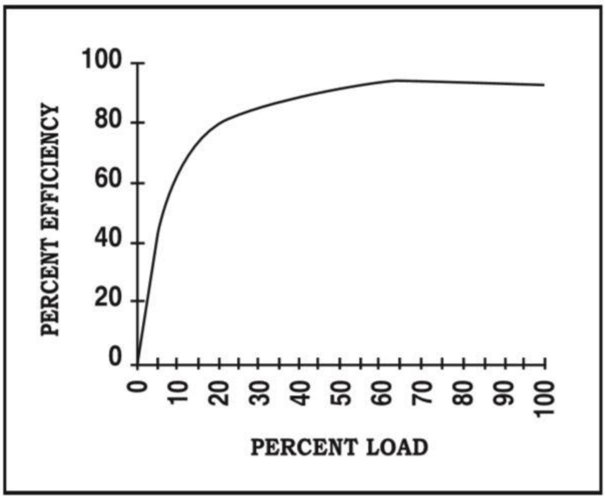


Figure 22: Effect of motor loading on efficiency (Source: BEE)

However, the following method can be also used to determine the motor efficiency.

Step-1: Perform the following actions under no load conditions

- Using a resistance meter, measure stator resistance at ambient temperature.
- Run the motor at rated voltage and frequency without any shaft load
- Using a hand-held clamp meter or three-phase power analyser, measure the power (Watts) and current.
- Calculate the iron plus friction and windage loss using below formula
- *Iron plus friction and windage loss (Watts) =No load power (Watts) - (no load current)^2 X Stator resistance*

Step-2: Perform the following actions under load conditions

- Run the motor at rated voltage and frequency with full load
- Using a hand-held clamp meter or three-phase power analyser, measure the power (Watts) and current
- Using a non-contact type infra-red thermometer, measure operating temperature of motor
- The stator resistance measured at ambient temperature must be corrected for the operating temperature. The correction factor is as follows:

$$R_{operating} = R_{ambient}\ X\ \frac{235 + operating\ temperature}{235 + ambient\ temperature}$$

Where,
$R_{operating}$ is resistance corrected for operating temperature
$R_{ambient}$ is resistance measured at ambient temperature

- Calculate the stator copper loss at full load using below formula

Stator copper loss at full load (Watts) = I^2 *(full load current) X* $R_{operating}$

Step-3: Calculate the rotor power

- Run the motor at rated voltage and frequency with full load
- Using a stroboscope or non-contact type tachometer, measure the speed of the motor in RPM (revolutions per minute) at full load.
- Calculate slip by using below formula. Where, synchronous speed is the motor nameplated rated speed

$$Slip\ (S) = \frac{Synchronous\ speed - full\ load\ speed}{Synchronous\ speed}$$

- Calculate rotor power using below formula

$$Rotor\ power\ (Watts) = \frac{Motor\ nameplate\ rated\ power}{1 - Slip}$$

Step-4: Calculate motor full load input power

- Use the below formula to calculate the motor full load input power

Motor full load input power = Iron plus windage and friction loss + Stator copper loss at full load + Rotor power + Stray losses

- Use the below **Table 5** adapted from IEEE for stray losses as measurement of stray losses is a complicated process which is not possible on shop floor.

Table 5: Motor rating versus stray losses (adapted from IEEE)

Motor rating	Stray losses
0.75 – 93 kW	1.8%
93 – 373 kW	1.5%
373 – 1863 kW	1.2%
1864 and above	0.9%

Step-5: Calculate motor efficiency

- Use the below formula to calculate the motor efficiency

$$Motor\ efficiency\ (\eta) = \frac{Motor\ nameplate\ rated\ power}{Motor\ full\ load\ input\ power}$$

5.3.10. Energy savings opportunities in motor

1. Improve motor loading

For motors, which consistently operate at loads below 40% of rated capacity, an inexpensive and effective measure is to operate in star mode.

A change from the standard delta operation to permanent star operation involves re-configuring the wiring at terminal box and resetting of the

over-current relay. Operating in the star mode leads to a voltage reduction by a factor of '√3'. Motor is electrically downsized by one-third (1/3rd) in star mode operation, but performance characteristics as a function of load remain unchanged. For example, if a motor is rated for 15 kW in delta mode, its de-rated capacity is 5kW in star mode. Thus, full-load operation in star mode gives higher efficiency and power factor than partial load operation in the delta mode. However, motor operation in the star mode is possible only for applications where the torque-to-speed requirement is lower at reduced load.

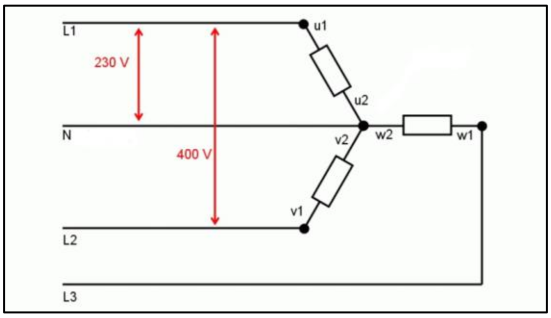


Figure 23: Star connection

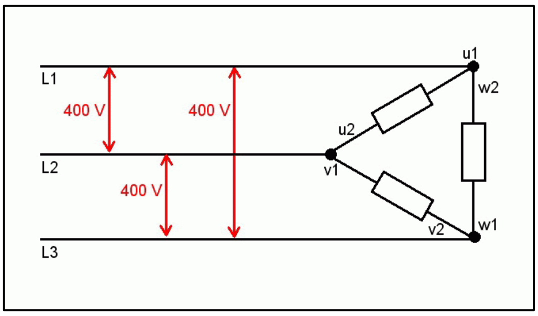


Figure 24: Delta connection

As speed of the motor reduces in star mode this option may be avoided in case the motor is connected to a production facility whose output is related to the motor speed. Further, in star mode the motor loading should not be allowed to cross de-rated capacity. For example, in above case of 15 kW delta connected electric motor, should not be loaded above 5 kW when delta to star switchover takes place.

For applications with high initial torque and low running torque needs, automatic Star-Delta-Star converters are also available, which help in load following de-rating of electric motors after initial start-up.

2. Motor power factor (PF) correction

Induction motors which operate at power factors less than unity, leads to lower overall efficiency and higher overall operating cost associated with a facility's electrical system. Capacitors connected in parallel (shunted) with the motor are typically used to improve the power factor. The benefits of PF correction are as below:

- Reduced apparent power (kVA) demand and hence reduced utility demand charges.
- Reduced copper losses (I^2R) in cables upstream of the capacitor and hence reduced energy charges.
- Reduced voltage drop in the cables leading to improved voltage regulation.

- Increase in the overall efficiency of the plant electrical system.

The various methods of power factor correction are central compensation, group compensation and individual compensation. Depending upon the size and the rate of change of loads in an industry, any one or combination of the above methods can be employed. Specifically, in case of some small-scale industries with a few motor loads, the power factor correction can be done by connecting shunt capacitors directly to the motors. This method of compensation is called direct compensation. This is simple and ideal method for reactive power compensation, as this would result in rating optimization of all the upstream switchgear and cables, which reduces overall system losses.

Direct motor compensation can be done in two methods, configuration of both methods is described below:

Method-1

As shown in the **Figure 25,** the capacitor is connected directly to the motor terminals, after the starter. The capacitors would start supplying reactive power as soon as the motor is switched ON. This method of compensation can be used for motors with direct online starters. Usually the kVAr rating for a particular motor is given by the respective motor manufacturers, as the kVAr ratings are motor specific.

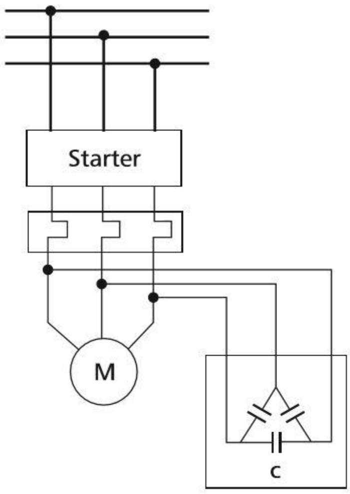


Figure 25: Method 1- Capacitor is connected directly to the motor

Even though this is the effective method of power factor compensation, there is a limitation in sizing of the capacitors. That is, *the maximum kVAr should be decided such that, the rated capacitor current is less than 90% of the motor's no-load current*. If this condition is not met, self-excitation may occur, in which the motor acts as a generator. This happens when a motor has enough inertia to keep rotating even after being disconnected from the power system and the capacitor is large enough to supply the reactive power needs of the motor. Self-excitation would result in high voltage at the terminals of the motor and this can damage the contactor and the capacitor.

Method – 2:
In this method, the capacitor is connected to the motor before the starter and it is switched through a separate capacitor duty contactor as shown in **Figure 26**. The capacitors are disconnected as soon as the motor is switched off hence, self-excitation is avoided. There is no need of any limitations in capacitor sizing and unity power factor can be achieved by this method.

The capacitor size (in kVAr) can be calculated by the below formula:

$kVAr = kW\ (\tan\Phi_1 - \tan\Phi_2)$

Where, $\Phi_1 = \cos^{-1}$ *(initial PF) and* $\Phi_2 = \cos^{-1}$ *(target PF)*

The limitations in this method are the manual switching of the capacitors and the extra cost incurred for the contactors. Moreover, when the number of motors increase in future, managing all at a time would be difficult.

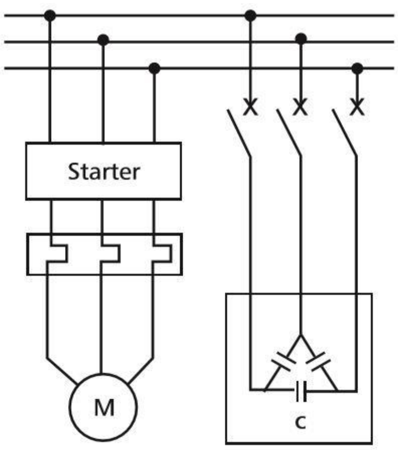


Figure 26: Method 2 - Capacitor is connected to the motor before starter

Points to remember:

- The operating power factor varies with respect to the percentage loading of the motors. Hence with the varying load, the fixed capacitors would not be able to maintain the unity power factor continuously.
- After switching off the capacitor, it is very important to maintain a minimum time delay of 60 seconds, for switching ON the capacitor again. Else, there are more chances of contactor damage because of charged capacitor.
- If the motor is operated with any drives/converters, it is recommended to detune the capacitors by adding series reactors.
- It is recommended to use capacitor duty contactors for minimizing the inrush current and hence to maximize the life of contactors and the capacitors.

3. Energy efficient motor technical characteristics

The IEC (International Electrotechnical Commission) has contributed to the development of energy efficient electric motor systems through the internationally relevant test standard IEC 60034-2-1 for electric motors and the IEC 60034-30-1 classification scheme comprising four levels of motor efficiency:

- IE1 Standard Efficiency
- IE2 High Efficiency
- IE3 Premium Efficiency
- IE4 Super premium Efficiency

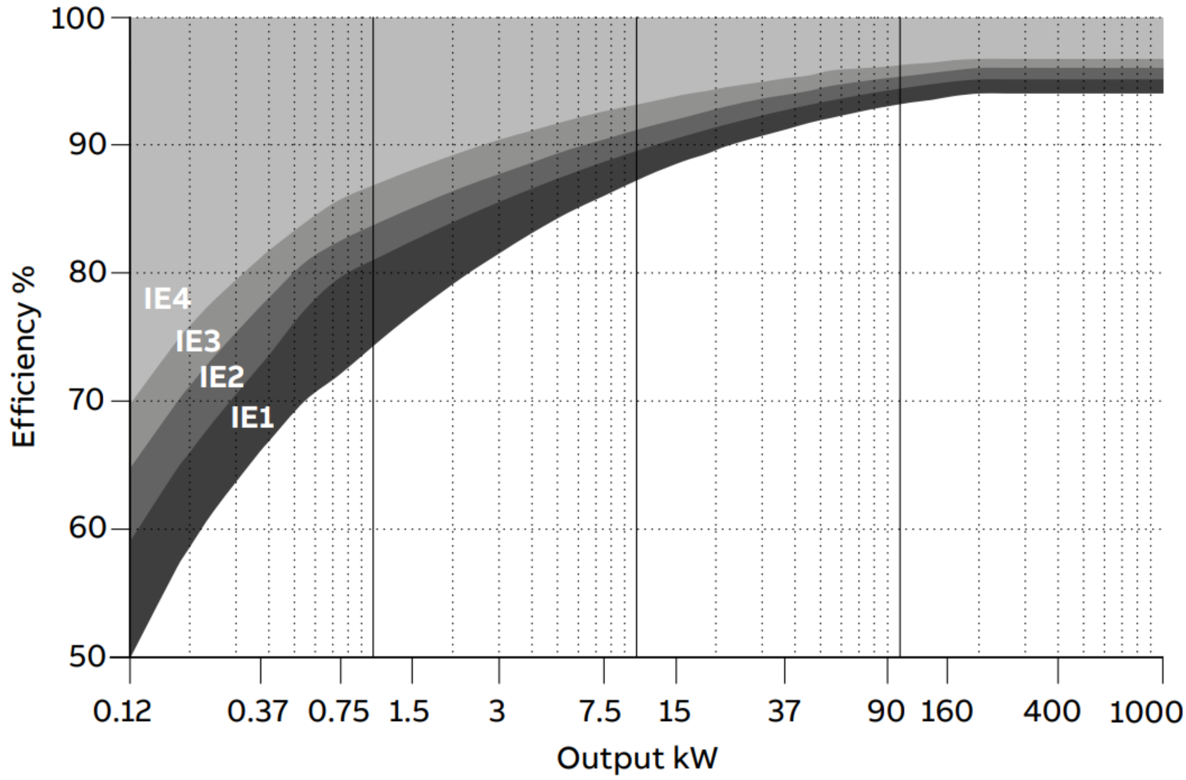


Figure 27: IE efficiency classes for 4 pole motors at 50 Hz (Source: ABB)

Acknowledging the need for energy saving in view of the energy scarcity, climate change mitigations and the potential that exists with energy efficient motors, number of countries have issued directives to withdraw lower efficiency classes and adopt higher efficiency class motors as per IEC 60034-30-1: 2014, thus defining minimum efficiency performance standards (MEPS) in their countries. Such regulations are expected to impose technical barriers to all the imports of motors which are with lower efficiency classes than the MEPS into their countries.

The European Union sets motor MEPS levels at IE3 (or IE2 in combination with VFD) from 2017 covering motors with 0.75 kW up to 375 kW. In 2018, India also sets efficiency class IE2 as Minimum Energy Performance Standard (MEPS) for LT motors.

4. Cost effectiveness of energy efficient motors

The energy savings by motor replacement can be worked out by a simple formula:

$$Power\ savings\ (kW) = \ Power\ output\ (kW)\ \ X\ \frac{1}{\eta_{old}} - \frac{1}{\eta_{new}}$$

Where, η_{old} is efficiency of the existing old motor

Where, η_{new} is efficiency of the proposed new motor

Annual energy savings = Power savings (kW) X annual operating hours of the motor

To illustrate the above formula, an example has shown below:
Example: During an energy audit following data were obtained on a 3-phase induction motor:
Rated values: 37 kW, 415 V, 66 A, PF = 0.88, η = 0.88
Measured values: 410 V, 49 A, PF = 0.76 pf, P = 26.44 kW

The plant operates for 7000 hours per year, and it is proposed to replace the existing motor by a 30 kW, new energy efficient motor with rated efficiency of 92%.

a) Determine loading% of the existing motor.
b) Determine the energy savings with new energy efficient motor

Solution: Rated input power of the motor = Rated power / efficiency (η)

Parameters	Calculations
Rated input power of the existing motor at full load	= 37 / 0.88 = 42 kW
Loading of the existing motor	= measured power / rated input power = 26.44 / 42 = **63%**
Shaft power or motor output of the existing motor	= 37 X 63% =23.31 kW
New energy efficient motor rating	= 30 kW
Actual shaft power or motor output required	= 23.31 kW
Loading% of new energy efficient motor	= 23.31 / 30 = 77.7%
Power savings	= 23.31 (1/0.88 – 1/0.92) = 1.16 kW
Annual energy savings	= 1.16 X 7000 = **8,120 kWh**

Points to be noted: *Though the new energy efficient motor is of 30 kW, but the energy savings will be calculated at the actual shaft power delivered by the motor or the motor output required.*

5. Motor rewinding effects on energy efficiency

It is common practice in industry to rewind burnt-out motors. Careful rewinding may sometimes maintain motor efficiency at previous levels, but in most cases rewinding results in efficiency loss.

Loss in efficiency of rewound motors is due to several reasons. For example, a common problem occurs when heat is applied to old strip windings, the insulation between laminations can be damaged, thereby increasing eddy current losses. A change in the air gap may affect power factor and output torque.

The impact of rewinding on motor efficiency and power factor can be easily assessed if the no-load losses of a motor are known before and after rewinding. Maintaining documentation of no-load losses and no-load speed from the time of purchase of each motor can facilitate assessing this impact.

For example, comparison of no load current and stator resistance per phase of a rewound motor with the original no-load current and stator resistance at the same voltage can be one of the indicators to assess the efficacy of rewinding. A relatively simple procedure for evaluating rewinding quality is to keep a log of no-load input current for each motor installed in the facility and to update the log each time a motor is returned after rewinding.

Small and medium range motors (say up to 30 kW rating) have a significant repair/rewinding cost (around 45% of its purchase price) so it is recommended that after 3 time rewinding the motor should be replaced with a premium efficiency (IE3) motor. Many large process plants have a made a policy of replacing small & medium LT motors which have been rewound thrice previously.

6. Stop idle running of motors

Motors running during periods when the equipment or process they are driving is idle is called idle running of motors. Idle running of motors causes unnecessary energy loss which can be control by following method:

a. Reduce equipment operation time to minimum required by turning off the equipment during lunch and breaks, or other times when it is not required. But this method is only as reliable as the operator.
b. Interlock equipment with a related process i.e. if a particular piece of equipment is dedicated to specific process that requires additional equipment, they can all be interlocked so all will be de-energised when the operator turns off one piece of equipment.
c. Operate equipment such as a grinder in batches then shut off. A piece of equipment like a grinder may run continuously although material only runs through it occasionally. An alternative approach with no installation cost is to allow material to collect and assign someone to periodically turn it on to process the material in batches but remember:
    i. If material collection is left unmonitored, the collection bin can overflow requiring additional labour for clean-up. Jamming problems could also develop.
    ii. Batch processing also has potential for increasing demand charges if the equipment is more heavily loaded.

d. Install timers, level sensors, material sensors, or other controls for automatic operation and/or to shut off equipment as required. For example: Install material sensor and timer on equipment such as a grinder – set to turn on with set accumulation of material and turn off after allowable idle time and care must be taken to avoid creating a safety hazard.

7. Motor speed control with variable frequency drive (VFD) or variable speed drive (VSD)

Concept of Variable frequency drive

The speed of an induction motor is proportional to the frequency of the alternating current (AC) voltage applied to it, as well as the number of poles in the motor stator. This is given by the equation:

RPM = (120 X f) / No. of poles

Where, f is the frequency in the hertz

Therefore, if the frequency applied to the motor is changed, the motor speed changes in direction proportion to frequency changes. The basic function of the VFD is to act as a variable frequency generator in order to vary speed of the motor as per the user setting.

The VFD's basic principle of operation is to convert the electrical system frequency and voltage to the frequency and voltage required to drive a motor at a speed other than its rated speed. The two most basic functions of a VFD are to provide power conversion from one frequency to another and to enable control of the output frequency.

As shown in **Figure 28**, there are two basic components, a rectifier and an inverter, to accomplish power conversion. The rectifier receives the 50-Hz AC voltage and converts it to direct current (DC) voltage. A DC bus inside the VSD functions as a parking lot for the DC voltage. The DC bus energizes the inverter, which convert it back to the AC voltage again. The inverter can be controlled to produce an output frequency of the proper value for the desired motor shaft speed.

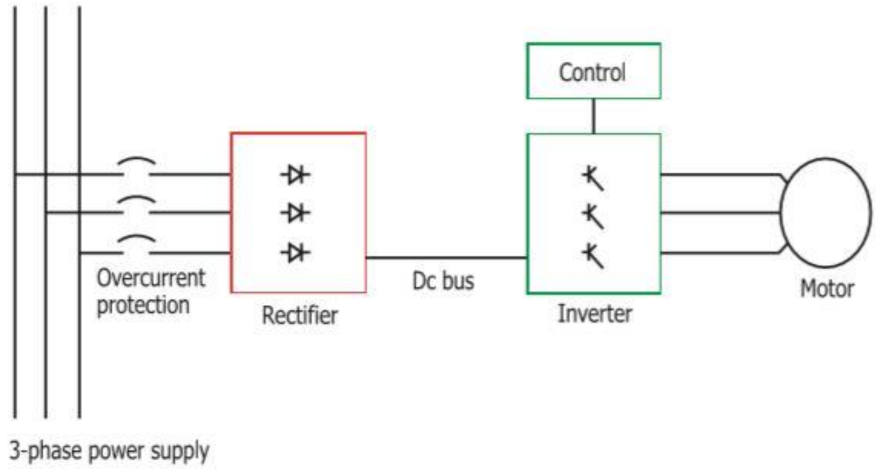


Figure 28: Component of VFD system

In many applications, the input power is a function of the speed like fan, blower, pump, conveyor and so on. In these types of loads, the torque is proportional to the square of the speed and the power is proportional to the cube of speed.

$$Power\ \alpha\ (speed)^3$$

Variable speed, depending upon the load requirement, provides significant energy saving. A reduction of 20% in the operating speed of the motor from its rated speed will result in an almost 50% reduction in the input power to the motor. This is not possible in a system where the motor is directly connected to the supply line. In many flow control applications, a mechanical throttling device is used to limit the flow. Although this is an effective means of control, it wastes energy because of the high losses and reduces the life of the motor valve due to generated heat.

5.3.11. Factors for successful implementation of variable frequency drives

a) Understanding load type for Variable Frequency Drives

The main consideration is whether the variable frequency drive application requires a variable torque or constant torque drive. If the equipment being driven is centrifugal, such as a fan or pump, then a variable torque drive will be more appropriate. Energy savings are usually the primary motivation for installing variable torque drives for centrifugal applications. For example, a fan needs less torque when running at 50% speed than it does when running at full speed. Variable torque operation allows the motor to apply only the torque needed, which results in reduced energy consumption.

Conveyors, positive displacement pumps, punch presses, extruders, and other similar type applications require constant level of torque at all speeds. In which case, constant torque variable frequency drives would be more appropriate for the job. A constant torque drive should have an overload current capacity of 150% or more for one minute. Variable torque variable frequency drives need only an overload current capacity of 120% for one minute since centrifugal applications rarely exceed the rated current.

b) Collecting motor information

The following motor information will be needed to select the proper variable frequency drive:

Full load current rating: Using a motor's power rating is an unreliable way to size variable frequency drives. Full load current rating of the motor shall be considered to estimate VFD size.

Speed range: Generally, a motor should not be run at any speed less than 20% of its specified maximum speed allowed. If it is run at a speed less than this without auxiliary motor cooling, the motor will overheat. Auxiliary motor cooling should be used if the motor must be operated at very slow speeds.

Multiple motors: To size a variable frequency drive that will control more than one motor, add together the full load current ratings of each of the motors. All motors controlled by a single drive must have an equal voltage rating.

c) Efficiency and power factor of VFD

The variable frequency drive should have an efficiency rating of 95% or more at full load. Variable frequency drives should also offer a true system power factor of 0.95 or more across the operational speed range, to save on demand charges, and to protect the equipment (especially motors).

d) Protection circuits for VFD

Motor overload Protection for instantaneous trip and motor over current should be provided. Additional protection circuits shall also be provided for over and under voltage, over temperature, ground fault, control or microprocessor fault. These protective circuits should provide an orderly shutdown of the VFD, provide indication of the fault condition, and require a manual reset (except under voltage) before restart. Under voltage from a power loss shall be set to automatically restart after return to normal. The history of the previous three faults shall remain in memory for future review.

e) Selection of equipment for VFD operation

The first step is to identify the operating hours of the equipment at various load conditions. This can be done using a power analyser with continuous data storage or by a simple energy meter with periodic reading being taken.

To determine if the equipment under consideration is the right choice for a variable speed drive, the load patterns should be thoroughly studied before exercising the option of VFD. In effect the load should be of a varying nature to demand a VFD

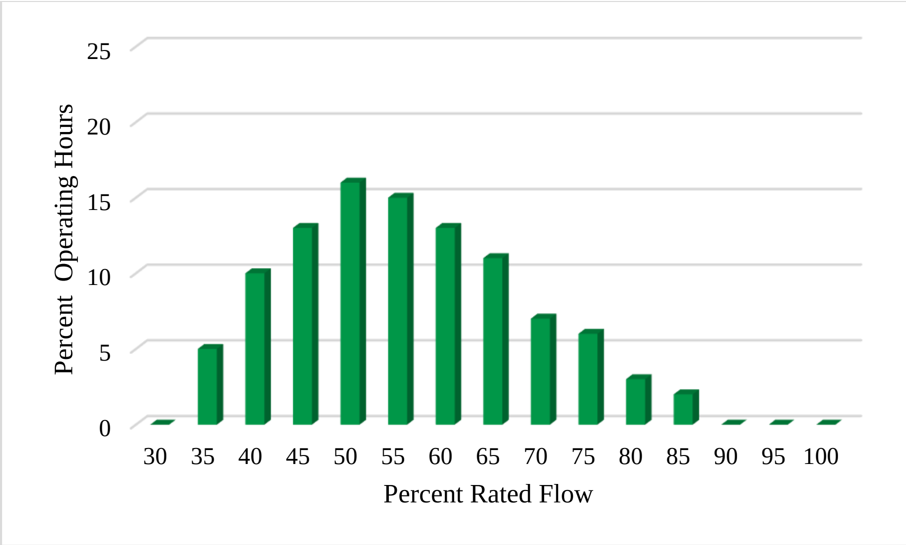


Figure 29: Example of an excellent variable speed drive candidate

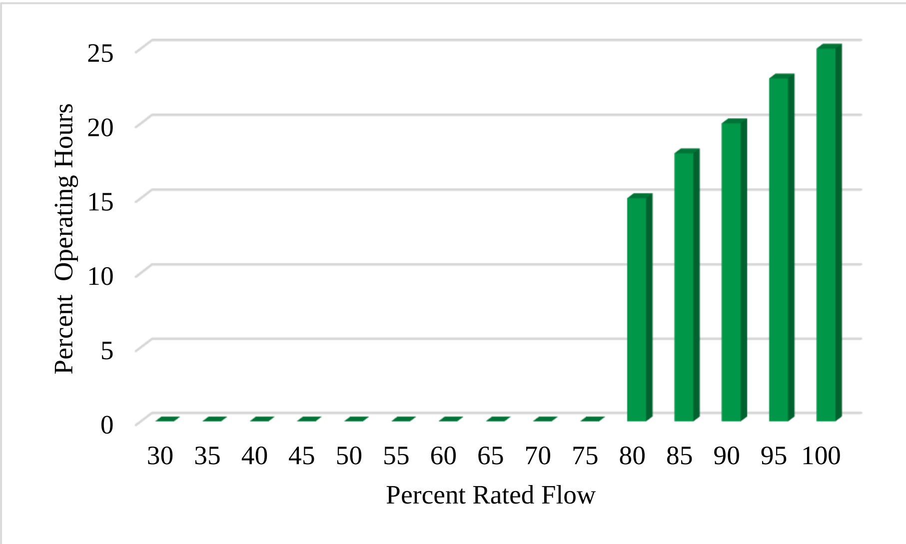


Figure 30: Example of a poor variable speed drive candidate

5.4. Air Compressors – energy performance assessment

5.4.1. Introduction

Air compressors account for significant amount of electricity used in industries. In fact, over the lifespan of a typical compressor, energy typically costs several times more than the purchase price of the compressor. Air compressors are used in a variety of industries to supply process requirements, to operate pneumatic tools and equipment, and to meet instrumentation needs. Only 10~30% of energy reaches the point of end-use, and balance 70~90% of energy of the power of the prime mover being converted to unusable heat energy and to a lesser extent lost in form of friction, misuse and noise.

5.4.2. Types of Compressor

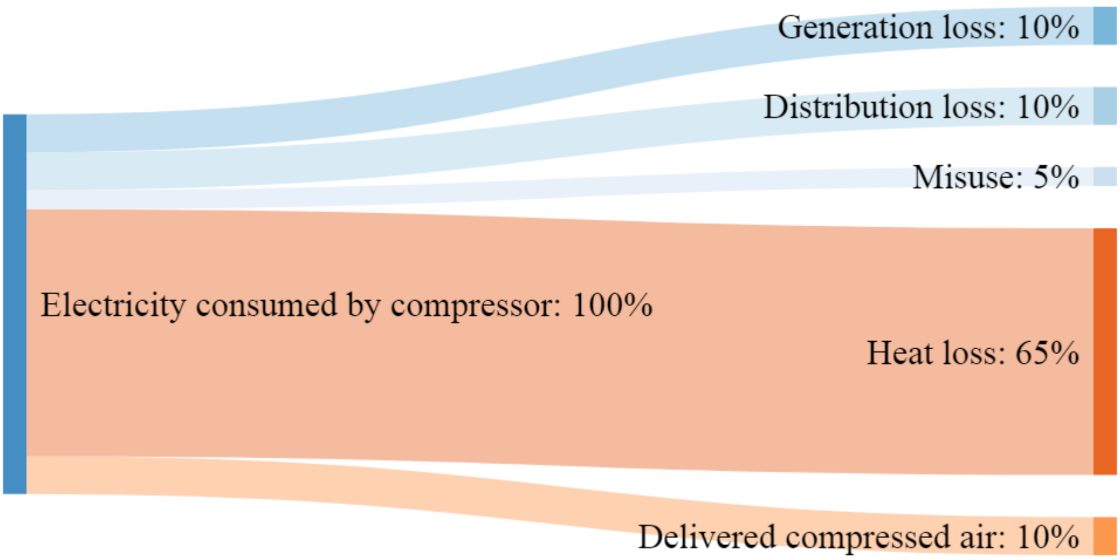


Figure 31: Sankey diagram of compressed air losses

Compressors are broadly classified as:

- **Positive displacement compressor:** Positive displacement compressors increase the pressure of the gas by reducing the volume. Positive displacement compressors are further classified as reciprocating and rotary compressors.
- **Dynamic compressor:** Dynamic compressors increase the air velocity, which is then converted to increased pressure at the outlet. Dynamic compressors are basically centrifugal compressors and are further classified as radial and axial flow types.

The flow and pressure requirements of a given application determine the suitability of a type of compressor.

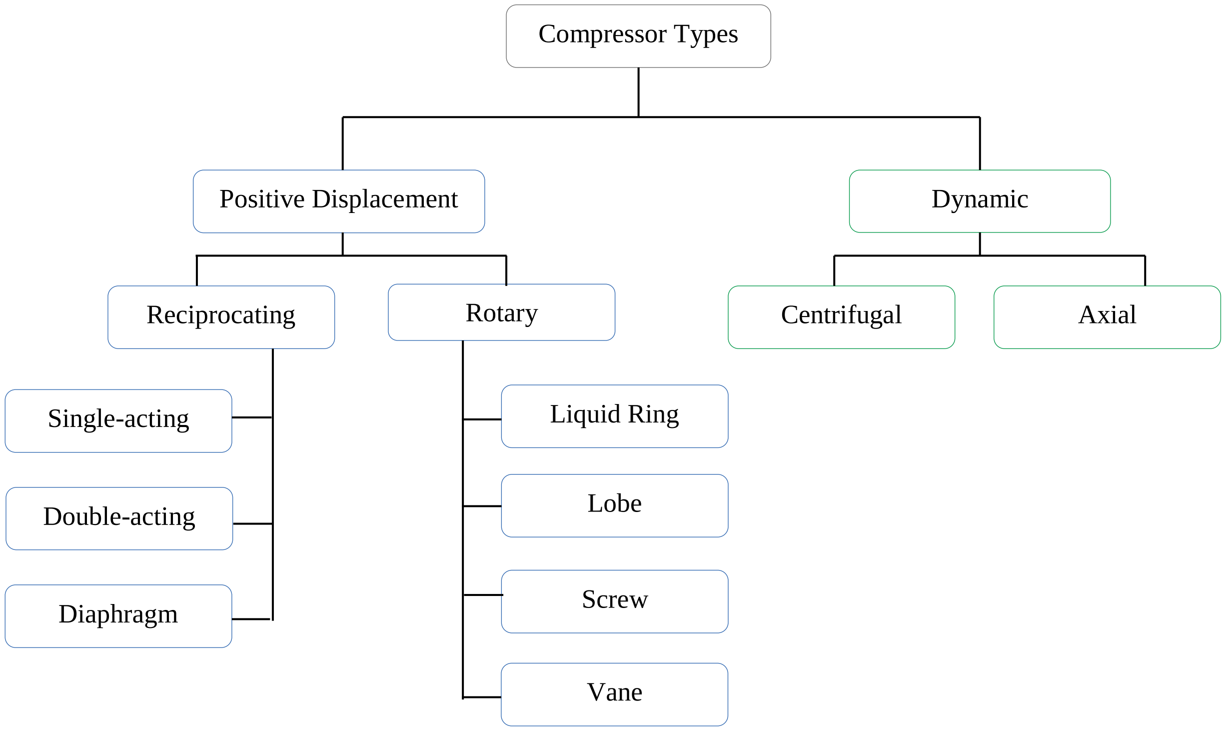


Figure 32: Types of compressors

5.4.3. Data collection

1. Following data shall be collected during audit of compressor from compressor name plate and by interviewing the motor operator or plant supervisor:
    - Compressor make
    - Type of compressor- Reciprocating/Screw/Centrifugal/Other
    - Sub type- Lubricated/Non lubricated/Air cooled/water cooled
    - Model of compressor
    - Rated Free air delivery (cfm or m^3/min or m^3/hr)
    - Rated power
    - Rated specific power consumption
    - Rated motor speed (RPM)
    - Cut-in and cut-off pressure

While collecting information, it should also be checked, whether the compressors are installed with variable speed drive, synthetic flat belt, pressure controllers, auto cut off valves or any other energy saving retrofits.

2. Details of compressed air network

The compressed air network diagram should be collected or made depicting the major compressed air consuming equipment. It is necessary to collect the pressurized air requirement and information pertaining to the major users as shown in **Table 6**

Table 6: Equipment wise compressed air requirement

Equipment	Section	Compressed air pressure requirement kg/cm^2	Compressed air requirement, CFM or m^3/min	Application

3. Details of air dryer installed
4. Schematic diagram of compressed air network

5.4.4. Elements of compressed air system:

Following **Figure 33** shows different elements of compressed air system.

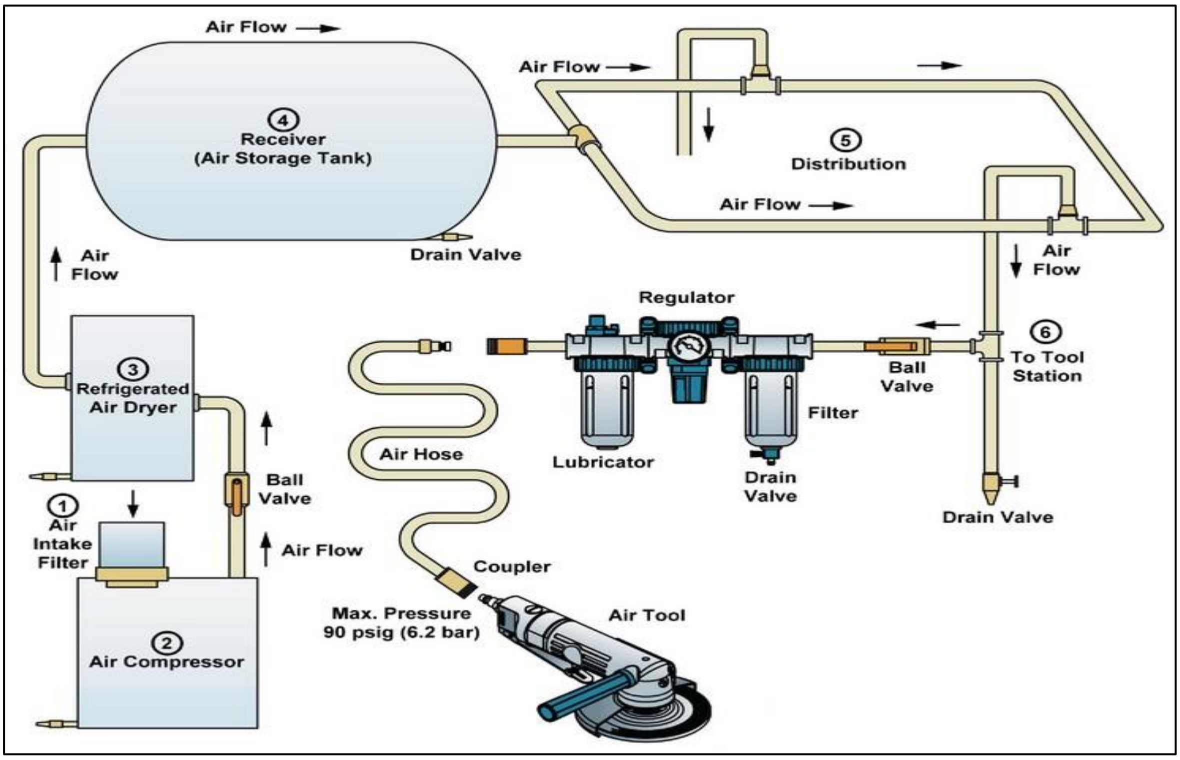


Figure 33: Figure of elements of compressed air system showing generation, distribution, and usage (Source: Gison Pneumatics)

As shown in the above **Figure 33** Compressed air system in any industry can be divided into three stages of

A. Generation
B. Distribution
C. Usage

While look for energy saving option in compressed air system, assessment should also follow the same stages of system.

5.4.5. Instruments required

- Hand-held clamp meter or three-phase power analyser
- Ultrasonic leak detector
- Stopwatch
- Measuring tape
- IR thermometer or thermal imaging camera

5.4.6. Performance terms

- Actual free air delivery (FAD) of the compressor
- Specific power requirement
- Compressed air leakage in the compressed air systems

5.4.7. Assessment of compressed air system:

Assessment of compressed air system according to different stages are explained below:

1. Performance test of compressor

The purpose of the performance test of compressor is to find out:

- Actual free air delivery (FAD) of the compressor
- Specific power requirement

The actual performance of the compressor is to be compared with design/rated values of the compressor for assessing the energy efficiency of compressor.

Capacity of a compressor is the full rated volume of flow of gas compressed and delivered at conditions of total temperature, total pressure, and composition prevailing at the **compressor inlet**. It sometimes means actual flow rate, rather than rated volume of flow. This also termed as **Free Air Delivery (FAD)** i.e. air at atmospheric conditions at any specific location. Because the altitude, barometer, and temperature may vary at different localities and at different times, it follows that this term does not mean air under identical or standard conditions.

Due to ageing of the compressors and inherent inefficiencies in the internal components, the free air delivered may be less than the design value, despite good maintenance practices. Sometimes, other factors such as poor maintenance, fouled heat exchanger and effects of altitude also tend to reduce free air delivery. To meet the air demand, the inefficient compressor may have to run for more time, thus consuming more power than required.

The power wastage depends on the percentage deviation of FAD capacity. For example, a worn-out compressor valve can reduce the compressor capacity by as much as 20%. A periodic assessment of the FAD capacity of each compressor has to be carried out to check its actual capacity. If the **deviations are more than 10% from rated,** corrective measures should be taken to rectify the same through overhauling of the compressor. A well-maintained air compressor is expected to deliver 90 to 100% of the rated volumetric flow (free air delivery).

The simplest method to determine free air delivery of compressor is pump up method which is described below.

Instruments required for FAD test:

- Hand-held clamp meter or three-phase power analyser
- Stopwatch
- Measuring tape

Steps for Free Air Delivery (FAD) test

Step 1: Isolate the compressor along with its individual receiver being taken for test from main compressed air system by tightly closing the isolation valve or blanking it, thus closing the receiver outlet.

Step 2: Open water drain valve and drain out water fully and empty the receiver and the pipeline. Make sure that water trap line is tightly closed once again to start the test.

Step 3: Start the compressor and activate the stopwatch.

Step 4: Note the time taken to attain the normal operational pressure P_2 (in the receiver) from initial pressure P_1.

Step 5: Calculate the capacity as per the formulae given below

$$Q = \frac{P_2 - P_1}{P} X \frac{V}{T}$$

Where,

Q= Free air delivery in Nm^3/minute
P_1= Initial pressure in kg/cm^2 after draining
P_2= Final pressure after filling (kg/cm^2)
V= Storage volume in m^3 which includes receiver tank, volume of after cooler, and volume of delivery pipe before isolation valve.
T= Time taken to build up pressure to P_2 in minutes
The above equation is relevant where the compressed air temperature is same as the ambient air temperature, i.e., perfect isothermal compression.

In case the actual compressed air temperature at discharge, say t_2°C is higher than ambient air temperature say t_1°C (as is usual case), the FAD is to be corrected by a multiplying factor of $(273 + t_1) / (273 + t_2)$.

Example: An instrument air compressor capacity test gave the following results (assume the final compressed air temperature is same as the ambient temperature). Calculate the FAD?

Parameters	Values
Rated compressor capacity	= 14.75 m^3/minute @ 7 kg/cm^2
Receiver Volume	= 7.79 m^3
Additional hold up volume, i.e., pipe, water cooler, etc.	= 0.4974 m^3

Parameters	Values
Total volume	= 7.79 + 0.4974 =8.322 m^3
Initial pressure P_1	= 0.5 kg/cm^2
Final pressure P_2	= 7.03 kg/cm^2
Time taken, T	= 4.021
Atmospheric pressure	= 1.026 kg/cm^2
Measured power	= 45 kW

Solution: Using the formula as given in above **Step 5**

$$Q = \frac{7.03 - 0.5}{1.026} X \frac{8.322}{4.021} = 13.17$$

Q, Free air delivery = 13.17 m^3/minute or 790.2 m^3/hr

Capacity shortfall with respect to rated compressor capacity
= 14.75 – 13.17
= 1.577 m^3/minute or 94.62m^3/hr

i.e., capacity shortfall by 10.69 %, which indicates compressor performance needs to be investigated further.

Assessment of specific power requirement

$$Specific\ power\ consumption = \frac{Actual\ power\ consumed\ by\ the\ compressor}{Measured\ free\ air\ delivery}$$

In the above example, the measured power consumption is 45 kW and free air delivery is 790.2 m^3/hr.

Specific power requirement = 45 / 790.2

= 0.057 kW/m^3/hr

2. Compressed air leaks

The major opportunity to save energy is in the prevention of leaks in the compressed air system. Leaks frequently occur at air receivers, relief valves, pipe and hose joints, shut off valves, quick release couplings, tools and equipment. In most cases, they are due to poor maintenance and sometimes, improper installations etc.

Table 7 gives the amount of free air wasted for different nozzles sizes and pressure.

Table 7: Discharge of air (m^3/min) through Orifice (Orifice constant c_d-1.0) (Source: BEE)

Orifice size in mm	0.5 mm	1 mm	2 mm	3 mm	5 mm	10 mm	12.5 mm
Gauge Pressure (Bar)	**Air loss in (m^3/min) for different orifice sizes**						
0.5	0.06	0.22	0.92	2.1	5.7	22.8	35.5
1.0	0.08	0.33	1.33	3.0	8.4	33.6	52.5
2.5	0.14	0.58	2.33	5.5	14.6	58.6	91.4
5.0	0.25	0.97	3.92	8.8	24.4	97.5	152.0
7.0	0.33	1.31	5.19	11.6	32.5	129.0	202.0

Compressed air leakage test in distribution system:

Step 01: Shut off compressed air operated equipment. Ensure no equipment is using compressed air.

Step 02: Run the compressor to charge the system to set pressure of operation

Step 03: Note the sub-sequent time taken for ‘load’ and ‘unload’ cycles of the compressors. For accuracy, take ON & OFF times for 8 – 10 cycles continuously.

Step 04: Calculate total ‘ON’ Time (T) and Total ‘OFF’ time (t).

Step 05: The system leakage is calculated as:

$$Leakage\ \% = \frac{T}{T+t}\ X\ 100$$

Step 06: Calculate compressed air system leakage quantity.

$$System\ leakage\ quantity\ (m^3/min) = Q\ X\ \frac{T}{T+t}$$

Where, Q is output of compressor measured by free air delivery test.

Example:
In the leakage test in a process industry, following results were observed:

Parameter	Values
Compressor capacity (m^3/minute)	= 35
Cut in pressure, kg/cm^2	= 6.8
Cut out pressure, kg/cm^2	= 7.5
Load Power	= 188 kW
Unload Power	= 54 kW
Average ‘Load’ time	= 1.5 minutes
Average ‘Unload’ time	= 10.5 minutes

Find leakage quantity and energy loss due to air leakages?

Solution:

$$Leakage\ quantity\ (m^3/min)\ = 35\ X\ \frac{1.5}{1.5 + 10.5} = 4.375\ \ (m^3/min)$$

$$Leakage\ quantity\ per\ day\ = 4.375\ X\ 60\ X\ 24 = 6300\ (m^3/day)$$

$$Specific\ power\ for\ compressed\ air\ generation = \frac{188}{35\ X\ 60} = 0.0895\ kWh/m^3$$

$$Energy\ lost\ due\ to\ leakages\ per\ day\ = 0.0895\ X\ 6300 = 564\ (kWh/day)$$

Leakage detection by Ultrasonic Leak Detector:

Leakage tests are conducted by a leak detector having a sensing probe, which senses when there are leakages in compressed air systems at high temperatures-beneath insulated coverings, pipelines, manifolds etc.

The leak is detected by ultrasonic vibration. Leak testing is done by observing and locating sources of ultrasonic vibrations created by turbulent flow of gases passing through leaks in pressurized or evacuated systems

3. Pressure Settings

Compressor operates between pressure ranges called as loading (cut-in) and unloading (cut-out) pressures. For example, a compressor operating between pressure setting of 6 to 7 kg/cm^2 means that the compressor unloads at 7 kg/cm^2 and loads at 6 kg/cm^2. Loading and unloading is done using a pressure switch.

For the same capacity, a compressor consumes more power at higher pressures. They should not be operated above their optimum operating pressures as this not only wastes energy, but also leads to excessive wear, leading to further energy wastage. The volumetric efficiency of a compressor is also less at higher delivery pressures.

4. Reducing delivery pressure

The possibility of lowering (optimising) the delivery pressure settings should be explored by careful study of pressure requirements of various equipment, and the pressure drop in the line between the compressed air generation and utilization points. Typical power savings through pressure reduction is shown in below **Table 8**

Table 8: Typical power savings through pressure reduction (Source: BEE)

Pressure Reduction		Power Savings (%)		
From (bar)	To (bar)	Single stage Water cooled	Two stage Water cooled	Two stage Air cooled
6.8	6.1	4	4	2.6
6.8	5.5	9	11	6.5

The pressure switches must be adjusted such that the compressor cuts-in and cuts-out at optimum levels. A reduction in the delivery pressure by 1 bar in a compressor would reduce the power consumption by 6 ~ 10 %. For example, reduction of delivery pressure by 1 kg/cm^2 (from 8 kg/cm^2 to 7 kg/cm^2) would result in 9% input power savings.

5. Compressor modulation by optimum pressure settings

Very often in industry, different types, capacities and makes of compressors are connected to a common distribution network. In such situations, proper selection of a right combination of compressors and optimal modulation of different compressors can conserve energy.

Where more than one compressor feeds a common header, compressors must be operated in such a way that the cost of compressed air generation is minimal.

- If all compressors are similar, the pressure setting can be adjusted such that only one compressor handles the load variation, whereas the others operate at full load.
- If compressors are of different sizes, the pressure switch should be set such that only the smallest compressor can modulate (vary in flow rate).
- If different types of compressors are operated together, unload power consumptions are significant. The compressor with the lowest no load power must be modulated.
- In general, the compressor with lower part load power consumption should be modulated.
- Compressors can be graded according to their specific energy consumption, at different pressures and energy efficient ones must be made to meet most of the demand.

Assessing compressed air system study for a plant section gave following results. Comment on the results?

- Compressors online A, B, C, D, E (all type)
- Trial observation Summary

Compressor Reference	Measured Capacity (m^3/min)	On load kW	Unload kW	Load time Minute	Unload time Minute
A	13.17	115.30	42.3	Full Time[3]	Nil
B	12.32	117.20	51.8	Full Time	Nil
C	13.14	108.30	43.3	Full Time	Nil
D	12.75	104.30	29.8	Full Time	Nil
E	13.65	109.30	39.3	5.88	39.12

Analysis:

For a cycle time (Load + Unload) = 5.88 + 39.12 = 45 minutes

[3] Compressors running in load conditions and not getting unloaded during normal operations

Parameters	Calculations
Compressed air generated in m^3	= 45 (13.17) + 45 (12.32) + 45 (13.14) + 45 (12.75) + 5.88 (13.65) = 2392.36 m^3
Power consumption, kWh	= 45/60 (115.3) + 45/60 (117.20) + 45 / 60 (108.3) + 45/60 (104.3) + 5.88/60 (109.8) + ((39.12) / 60) 39.3 = 370.21 kWh/45 mins
Compressed air generation actual capacity online in m^3	= 45 (13.17 + 12.32 + 13.14 + 12.75 + 13.65) = 2926.35 m^3
The consumption rate of the section connected	= 2392.36 / 45 = 53.16 m^3/minute
Compressor air drawable as % of capacity online	= (2392.36 / 2926.35) × 100 = 81.75 %
Specific power consumption	= 370.21 / 2392.36 = 0.155 kW/m^3
Idle power consumption due to unload operation	= 25.62 kWh in every 45 minutes cycle i.e., **34.16 kWh per hour**.

Inferences

1. It would be favourable in short term and energy efficient to keep the compressor 'D' in cycling mode on account of lower un-load losses and hence capacity. Speed of the compressor can also be reduced by reducing motor pulley size.
2. A suitable smaller capacity compressor can be planned to replace the compressor with highest unload losses.
3. An investigation is called for, as to why such a large variation of unload power drawn, exists although all compressors have almost the same rated capacity.

6. Segregating low- and high-pressure air requirements

If the low-pressure air requirement is considerable, it is advisable to generate low pressure and high-pressure air separately, and feed to the respective sections instead of reducing the pressure through pressure reducing valves, which invariably waste energy.

7. Minimum pressure drops in air lines

Pressure drop in air-pipelines depends upon the quantity of air flow, diameter of the pipeline, pipe length and the bends in the pipelines. Excess pressure drops due to inadequate pipe sizing, choked filter elements, improperly sized couplings and hoses represent energy wastage. Typical acceptable pressure drop-in industrial practice is 0.3 bar in mains header at the farthest point and 0.5 bar in distribution system.

The pipelines should be with minimum number of joints, bends and fittings. Further to minimise the joints, it should be ensured that joints are welded instead of flexible or screwed joints.

8. Location of compressors

The location of air compressors and the quality of air drawn by the compressors will have a significant influence on the amount of energy consumed. Compressor performance as a breathing machine improves with cool, clean, dry air at intake. Hence, the compressor shall be placed in such locations which has to access to cool, clean, and dry air at intake.

9. Cool air intake

Cool air is more dense than warm air. Therefore, lower energy is needed to further compress cool air entering the air compressor than would be required if hot air were to be fed to the air compressor. Every 4ºC rise in inlet air temperature results in a higher energy consumption by 1% to achieve equivalent output

Hence, cool air intake leads to a more efficient compression as shown in below **Table 9.**

Table 9: Effect of intake air temperature on power consumption (Source: BEE)

Inlet temperature	Relative air delivery (%)	Power saved (%)
10	102	+1.4
15.5	100	Nil
21.1	98.1	-1.3
26.6	96.3	-2.5
32.2	94.1	-4.0
37.7	92.8	-5.0
43.3	91.2	-5.8

It is preferable to draw cool ambient air from outside, as the temperature of air inside the compressor room will be a few degrees higher than the ambient temperature. While extending air intake to the outside of room, care should be taken to minimize excess pressure drop in the suction line, by selecting a bigger diameter duct with minimum number of bends.

10. Dust free air intake

Dust in the suction air causes excessive wear of moving parts and results in malfunctioning of the valves due to abrasion. Suitable air filters should be provided at the suction side. Air filters should have high dust separation capacity, low-pressure drops, and robust design to avoid frequent cleaning and replacement. See **Table 10** for the effect of pressure drop across air filter on power consumption. For every 250 mm WC pressure drop increase across at the suction path due to choked filters, the compressor power consumption increases by about 2% for the same output.

Table 10: Effect of pressure drop across air inlet filter on power consumption (Source: BEE)

Pressure drop across air filter (mmWC)	Increase in power consumption (%)
0	0
200	1.6
400	3.2
600	4.7
800	7.0

Air filters should be selected based on the compressor type and installed as close to the compressor as possible. It is advisable to clean inlet air filters at regular intervals to minimize pressure drops. Manometers or differential pressure gauges across filters may be provided for monitoring pressure drops to plan filter-cleaning schedules.

11. Dry air intake

Atmospheric air always contains some amount of water vapour, depending on the relative humidity, being high in wet weather. The moisture level will also be high if air is drawn from a damp area - for example locating compressor close to cooling tower, or dryer exhaust is to be avoided, see below **Table 11**

Table 11: Moisture in ambient air at various humidity levels (Source: BEE)

% Relative Humidity	Kg of water vapour per hour for every hour for every 1000 m^3/min of air at 30°C
50	27.60
80	45.00
100	68.22

The moisture-carrying capacity of air increases with a rise in temperature and decreases with increase in pressure.

12. Air Dryers

The atmospheric air has certain amount of moisture. The moisture holding capacity of air depends on the ambient temperature. Higher the temperature more is the moisture holding capacity of air in the form of water vapour and vice versa. Saturated air at a given temperature is the air that contains the maximum amount of water in the form of water vapour. Any excess water vapour will be condensed in the form of water.

About 60 to 75% of moisture in compressed air is removed at the after cooler. As compressed air leaves the after cooler and passes through the compressed air lines, the temperature of the compressed air further reduces. The remaining water vapour in the air starts condensing. The effects of water particles in the compressed air are given below.

- The water particles travel at the same velocity of compressed air and damages the pneumatic valves or instruments at the user ends by erosion.
- Corrosion in the distribution pipe work.
- Impaired finishing processes particularly in paint spraying, sheet cleaning etc.

Hence, the water vapour from the compressed air has to be removed, for applications such as instrumentation and pneumatics. This can be achieved by passing the compressed air through the air dryers.

The extent of drying compressed air is expressed by the term "Atmospheric Dew Point" which is the temperature at which moisture present in the air starts condensing at atmospheric pressure. Lower the dew point, drier is the air. Air at -40°C atmospheric dew point means no moisture would

condense unless temperature of the air is reduced to less than -40°C, at atmospheric pressure. The performance of a dryer is quoted in terms of 'pressure dew point'. Increasing the pressure of the air also increases the dew point temperature of the air. Most used dryers in the industry are:

- Refrigerated dryers and
- Adsorption type can be of the following type
    - Blower reactivated
    - Heatless purge
    - Heat of compression

Refer **Table 12** for typical pressure dew point and power consumption data for dryers.

Table 12: Typical pressure dew point and power consumption (Source: BEE)

Type of dryer	Atmospheric Dew Point °C	Initial Cost	Operating Cost	Power consumption For 1000 m^3/hr
Refrigeration	-20	Low	Low	2.9 kW
Desiccant regenerative (Blower reactivated type)	-40	Medium	Medium	18.0 kW
Desiccant regenerative (heatless purge type)	-40	Low	High	20.7 kW
Desiccant regenerative (by recovery of heat of compression from compressed air)	-40	High	Extremely low	0.8 kW

13. Elevation

The altitude of a place has a direct impact on the volumetric efficiency of the compressor. The effect of altitude on volumetric efficiency is given in the below **Table 13**

Table 13: Effect of altitude on Volumetric Efficiency (Source: BEE)

Altitude in meters	Barometric Pressure in milli bar[4]	Percentage Relative Volumetric Efficiency compared with Sea Level	
		At 4 bar	At 7 bar
Sea level	1013	100.0	100.0
500	945	98.7	97.7
1000	894	97.0	95.2
1500	840	95.5	92.7
2000	789	93.9	90.0
2500	737	92.1	87.0

It is evident that compressors located at higher altitudes consume more power to achieve a delivery pressure than those at sea level, as the compression ratio is higher.

14. Avoiding misuse of compressed air

Misuse of compressed air for purposes like body cleaning, liquid agitation, floor cleaning, drying, equipment cooling, and other similar uses must be discouraged. Wherever possible, low-pressure air from a blower should be substituted for compressed air, for example secondary air for combustion in a boiler / furnace.

The following **Table 14** gives an idea of savings by stopping use of compressed air by choosing alternative methods to perform the same task.

Table 14: Typical power requirements for pneumatic and electrical Tools (Source: BEE)

Tool	Wheel diameter mm	Speed Rpm	Air consumption m^3/hr	Power kW
Pneumatic angle grinder	150	6000	102 m^3/hr at 6 bar	10.2
Electric angle grinder	150	5700-8600	N. A	1.95-2.90
Pneumatic jet grinder	35	30000	32.3 m^3/hr at 6 bar	3.59
Electric straight grinder	35	22900-30500	N. A	0.18

[4] 1 milli bar = 1.01972 x 10^{-3} kg/cm^2

5.4.8. Energy saving opportunities in compressed air network

- Ensure air intake to compressor is not warm and humid by locating compressors in well-ventilated area or by drawing cool air from outside.
  "Every 4°C rise in air inlet temperature will increase power consumption by 1%"
- Clean air-inlet filters regularly. Compressor efficiency will be reduced by 2% for every 250 mm WC pressure drop across the filter.
- Minimize low-load compressor operation; if air demand is less than 50% of compressor capacity, consider change over to a smaller compressor or reduce compressor speed appropriately (by reducing motor pulley size) in case of belt driven compressors.
- Consider the use of regenerative air dryers, which uses the heat of compressed air to remove moisture.
- If more than one compressor is feeding to a common header, compressors must be operated in such a way that only one small compressor should handle the load variations whereas other compressors will operate at full load.
- The possibility of heat recovery from hot compressed air to generate hot air or water for process application must be economically analysed in case of large compressors.
- If pressure requirements for processes are widely different (e.g. 3 bar to 7 bar), it is advisable to have two separate compressed air systems.
- Reduce compressor delivery pressure, wherever possible, to save energy.
- Retrofit with variable speed drives in big compressors, say over 100 kW, to eliminate the `unloaded' running condition altogether.
- Keep the minimum possible range between load and unload pressure settings.
- Automatic timer-controlled drain traps waste compressed air every time the valve opens. So, frequency of drainage should be optimized.
- Compressed air leakage of 40~50% is not uncommon. Carry out periodic leak tests to estimate the quantity of leakage and institute repair of leaks to below 5~8%.
- Install equipment interlocked solenoid cut-off valves in the air system so that air supply to a machine can be switched off when not in use.
- Compressed air piping layout should be made preferably as a *ring main* to provide desired pressures for all users.
- A smaller dedicated compressor can be installed at load point, located far off from the central compressor house, instead of supplying air through lengthy pipelines.
- Misuse of compressed air such as for body cleaning, agitation, general floor cleaning, and other similar applications must be discouraged in order to save compressed air and energy.
- Pneumatic tools such as drill, and grinders consume about 20 times more energy than motor driven tools. Hence, they must be used efficiently. Wherever possible, they should be replaced with electrically operated tools.
- Where possible welding is a good practice and should be preferred over threaded connections.

5.5. Heating, ventilation, air conditioning & refrigeration systems

5.5.1. Introduction

The Heating, Ventilation, Air Conditioning (HVAC) and refrigeration system transfers the heat energy from or to the products or building environment. Energy in form of electricity or heat is used to power mechanical equipment designed to transfer heat from a colder, low-energy level to a warmer, high-energy level.

Refrigeration deals with the transfer of heat from a low temperature level at the heat source to a high temperature level at the heat sink by using a low boiling refrigerant. There are several heat transfer loops in the refrigeration system as described below:

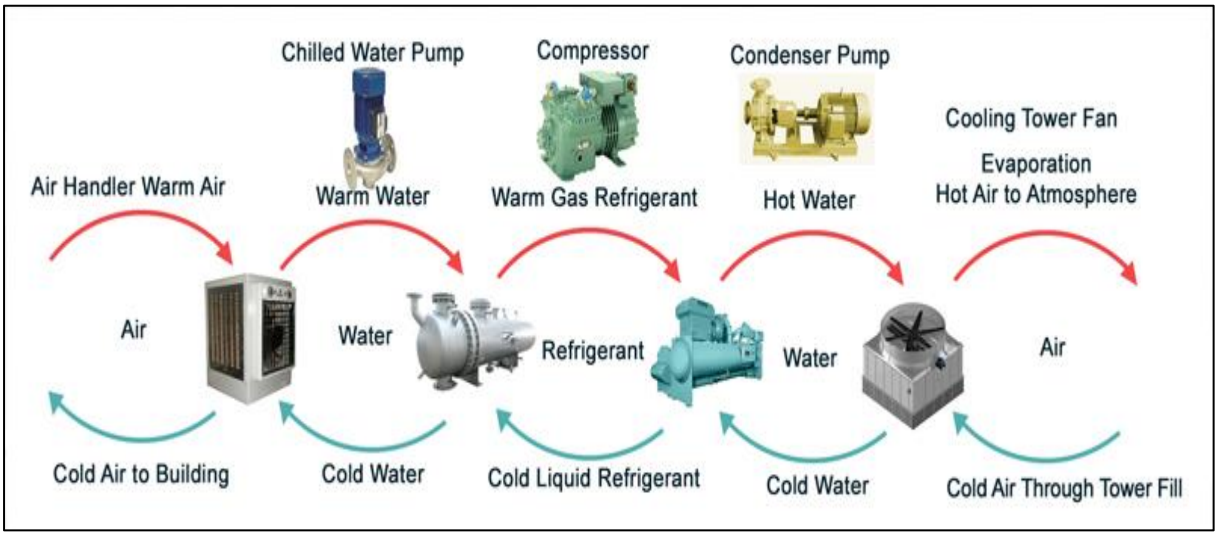


Figure 34: Heat Transfer Loops in refrigeration system

In **Figure 34** thermal energy moves from left to right as it is extracted from the space and expelled into the outdoors through five loops of heat transfer:

Indoor air loop: In the leftmost loop, indoor air is driven by the supply air fan through a cooling coil, where it transfers its heat to chilled water. The cool air then cools the building space.

Chilled water loop: Driven by the chilled water pump, water returns from the cooling coil to the chiller's evaporator to be re-cooled.

Refrigerant loop: Using a phase-change refrigerant, the chiller's compressor pumps heat from the chilled water to the condenser water.

Condenser water loop: Water absorbs heat from the chiller's condenser, and the condenser water pump sends it to the cooling tower.

Cooling tower loop: The cooling tower's fan drives air across an open flow of the hot condenser water, transferring the heat to the outdoors.

5.5.2. Psychrometries and air-conditioning processes

Psychrometric is the science of moist air properties and processes, which is used to illustrate and analyse air-conditioning cycles. It translates the knowledge of heating or cooling loads (which are in kW or tons) into volume flow rates (in m^3/s or cfm) for the air to be circulated into the duct system.

Water vapour is lighter than dry air. The amount of water vapour that the air can carry increases with its temperature. Any amount of moisture that is present beyond what the air can carry at the prevailing temperature can only exist in the liquid phase as suspended liquid droplets (if the air temperature is above the freezing point of water), or in the solid state as suspended ice crystals (if the temperature is below the freezing point).

The most commonly used psychrometric quantities include the dry and wet bulb temperatures, dew point, specific humidity, and relative humidity.

Psychrometric Chart

Psychrometric chart is a chart indicating the psychrometric properties of air such as dry-bulb temperature, wet-bulb temperature, specific humidity, enthalpy of air in kJ/kg dry air, specific volume of air in m^3/kg and relative humidity (Φ) in percentage (%). It helps in quantifying and understanding air conditioning process. A sample Psychrometric chart is shown in Figure 35.

Example: Assume that the outside air temperature is 32°C with a relative humidity of Φ = 60%. Use the psychrometric chart to determine the air properties (Use **Figure 35)**.

Solution: Air properties of air at 32°C dry bulb temperature and relative humidity (RH) of 60%

Specific humidity ω = 18 gm-moisture/kg-air

Enthalpy, h = 78 kJ/kg-air

Wet-bulb temperature T_{wb} = 25.5°C

Dew-point temperature, T_{dp} = 23°C

Specific volume of the dry air V = 0.89 m^3/kg

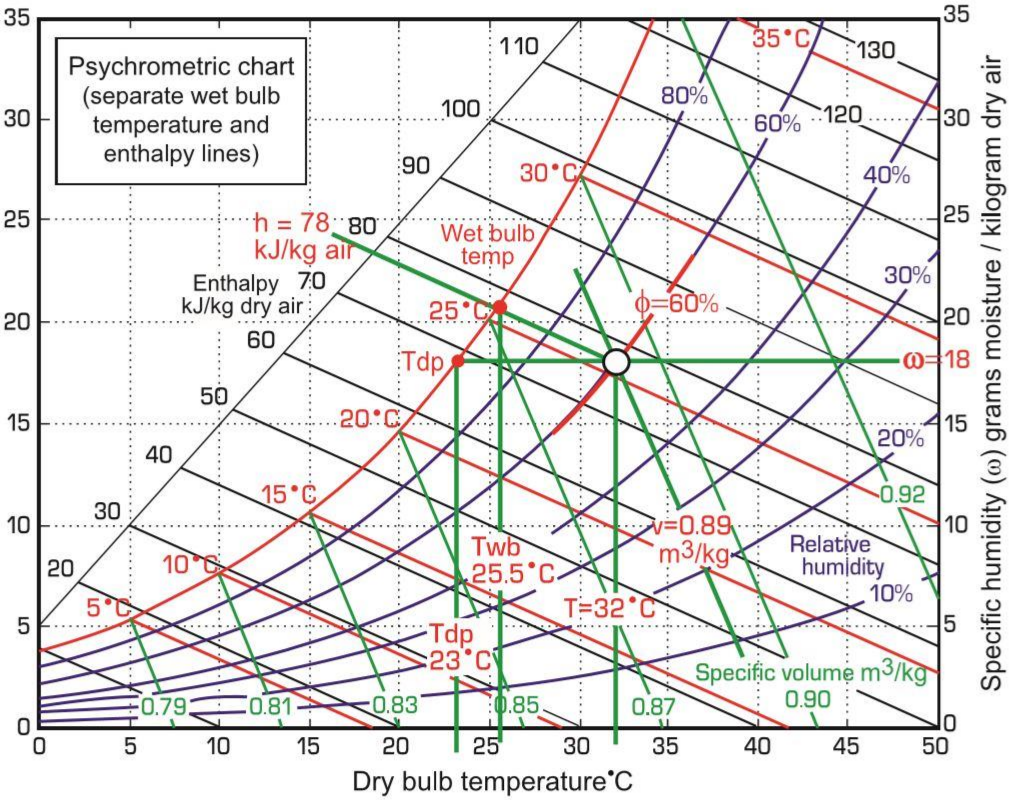


Figure 35: Psychrometric chart (Source: BEE)

5.5.3. Comfort zone

One of the major applications of the Psychrometric Chart is in air conditioning, and we find that most humans feel comfortable when the temperature is between 22°C and 27°C, and the relative humidity between 40% and 60%. This defines the "comfort zone" which is portrayed on the Psychrometric Chart as shown in **Figure 36.** Thus, with the aid of the chart we either heat or cool, add moisture or dehumidify as required in order to bring the air into the comfort zone.

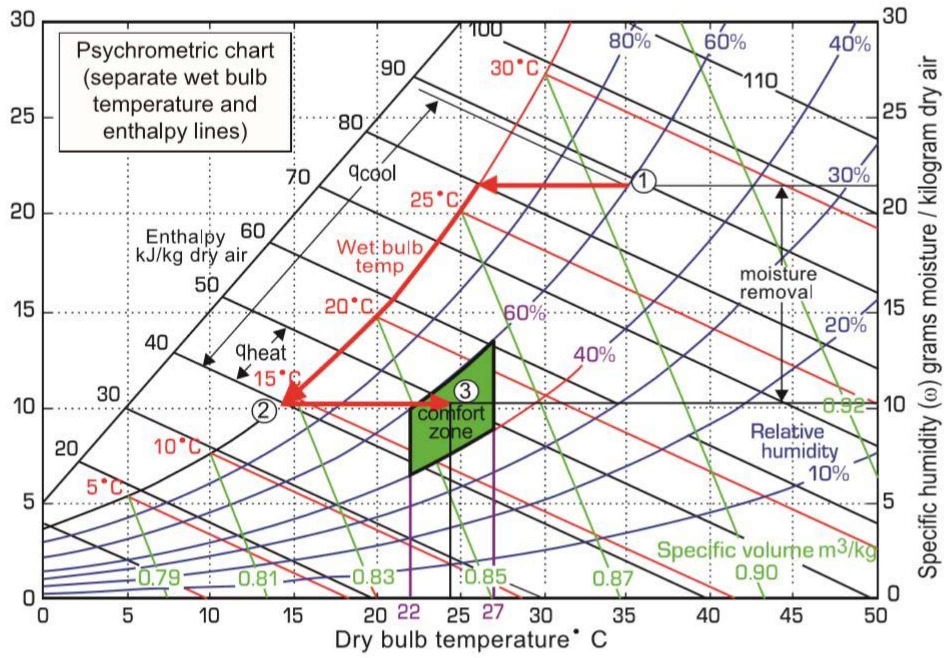


Figure 36: Psychrometric chart depicting human comfort zone (Source: BEE)

5.5.4. Refrigeration systems (for processes)

- Small capacity modular units of direct expansion type like domestic refrigerators, small capacity refrigeration units.
- Centralized chilled water plants with chilled water as a secondary coolant for temperature range over 5°C typically. They can also be used for ice bank formation, if needed.
- Brine plants, which use brines as lower temperature, secondary coolant, for typically sub-zero temperature applications, which come as modular unit capacities as well as large centralized
  plant capacities.
- The plant capacities up to 50 TR are usually considered as small capacity, 50 - 250 TR as medium capacity and over 250 TR as large capacity units.

A large industry may have a bank of such units, often with common chilled water pumps, condenser water pumps, cooling towers, as an off-site utility. The same industry may also have two or three levels of refrigeration and air conditioning such as:

- Comfort air conditioning (20~25°C)
- Chilled water system (8~10°C)
- Brine system (sub-zero applications)

5.5.5. Data collection

Following data shall be collected during audit from nameplate and by interviewing the operator or supervisor:

- Schematic diagram of HVAC system
- Rated capacity (TR)
- Refrigerant used
- Design parameter and make of chiller, condenser, cooling tower and AHUs

- Rated pump, motor, and fan specification
- Rated Specific energy consumption of the system

In addition to above, following data shall be collected through measurements:

- Water inlet temperature °C to evaporator
- Water outlet temperature °C from evaporator
- Water inlet temperature °C to condenser
- Water outlet temperature °C from condenser
- Ambient air wet bulb and dry bulb temperature °C
- Water flow rate ($m^{3/}$hr) in evaporator
- Water flow rate ($m^{3/}$hr) in condenser
- Primary and secondary pump power (kW)
- Primary and secondary operating pressure (kg/cm^2)
- AHU Air flow (m^3/hr) & temperature of air °C inlet and outlet

5.5.6. Instruments required

- Ultrasonic water flow meter
- Hand -held clamp meter or three-phase power analyser
- Sling psychrometer
- pen-type thermometer
- Anemometer
- TDS-conductivity meter
- Measuring tape
- Water flow meter
- Thermal camera or IR gun

5.5.7. Purpose of the performance test

The purpose of performance assessment is to verify the performance of a refrigeration system by using field measurements. The test will measure net cooling capacity (tons of refrigeration) and energy requirements at the actual operating conditions. The objective of the test is to estimate the energy consumption at actual load vis-a-vis design conditions.

5.5.8. Performance terms and definitions

Tons of Refrigeration (TR): One ton of refrigeration is the amount of cooling obtained by one ton of ice melting in 24 hours, which is equivalent to 3,024 kcal/h, 12,000 Btu/h or 3.516 thermal kW.

Net Refrigerating Capacity: A quantity defined as the mass flow rate of the evaporator water multiplied by the difference in enthalpy of water entering and leaving the cooler expressed in kcal/h or tons of Refrigeration. In general, it refers to the actual operating TR.

kW/ton rating: The ratio of power input to the compressor motor to the tons of cooling produced. This term is commonly referred as efficiency. Lower kW/ton indicates higher efficiency of equipment.

Coefficient of Performance (COP): The COP is the ratio of heating or cooling provided to work required. The most basic formula to COP is Q/W, where Q is the heat supplied to or removed from the reservoir and W is the work done by the compressor. Chiller efficiency measured in Watt output (heating) divided by Watt input (electric power).
In general, COP refers to heating efficiency of an air conditioner or heat pump. For example, if an air conditioner generates 5 kW of heat from one kW electrical input, its COP is said to be 5.0. Higher COP indicates higher efficiency of the equipment.

Energy Efficiency Ratio (EER): Performance of smaller chillers and split AC's is frequently measured in EER rather than kW/ton. EER is calculated by dividing a chiller's cooling capacity (in Watts) by its power input (in Watts) at full-load conditions.
In general, EER is the cooling efficiency of an air conditioner. For example, if an air conditioner generates 4000 W (1.14 TR) of cooling from 1000 W electrical input, its EER is said to be 4.0. Higher EER indicates higher efficiency of the equipment.

5.5.9. Components of HVAC system

The main components of HVAC systems are:

- Evaporator unit
- Compressor unit (in Vapour compression refrigeration system)
  or
  Absorber and Generator Unit (in vapour absorption refrigeration system)
- Condenser Unit (air cooled / water cooled and condenser fans / cooling tower fans)
- Air Handling Units (AHU), with fans and blowers
- Primary and secondary chilled / cooling water pumps

The most widely used and commonly found systems are vapour compression refrigeration system, hence only performance evaluation of vapour compression systems are explained in detail in next section.

5.5.10. Vapour compression refrigeration

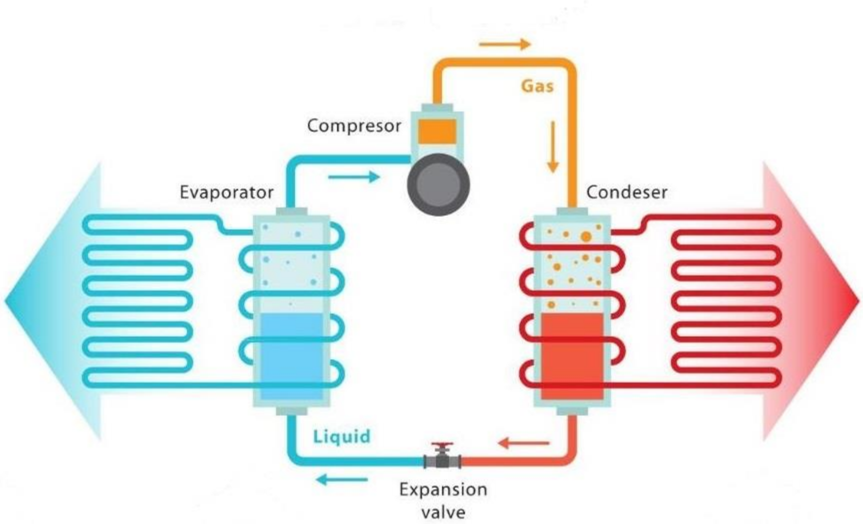


Figure 37: Vapour compression refrigeration system

Heat flows naturally from a hot to a colder body. In a refrigeration system the opposite must occur i.e. heat flows from a cold body to a hotter body. This is achieved by using a substance called refrigerant, which absorbs heat and hence boils or evaporates at a low pressure to form a gas. This gas is then compressed to a higher pressure, such that it transfers the heat it has gained to ambient air or water and turns back (condenses) into a liquid. In this way heat is absorbed, or removed, from a low temperature source and transferred to a higher temperature source.

The refrigeration cycle can be broken down into the following stages (see **Figure 37**):

1. Low pressure liquid refrigerant in the evaporator absorbs heat from its surroundings, usually air, water, or some other process liquid. During this process it changes its state from a liquid to a gas, and at the evaporator exit is slightly superheated.

2. The superheated vapour enters the compressor where its pressure is raised. There will also be a big increase in temperature, because a proportion of the energy input into the compression process is transferred to the refrigerant.

3. The high pressure superheated gas passes from the compressor into the condenser. The initial part of the cooling process de-superheats the gas before it is then turned back into liquid. The cooling for this process is usually achieved by using air or water. A further reduction in temperature happens in the pipe work and liquid receiver, so that the refrigerant liquid is sub-cooled as it enters the expansion device.

4. The high-pressure sub-cooled liquid passes through the expansion device, which both reduces its pressure and controls the flow into the evaporator.

5.5.11. Procedure for performance evaluation of vapour compression refrigeration system

After establishing steady state conditions of HVAC system, three sets of data shall be taken preferably at a minimum of five-minute interval. To minimize the effects of transient conditions, test readings should be taken simultaneously to the extent possible in all components of HVAC system.

1. Determine the compressor power

Using a three-phase power analyser, measure the compressor power. It is suggested to set-up the three-phase analyser at the beginning of assessment and start the recording for the full duration of assessment period.

2. Determine the net refrigeration capacity at the evaporator

Step-1: Using a portable ultrasonic water flow meter, measure the chilled water flow rate (m_e) flowing through the evaporator pipes. *This is a non-invasive method; flow shall be measured without disturbing the routine operations.*

Step-2: Using a pen-type thermometer, measure the chilled water (inlet) temperature (t_{in}) entering to the evaporator by slightly opening the valves installed near the evaporator. Ensure to close the valves firmly after taking the readings. *The accurate temperature measurement is very crucial in refrigeration and air conditioning and least count should be at least one decimal.*

Step-3: Using a pen-type thermometer, measure the chilled water (outlet) temperature (t_{out}) leaving from the evaporator by slightly opening the valves installed near the evaporator. Ensure to close the valves firmly after taking the readings.

Step-4: The heat removed from the chilled water is equal to the product of the chilled water flow rate, the temperature difference of chilled water, and the specific heat of water. The net refrigeration capacity in TR shall be obtained by the following equation:

$$Net\ refrigeration\ capacity\ \ at\ Evaporator\ (TR) = \frac{m_e\ X\ c_P\ X\ (t_{in} - t_{out})}{3024}$$

Where,

m_e – mass flow rate of chilled water, kg/h

C_p – Specific heat of water, kcal/kg°C

t_{in} – Chilled water temperature inlet, °C

t_{out} – Chilled water temperature outlet, °C

3. Determine the heat rejected at the condenser

The heat rejected by the condenser can be derived by following relation:

Heat rejected at condenser = cooling load + work done by compressor

$$Heat\ rejected\ (TR) = \ (Net\ refrigeration\ capacity\ at\ Evaporator\ TR) + \frac{Shaft\ power\ (kW)}{3.516}$$

Where, Shaft power (kW) absorbed (work done) by the compressor can be derived by following formula:

Shaft power (kW) = Motor input power X rated efficiency (η)

Heat rejected at the condenser can be measured as follows:

a) For water-cooled condenser

Step-1: Using a portable ultrasonic water flow meter, measure the cooling water flow rate (m_c) flowing through the condenser pipes. *This is a non-invasive method; flow shall be measured without disturbing the routine operations.*

Step-2: Using a pen-type thermometer, measure the cooling water (inlet) temperature (t_{in}) entering to the condenser by slightly opening the valves installed near the condenser. Ensure to close the valves firmly after taking the readings.

Step-3: Using a pen-type thermometer, measure the cooling water (outlet) temperature (t_{out}) leaving from the condenser by slightly opening the valves installed near the chiller. Ensure to close the valves firmly after taking the readings.

Step-4: The heat rejected at the condenser is equal to the product of the cooling water flow rate, the temperature difference of cooling water, and the specific heat of water. The heat rejected in TR shall be obtained by the following equation:

$$Heat\ rejected\ \ at\ Condenser\ (TR) = \frac{m_c\ X\ c_P\ X\ (t_{out} - t_{in})}{3024}$$

Where,
m_c – mass flow rate of cooling water, kg/h
C_p – Specific heat of water, kcal/kg°C
t_{out} – Cooling water temperature at condenser outlet, °C
t_{in} – Cooling water temperature at condenser inlet, °C

b) For air-cooled condenser

Step-1: Using an anemometer, measure the air quantity flowing across condenser coil. The least count for anemometer should be 0.1m/s. Air flow rate is calculated as the multiplication product of the average air velocity in the plane of measurement and flow area.

Step-2: Using digital thermometer, measure the inlet and outlet temperature of air at condenser.

Step-3: The heat rejected at the condenser is equal to the product of the mass flow rate of the air, the temperature difference of cooling air, and the specific heat of air. The heat rejected in TR shall be obtained by the following equation:

$$Heat\ rejected\ \ at\ Condenser\ (TR) = \frac{m_a\ X\ c_P\ X\ (t_{out} - t_{in})}{3024}$$

Where,
m_a – mass flow rate of air, kg/h
C_p – Specific heat of air, kcal/kg°C
t_{out} – Cooling air temperature at condenser outlet, °C
t_{in} – Cooling air temperature at condenser inlet, °C

5.5.12. Performance evaluation of air handling units (AHU)

For centralized air conditioning systems, the air flow at the air handling unit (AHU) can be measured with help of an anemometer. Using a hygrometer, the dry bulb and wet bulb temperatures can be measured at the AHU inlet and outlet. The data can be used along with a psychrometric chart to determine the enthalpy (heat content of air at the AHU inlet and outlet). The following relation can be used to calculate the heat load:

$$Heat\ load\ (TR) = \frac{m_a\ \ (h_{in} - h_{out})}{4.18\ X\ 3024}$$

Where,
m_a – mass flow rate of air, kg/h
h_{in} – enthalpy of inlet air at AHU, KJ/kg
h_{out} – enthalpy of outlet air at AHU, KJ/kg

Heat load can also be calculated theoretically by estimating the various heat loads, both sensible and latent in the air-conditioned room (refer standard air conditioning handbooks).The difference between these two indicates the losses by way of leakages unwanted loads, heat ingress etc.

5.5.13. Energy savings opportunities in HVAC system

1. Chilled water supply temperature set-point

Resetting chiller water supply temperature in accordance with the season can increase the efficiency of the overall HVAC system and create monetary savings. In cooler and moderate months, increasing the chilled water supply temperature makes logical sense if the cooling load is less than the design load. Within a building's HVAC system, the chilled water supply is sent to the building's air handling units (AHUs), which use the chilled water to achieve set points on how cold the air supplied to the space needs to be. The system works as a loop, so when the water returns from the AHU to the chiller plant, the heat exchanger doesn't have to work as hard to reduce the temperature of the water, if the water supply temperature set point has risen. This tactic lessens the workload and energy consumption of the compressor. Raising evaporator set temperature by 1°C can help to reduce power consumption by around 3%

2. Maintenance of heat exchanger surfaces

Effective maintenance holds key to optimizing power consumption. Heat transfer can also be improved by ensuring proper separation of the lubricating oil and the refrigerant, timely defrosting of coils, and increasing the velocity of secondary coolant (air, water, etc.). However, increased velocity results in larger pressure drops in the distribution system and higher power consumption in pumps /fans. Therefore, careful analysis is required to determine the most effective and efficient option.

Fouled condenser tubes force the compressor to work harder to attain the desired capacity. For example, a 0.8 mm scale build-up on condenser tubes can increase energy consumption by as much as 35%. Similarly, fouled evaporators due to residual lubricating oil or infiltration of air result in increased power consumption. Equally important is maintenance of cooling towers; reduction of 0.5°C temperature in water returning from the cooling tower reduces compressor power consumption by 3%. Case study results on effect of poor maintenance of heat exchanger on a 15-ton reciprocating compressor based system have been shown in **Table 15.**

Table 15: Effect of poor compressor maintenance in HVAC system

Effect of poor maintenance on compressor power consumption (case study)					
Condition	**Evaporator temperature (°C)**	**Condenser temperature (°C)**	**Refrigeration capacity (tons)**	**Specific power consumption (kW/ton)**	**Increase in kW/ton (%)**
Normal	7.2	40.5	17.0	0.69	-
Fouled condenser	7.2	46.1	15.6	0.84	20.4

Effect of poor maintenance on compressor power consumption (case study)					
Condition	**Evaporator temperature (°C)**	**Condenser temperature (°C)**	**Refrigeration capacity (tons)**	**Specific power consumption (kW/ton)**	**Increase in kW/ton (%)**
Fouled evaporator	1.7	40.5	13.8	0.82	18.3
Fouled evaporator and condenser	1.7	46.1	12.7	0.96	38.7

It can be observed from above table that increase in kW/ton or percentage increase in power consumption due to fouled condenser and evaporator is indicative of the effect of poor maintenance.

3. Possible solutions for maintenance of condensers

With time the fouling of tube in condenser shell and tube heat exchanger of chiller starts. The reason behind is the cooling tower water because it contains minerals, such as calcium and magnesium that precipitate to form deposits on heat transfer surfaces. Cooling water systems are also commonly plagued by biological growth that forms slime or algae on heat transfer areas. Additional foulants include mud, silt, corrosion products, petroleum products, etc. All of these foulants reduce the heat transfer efficiency of even the best-designed heat exchangers, induce localized corrosion leading to early equipment failure, and force shutdowns of the cooling process. So, with time practice various cleaning methodologies which require periodic shutdown of the process for heat exchanger cleaning via hydro blasting, scrapers, nylon or metallic brushes, or chemical cleaning. But the major disadvantages of an off-line cleaning approach are that the processing unit has to be removed from service for cleaning, and that the process efficiency immediately degrades after being placed back into service.

Also, there is option of installation of **Automatic Tube Cleaning System** (ATCS) if the cost economics allows. This system allows continuous online cleaning of tubes of the heat exchanger.

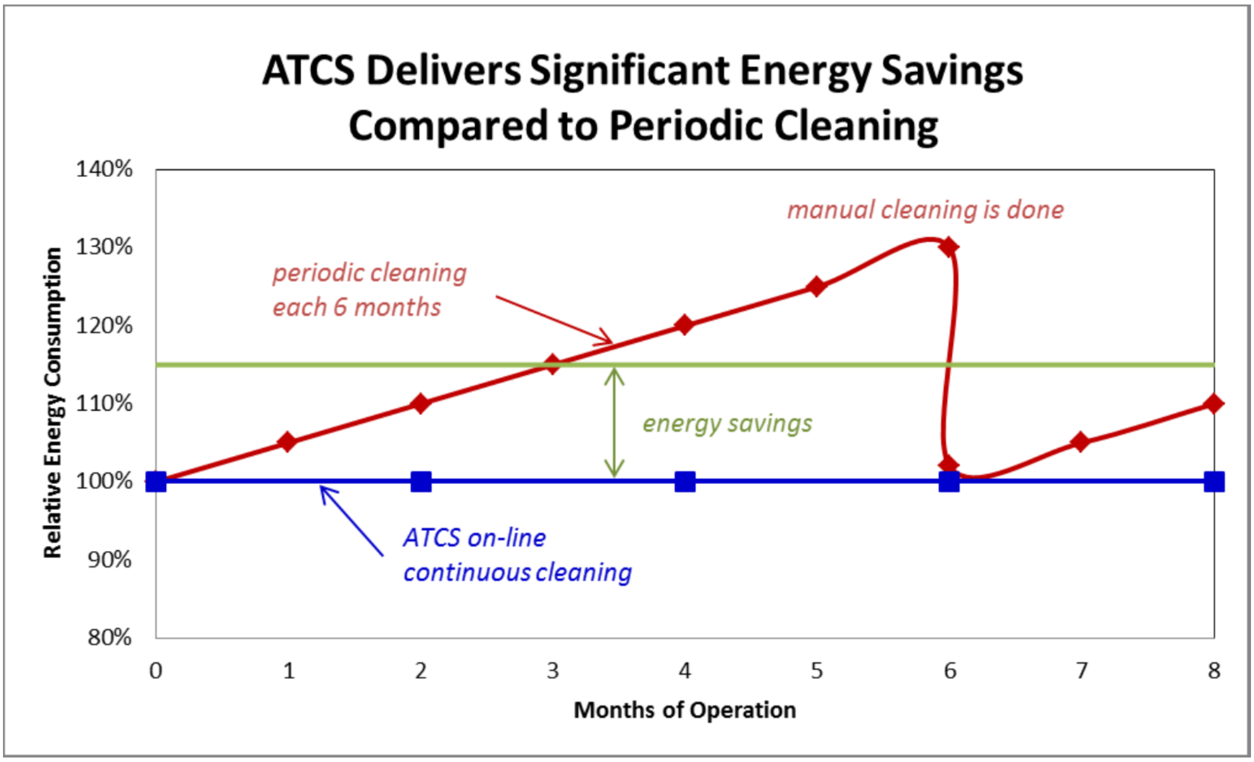


Figure 38: Benefit of automatic tube cleaning system (Source: Trane)

Figure 38 shows the energy savings increases with time. And there are instances in continuous running plants often cleaning done in twice a year. The average saving potential varies from 10~15%.

4. Temperature and timer-based control

It is common practice in large space cooling large numbers of package ACs are installed and which are all ON throughout the day until someone stops all from main MCBs. During the peak times it is fully occupied, and all the air conditioners are kept working while in off peak hours, the occupancy in is scattered. In this case a/c machines can be controlled cyclically by using programmable timers so that the whole space is air-conditioned work comfortably according to the heat load in a much uniform fashion.

Programming can be done based on average occupancy with time like in lunch, tea hours, shifts change etc. These timer-based switches are simple and not expensive. Based on the experience at other installations, the minimum energy saving potential is about 5-10% per air conditioner.

5. Replacement of old chiller

The old chillers compressors use refrigerant R11, which is a CFC refrigerant that has been globally banned as it affects the ozone layer. These chillers have specific power consumption values in the range of 0.79 kW/TR to 0.90 kW/TR. The average compressor power consumption is 0.85 kW/TR. After considering motor losses, the average power input to the existing chillers is estimated to be 0.89 kW/TR. Modern compressors of chillers with VSD use either HFC-123 or HFC-134a and have a maximum specific power consumption of 0.55 kW/TR at compressor shaft); considering motor losses, the specific power consumption is expected to 0.59 kW/TR (considering motor losses). The energy saving of approx. 0.30 kW/TR can be achieved. The energy savings also lead to environmental benefits, the banned refrigerant will be no more in use.

Table 16: Refrigerant phase-out dates

Eighty percent of today's existing chillers are centrifugal chillers that use R-11 as refrigerant. The newer, non-CFC alternative to R-11 is HCFC-123. Some centrifugal chillers use R-12; its non-CFC alternative is HFC-134a. Unitary A/C units typically use R-22, which will be phased out in the future.		
Phase-Out Dates	**Refrigerants**	**Action**
1996	R-11, R-12, R-500, HCFC-152A, CFC-114	Production of these refrigerants is stopped. Equipment using these refrigerants is no longer manufactured.
2010	HCFC-22	Manufacture of equipment using this refrigerant is stopped
2020	HCFC-22	Production of this refrigerant is stopped
2020	HCFC-123	Manufacture of equipment using this refrigerant is stopped.
2030	HCFC-123	Production of this refrigerant is stopped

6. Injecting nano fluid in old chiller compressors to improve heat transfer effect

With time the compressors oil of chillers reduces their heat transfer effect. The Nano- fluids/ nano lubricants additives acts as a booster to improve the transfer efficiency. By adding 5-10% by volume with compressor refrigeration oil operating and maintenance cost are reduced. Depending on the condition of the system, energy cost drop between 6% and 20% due to reduced compressor friction and improved unit capacity.

This special anti-friction additives improve the compressor's mechanical efficiency to reduce power consumption. In addition, the supplement contains additives that improve coil heat transfer. This improved thermal efficiency (heat duty) increases the unit's capacity, thus allowing it to run fewer hours per a day for the same amount of cooling. The reduced wear and tear that accompanies improved system operations extends equipment life and reduces overall maintenance costs.

7. Throttling of valve

Throttling of valves are common practice and seen very commonly at the pumps and at various pipelines. In evaporator also throttling of chill water chiller inlet pipeline is practiced. In this situation primary pump consumes same energy as when valve is fully open. In this case it is always recommended to practice the use of VSD at the primary pump which will lead to energy saving at pump also energy consumption will minimize when the chiller is also VSD driven.

8. Cold Insulation

Insulate all cold lines using economic insulation thickness to minimize heat gains and choose appropriate (correct) insulation.

Difference in temperature between ambient and surface (°C)	Heat ingress Kcal/m^2/hr	Exposed area per tonne of refrigeration
5	35	86
10	73	41
15	113	27
20	154	19
Basis: Ambient temperature - 35°C, emissivity – 0.8, still air conditions Allowable heat ingress – 10 –15 Kcal/m^2/hr		

Thumb rules for cold Insulation

- Chilled water pipe insulation (Use 50 to 75 mm thick insulation)
- Duct insulation (Use 25 to 50 mm thick insulation)
- Suction line refrigerant pipe insulation (Use 50 to 75 mm thick insulation)

9. Avoid heat producing equipment's inside the cooled area

It is often seen the air conditioning is done in pantry, toilets and kitchen. At many places the air conditioning is done in the toilets with the exhaust ON. Similarly, in data centres and server rooms which are maintaining temperature of 18-20 ºC and battery bank is placed inside it. Always track the equipment which generate heat and are stored in cooled area. Moving heat producing equipment out of air-conditioned areas brings dual impact.

10. Building Envelope

Optimise air conditioning volumes by measures such as use of false ceiling and segregation of critical areas for air conditioning by air curtains.

11. Building heat loads minimization

Minimise the air conditioning loads by measures such as roof cooling, roof painting, efficient lighting, pre-cooling of fresh air by air-to-air heat exchangers, variable volume air system, optimal thermo-static setting of temperature of air conditioned spaces, sun film applications, etc.

12. Process heat load minimization

Ensure adequate chilled water flow flows, avoid bypass flows by closing valves of idle equipment. Minimise part load operation by matching loads and plant capacity online, adopt variable frequency drive for varying process load. Avoid wastages like loss of chilled water due to leakages or idle flows. Ensure frequent cleaning and descaling of all heat exchangers.

5.5.14. Cold Storage systems

A Refrigerated storage which includes cold storage and frozen food storage is the best-known method of preservation of food to retain its value and flavour. The refrigeration system in a cold storage is usually a vapour compression system comprising the compressor, condenser, receiver, air cooling units and associate piping and controls.

In smaller cold rooms and walk-ins, the practice is to use air cooled condensing units with sealed, semi-sealed or open type compressors. In the light of the CFC phased out, the trend now is to use HCFC-22, HFC-134a or other substitute refrigerants. In the medium and large sized units, the practice is to use a central plant with ammonia as the refrigerant. In some present day medium and large sized units with prefabricated (insulated) panel construction the trend is to use modular HCFC-22/HFC units which are compact, lightweight, and easy to maintain.

5.5.15. Energy saving opportunities in cold storage systems

1. Re-piping of existing facilities

Cold storage facilities that were in operation for more than 10-15 years could be re-piped. Any refrigeration distribution network with a pressure drop between the evaporator and condenser of over 0.2 bar may require re-piping. A thumb rule indicates that about 0.1 bar pressure drop corresponds to almost two degrees in lower suction pressure and about 7% power consumption. The pressure drops between generation and end-use points can be measured by installing two identical calibrated pressure gauges at the compressor and at the evaporator. Along with this, cold storage facilities having poor insulated pipes, particularly corrosive, should be examined. Improper insulation of pipes is quite common. Insulation also deteriorates due to poor maintenance practices. It is necessary to examine all pipes periodically with check list and master installation scheme. Frost piping or valves indicate that these require re-insulation or maintenance of existing insulation and the valves, which are required to operate on regular basis, may be kept open/un-insulated. An un-insulated pipe may increase the load on refrigeration system up to 0.035 tonne per m^2. Replacement of pipe and insulation, together with valves, may reduce the electricity consumption up to 5–8% with payback period of maximum one year.

2. Refrigeration system controls

The major components of refrigeration system in a cold storage facility include compressors, evaporators, and condensers. The role of a control system in refrigeration system is to operate the system based on minimum temperature requirements and maximum temperature changes in the chambers while maintaining specific power consumption (kW/TR) close to design values. Most of the cold storage facilities do not have automatic control system for operation of evaporators, compressor, and condensers. In general, older facilities use temperature display of chambers either in machine room or at entry door of chamber and the evaporator fans are operated on continuous basis and there is generally no provision to reduce or alter the speed.

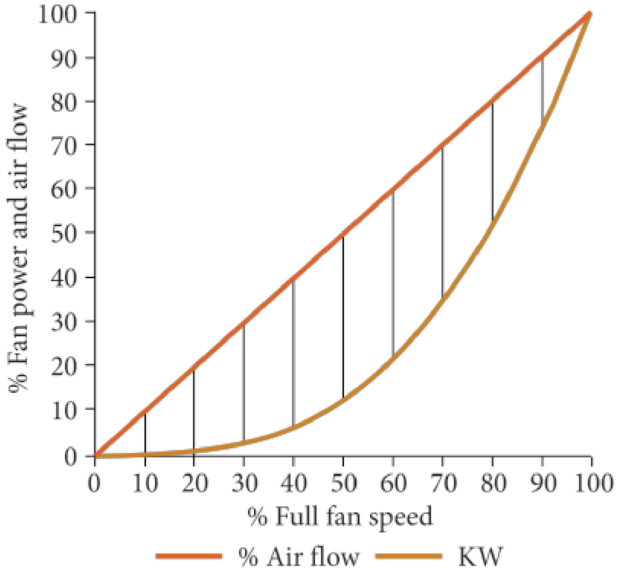


Figure 39: Effect of speed on power and air volume

Control of evaporator fans is a key to reduce energy consumption in a cold storage facility. When the chamber reaches the set temperature, the evaporator fans should be switched off or the speed must be minimized. In absence of control system, motor heat from evaporator fans enters cold chambers and forces compressors and condensers to operate resulting in additional electricity consumption. To overcome this issue, a combination of evaporator variable frequency drive (VFD) and ON/OFF system may be provided. This will allow evaporator fans to circulate air at lower speeds upon achieving set temperature. For operation of compressor, condenser, and evaporator in a closed loop system, the control assembly would require sensors to capture correct temperature of entire chamber, VFDs, and monitoring system.

3. VFDs on condenser fans

The electricity consumption of compressors increases with its discharge pressure. It is always recommended to operate the refrigeration unit at lowest possible discharge pressure. However, factors other than condenser capacity limit theoretical minimum discharge pressure. This is the pressure differential required for expansion valves to feed evaporators and pressure vessels at full capacity and for hot gas defrost systems to operate at sufficiently high-pressure conditions. Refrigeration units are generally designed to operate for peak load conditions and the condenser capacity must be controlled to maintain optimum operating conditions. To maintain the most efficient plant discharge pressures, the use of VFDs on condenser fans can be used, which will reduce electricity consumption by about 25%. As a thumb rule, about 20% reduction in fan speed will reduce power consumption by about 50%.

4. Improved door design

In cold storage facilities, there are daily movements of materials from loading docks to the chambers that use forklifts and pallet trucks. The movements lead to multiple times door openings requiring defrosting on daily basis. The major heat loads in the cold chambers include: Infiltration of hot and humid air from outside areas and leakage of refrigerated air to atmosphere. To maintain optimum efficiency and cost effectiveness of refrigeration system, it is essential to control number and size of doors provided in the facilities. To avoid heat losses from cold chamber or heat or air ingress into the chamber, all product receivables and loadouts must be undertaken in a refrigerated loading area and pallets should be transported into the storage areas through mechanical conveyors and port-holes in chamber walls. Some of the measures to reduce refrigerated air in newer cold storage systems and which may be retrofitted in older facilities are the following:

- Airlocks/air curtains on all access doors and anteroom doors
- Inter-locking of inflatable airbag operation to dock doors
- Airlocks on forklift ramps/anteroom entry doors
- Periodic check and maintenance on door seals, door self-closers, and airbags.

5. Create buffer area (anterooms)

A significant amount of heat is added to cold storage rooms during loading and unloading processes of materials, which may be attributed to improper use of anteroom/buffer area. The main reason for such large ingression of heat is significant temperature difference between cold storage room and the ambient. To avoid such air ingress, ante rooms need to be created that would act as buffer area between cold storage room and ambient. About 3–5% energy savings over baseline has been estimated with creation of anterooms.

6. Use of high-efficiency/low-heat illumination system

The electricity share of illumination system in a typical cold storage is about 4–5%. Use of inefficient lighting/ lamps leads to heat generation, which needs to be removed by refrigeration system. To avoid additional load due to illumination system, energy-efficient lighting sources, which produce low level of heat and equal lumen level should be installed. LED light is one of the best options that produces quite small quantity of heat but delivers equal lux level with comparatively very less power.

7. Ventilation system

Ventilation can be simply described as air circulation, the extraction of stale, overheated and contaminated air and supply and distribution of fresh air in amounts necessary to provide healthy and comfortable conditions for the occupants of the room. The ventilation effectiveness is dictated by number of Air Changes per Hour (ACH). The number of air changes depend on the purpose and function. Recommended air changes for various operations are provided in below **Table 17**

Table 17: Recommended air changes per hour

Typical air changes per hour	
Location	**Air changes per hour**
Boiler room	15-30
Compressor room	10-12
Conference rooms	10-20
Engine rooms	15-30
Lavatories	6-15

Typical air changes per hour	
Offices	6-10
Welding shops	15-30

Calculation of ventilation rate: If the compressor room size is 15 m (length, L) X 10 m (breadth, B) X 4 m (height, H) then,

Ventilation rate =L x B X H X air changes per hour = 15 X 10 X 4 X 10 = 6000 m^3/hr

5.5.16. Heat pumps - Introduction

A heat pump is same as an air conditioner except that the heat rejected in air conditioner becomes the useful heat. Heat flows naturally from a higher temperature to a lower temperature. Heat pumps, however, can force the heat flow in the other direction, using a relatively small amount of high-quality drive energy (electricity, fuel, or high-temperature waste heat). As shown in **Figure 40** the heat pumps take 2-3 units of energy from atmosphere and with an additional one unit by way of compressor is able to provide four units of energy at a higher temperature. Thus, heat pumps can transfer heat from natural heat sources in the surroundings, such as the air, ground or water, or from man-made heat sources such as industrial or domestic waste, to a building or industrial application.

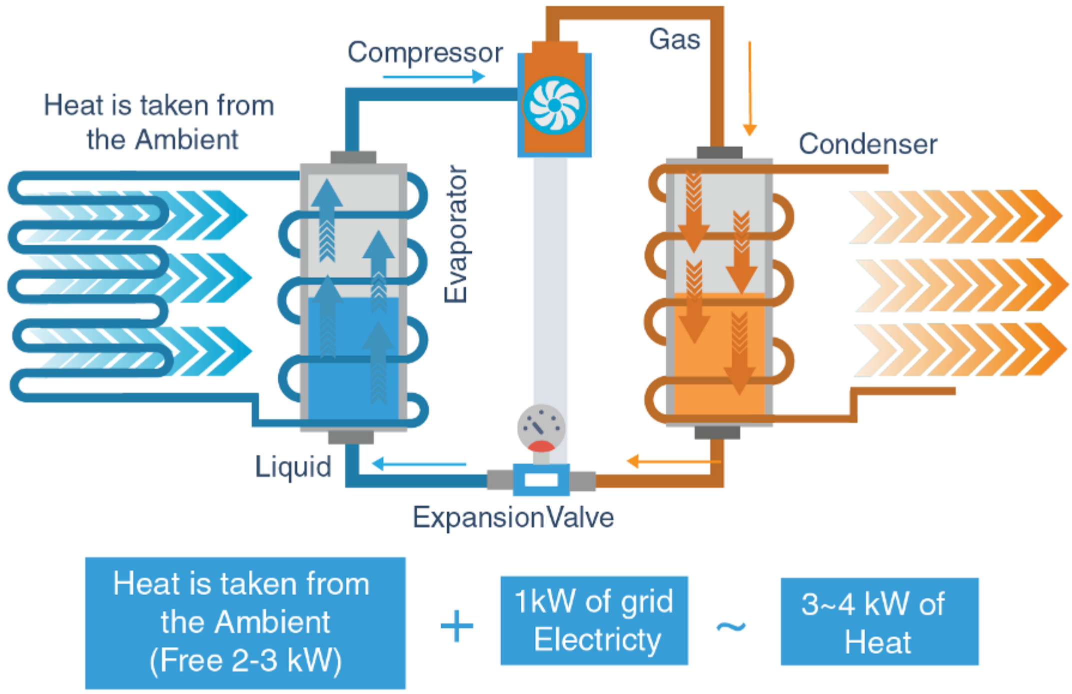


Figure 40: Heat Pump working (Source: Aspiration energy)

In order to transport heat from a heat source to a heat sink, external energy is needed to drive the heat pump. Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied. Electrically driven heat pumps for heating buildings typically supply 100 kWh of heat with just 20-40 kWh of electricity. Many industrial heat pumps can achieve even higher performance and supply the same amount of heat with only 3-10 kWh of electricity.

Heat pumps usually can be used either in heating mode or cooling mode.

Technically the heat pump uses a mechanical compression cycle refrigeration system that can be reversed to either heat or cool a controlled space. They are also increasingly used to heat domestic hot water, the hot water used for kitchens, bathrooms, clothes washers, etc. Heat pumps are significantly more energy efficient than simple electrical resistance heaters therefore can save a lot of money where heat is required. The majority of heat pumps work on the principle of the vapor compression cycle. The most common design of a heat pump involves a condenser, an expansion valve, an evaporator and a compressor. The heat transfer takes place using refrigerants.

The heat pump was developed as a space heating system where low temperature energy from the ambient air, water, or earth is raised to heating system temperatures by doing compression work with an electric motor-driven compressor. The potential for application of heat pump is growing and number of industries have been benefited by recovering low grade waste heat by upgrading it and using it in the main process stream.

Types of heat pumps are categorized on the type of source and sink. There are three types of heat pumps:

- Air-to-air
- Water source
- Geothermal

Performance terms and definitions

Common terms use to define the heat pump performance are: Energy Efficiency Ratio (EER) or Coefficient of performance (COP), The higher the number, the more efficient a heat pump is, the less energy it consumes, and the more cost-effective it is to operate. There are several factors that will affect the efficiency of a heat pump, such as auxiliary equipment, technology, size and control system, but also temperature and humidity conditions. The efficiency drops when the temperature difference increases or when freezing can occur.

Performance evaluation of heat pumps

The main components of heat pumps are evaporator, compressor and condenser, refer **Section 5.5.11** for performance evaluation procedure.

Application of heat pump

Heat Pumps are being used in several industrial processes. In industries the heat energy can be used as waste heat flows or process heat. Waste heat flows are for example: wastewater, hot humid air, condenser heat from refrigeration systems, etc. Heat for processes are process water heating, central heating systems, blanchers, dryers, etc. In complex industrial applications, an analysis may be performed to assess the suitability of waste heat integration. Typical applications of heat pump in an industry are:

Drying process: The most common dryer type is one in which air is heated with steam, gas or hot water and then circulated over the wet product. Here the heat pump serves two purposes - heat the dryer and dehumidify and recirculate air. Heat pump assisted drying can give high efficiencies.

Washing process: The discharge heat from the washing machine present in the air have a large potential to be tapped and to be used with the help of heat pump for heating the water going into the washing machine.

Heat exhaust from the refrigeration system: The heat released from the condenser can be employed with a heat pump to provide hot water needed for the process and for cleaning purposes.

Pasteurization: For pasteurization a product needs to be heated above 70 °C. Afterwards the product is cooled down. The product temperature thus varies from cold before pasteurization to hot during pasteurization and back to cold again after pasteurization.

Other application: The heat pump is a promising technique with numerous applications in the industry for example food processing, air conditioning, process cooling, potable water cooling, boiler feed water preheating and liquid desiccants.

Although the functioning of a heat pump is known for a while, developing a cost-efficient system that would replace existing heating source while appealing to industries and hospitality sectors, became possible just recently. With the increase in popularity comes an increase in conflicting advice. Likewise, to the heat pump, there are lots of wrong information or misconception that go along with them, here are some of the misconceptions (Source: Aspiration energy) that one should ignore.

Misconception #1: Heat pumps are expensive
Renewable energy technology is often considered as an expensive investment. The truth is heat pumps are very affordable when one compares it with other types of heating systems. Heat pumps work for both heating and cooling, so one does not need to install two separate systems to provide these services. Heat pumps are also cheaper to operate.

Misconception #2: Cannot be integrated with existing heating system
It is not true always. Except with the heating system that uses biomasses as fuel, the heat pumps are very easy to integrate with an existing system, even if it is a complex heating system. What is so appealing about a heat pump is that it can be integrated in parallel to an existing system and can operate it as a hybrid system.

Misconception #3: Cannot be integrated directly to process tanks
In industries, the process applications use different chemical solutions that require heat to pre-treat or to wash the parts. It is commonly misunderstood that; the heat pump cannot handle the process fluids directly to its condenser. There are different grades of materials with chemical compatibility can be used to handle this fluid. Instead of using heat exchangers to transfer heat to the process fluids, the heat pump can be connected directly to the process tank and can result in monetary savings.

Misconception #4: Heat pumps are noisy
Back in the day, heat pumps and other heating systems were quite loud. However, with today's advances in technology, the amount of noise a heat pump produces are comparative to the noise

or sound that is produced from a boiler. So, though it might produce some noise, it will not be any more than the sounds any other industrial machine makes.

Misconception #5: Limited lifespan

Rumour is that heat pumps burn out quicker because they run year-round. The reality is that if heat pump is properly maintained, high-quality models will last at least 15-20 years.

Misconception #6: Not Efficient in cold climate

One of the biggest misconceptions about heat pumps is that they only work in more temperate climates which is not true. Since the ground source heat pump or water source heat pump takes heat from the constant temperature source, it can ensure an efficiency rate that is consistent all year round, regardless of the outside weather conditions. In contrast, the cost-efficiency of an air source heat pump is directly influenced by the outside temperatures, given that a pump like this extracts heat from the outside air masses. The efficiency of an air source heat pump will gradually diminish with the decrease in outside temperature levels. Still, the latest technological advancements in the field of thermodynamics, an air to water heat pump can work effectively at temperatures that do not fall below the 10°C mark.

Misconception #7: Costlier to operate

Heat pumps can help save over 30% on energy bill, compared to other conventional heating systems. While the upfront cost may be more than other options, an efficient heat pump paired with proper insulation will save money in the long run. Installing a heat pump requires careful consideration in a lot of factors.

5.6. Fans and Blowers – energy performance assessment

5.6.1. Introduction

Fans and blowers provide air for ventilation and industrial process requirements. Fans generate a pressure to move air (or gases) against a resistance caused by ducts, dampers, or other components in a fan system. The fan rotor receives energy from a rotating shaft and transmits it to the air.

Difference between Fans, Blowers and Compressors

Fans, blowers, and compressors are differentiated by the method used to move the air, and by the system pressure they must operate against. As per American Society of Mechanical Engineers (ASME) the specific ratio - the ratio of the discharge pressure over the suction pressure - is used for defining the fans, blowers, and compressors.

Table 18: Difference between Fan, Blowers and Compressor

Equipment	Specific ratio	Pressure rise (mmWg)
Fans	Up to 1.11	1136
Blowers	1.11to 1.20	1136-2066
Compressor	More than 1.20	-

Fan and blower selection depend on the volume flow rate, pressure, type of material handled, space limitations, and efficiency. Fan efficiencies differ from design to design and by types. Typical ranges of fan efficiencies are given in below **Table 19**

Table 19: Fan efficiencies

Type of Fan	Peak Efficiency Range
Centrifugal Fan	
Air foil, backward curved/inclined	79-83
Modified radial	72-79
Radial	69-75
Pressure blower	58-68
Forward curved	60-65
Axial fan	
Vanaxial	78-85
Tubeaxial	67-72
Propeller	45-50

Fans fall into two general categories: centrifugal flow and axial flow

In **centrifugal flow**, airflow changes direction twice - once when entering and second when leaving (forward curved, backward curved, or inclined, radial).

In **axial flow**, air enters and leaves the fan with no change in direction (propeller, tube axial, vane axial).

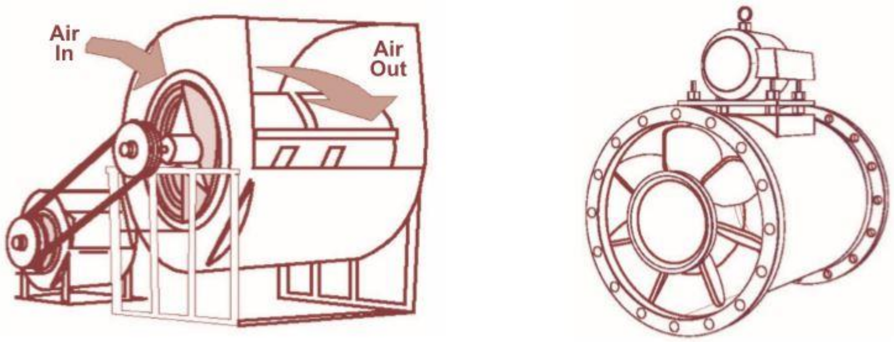


Figure 41: Centrifugal fan (left) and axial fan (right)

Centrifugal fan types
The major types of centrifugal fan are radial, forward curved and backward curved.

Radial fans are industrial workhorses because of their high static pressures (up to 1400 mm WC) and ability to handle heavily contaminated airstreams. Because of their simple design, radial fans are well suited for high temperatures and medium blade tip speeds.

Forward-curved fans are used in clean environments and operate at lower temperatures. They are well suited for low tip speed and high-airflow work - they are best suited for moving large volumes of air against relatively low pressures.

Backward-inclined fans are more efficient than forward-curved fans. Backward-inclined fans reach their peak power consumption and then power demand drops off well within their useable airflow range. Backward-inclined fans are known as "non-overloading" because changes in static pressure do not overload the motor.

Axial Flow Fan types
The major types of axial flow fans are tube axial, vane axial and propeller.

Tube axial fans have a wheel inside a cylindrical housing, with close clearance between blade and housing to improve airflow efficiency. The wheel turns faster than propeller fans, enabling operation under high-pressures 250 – 400 mm WC. The efficiency is up to 65%.

Vane axial fans are like tube axials, but with addition of guide vanes that improve efficiency by directing and straightening the flow. As a result, they have a higher static pressure with less dependence on the duct static pressure. Such fans are used generally for pressures upto 500 mmWC. Vane axials are typically the most energy-efficient fans available and should be used whenever possible.

Propeller fans usually run at low speeds and moderate temperatures. They experience a large change in airflow with small changes in static pressure. They handle large volumes of air at low pressure or free delivery. Propeller fans are often used indoors as exhaust fans. Outdoor applications include air-cooled condensers and cooling towers. Efficiency is low – approximately 50% or less.

The different types of fans, their characteristics and typical applications are given in following **Table 20**.

Table 20: Types of fan, characteristics, and typical application

Centrifugal Fans			Axial-Flow Fans		
Type	**Characteristics**	**Typical application**	**Type**	**Characteristics**	**Typical application**
Radial	High pressure, medium flow, efficiency close to tube-axial fans, power increases continuously	Various industrial applications, suitable for dust laden, moist air/gases	Propeller	Low pressure, high flow, low efficiency, peak efficiency close to point of free air delivery (zero static pressure)	Air-circulation, ventilation, exhaust
Forward-curved blades	Medium pressure, high flow, dip in pressure curve, efficiency higher than radial fans, power rises continuously	Low pressure HVAC, packaged units, suitable for clean and dust laden air / gases	Tube-axial	Medium pressure, high flow, higher efficiency than propeller type, dip in pressure-flow curve before peak pressure point.	HVAC, drying ovens, exhaust systems
Backward curved blades	High pressure, high flow, high efficiency, power reduces as flow increases beyond point of highest efficiency	HVAC, various industrial applications, forced draft fans, etc.	Vane-axial	High pressure, medium flow, dip in pressure-flow curve, use of guide vanes improves efficiency	High pressure applications including HVAC systems, exhausts
Airfoil type	Same as backward curved type, highest efficiency	Same as backward curved, but for clean air applications			

Common blower types

Blowers can achieve much higher pressures than fans, as high as 1.20 kg/cm^2. They are also used to produce negative pressures for industrial vacuum systems. Major types are centrifugal blower and positive-displacement blower.

Centrifugal blowers look more like centrifugal pumps than fans. The impeller is typically gear-driven and rotates as fast as 15,000 rpm. In multi-stage blowers, air is accelerated as it passes through each impeller. In single-stage blower, air does not take many turns, and hence it is more efficient.

Centrifugal blowers typically operate against pressures of 0.35 to 0.70 kg/cm^2 but can achieve higher pressures. One characteristic is that airflow tends to drop drastically as system pressure increases, which can be a disadvantage in material conveying systems that depend on a steady air volume. Because of this, they are most often used in applications that are not prone to clogging.

Positive-displacement blowers have rotors, which "trap" air and push it through housing. Positive-displacement blowers provide a constant volume of air even if the system pressure varies. They are especially suitable for applications prone to clogging since they can produce enough pressure - typically up to 1.25 kg/cm^2 - to blow clogged materials free. They turn much slower than centrifugal blowers (e.g. 3,600 rpm) and are often belt driven to facilitate speed changes.

5.6.2. Data collection

Following data shall be collected during audit of fan from fan motor name plate and by interviewing the operator or plant supervisor:

- Type of fan
- Application of fan
- Type of speed regulation and flow control
- Type of power transmission (belt driven or direct driven)
- Rated fan power (kW)
- Rated flow
- All other fan motor name plate details

In addition to above, following data shall be collected through measurements:

- Static pressure suctions and discharge side
- Differential velocity pressure
- Air Flow and suction area or area of filters
- Fan input power

5.6.3. Instruments required

- Hand-held clamp meter or three-phase power analyser
- Manometer with pitot tube
- Anemometer
- Measuring tape
- Sling psychrometer or digital thermometer

5.6.4. Performance terms and definitions

Static Pressure: The absolute pressure at a point minus the reference atmospheric pressure.

Dynamic Pressure: The rise in static pressure which occurs when air moving with specified velocity at a point is bought to rest without loss of mechanical energy. It is also known as velocity pressure.
Total Pressure: The sum of static pressures and dynamic pressures at a point.
Fan Shaft Power: The mechanical power supplied to the fan shaft
Fan motor input Power: The electrical power supplied to the terminals of an electric motor drive.

$$\textbf{\textit{Static fan efficiency}}, (\%) = \frac{Volume\ in\ m^3/s\ \ X\ \Delta p\ static\ pressure, mmWC}{102\ X\ Fan\ shaft\ power\ (kW)}\ X\ 100$$

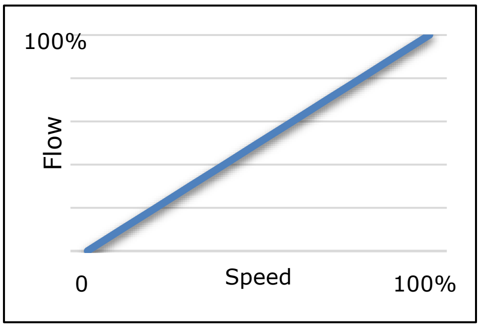
Where,

Δp static pressure, mmWC = Discharge static pressure – Suction static pressure

5.6.5. Fan laws

The fans operate under a predictable set of laws concerning speed, power, and pressure. A change in speed (revolutions per minute or RPM) of any fan will predictably change the pressure rise and power necessary to operate it at the new RPM.

a) Flow ∞ Speed

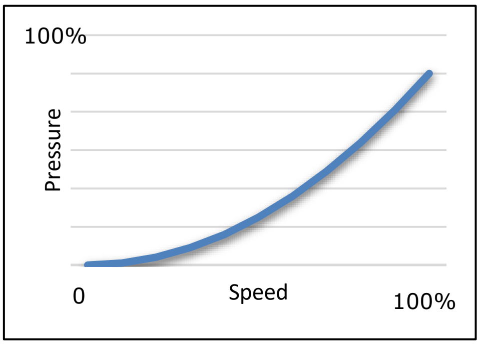


$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

Varying the RPM by 10% decreases or increases air delivery by 10%

Q – Flow
N- Speed (RPM)

b) Pressure ∞ (Speed)²

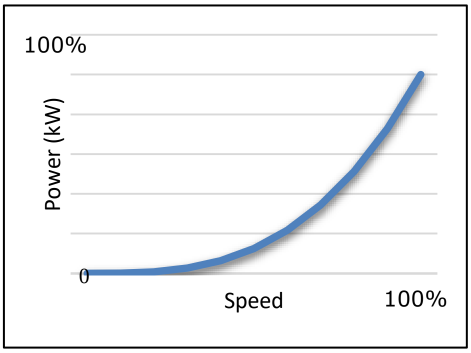


$$\frac{SP_1}{SP_2} = \left(\frac{N_1}{N_2}\right)^2$$

Reducing the RPM by 10% decreases the static pressure by 19% and an increase in RPM by 10% increases the static pressure by 21%.

SP – Static pressure
N- Speed (RPM)

c) Power ∞ (Speed)³

 	$\frac{kW_1}{kW_2} = \left(\frac{N_1}{N_2}\right)^3$ Reducing the RPM by 10% decreases the power requirement by 27% and an increase in RPM by 10% increases the power requirement by 33%. kW – Power N – Speed (RPM)

5.6.6. Performance evaluation

The fans are tested for field performance by measurement of pressure, flow, temperature, and power.

The fan flow is measured using pitot tube and manometer combination or with an anemometer. Care needs to be taken regarding number of traverse points, straight length section (to avoid turbulent flow regimes of measurement) upstream and downstream of measurement location. The measurements can be on the suction or discharge side of the fan and preferably both where feasible.

1. Static pressure measurement by pitot tube

The **Figure 42** shows how static pressure is measured using a pitot tube and a manometer. Total pressure is measured using the inner tube of pitot tube and static pressure is measured using the outer tube of pitot tube.

Static pressure should be measured on the suction and discharge sides of the fan are taken relative to the atmosphere pressure. This shall be done by using a manometer in combination with the static pressure connection of a pitot tube or a U tube manometer.

When using a pitot tube, it is necessary to carry out a traverse in the pressure measurement plane taking individual point pressure readings in a manner like that for determining flow rate. In general, a smaller number of readings will be found adequate where individual readings do not vary by more than 2% from each other. The average of all the individual readings shall be taken as the static pressure of that section.

2. Air-Velocity measurement

Instrument required: Velocity shall be measured by either pitot tube or a rotating vane anemometer.

a) Velocity measurement by anemometer

The indicated velocity shall be measured at each traverse point in the cross section by holding the anemometer stationary at each point for a period of not less than 1 minute. Each reading shall be converted to velocity in m/s and individually corrected in accordance with the anemometer calibration. The arithmetic mean of the corrected point velocities gives the average velocity in the air duct and the volume flow rate is obtained by multiplying the area of the air duct by the average velocity. This is the simplest method to measure air velocity.

b) Velocity measurement by pitot tube

The **Figure 42** shows how velocity pressure is measured using a pitot tube and a manometer. Total pressure is measured using the inner tube of pitot tube and static pressure is measured using the outer tube of pitot tube. When the inner and outer tube ends are connected to a manometer, velocity pressure is obtained.

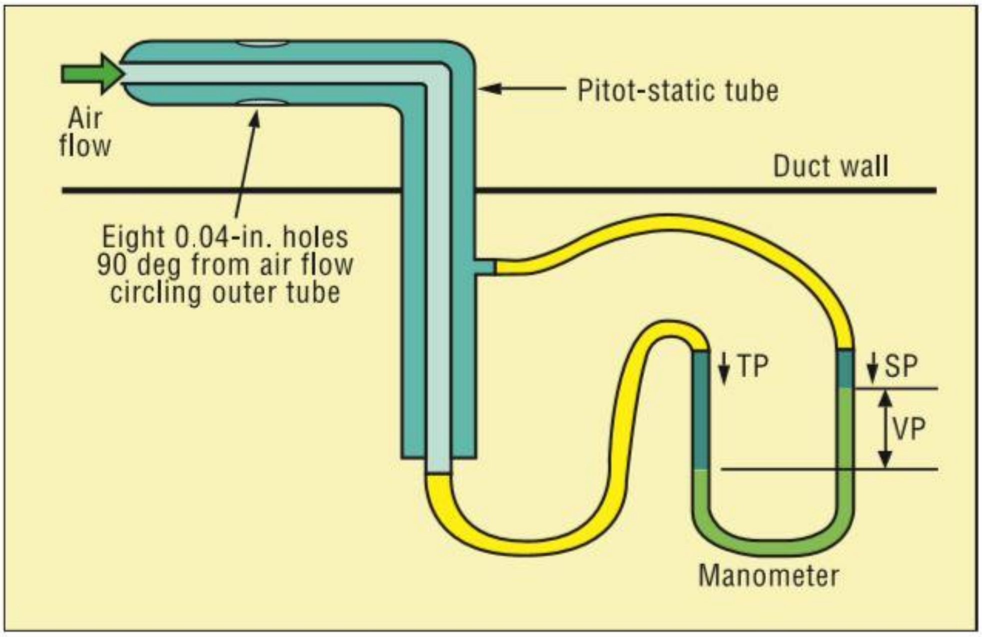


Figure 42: Measurement by pitot tube

For measuring low velocities, it is preferable to use an inclined tube manometer instead of U tube manometer.

To ensure accurate velocity pressure readings, the Pitot tube tip must be pointed directly into (parallel with) the air stream. As the Pitot tube tip is parallel with the static pressure outlet tube, the latter can be used as a pointer to align the tip properly. When the Pitot tube is correctly aligned, the pressure indication will be maximum.

When measuring velocity pressure, the duct diameter (or the circumference from which to calculate the diameter) should be measured as well. This will help in calculating the velocity and volume of air in the duct. In most cases, velocity must be measured at several places in the system.

Traverse readings: In practical situations, the velocity of the air stream is not uniform across the cross section of a duct. Friction slows the air moving close to the walls, so the velocity is greater in the centre of the duct.

To obtain the average total velocity in ducts of 100 mm diameter or larger, a series of velocity pressure readings must be taken at points of equal area. A formal pattern of sensing points across the duct cross section is recommended. These are known as traverse readings. Following **Figure 43** shows recommended Pitot tube locations for traversing round and rectangular ducts.

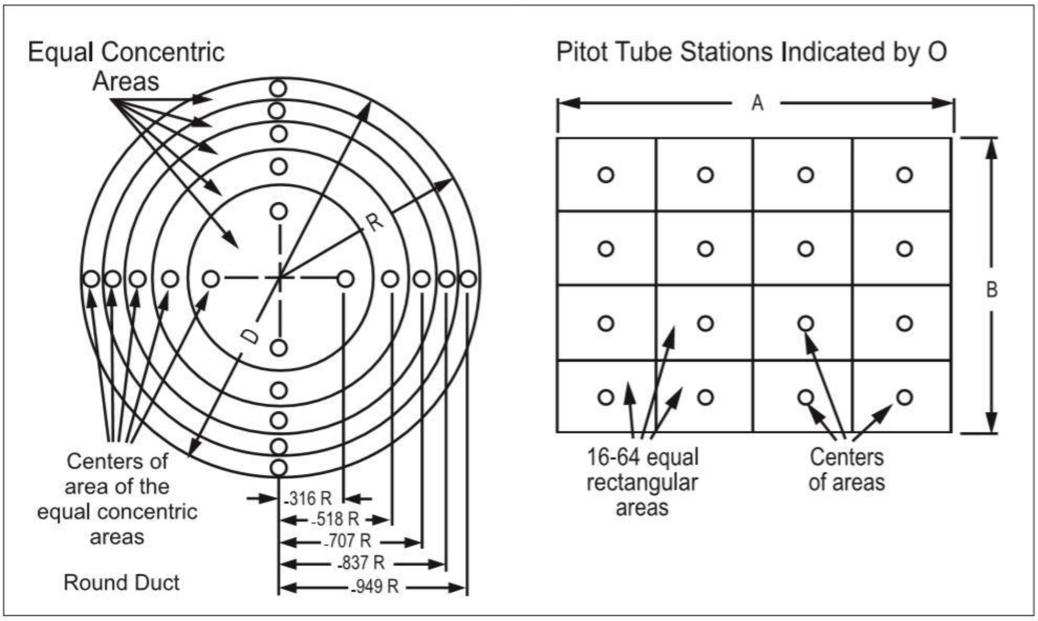


Figure 43: Traverse on round and square duct areas

In round ducts, velocity pressure readings should be taken at centres of equal concentric areas. At least 20 readings should be taken along two diameters. In rectangular ducts, a minimum of 16 and a maximum of 64 readings are taken at centres of equal rectangular areas. Actual velocities for each area are calculated from individual velocity pressure readings. This allows the readings and velocities to be inspected for errors or inconsistencies. The velocities are then averaged.

By taking Pitot tube readings with extreme care, air velocity can be determined within an accuracy of ± 2%.

Calculation of velocity: After taking velocity pressures readings, at various traverse points, the velocity corresponding to each point is calculated using the following expression.

Velocity (m/s) $= C_p \times \frac{\sqrt{2 \times 9.18 \times \Delta p \times \gamma}}{\gamma}$

Where, C_p=The pitot tube coefficient (Take manufacturer's value or assume 0.85)

Δp=The average velocity pressure measured using pitot tube and inclined manometer by taking number of points over the entire cross-section of the duct, mm Water Column

γ =Gas density, kg/m^3 corrected to normal temperature

Corrected gas density is given by= $\frac{273 \times 1.29}{273 + \text{Air temperature in °C}}$

3. Determination of air flow

Once the cross-sectional area of the duct is measured, the flow can be calculated as follows:

Air flow or Volume, (m^3/s) = Area of duct (m^2) x Velocity (m/s)

4. Power measurement

The power measurements can be done using three phase power analyser or a hand-held clamp meter.

Transmission systems: If fan is not connected to motor directly, transmission efficiency should be suitable assumed depending upon the type

Type of transmission	Transmission efficiency
For directly driven fan	100%
Properly lubricated precision spur gears	98% for each step
Flat belt drive	97%
V-belt drive	95%

Therefore,

Fan shaft power = Power input to motor × Efficiency of motor × Transmission system efficiency

Example:

A V-belt centrifugal fan is supplying air to a process plant. The performance test on the fan gave the following parameters

Parameters	Values
Density of air at 0°C	1.293 kg/m^3
Ambient air temperature	25°C
Diameter of the circular discharge air duct	0.8 m
Velocity pressure maintained by pitot tube in discharge duct	45 mmWC
Pitot tube coefficient	0.9
Static pressure at fan inlet	-20 mmWC
Static pressure at fan outlet	185 mmWC
Power drawn by the motor coupled with the fan	75 kW
Belt transmission efficiency	97%
Motor efficiency at the operating load	93%

Solution:

Parameters	Calculations
Corrected gas density, γ	(273 X 1.293) / (273 + 25) = 1.18
Velocity	$= C_p \times \frac{\sqrt{2 \times 9.18 \times \Delta p \times \gamma}}{\gamma}$ $= 0.9 \text{ X } \frac{\sqrt{2 \times 9.18 \times 45 \times 1.18}}{1.18} = 23.8$ m/s
Area of circular discharge duct	$= \pi \text{ X } (D^2/4) = 3.14 \text{ X } (0.8^2/4)$ $= 0.5024 \text{ m}^2$
Flow or volume (m^3/s)	= Area X Velocity $= 0.5024 \text{ X } 23.8 = 11.95 \text{ m}^3/s$
Fan shaft power, (kW)	= 75 X 0.97 X 0.93 = 67.65 kW
Fan static efficiency, (%)	$= \frac{Volume\ in\ m^3/s\ X\ \Delta p\ static\ pressure, mmWC}{102\ X\ Fan\ shaft\ power\ (kW)}\ X\ 100$ $= \frac{11.95\ \ X\ (185-(-20))}{102\ X\ 67.65}\ X\ 100$ **= 35.5%**

5.6.7. Energy saving opportunities

1. Adjust the pulley diameter

It is observed at many instances the actual air flow is higher than the rated air flow in the air handling units (AHU) which can be any type of system (chill water, washer, fresh air etc.). Also, when multiple no. of systems is there and overall air changes (ACH) are on the higher side as designed.

After overall study in any of the case the fan volume change is required on a permanent basis, and the existing fan can handle the change in capacity, the volume change can be achieved with a speed change. The simplest way to change the speed is with a pulley change. For this, the fan must be driven by a motor through a v-belt system. The fan speed can be increased or decreased with a change in the drive pulley or the driven pulley or in some cases, both pulleys. As shown in **Figure 44** a higher size fan operating with damper control was downsized by reducing the motor (drive) pulley size from 8” to 6”. The power reduction was 12 kW.

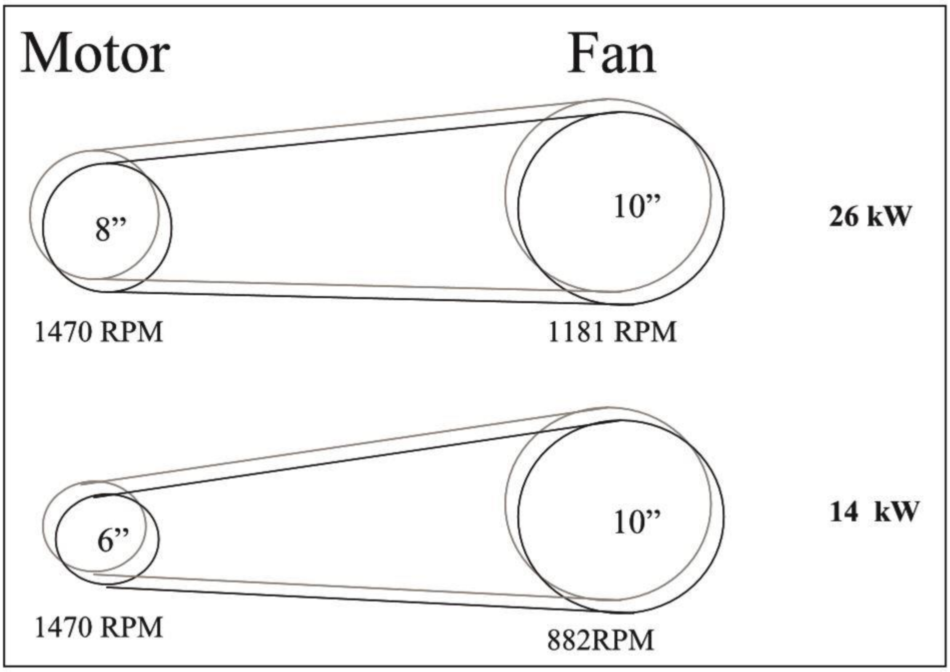


Figure 44: Pulley change

2. Consider replacing damper controls with VFD/VSD

Some fans are designed with damper controls. Dampers can be located at inlet or outlet. Dampers provide a means of changing air volume by adding or removing system resistance. This resistance forces the fan to move up or down along its characteristic curve, generating more or less air without changing fan speed. However, dampers provide a limited amount of adjustment and they are not energy efficient. Consider replacing the dampers control with variable speed drive wherever feasible and payback period is attractive. Since power input to the fan changes as the cube of law, this will usually be the most efficient form of capacity control. However, VSD may not be economical for systems, which have infrequent flow variations.

3. Minimizing demand on the fan

- Minimising excess air level in combustion systems to reduce FD fan and ID fan load.
- Minimising air in-leaks in hot flue gas path to reduce ID fan load, especially in case of kilns, boiler plants, furnaces, etc. Cold air in-leaks increase ID fan load tremendously, due to density increase of flue gases and in-fact choke up the capacity of fan, resulting as a bottleneck for boiler / furnace itself.
- In-leaks / out-leaks in air conditioning systems also have a major impact on energy efficiency and fan power consumption and need to be minimized.

4. Replace the existing belt driven blower/ fan with new direct driven motors

Old conventional blowers or centrifugal fan with induction motors (see **Figure 45**) installed in air handling unit (AHU) of any type of system (chill water, washer, fresh air, ventilation, etc.) can be replaced with plug fan with BLDC motor (see **Figure 46**)

Multiple combination of plug fan with BLDC motors is also possible (see **Figure 47**) for those blowers which are large in size and are not fully utilised. The brushless direct current motor (BLDC) which are also known electronically commuted motor (ECM) with plug fan. The possible energy savings by replacing the system can be in the range of 25-35% of existing energy consumption.

Figure 45: Centrifugal fan with induction motor

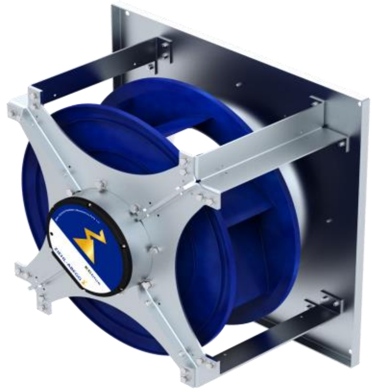


Figure 46: Plug fan with BLDC (single)

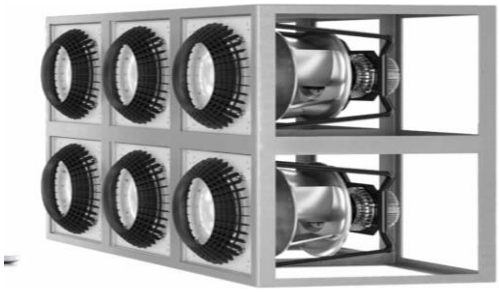


Figure 47: Plug fan with BLDC motors (combination)

5. Others

The findings of performance evaluation will automatically indicate potential areas for improvement, which could be one or more of the following:

- Change of impeller by a high efficiency impeller along with cone.
- Change of fan assembly, by a higher efficiency fan
- Impeller derating (by a smaller diameter impeller) as explained before
- Change of metallic / Glass reinforced Plastic (GRP) impeller by the more energy efficient hollow FRP impeller with aerofoil design, in case of axial flow fans, where significant savings have been reported
- Fan speed reduction by pulley diameter modifications for derating
- Option of two speed motors or variable speed drives for variable duty conditions
- Option of energy efficient flat belts, or, cogged raw edged V belts, in place of conventional V belt systems, for reducing transmission losses.

5.7. Pumps – energy performance assessment

5.7.1. Introduction

Pumping is the process of addition of kinetic and potential energy to a liquid to move it from one point to another. Pumps come in a variety of sizes for a wide range of applications. They can be classified according to their basic operating principle as dynamic or displacement pumps. Dynamic pumps can be sub-classified as centrifugal and special effect pumps. Displacement pumps can be sub-classified as rotary or reciprocating pumps.

The centrifugal pump is generally the most economical followed by rotary and reciprocating pumps. Although, positive displacement pumps are generally more efficient than centrifugal pumps, the benefit of higher efficiency tends to be offset by increased maintenance costs.

Since, worldwide, centrifugal pumps account for most of the electricity used by pumps, the focus of this chapter is on centrifugal pump.

5.7.2. System curve and pump curves

A system curve is a graphical representation of the head and flow characteristics of a hydraulic system. **Figure 48** shows system curve with high static head and **Figure 49** shows system curve with low static head.

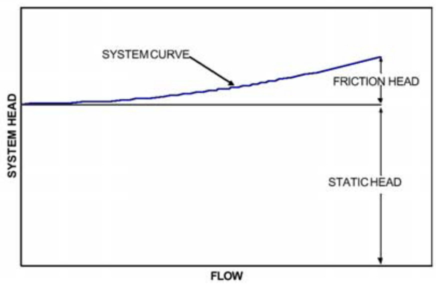


Figure 48 System curve with high static head

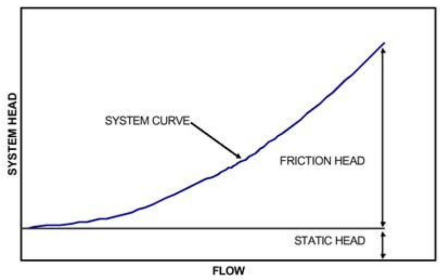


Figure 49 System head with low static head

The performance of a pump can be expressed graphically as head against flow rate. The centrifugal pump has a curve where the head falls gradually with increasing flow. This is called the pump characteristic curve (Head – Flow curve) as shown in the **Figure 50** . Typical pump curve provided by the pump manufactures is the plot the course of the parameters like head(H), power input(P), pump efficiency, Net positive suction head (NPSHr) against flow rate. A typical pump curve is shown in the **Figure 51**

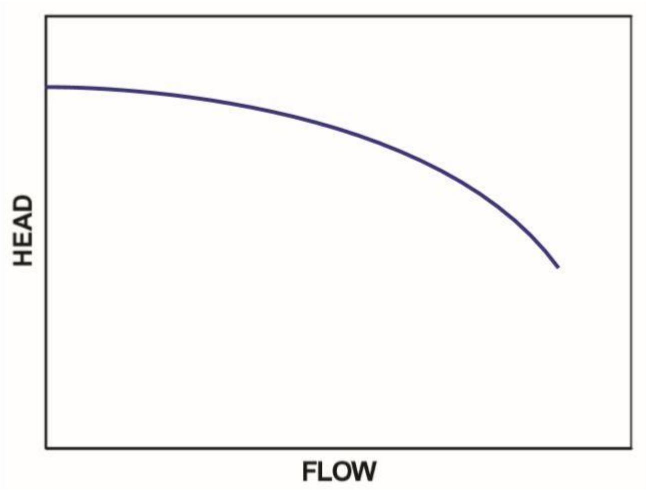


Figure 50: Head-Flow curve

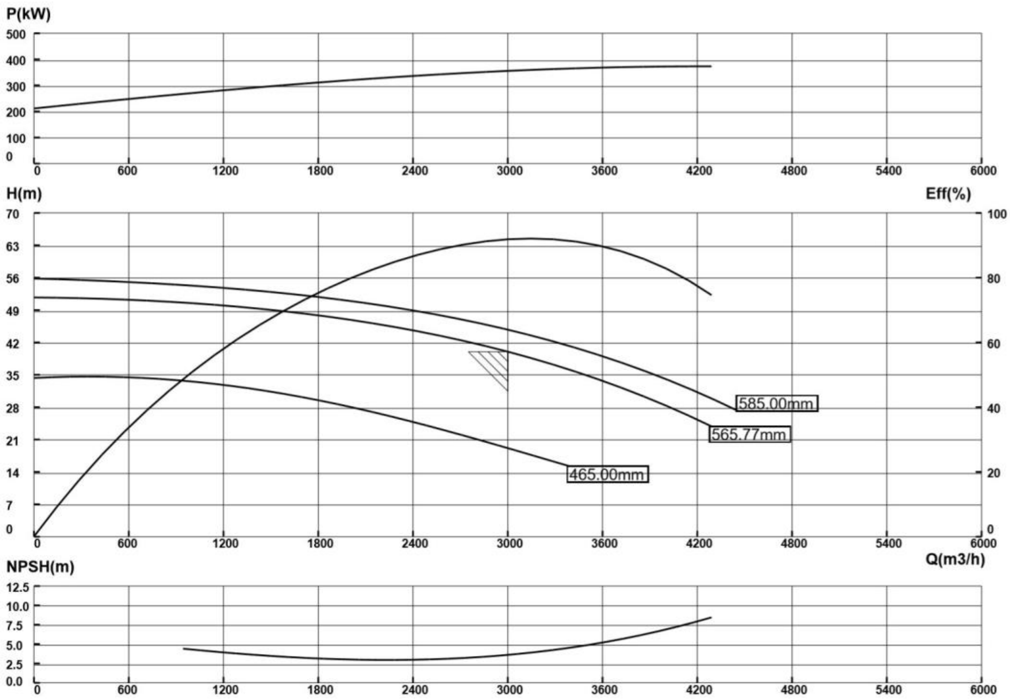


Figure 51: Typical pump curve provided by manufacturer

When a pump is installed in a system the effect can be illustrated graphically by superimposing pump and system curves. The operating point will always be where the two curves intersect as shown in **Figure 52**. If the actual system curve is different to that calculated, the pump will operate at a flow and head different to that expected.

An increasing system resistance will reduce the flow, eventually to zero, but the maximum head is limited as shown. Even so, this condition is only acceptable for a short period without causing problems. An error in the system curve calculation is also likely to lead to a centrifugal pump selection, which is less than optimal for the actual system head losses. Adding safety margins to the calculated system curve to ensure that a sufficiently large pump is selected will generally result in installing an oversized pump, which will operate at an excessive flow rate or in a throttled condition, which increases energy usage and reduces pump life.

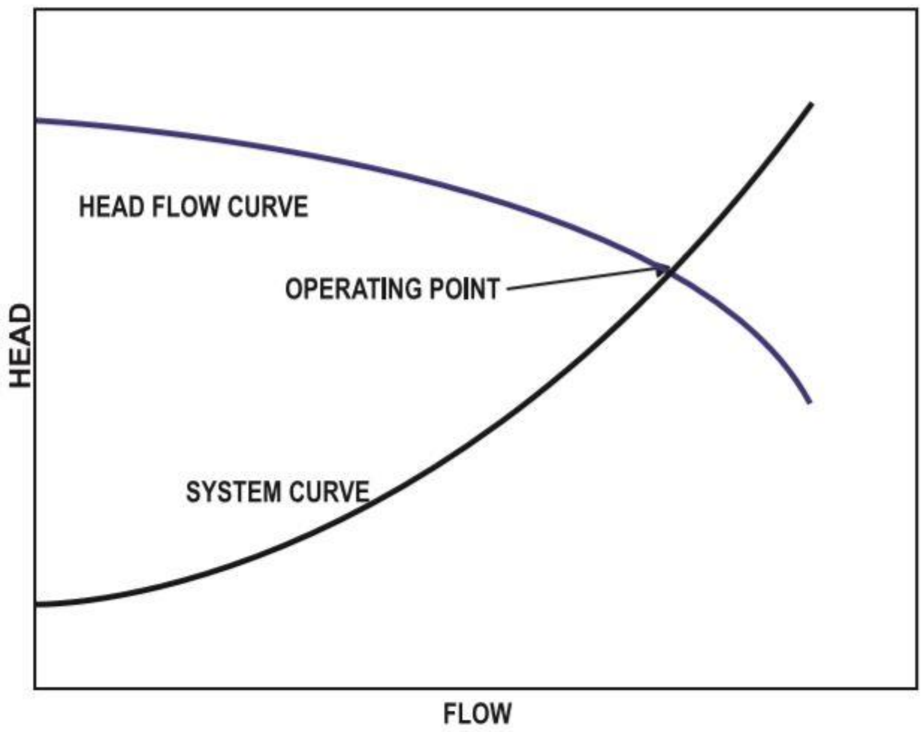


Figure 52: Pump operating point

5.7.3. Data collection

Following data shall be collected during audit from pump name plate and by interviewing the operator or plant supervisor:

- Specification of pump and motors
- Diagram of water distribution network
- Water pressure required for the system
- Number of pumps in operation
- Pump curves
- Details on existing flow control method
- All pumps and motors name plate details

In addition to above following data shall be collected through measurements on field:

- Flow
- Head
- Power
- Motor efficiency

5.7.4. Instruments required

- Ultrasonic water flow meter
- Pressure gauges
- Hand-held clamp meter
- Three-phase power analyser
- Measuring tape

5.7.5. Performance terms and definitions

Pump capacity, Q = Volume of liquid delivered by pump per unit time, m^3/s

Total developed head, H = The difference of discharge pressure and suction pressure

$$\textbf{Pump efficiency} = \frac{Hydraulic\ power}{Power\ input\ to\ the\ pump\ shaft}\ X\ 100$$

Hydraulic power (kW) = Q X ($h_d - h_s$) X P X g /1000

Q = volume flow rate (m^3/s), P = density of fluid (kg/m^3), g = acceleration due to gravity (m/s^2), (Discharge head, h_d- Suction head, h_s) = Total head (m)

5.7.6. Performance assessment

Flow measurement is the most crucial parameter as normally online flow meters are hardly available, in most of the pumping system. The following methods outlined below can be adopted to measure the flow depending on the availability and site conditions.

Motor efficiency can be obtained as described in the **section 5.3.9**

1. Flow measurement

The following are the method for flow measurement:

a) Ultrasonic flow measurement

Operating under Doppler effect principle these meters are non-invasive, meaning measurements can be taken without disturbing the system. Scales and rust in the pipes are likely to impact the accuracy.

- Ensure measurements are taken in a sufficiently long length of pipe free from flow disturbance due to bends, tees, and other fittings.
- The pipe section where measurement is to be taken should be hammered gently to enable scales and rusts to fall out.
- For better accuracy, a section of the pipe can be replaced with new pipe for flow measurements.

b) On-line flow meter

If the application to be measured is going to be critical and periodic then the best option would be to install an on-line flow meter which can get rid of the major problems encountered with other types.

c) Tank filling method

In open flow systems such as water getting pumped to an overhead tank or a sump, the flow can be measured by noting the difference in tank levels for a specified period during which the outlet flow from the tank is stopped. The internal tank dimensions should be preferably taken from the design drawings, in the absence of which direct measurements may be resorted to.

2. Head measurement

Suction head (hs)

This is taken from the pump inlet pressure gauge readings and the value to be converted into meters ($1kg/cm^2 = 10$ m). If not the level difference between sump water level to the centreline of the pump is to be measured. This gives the suction head in meters.

Discharge head (hd)
This is taken from the pump discharge side pressure gauge. Installation of the pressure gauge in the discharge side is a must, if not already available.

3. Power
Pump motor power should be measured from three phase power analyser. Power can also be measured by hand-held clamp meter. On measuring power from clamp on meter, readings should be taken on regular intervals and numbers of readings should be taken.

4. Operating efficiency and performance evaluation of pumps:
Determination of hydraulic power (Liquid horsepower):

Hydraulic power, P_h (kW) = Q x (hd - hs) x ρ x g / 1000

Where,

Q= Volume flow rate(m^3/sec)

ρ =density of the fluid(kg/m^3)

g= acceleration due to gravity(m/s^2)

(hd - hs) = Total head in metres

Pump shaft power
The pump shaft power P_s is calculated by multiplying the motor input power by motor efficiency at the existing loading.

$P_s = P_m \times \eta_{Motor}$

Pump efficiency
This is arrived at by dividing the hydraulic power by pump shaft power

$\eta_{Pump} = P_h / P_S$

Example:
An industry operates a cooling water pump for process cooling and refrigeration applications. During the performance testing the following operating parameters were obtained, determine the pump efficiency?

Parameter	Value
Pump water flow, Q	0.40 m^3/s
Power consumption, P	325 kW

Parameter	Value
Suction head, Tower basin level, h_1	+1 m
Delivery head, h_2	55 m
Motor efficiency	88%
Density of water	996 Kg/m^3
Type of drive	Direct

Solution:

Parameter	Calculations
Hydraulic power, P_h	= Q x (hd - hs) x ρ x g / 1000 =0.40 x (55-1) x 996 x 9.81/1000 = 211 kW
Actual power consumption, P_m	= 325 kW
Overall system efficiency, $\eta_{Overall}$	= P_h / P_m = (211 x 100) / 325 = 65 %
Pump efficiency, η_{Pump}	= 65/0.88 = **74 %**

5.7.7. Energy savings opportunities in pumping systems

The first step to achieve energy efficiency in pumping system is to target the end-use. A plant water balance would establish usage pattern and highlight areas where water consumption can be reduced or optimized. Good water conservation measures, alone, may eliminate the need for some pumps.

Once flow requirements are optimized, then the pumping system can be analysed for energy conservation opportunities. Basically, this means matching the pump to requirements by adopting proper flow control strategies. Common symptoms that indicate opportunities for energy efficiency in pumps are given in the below **Table 21**

Table 21: Symptoms that indicate opportunity for energy saving

Symptoms that Indicate Opportunity for Energy Saving		
Symptom	**Likely Reason**	**Best Solutions**
Throttle valve-controlled system	Oversized pump	Variable speed drive, trim impeller, small impeller, two speed drive, lower rpm
Bypass line (partially or completely) open	Oversized pump	Variable speed drive, trim impeller, small impeller, two speed drive, lower rpm
Multiple parallel pump system with the same number of pumps always operating	Pump use not monitored or controlled	Install controls
Constant pump operation in a batch environment	Wrong system design	On-off controls
High maintenance cost (seals, bearings)	Pump operated far away from Best efficiency point	Match pump capacity with system requirement

1. Flow control by speed variation

Flow control by speed regulation is always more efficient than by control valve. At various speed of rotation, a centrifugal pump has different characteristic curves, which are related to each other by the affinity laws.

The affinity laws are a set of formulas that predict the impact of a change in rotational speed or impeller diameter on the head and flow produced by a pump and power demanded by a pump.

$Q_1/Q_2 = (N_1/N_2)$

$H_1/H_2 = (N_1/N_2)^2$

$P_1/P_2 = (N_1/N_2)^3$

Where:

Q = Flow rate, H = Head, P = Power absorbed, N = Rotating speed

For example, if speed of pump is reduced from 3500 rpm to 1750 rpm, its effect on flow head and power is calculated below.

Flow is proportional to the speed

$Q_1/Q_2 = (N1/N2)$, where $Q_1 = 100\ m^3/hr$

$100/Q_2 = 1750/3500$

$Q_2 = 200\ m^3/hr$

Head is proportional to the square of speed

$H_1/H_2 = (N_1/N_2)^2$, where $H_1 = 100m$

Example: $100/H_2 = 1750^2/3500^2$

$H_2 = 400m$

Power is proportional to the cube of speed

$P_1/P_2 = (N_1/N_2)^3$, Where $P_1 = 5kW$

Example: $5/P_2 = 1750^3/3500^3$

$P_2 = 40kW$

As can be seen from the above laws, doubling the speed of the centrifugal pump will increase the power consumption by 8 times. Conversely a small reduction in speed will result in drastic reduction in power consumption. This forms the basis for energy conservation in centrifugal pumps with varying flow requirements.

2. Fixed flow reduction by impeller trimming

Impeller trimming refers to the process of machining the diameter of an impeller to reduce the energy added to the system fluid.

Impeller trimming offers a useful correction to pumps that, through overly conservative design practices or changes in system loads are oversized for their application.

Trimming an impeller provides a level of correction below buying a smaller impeller from the pump manufacturer. But in many cases, the next smaller size impeller is too small for the pump load. Also, smaller impellers may not be available for the pump size in question and impeller trimming is the only practical alternative short of replacing the entire pump/motor assembly. (see **Figure 53 & Figure 54**) for before and after impeller trimming).

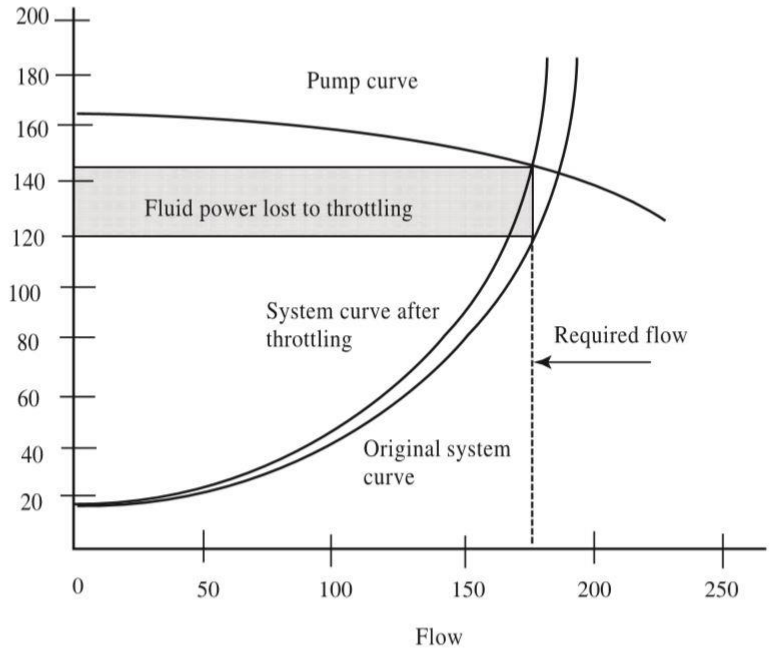


Figure 53: Before impeller trimming

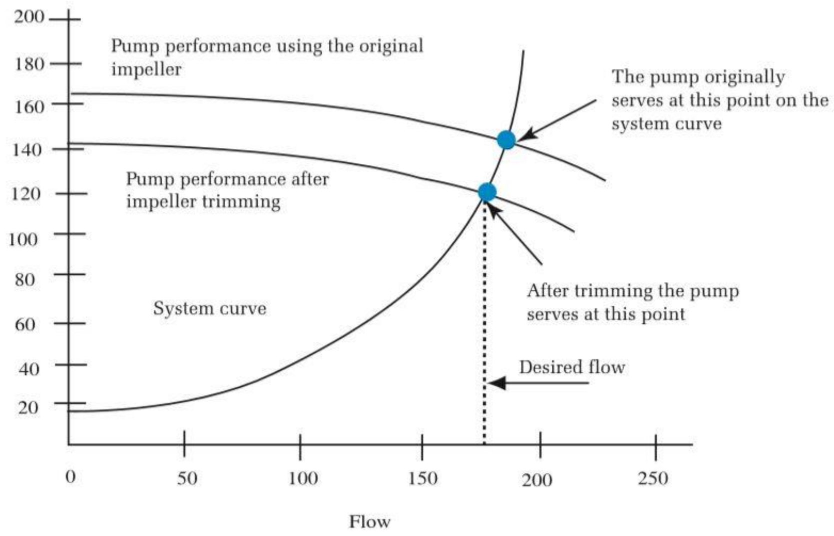


Figure 54: After impeller trimming

Impeller trimming reduces tip speed, which in turn directly lowers the amount of energy imparted to the system fluid and lowers both the flow and pressure generated by the pump.

The Affinity Laws, which describe centrifugal pump performance, provide a theoretical relationship between impeller size and pump output (assuming constant pump speed):

Changing the impeller diameter follows that there are equations, like the affinity laws, for the variation of performance with impeller diameter D:

$Q_1/Q_2 = (D_1/D_2)$

$H_1/H_2 = (D_1/D_2)^2$

$P_1/P_2 = (D_1/D_2)^3$

Efficiency varies when the diameter is changed within a casing. Diameter changes are generally limited to reducing the diameter to about 75% of the maximum, i.e. a head reduction to about 50%. Beyond this, efficiency and NPSH are severely affected. However, speed change can be used over a wider range without seriously reducing efficiency. For example, reducing the speed by 50% typically results in a reduction of efficiency by 1 or 2 percentage points. The reason for the small loss of efficiency with the lower speed is that mechanical losses in seals and bearings, which generally represent <5% of total power, are proportional to speed, rather than speed cubed. It should be noted that if the change in diameter is more than about 5%, the accuracy of the squared and cubic relationships can fall off and for precise calculations, the pump manufacturer's performance curves should be referred to.

3. Flow control valve/Throttling

This is a simplest and commonly used method. It is a most inefficient for flow control. While auditing always look for opportunity to replace throttling by energy efficient methods describe above.

4. Bypass control

With this control approach, the pump runs continuously at the maximum process demand duty, with a permanent by-pass line attached to the outlet. When a lower flow is required the surplus liquid is bypassed and returned to the supply source. This is even less energy efficient than a control valve because there is no reduction in power consumption with reduced process demand.

5. Flow control by varying speed

Benefits of speed change are different in the system where no or extremely low static head and system with a high static head. In **Figure 55** reducing speed in the friction loss system moves the intersection point on the system curve along a line of constant efficiency.

- The operating point of the pump, relative to its best efficiency point, remains constant and the pump continues to operate in its ideal region.
- The affinity laws are obeyed which means that there is a substantial reduction in power absorbed accompanying the reduction in flow and head, making variable speed the ideal control method for systems with friction loss.

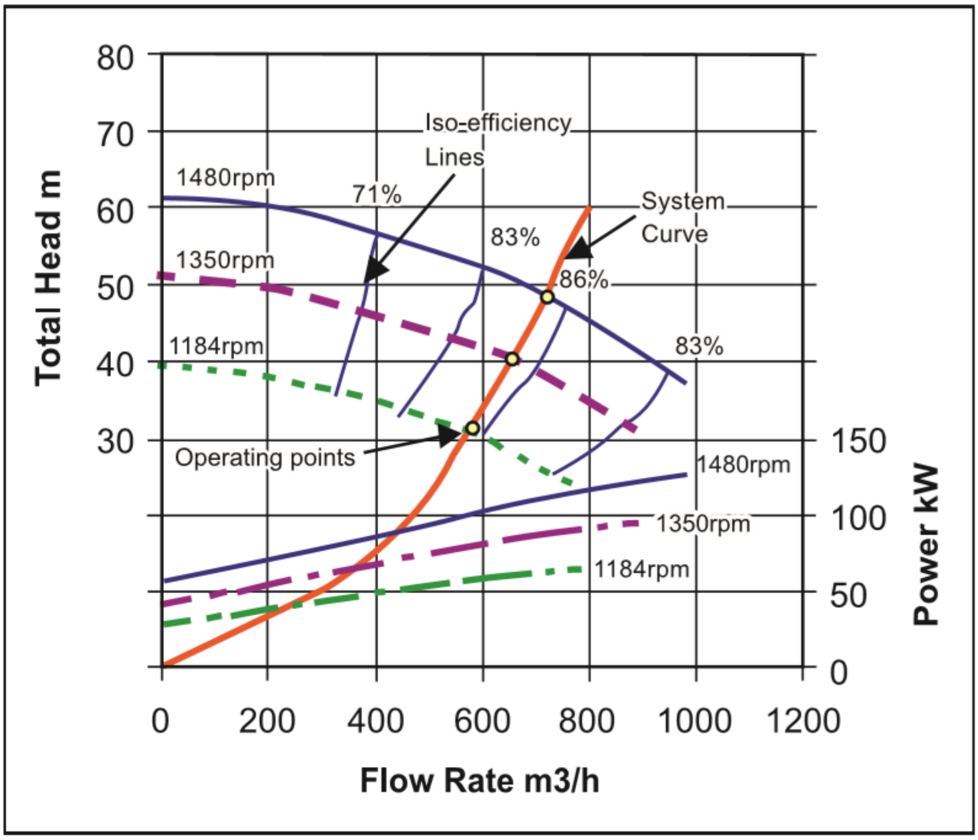


Figure 55: Effect of speed change in a system with no static head

In a system where static head is high, as illustrated in **Figure 56**

- Operating point for the pump moves relative to the lines of constant pump efficiency when the speed is changed.
- The reduction in flow is no longer proportional to speed.

A small turn down in speed could give a big reduction in flow rate and pump efficiency, which could result in the pump operating in a region where it could be damaged if it ran for an extended period of time even at the lower speed. At the lowest speed illustrated at 1184 rpm in **Figure 56**, the pump does not generate sufficient head to pump any liquid into the system, i.e. pump efficiency and flow rate are zero and with energy still being input to the liquid, the pump becomes a water heater and damaging temperatures can quickly be reached. The drop in pump efficiency during speed reduction in a system with static head, reduces the economic benefits of variable speed control. There may still be overall benefits, but economics should be examined on a case-by-case basis.

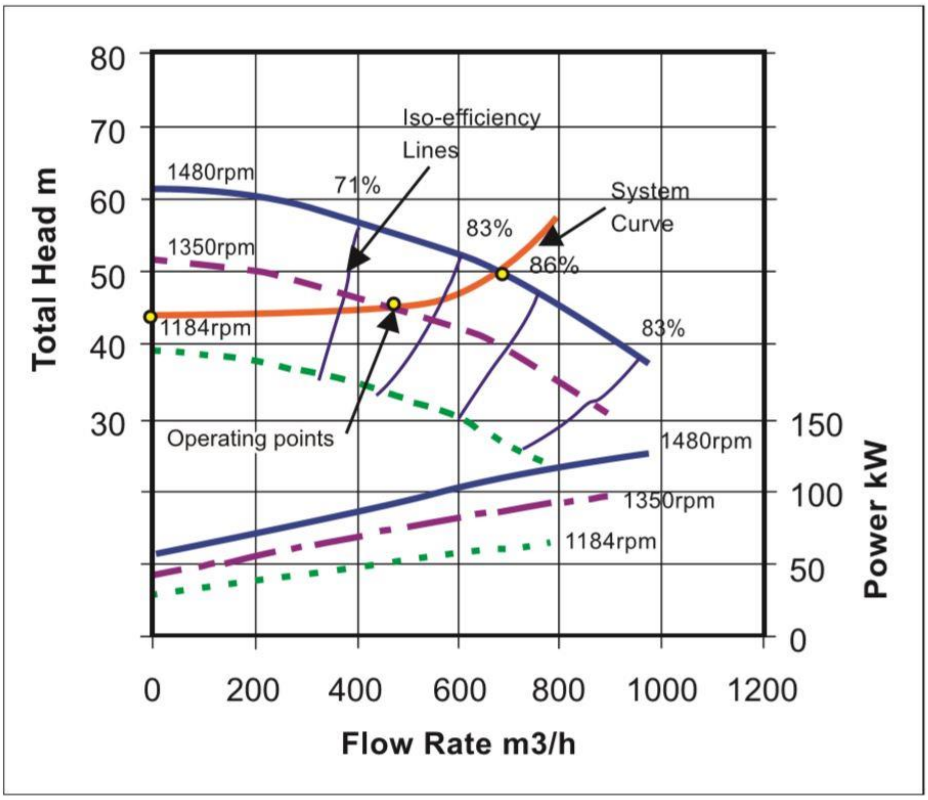


Figure 56: Effect of speed change in a system with high static head

6. Pump speed control by Variable Speed Drives (VSDs)

In contrast, pump speed adjustments provide the most efficient means of controlling pump flow. By reducing pump speed, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. There are two primary methods of reducing pump speed: multiple-speed pump motors and variable speed drives (VSDs).

Although both directly control pump output, multiple-speed motors and VSDs serve entirely separate applications. Multiple-speed motors contain a different set of windings for each motor speed; consequently, they are more expensive and less efficient than single speed motors. Multiple speed motors also lack subtle speed changing capabilities within discrete speeds.

VSDs allow pump speed adjustments over a continuous range, avoiding the need to jump from speed to speed as with multiple-speed pumps. VSDs control pump speeds using several different types of mechanical and electrical systems. Mechanical VSDs include hydraulic clutches, fluid couplings, and adjustable belts and pulleys. Electrical VSDs include eddy current clutches, wound-rotor motor controllers, and variable frequency drives (VFDs). VFDs adjust the electrical frequency of the power supplied to a motor to change the motor's rotational speed. VFDs are by far the most popular type of VSD.

However, pump speed adjustment is not appropriate for all systems. In applications with high static head, slowing a pump risks inducing vibrations and creating performance problems that are like those found when a pump operates against its shutoff head. For systems in which the static head represents a large portion of the total head, caution should be used in deciding whether to use VFDs. Operators should review the performance of VFDs in similar applications and consult VFD manufacturers to avoid the damage that can result when a pump operates too slowly against high static head.

For many systems, VFDs offer a means to improve pump operating efficiency despite changes in operating conditions. The effect of slowing pump speed on pump operation is illustrated by the three curves in **Figure 57.** When a VFD slows a pump, its head/flow and brake horsepower (BHP) curves drop down and to the left and its efficiency curve shifts to the left. This efficiency response provides an essential cost advantage; by keeping the operating efficiency as high as possible across variations in the system's flow demand, the energy and maintenance costs of the pump can be significantly reduced.

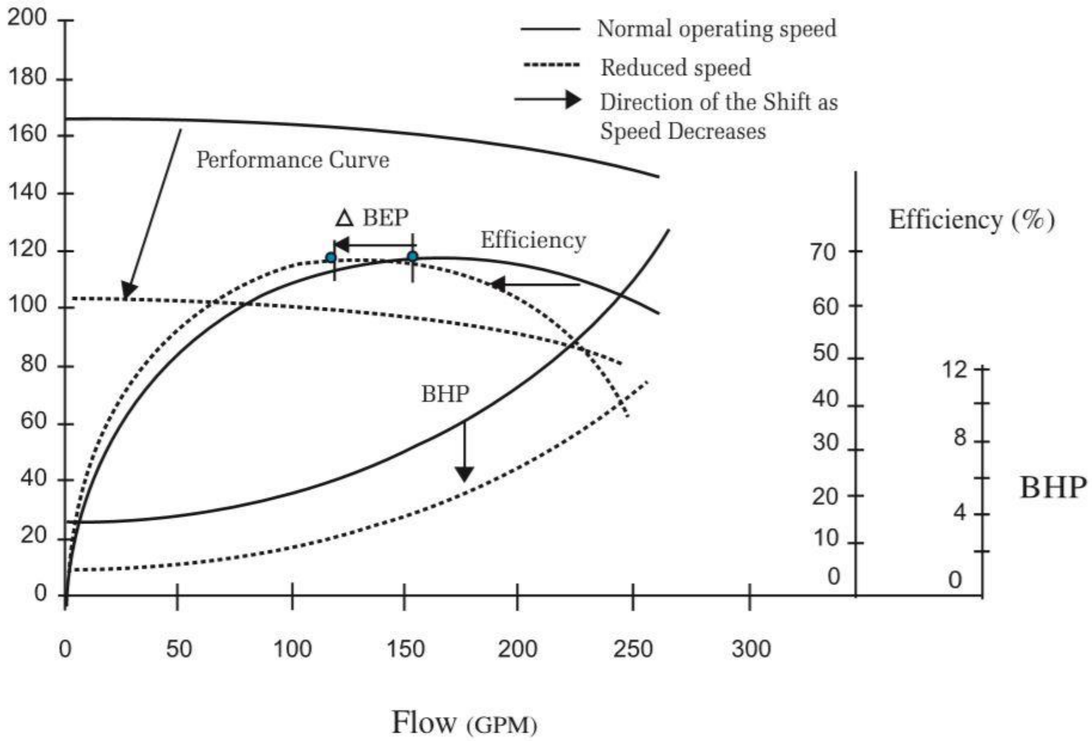


Figure 57: Effect of VFD

VFDs may offer operating cost reductions by allowing higher pump operating efficiency, but the principal savings derive from the reduction in frictional or bypass flow losses. Using a system perspective to identify areas in which fluid energy is dissipated in non-useful work often reveals opportunities for operating cost reductions.

For example, in many systems, increasing flow through bypass lines does not noticeably impact the backpressure on a pump. Consequently, in these applications pump efficiency does not necessarily decline during periods of low flow demand. By analysing the entire system, however, the energy lost in pushing fluid through bypass lines and across throttle valves can be identified.

Another system benefit of VFDs is a soft start capability. During start-up, most motors experience in-rush currents that are 5 - 6 times higher than normal operating currents. These high current fades when the motor spins up to normal speed. VFDs allow the motor to be started with a lower start up current.

7. Pumps in parallel switched to meet demand

Another energy efficient method of flow control, particularly for systems where static head is a high proportion of the total, is to install two or more pumps to operate in parallel. Variation of flow rate is achieved by switching on and off additional pumps to meet demand. The combined pump curve is obtained by adding the flow rates at a specific head. The head/flow rate curves for two and three pumps are shown in **Figure 58.**

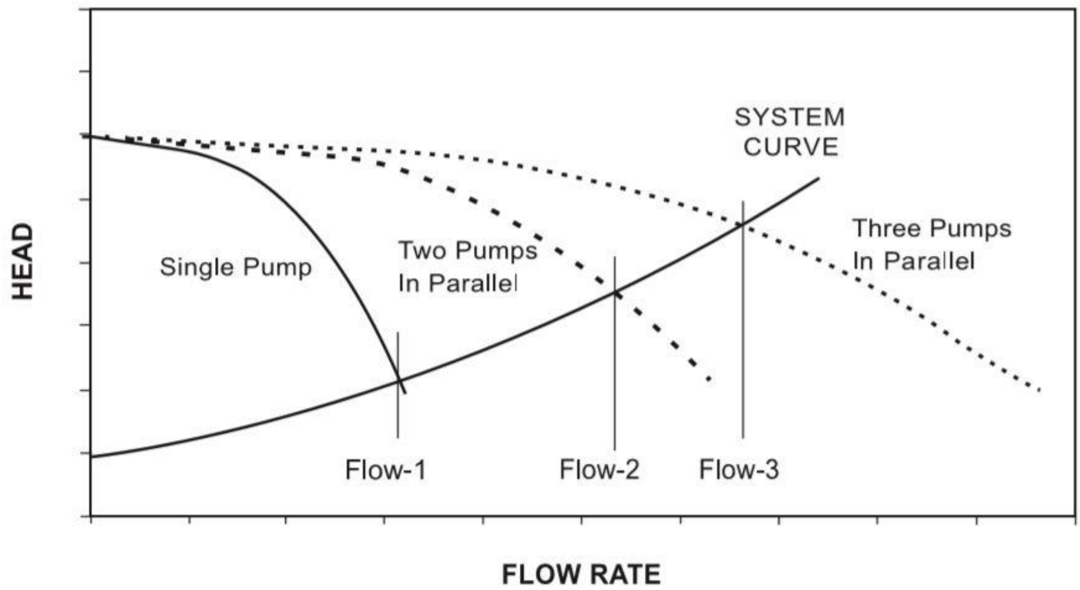


Figure 58: Typical head-flow curve for pumps in parallel operation

8. Other energy savings opportunities

- Use booster pumps for small loads requiring higher pressures.
- Repair seals and packing to minimise flows and reduce pump power requirements.
- Avoid unnecessary cooling water recirculation in DG sets, compressors, refrigeration systems, cooling towers feed water pumps, condenser pumps and process pumps.
- In multiple pump operations, carefully combine the operation of pumps to avoid throttling.
- Replace old pumps by new energy efficient pumps

5.8. Cooling towers – energy performance assessment

5.8.1. Introduction

Cooling towers are an important part of many plants. The primary task of a cooling tower is to reject heat into the atmosphere. They represent a relatively inexpensive and dependable means of removing low-grade heat from cooling water. The make-up water source is used to replenish water lost to evaporation. Hot water from heat exchangers is sent to the cooling tower. The water exits the cooling tower and is sent back to the exchangers or to other units for further cooling. Typical closed loop cooling tower system is shown in following **Figure 59**

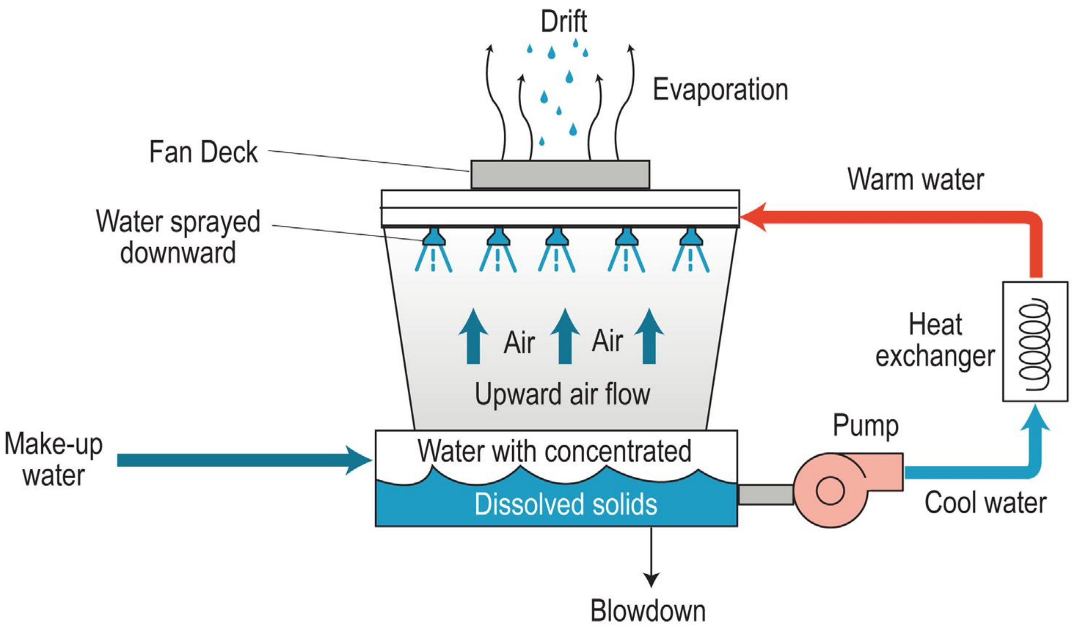


Figure 59: Cooling tower with closed loop

Cooling towers fall into two main categories:

Natural draft: Natural draft towers use large concrete chimneys to introduce air through the media. Due to the large size of these towers, they are generally used for water flow rates above 45,000 m^3/hr. These types of towers are used only by utility power stations.

Mechanical draft: Mechanical draft towers utilize large fans to force or suck air through circulated water. The water falls downward over fill surfaces, which help increase the contact time between the water and the air - this helps maximise heat transfer between the two. Cooling rates of Mechanical draft towers depend upon their fan diameter and speed of operation. Since, the mechanical draft cooling towers are much more widely used, the focus is on them in this chapter. Mechanical draft towers are available in a large range of capacities. Normal capacities range from approximately 10 tons, 2.5 m^3/hr flow to several thousand tons and m^3/hr. Towers can be either factory built or field erected – for example concrete towers are only field erected. The **Figure 60** illustrates various cooling tower types.

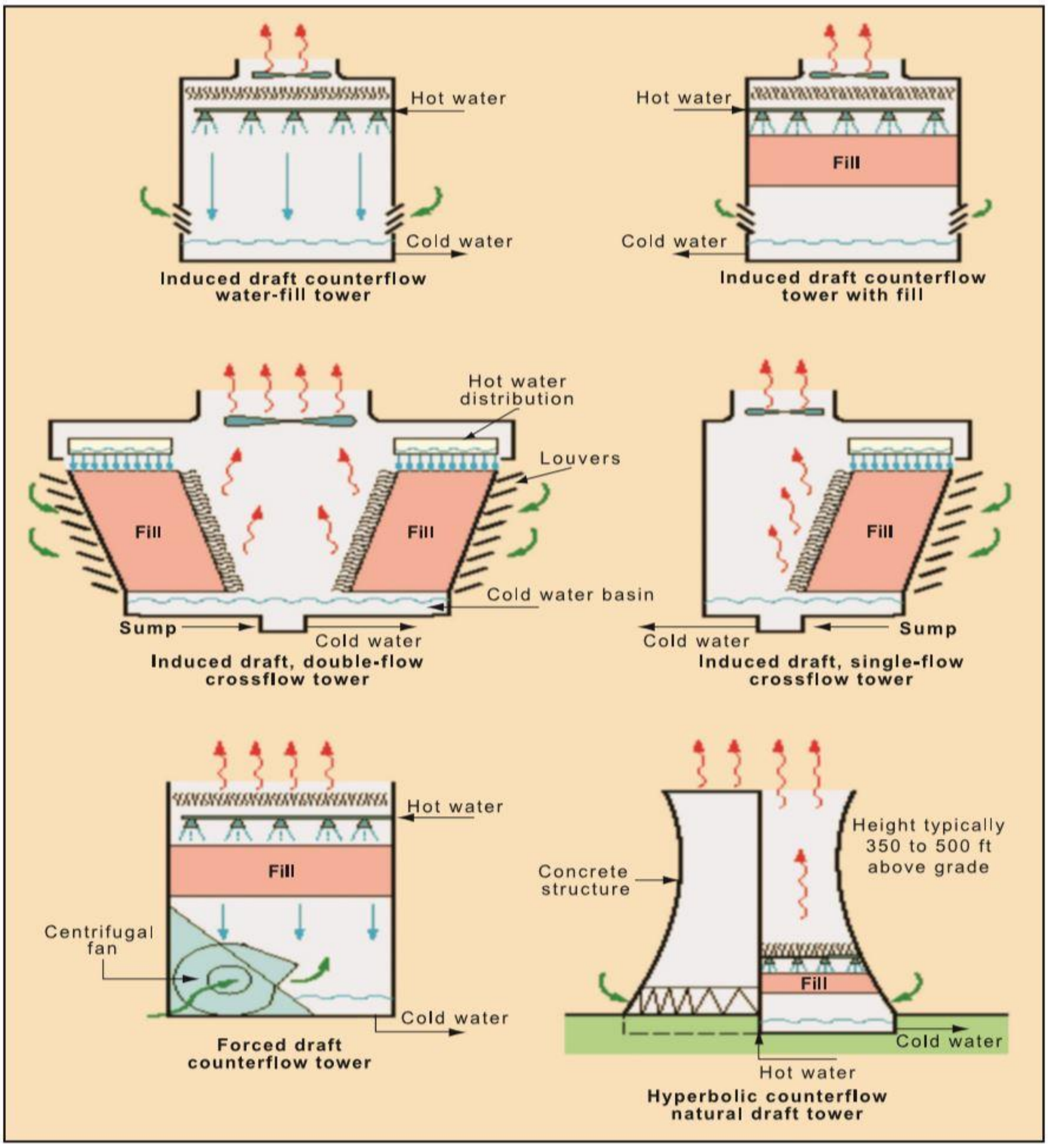


Figure 60: Types of cooling tower (Source: BEE)

Mechanical draft towers are available in the following airflow arrangements:

1. Counter flows induced draft

In the counter flow induced draft design, hot water enters at the top, while the air is introduced at the bottom and exits at the top. Both forced and induced draft fans are used.

2. Cross flow induced draft

In cross flow induced draft towers, the water enters at the top and passes over the fill. The air, however, is introduced at the side either on one side (single-flow tower) or opposite sides (double-flow tower). An induced draft fan draws the air across the wetted fill and expels it through the top of the structure.

5.8.2. Data collection

Following data shall be collected during audit from cooling tower motor and fan nameplate and by interviewing the operator or supervisor:

- Rated capacity (TR)

- Rated fan, pump, motor, specifications
- Design parameters of cooling tower

In addition to above, following data shall be collected through measurements:

- Cooling water inlet temperature °C
- Cooling water outlet temperature °C
- Ambient air wet bulb and dry bulb temperature °C
- Cooling water flow ($m^{3/}hr$)
- Fan power (kW)
- Air flow (m^3/hr)
- Cooling water TDS

5.8.3. Instruments required

- Ultrasonic water flow meter
- Hand -held clamp meter or three-phase power analyser
- Sling psychrometer
- pen-type thermometer
- Anemometer
- TDS-conductivity meter
- Measuring tape

5.8.4. Performance terms and definitions

1. Range and Approach

Range is the difference between the cooling tower water inlet and outlet temperature.

Approach is the difference between the cooling tower outlet cold water temperature and ambient wet bulb temperature.

Although, both range and approach should be monitored, the `Approach' is a better indicator of cooling tower performance.

Range is determined not by the cooling tower, but by the process it is serving. The range at the exchanger is determined entirely by the heat load and the water circulation rate through the exchanger and on to the cooling water.

Range = Heat Load in kcals/hour / Water Circulation Rate in l/hr

Thus, Range is a function of the heat load and the flow circulated through the system.

Cooling towers are usually specified to cool a certain flow rate from one temperature to another temperature at a certain wet bulb temperature. For example, the cooling tower might be specified to cool 4540 m^3/hr from 48.9°C to 32.2°C at 26.7°C wet bulb temperature.

Cold Water Temperature 32.2°C – Wet Bulb Temperature (26.7°C) = Approach (5.5°C)

As a generalization, the closer the approach to the wet bulb, the more expensive the cooling tower due to increased size. Usually a 2.8°C approach to the design wet bulb is the coldest water temperature that cooling tower manufacturers will guarantee. If flow rate, range, approach, and wet bulb had to be ranked in the order of their importance in sizing a tower, approach would be first with flow rate closely following the range and wet bulb would be of lesser importance.

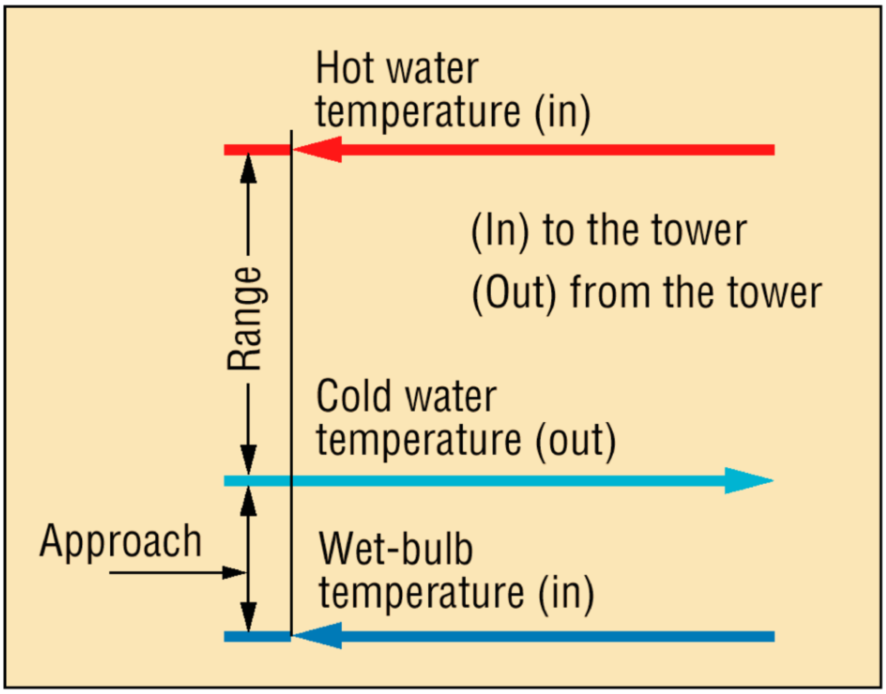


Figure 61: Range and Approach

2. Approach and flow

Suppose a cooling tower is installed that is 21.65 m wide × 36.9 m long × 15.24 m high, has three 7.32 m diameter fans and each powered by 25 kW motors. The cooling tower cools from 3632 m^3/hr water from 46.1°C to 29.4°C at 26.7°C wet bulb temperature (WBT) dissipating 60.69 million kcal/hr. The **Table 22** shows what would happen with additional flow but with the range remaining constant at 16.67°C. The heat dissipated varies from 60.69 million kcal/hr to 271.3 million kcal/hr.

Table 22: Flow and approach for given tower

Flow m^3/hr	Approach °C	Cold Water °C	Hot Water °C	Million kcal/hr
3,632	2.78	29.40	46.11	60.691
4,086	3.33	29.95	46.67	68.318
4,563	3.89	30.51	47.22	76.25
5,039	4.45	31.07	47.78	84.05
5,516	5.00	31.62	48.33	92.17
6,060.9	5.56	32.18	48.89	101.28
7,150.5	6.67	33.29	50.00	119.48
8,736	8.33	35.00	51.67	145.63

Flow m^3/hr	Approach °C	Cold Water °C	Hot Water °C	Million kcal/hr
11,590	11.1	37.80	54.45	191.64
13,620	13.9	40.56	57.22	226.91
16,276	16.7	43.33	60.00	271.32

For meeting the increased heat load, few modifications would be needed to increase the water flow through the tower. However, at higher capacities, the approach would increase.

3. Heat load

The heat load imposed on a cooling tower is determined by the process being served. The degree of cooling required is controlled by the desired operating temperature level of the process. In most cases, a low operating temperature is desirable to increase process efficiency or to improve the quality or quantity of the product. In some applications (e.g. internal combustion engines), however, high operating temperatures are desirable. The size and cost of the cooling tower is proportional to the heat load. If heat load calculations are low undersized equipment will be purchased. If the calculated load is high, oversize and more costly, equipment will result.

Process heat loads may vary considerably depending upon the process involved. Determination of accurate process heat loads can become complex but proper consideration can produce satisfactory results. On the other hand, air conditioning and refrigeration heat loads can be determined with greater accuracy.

4. Range, flow and heat load

Range is a direct function of the quantity of water circulated and the heat load. Increasing the range because of added heat load does require an increase in the tower size. If the cold water temperature is not changed and the range is increased with higher hot water temperature, the driving force between the wet bulb temperature of the air entering the tower and the hot water temperature is increased, the higher level heat is economical to dissipate.

If the hot water temperature is left constant and the range is increased by specifying a lower cold-water temperature, the tower size would have to be increased considerably. Not only would the range be increased, but the lower cold-water temperature would lower

5. Approach & wet bulb temperature

The design wet bulb temperature is determined by the geographical location. Usually the design wet bulb temperature selected is not exceeded over 5 percent of the time in that area. Wet bulb temperature is a factor in cooling tower selection; the higher the wet bulb temperature, the smaller the tower required to give a specified approach to the wet bulb at a constant range and flow rate.

A 4540 m^3/hr cooling tower selected for a 16.67°C range and a 4.45°C approach to 21.11°C wet bulb would be larger than a 4540 m^3/hr tower for same range and approach selected to a 26.67°C wet bulb. Air at the higher wet bulb temperature can pick up more heat. Assume that the wet bulb temperature of the air is increased by approximately 11.1°C. As air removes heat from the water in the tower, each kg of air entering the tower at 21.1°C wet bulb would contain

18.86 kcal and if it were to leave the tower at 32.2°C wet bulb it would contain 24.17 kcal per kg of air.

In the second case, each kg of air entering the tower at 26.67°C wet bulb would contain 24.17 kcals and were to leave at 37.8°C wet bulb it would contain 39.67 kcal per kg of air.

In going from 21.1°C to 32.2°C, 12.1 kcal per kg of air is picked up, while 15.5 kcal/kg of air is picked up in going from 26.67°C to 37.8°C.

6. Effectiveness

Cooling tower effectiveness (in percentage) is the ratio of range, to the ideal range, i.e., difference between cooling water inlet temperature and ambient wet bulb temperature,

Effectiveness= Range / (Range + Approach).

7. Cooling capacity

Cooling capacity is the heat rejected in kcal/hr or TR, given as product of mass flow rate of water, specific heat, and temperature difference.

8. Evaporation loss

Evaporation loss is the water quantity evaporated for cooling duty and, theoretically, for every 1,000,000 kcal heat rejected, evaporation quantity works out to 1.8 m^3.

An empirical relation used often is:
Evaporation Loss (m^3/hr) = 0.00085 x 1.8 x circulation rate (m^3/hr) x (T_1-T_2)

T_1-T_2 = Temp. difference between inlet and outlet water.

9. Cycles of concentration (C.O.C)

Cycles of concentration (C.O.C) is the ratio of dissolved solids in circulating water to the dissolved solids in makeup water. The COC specifies, how often a fresh water added into the loop, can be used or pumped around, before the water has to blow down or bleed off from the cooling tower

10. Blow down

Blow down losses depend upon cycles of concentration and the evaporation losses and is given by relation:

Blow Down = Evaporation Loss / (C.O.C. – 1)

11. Liquid to Gas ratio

Liquid/Gas (L/G) ratio, of a cooling tower is the ratio between the water and the air mass flow rates. Against design values, seasonal variations require adjustment and tuning of water and air flow rates to get the best cooling tower effectiveness through measures like water box loading changes, blade angle adjustments.

Thermodynamics also dictate that the heat removed from the water must be equal to the heat absorbed by the surrounding air:

$L(T_1-T_2) = G(h_2-h_1)$

$L/G = (h_2-h_1)/(T_1-T_2)$

L/G=liquid to gas mass flow ratio (kg/kg)
T_1= hot water temperature (°C)
T_2= cold water temperature (°C)
h_2 = enthalpy of air-water vapor mixture at exhaust wet-bulb temperature
h_1 = enthalpy of air-water vapor mixture at inlet wet-bulb temperature

12. Fill media effect

In a cooling tower, hot water is distributed above fill media which flows down and is cooled due to evaporation with the intermixing air. Air draft is achieved with use of fans. Thus, some power is consumed in pumping the water to a height above the fill and also by fans creating the draft.

An energy efficient or low power consuming cooling tower is to have efficient designs of fill media with appropriate water distribution, drift eliminator, fan, gearbox, and motor. Power savings in a cooling tower, with use of efficient fill design, is directly reflected as savings in fan power consumption and pumping head requirement.

Function of fill media in a cooling tower

Heat exchange between air and water is influenced by surface area of heat exchange, time of heat exchange (interaction) and turbulence in water affecting thoroughness of intermixing. Fill media in a cooling tower is responsible to achieve all of the above.

Splash and film fill media

As the name indicates, splash fill media generates the required heat exchange area by splashing action of water over fill media and hence breaking into smaller water droplets. Thus, surface of heat exchange is the surface area of the water droplets, which is in contact with air.

Film fill and its advantages

In a film fill, water forms a thin film on either side of fill sheets. Thus, area of heat exchange is the surface area of the fill sheets, which is in contact with air.

Table 23: Typical comparison between various fill media

Parameter	Splash Fill	Film Fill	Low Clog Film Fill
Possible L/G ratio	1.1-1.5	1.5-2.0	1.4-1.8
Effective Heat Exchange Area	3.-45 m^2/m^3	150 m^2/m^3	85-100 m^2/m^3
Fill Height Required	5-10 m	1.2-1.5 m	1.5-1.8 m
Pumping Head Requirement	9-12 m	5-8 m	6-9 m

Parameter	Splash Fill	Film Fill	Low Clog Film Fill
Quantity of air Requirement	High	Much low	Low

Due to fewer requirements of air and pumping head, there is a tremendous saving in power with the invention of film fill. Recently, low-clog film fills with higher flute sizes have been developed to handle high turbid waters. For sea water, low clog film fills are considered as the best choice in terms of power saving and performance compared to conventional splash type fills.

5.8.5. Efficient system operation

1. Cooling water treatment

Cooling water treatment is mandatory for any cooling tower whether with splash fill or with film type fill for controlling suspended solids, algae growth, etc. With increasing costs of water, efforts to increase Cycles of Concentration (COC), by Cooling Water Treatment would help to reduce make up water requirements significantly. In large industries, power plants, COC improvement is often considered as a key area for water conservation. Assumed the feed water has 100 TDS and the cooling water in the loop has 400 TDS, the COC will be 4. As higher the COC as less water is needed for replacement. At the same time the higher cycle of concentration increases the dissolved solids concentration in circulating cooling water which results in scaling and fouling of process heat transfer equipment.

2. Water side problems

Usually the typical problems that any (Open) cooling system meets with are:

- Corrosion and/or Scale formation
- Biologica1/Micro-biological fouling

Corrosion:

Corrosion is a function of various factors such as high salinity of the water, low PH, low Alkalinity, presence of corrosive gases (mainly oxygen and CO_2, dissimilarity of the metals etc. Corrosion can either lead to failure of the metallurgy (leakages in the heat exchangers) and/or deposit formation of corrosion products.

3. Scale formation

The main sources for the scale formation in the Open Evaporative Condenser circuit are:

Hard water containing, high levels of Calcium and Magnesium, high level of PH and Alkalinity. An open evaporative cooling system (condenser water systems) operated on softened water can meet with severe scaling problems when

- PH of the circulating water is above 9.0
- The total Alkalinity as CaC03 is above 550 ppm
- Temporary hardness in the sources of make-up is above 200 ppm

To control corrosion and scale formation depending upon the severity of each of the problem, either or both chemicals should be used and the selection of the chemicals should be made in accordance with the quality of the make-up water available for plant operation.

4. Bio Dispersants and Biocides

To combat problems arising due to the growth of biological and micro biological species, such as algae, fungi, slime, bacteria etc. It is very essential to select a combination of oxidizing and non-oxidizing biocides. Bio-dispersants are used to remove the upper layer of the biological masses and allow better penetration of biocides in the lower layers of biomasses.

5. Chlorination

Chlorination is the most effective and most economical oxidizing biocide. Chlorination for the smaller systems may be done with hypo chlorite-based products and for the larger systems having hold-up volume in excess of $100m^3$ be done with suitable gas chlorinators. The safest gas chlorination equipment are vacuum gravity feed types which can be easily installed on either 50 kg or 100 kg chlorine cylinders.

6. Drift loss

It is difficult to ignore drift problem in cooling towers. Now-a-days most of the end user specification calls for 0.02% drift loss. With technological development and processing of PVC, manufacturers have brought large change in the drift eliminator shapes and the possibility of making efficient designs of drift eliminators that enable end user to specify the drift loss requirement to as low as 0.003 – 0.001%.

7. Cooling tower fan

The purpose of a cooling tower fan is to move a specified quantity of air through the system, overcoming the system resistance which is defined as the pressure loss. The product of air flow and the pressure loss is air power developed/work done by the fan; this may be also termed as fan output and input kW depends on fan efficiency.

Metallic fans are manufactured by adopting either extrusion or casting process it is always difficult to generate the ideal aerodynamic profiles. The FRP blades are normally hand moulded which facilitates the generation of optimum aerodynamic profile to meet specific duty condition more efficiently. Cases reported where replacement of metallic or Glass fibre reinforced plastic fan blades have been replaced by efficient hollow FRP blades, with resultant fan energy savings of the order of 20-30% and with simple payback period of 6 to 7 months.

Also, due to lightweight, FRP fans need low starting torque resulting in use of lower HP motors. The lightweight of the fans also increases the life of the gear box, motor and bearing is and allows for easy handling and maintenance

5.8.6. Performance assessment of cooling towers

On field performance assessment, the typical measurements and observations involved are:

1. Using a pen-type digital thermometer, measure cooling water (CW) inlet temperature at risers or top of tower
2. Using a pen-type digital thermometer, measure cooling water (CW) outlet temperature at full bottom
3. Using a sling psychrometer, measure intake (ambient) air wet-bulb temperature (WBT) and dry-bulb temperature at each cell at ground level
4. Using an ultrasonic water flow meter, measure cooling water flow measurements,
5. Using a hand-held clamp meter, measure cooling tower fan (CT fan) power (kW) consumption.
6. Using an anemometer, measure the air flow rate of cooling tower fan.
7. Using TDS (total dissolved solids) meter, measure TDS of cooling water
8. Make observations on nozzle flows, drift eliminators, condition of fills, splash bars, etc.

An example has given below to illustrate the performance assessment of cooling towers

Example:

The findings of one typical trial pertaining to the Cooling Towers of an industry is given below:

Parameter	Measured Value	Rated Value
Inlet Cooling Water Temperature, T_1	44°C	43°C
Outlet Cooling Water Temperature, T_2	37.6 °C	33°C
Air Wet Bulb Temperature near cooling tower	29.3 °C	27.5°C
Air Dry Bulb Temperature near cooling tower	40.8 °C	-
Cooling Water flow	1565 m^3/hr	1875 m^3/hr
Measured cooling tower fan flow	989,544 m^3/hr	997,200 m^3/hr
L/G ratio	Calculated below	1.74

Solution:

Parameter	Calculations
Cooling tower (CT) range	= 44 – 37.6 = 6.4°C
Cooling tower approach	= 37.6 – 29.3 = 8.3°C
Cooling tower effectiveness	=Range/ (Range+ Approach) × 100

Parameter	Calculations
	= 6.4/ (6.4+8.3) × 100 **=43.5%**
Cooling water flow	= 1565 m^3/hr = 1,565,000 kg/hr
Cooling tower fan flow	= 9,89,544 m^3/hr = 1,068,708 kg/hr (@ density of 1.08 kg/m^3)
L/G ratio of cooling tower kg/kg	= 1,565,000/1,068,708 = 1.46
Evaporation losses	=0.00085 x 1.8 x circulation rate (m^3/hr) x (T_1-T_2) =0.0085×1.8×1565 × (44-37.6) =15.32 m^3/hr
Evaporation losses in %	=15.32/1565×100 =0.97%

Comments:

- Cooling water flow is much lower, almost by 16.5%, need to investigate cooling water pump and system performance for improvements. Increasing cooling water flow through cell was identified as a key result area for improving performance of cooling towers.

Other findings (example)

- Algae growth identified in cooling tower cells.
- Cooling tower fans are of GRP (glass reinforced polypropylene) type drawing 36.2 kW average. Replacement by efficient hollow FRP (fiber reinforced plastic) fan blades is recommended.

5.8.7. Energy saving opportunities in cooling towers

- Optimise cooling tower fan blade angle on a seasonal and/or load basis and correct excessive and/or uneven fan blade tip clearance and poor fan balance.
- On old counter-flow cooling towers, replace old spray type nozzles with new square spray ABS practically non-clogging nozzles.
- Replace splash bars with self-extinguishing PVC cellular film fill.
- Install new nozzles to obtain a more uniform water pattern
- Periodically clean plugged cooling tower distribution nozzles.
- Balance flow to cooling tower hot water basins.
- Cover hot water basins to minimise algae growth that contributes to fouling.
- Optimise blow down flow rate, as per COC limit.
- Replace slat type drift eliminators with low pressure drop, self-extinguishing, PVC cellular units.
- Segregate high heat loads like furnaces, air compressors, DG sets, and isolate cooling towers for sensitive applications like A/C plants, condensers of captive power plant etc.
- Monitor L/G ratio, CW flow rates w.r.t. design as well as seasonal variations. It would help to increase water load during summer and times when approach is high and increase air flow during monsoon times and when approach is narrow.
- Monitor approach, effectiveness, and cooling capacity for continuous optimisation efforts, as per seasonal variations as well as load side variations.
- Consider COC improvement measures for water savings.
- Consider energy efficient FRP blade adoption for fan energy savings.
- Consider possible improvements on CW pumps w.r.t. efficiency improvement.
- Control cooling tower fans based on leaving water temperatures especially in case of small units.

5.9. Lighting system – energy performance assessment

5.9.1. Introduction

Light is usually described as the type of electromagnetic radiation that has a wavelength visible to the human eye, roughly 400 to 700 nanometres. Light exists as tiny packets called photons and exhibits the properties of both particle and wave. Visible light rep-resents a narrow band between ultraviolet light (UV) and infrared energy (heat). These waves can exit the eye's retina, which results in a visual sensation called sight. Therefore, seeing requires a functioning eye and visible light.

Lighting is provided in industries, commercial buildings, indoor and outdoor for providing comfortable working environment. The primary objective is to provide the required lighting effect for the lowest installed load i.e highest lighting at lowest power consumption.

The purpose of performance test is to calculate the installed efficacy in terms of lux/watt/m² (existing or design) for general lighting installation. The calculated value can be compared with the norms for specific types of interior installations for assessing improvement options.

The installed load efficacy of an existing (or design) lighting installation can be assessed by carrying out a survey as indicated in the following pages.

5.9.2. Data collection

Following data shall be collected before conducting assessment

- Collect the single line diagram of electrical drawing pertaining to lighting.
- Following fixture details
    - Type of fixtures
    - Number of fixtures
    - Wattage of each fixture
- Department or section wise room dimension Length, width, and Height.
- Standard required lux level

Typical data format is given below.

Department Or section	Fixture type	Wattage of each fixture	No. of fixture	Total wattage	Room dimension	Illuminance required	Power Feeder detail

5.9.3. Instruments required

For lighting assessment following instruments are required:

- Hand-held clamp meter
- Three-phase power analyser
- LUX meter
- Digital distance meter or measuring tape

5.9.4. Performance terms and definition

- **Luminous flux:** The luminous flux describes the quantity of light emitted by a light source. It is a measure of a lamp's economic efficiency. The most common measurement or unit of luminous flux is the lumen (lm). The lumen rating of a lamp is a measure of the total light output of the lamp. Light sources are labelled with an output rating in lumen.
- **Illuminance (E)**: It is the quotient of the luminous flux incident on an element of the surface at a point, by the area of that element.
  The lighting level produced by a lighting installation is usually qualified by the illuminance produced on a specified plan. In most cases, this plan is the major plan of the task carried out in the interior and is common called the working plan. The illuminance provided by an installation affects both the performance of the tasks and the appearance of the space.
- **Lux (lx):** This is the illuminance produced by a luminous flux of one lumen, uniformly distributed over a surface area of one square metre. One lux is equal to one lumen per square meter.
  - Luminous Efficacy (lm/W): This is the ratio of luminous flux emitted by a lamp to the power consumed by the lamp. It reflects efficiency of energy conversion from electricity to light form.
  - Installed Load Efficacy: It is the average-maintained illuminance provided on a horizontal working plane per circuit watt with general lighting of an interior. Unit: lux per watt per square metre (lux/W/m²)
  - Colour Rendering Index (RI): Is a measure of the degree to which the colours of surfaces illuminated by a given light source confirm to those of the same surfaces under a reference illuminate; suitable allowance having been made for the state of chromatic adaptation.

5.9.5. Steps for conducting lighting audit

Step 1: Calculate minimum number of measurement points with Room index and Lux measurement. Room index used to determine the minimum number and positions of measurement points in a room.

Room Index=$L \times W / H_m (L+W)$

Where L = length of interior; W = width of interior; H_m = the mounting height, which is the height of the lighting fittings above the horizontal working plane. The working plane is usually assumed to be 0.75m above the floor in offices and at 0.85m above floor level in manufacturing areas.

It does not matter whether these dimensions are in metres, yards, or feet if the same unit is used throughout. Ascertain the minimum number of measurement points from **Table 24.**

Table 24: Determination of measurement points

Room Index	Minimum number of measurement points
Below 1	9
1 and below 2	16

Room Index	Minimum number of measurement points
2 and below 3	25
3 and above	36

Carry out Lux level measurement on minimum measurement points.

Calculate load efficacy ratio (ILER): follow the steps below to calculate ILER.

Step 2	Measure the floor area of the interior	Area = ----- m²
Step 3	Determine the total circuit watts of the installation by a power analyser if a separate feeder for lighting is available. If the actual value is not known a rated value can be obtained including the ballasts	Total watts = -------
Step 4	Calculate Watts per square metre, Value of step 3 divided by value of step 2	W/m² = --------
Step 5	Divide average lux level maintained measured in step 1 by step 4 to calculate installed load efficacy lux per watt per square metre	Lux/W/m² = -----
Step 6	Obtain target Lux/W/m² lux for type of the type of interior/application (given Table 25)	Target Lux/W/m² =
Step 7	Calculate Installed Load Efficacy Ratio (5 ÷ 6).	ILER =

Below **Table 25** gives the target lux/W/m^2 (W/m^2/100lux) values for maintained illuminance on horizontal plane for all room indices and applications:

Table 25: Target load efficacy (ILER)

Room Index	Commercial lighting (Offices, Retail stores etc) and very clean industrial applications Colour rendering required Ra-40-85 (Standard or good)	Industrial lighting (Manufacturing area, Workshops, warehousing etc.) Colour rendering required Ra-40-85 (Standard or good)	Industrial lighting installation where only colour discrimination is required. Colour rendering required Ra-20-40 (not essential)
5	53 (1.89)	49 (2.04)	67 (1.49)
4	52 (1.92)	48 (2.08)	66 (1.52)
3	50 (2.00)	46 (2.17)	65 (1.54)
2.5	48 (2.08)	44 (2.27)	64 (1.56)
2	46 (2.17)	42 (2.38)	61 (1.64)
1.5	43 (2.33)	39 (2.56)	58 (1.72)
1.25	40 (2.50)	36 (2.78)	55 (1.82)
1	36 (2.78)	33 (3.03)	52 (1.92)

ILER assessment

Compare the calculated ILER with the information in below **Table 26**

Table 26: Indicators of performance

Calculated ILER	Assessment
0.75 or above	Satisfactory or good
0.51-0.74	Review suggested
0.5 or less	Urgent action required

Existing installations with ratios of 0.51 - 0.74 certainly merit investigation to see if improvements are possible. Of course there can be good reasons for a low ratio, such as having to use lower efficacy lamps or less efficient luminaires in order to achieve the required lighting result –but it is essential to check whether there is a scope for a more efficient alternative. Existing installations with an ILER of 0.5 or less certainly justify close inspection to identify options for converting the installation to use more efficient lighting equipment.

Estimate the energy potential energy saving. For a given installation:

Annual energy saving potential (in kWh) = (1.0 - ILER) x Total load (kW) x annual operating hours (h)

If the calculated ILE (lux/W/m²) is less than the target value, then it is advisable to ascertain the reasons. It may be that the requirements dictate a type of luminaire that is not as efficient as the best, or the surface reflectance are less than the normal maxima, or the environment is dirty, etc., Whatever the reasons, they should be checked to see if a more efficient solution is possible.

Example of ILER calculation:

The dimensions of an interior are: Length = 9m, Width = 5m, Height of luminaires above working plane (Hm) = 2m

Step 1: Room index = 9x5/2(9+5) = 1.607

From **Table 24** the minimum number of measurement points is 16. As it is not possible to approximate a "square array" of 16 points within such a rectangle it is necessary to increase the number of points to say 18, i.e. 6 x 3.

After taking measurement by lux meter on 18 points in the room the average illumination measured was= 700 lux.

Step 2	Measure the floor area of the interior	Area = 45m²
Step 3	Determine the total circuit watts of the installation by a power analyser if a separate feeder for lighting is available. If the actual value is not known a rated value can be obtained including the ballasts	Total watts = 990 W

Step 4	Calculate Watts per square metre, Value of step 3 divided by value of step 2	22 W/m²
Step 5	Divide average lux level maintained measured in step 1 by step 4 to calculate installed load efficacy (lux per watt per square metre)	31.8 Lux/W/m²
Step 6	Obtain target Lux/W/m² lux for type of the type of interior/application (given in **Table 25**)	Target Lux/W/m² = 46
Step 7	Calculate Installed Load Efficacy Ratio (5 ÷ 6).	ILER = 0.7

Referring to Table 26 ILER of 0.7 means that there is scope for review of the lighting system.

Annual energy saving potential = (1 – ILER) x watts x no. of operating hours

= (1 – 0.7) x 990 x 8 hrs/day x 300 days

= 712 kWh/annum

5.9.6. Alternative method of lighting audit

Alternative step by step approach for assessing energy efficiency of lighting system is given below:

Step 01*:* Prepare and inventory of the Lighting System elements, & transformers in the facility by recording the type, rating and quantity of each type of light fixture.

Step 02*:* With the aid of a lux meter, measure and document the lux levels at various plant locations at working level, as daytime lux and night-time lux values alongside the number of lamps "ON" during measurement.

Step 03*:* With the aid of portable load analyser, measure and document the voltage, current, power factor and power consumption at various input points, namely the distribution boards or the lighting voltage transformers at the same as that of the lighting level audit.

Step 04*:* Compare the measured lux values with standard values as reference and identify locations as under lit and over lit areas.

Standard lux value as per IS 3646 is given below or for recommended illumination, reader may refer **Illuminating Engineers Society Recommendations Handbook.**

Record summary of lighting measurement as per given **Table 27**

Table 27: Summary of lighting measurement

Location/Section	Type of lamp	Measured average lux level	Standard Lux level (as per IS 3646)	Measured power

The following **Table 28** gives the recommended illuminance range for different tasks and activities for a plant. The values are related to the visual requirements of the task, to user's satisfaction, to practical experience and to the need for cost effective use of energy. For other sectors please refer source IS 3646 (Part I): 1992

Table 28: Standard Lux level for plant (Source: IS 3646)

Sl. No.	Type of Interior or Activity	Range of Service Illuminance in lux
General plant		
1	Turbine house (operating floor)	150-200-300
2	Boiler and turbine house basements	50-100-150
3	Boiler house, platform, areas around burner	50-100-150
4	Switch rooms, meter rooms, oil plant room, HV substation (indoor)	100-150-200
5	Control rooms	200-300-500 Localize lighting of control display and the control desk may be appropriate
6	Relay and telecommunication rooms	200-300-500
7	Diesel generator rooms, compressor rooms	100-150-200
8	Pump houses, water treatment plant houses	100-150-200
9	Battery rooms, charges, rectifiers	50-100-150
10	Cable tunnels and basements, circulating water culverts and screen chambers, storage tanks (indoor), operating areas and filling at outdoor tanks	30-50-100
Coal Plants		
1	Conveyors, gantries, junction tower, unloading hopers, ash handling plants, settling pits, dust hoppers outlets	50-100-150
2	Other areas where operators may be in attendance	100-150-200
Welding and Soldering Shops		
1	Gas and arc welding, rough spot welding	200-300-500
2	Medium soldering, brazing, spot welding	300-500-750
3	Fine soldering, fine spot welding	750-1000-1500 Local light is desirable

Sl. No.	Type of Interior or Activity	Range of Service Illuminance in lux
General Building Area		
1	Entrance halls, lobbies, waiting rooms	150-200-300
2	Enquiry desks	300-500-750 Localised lighting may be appropriate
3	Gatehouses	150-200-300
Circulation Areas		
1	Lifts	50-100-150
2	Corridors, passageways, stairs	50-100-150
3	Escalators, travellators	100-150-200
Medical and First Aid Centres		
1	Consulting rooms, treatment rooms	300-500-750
2	Rest rooms	100-150-200
3	Medical Stores	100-150-200
Staff rooms		
1	Changing, locker and cleaners' rooms, cloakrooms. Laboratories	50-100-150
2	Rest rooms	100-150-200
Staff Restaurants		
1	Canteen, cafeterias, dining rooms, mess rooms	150-200-300
2	Server, vegetable preparation, washing up area	200-300-500
3	Food preparation and cooking	300-500-750
4	Food stores and cellars	100-150-200
Communications		
1	Switchboard rooms	200-300-500
2	Telephone apparatus rooms	100-150-200
3	Telex rooms, post room	300-500-750
4	Reprographic room	200-300-500
Boiler House		
1	General	50-100-150
2	Boiler front	100-150-200
3	Boiler control room	200-300-500 Localised lighting may be appropriate
4	Mechanical plant room	100-150-200
5	Electrical power supply and distribution room	100-150-200
6	Storerooms	50-100-150
Car parks		
1	Floors	5-20
2	Ramps and corners	30

Sl. No.	Type of Interior or Activity	Range of Service Illuminance in lux
3	Entrance and exits	50-100-150
4	Control booths	150-200-300

Step 05: Based on careful assessment and evaluation, bring out improvement options.

5.9.7. Energy savings opportunities

While conducting the energy audit various energy savings measures may be explored such as:

- Natural lighting opportunities through windows and other openings. Suggest ways to improve natural lighting during the daytime and maximize sunlight use through use of translucent roof sheets, north light roof, etc.
- Explore the scope for introducing translucent polycarbonate sheets.
- Examine scope for replacements of lamps by more energy efficient lamps, with due consideration to luminaries, colour rendering index, lux level as well as expected life. Performances of luminaries which are commonly used are given in **Table 29**

Table 29: Luminous performance characteristics of commonly used luminaries

Type of Lamp	Lumens/watt		Colour Rendering Index	Typical Application	Typical Life (Hours)
	Range	Average			
Incandescent	8-18	14	Excellent (100)	Homes, restaurants, general lighting, emergency lighting	1000
Fluorescent Lamps	46-60	50	Good (67-77)	Offices, shops, hospitals, homes	5000
Compact fluorescent lamps (CFL)	40-70	60	Very good (85)	Hotels, shops, homes, offices	8000-10000
High pressure mercury (HPMV)	44-57	50	Fair (45)	General lighting in factories, garages, car parking, flood lighting	5000
Halogen lamps	18-24	20	Excellent (100)	Display, flood lighting, stadium exhibition grounds, construction areas	2000-4000
High pressure sodium (HPSV) SON	67-121	90	Fair (22)	General lighting in factories, warehouses, street lighting	6000-12000
Low pressure sodium (LPSV) SOX	101-175	150	Poor (10)	Roadways, tunnels, canals, street lighting	6000-12000

Type of Lamp	Lumens/watt		Colour Rendering Index	Typical Application	Typical Life (Hours)
	Range	Average			
Metal halide lamp	75-125	100	Good (70)	Industrial bays, spot lighting, flood lighting, retail stores	8000
LED lamps	50-130	90	Very good (80)	Office, industries, outdoor, retail, hospitality, etc	30,000-60,000
Induction Lamps	65-90	75	Very good (80)	General lighting, factories, warehouse, street lighting, flood lighting, etc	60,000-1,00,000

- Use of energy efficient lighting methods / products / equipment / retrofits Replace conventional magnetic ballasts by more energy efficient ballasts, with due consideration to life and power factor apart from watt loss.
- Select interior colours for light reflection.
- Assess scope for re-arrangement of lighting fixtures and modify layout for optimum lighting.
- Provide individual / group controls for lighting for improving energy efficiency such as, on / off type voltage regulation type (for illumination control)
- Look for the opportunity to install occupancy sensors and timer operated controls
- Modified switches / electrical circuits
- Install input voltage regulators / controllers for higher energy efficiency as well as longer life expectancy for lamps where high voltages / fluctuations are expected.
- Replace energy efficient displays with LEDs in place of lamp type

5.10. Boilers – energy performance assessment

5.10.1. Introduction

A boiler is an enclosed vessel that provides a means for combustion heat to be transferred into water until it becomes heated water or steam. The hot water or steam under pressure is then usable for transferring the heat to a process. Water is a useful and cheap medium for transferring heat to a process. When water is boiled into steam its volume increases about 1,600 times, producing a force that is almost as explosive as gunpowder. This causes the boiler to be extremely dangerous equipment that must be treated with utmost care.

The process of heating a liquid until it reaches its gaseous state is called evaporation. Heat is transferred from one body to another by means of (1) radiation, which is the transfer of heat from a hot body to a cold body without a conveying medium, (2) convection, the transfer of heat by a conveying medium, such as air or water and (3) conduction, transfer of heat by actual physical contact, molecule to molecule.

The heating surface is any part of the boiler metal that has hot gases of combustion on one side and water on the other. Any part of the boiler metal that contributes to making steam is heating surface. The amount of heating surface of a boiler is expressed in square meters. The quantity of the steam produced is indicated in tons of water evaporated to steam per hour. Maximum continuous rating is the hourly evaporation that can be maintained for 24 hours.

5.10.2. Boiler system

The boiler system comprises of:

- Feed water system,
- Fuel system
- Boiler
- Steam system

The feed water system provides water to the boiler and regulates it automatically to meet the steam demand. Various valves provide access for maintenance and repair. The fuel system includes all equipment used to provide fuel to generate the necessary heat. The equipment required in the fuel system depends on the type of fuel used in the system. Boiler is where the fuel is burnt to generate heat and convert water to steam. The steam system collects and controls the steam produced in the boiler. Steam is directed through a piping system to the point of use. Throughout the system, steam pressure is regulated using valves and checked with steam pressure gauges.

The water supplied to the boiler that is converted into steam is called feed water. The two sources of feed water are: (1) Condensate or condensed steam returned from the processes and (2) Makeup water (treated raw water) which must come from outside the boiler room and plant processes. For higher boiler efficiencies, the feed water is preheated by economizer, using the waste heat in the flue gas.

5.10.3. Boiler types and classifications

Boilers generally fall into main two category as follows:

Fire tube Boiler

Fire tube or "fire in tube" boilers; contain long steel tubes through which the hot gasses from a furnace pass and around which the water to be converted to steam circulates. (Refer **Figure 62)**. Fire tube boilers, typically have a lower initial cost, are more fuel efficient and easier to operate, but they are limited generally to capacities of 25 tons/hr and pressures of 17.5 kg/cm^2.

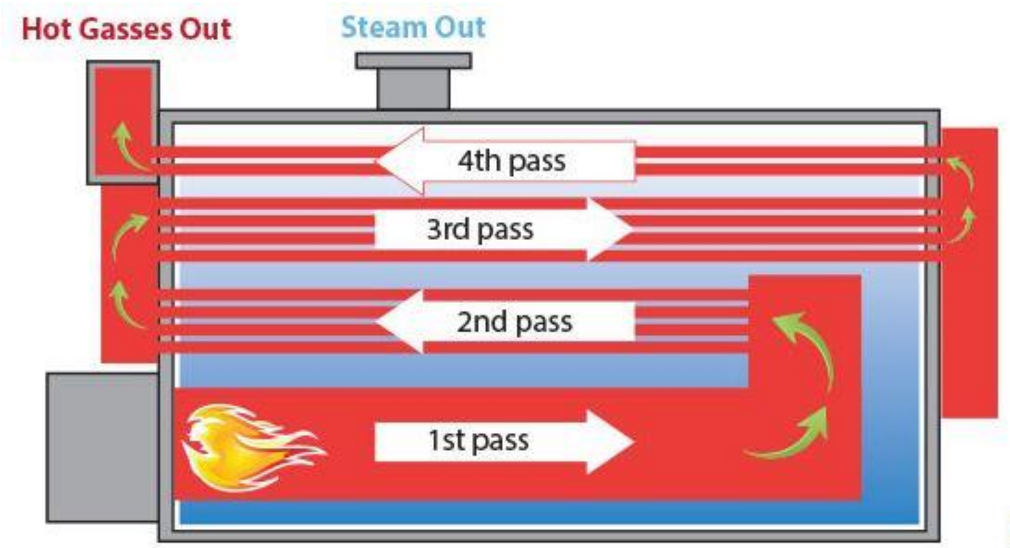


Figure 62: Fire tube boiler

Water tube Boiler

Water tube or "water in tube" boilers in which the conditions are reversed with the water passing through the tubes and the hot gasses passing outside the tubes. These boilers can be of single- or multiple-drum type. These boilers can be built to any steam capacities and pressures and have higher efficiencies than fire tube boilers. See **Figure 63**

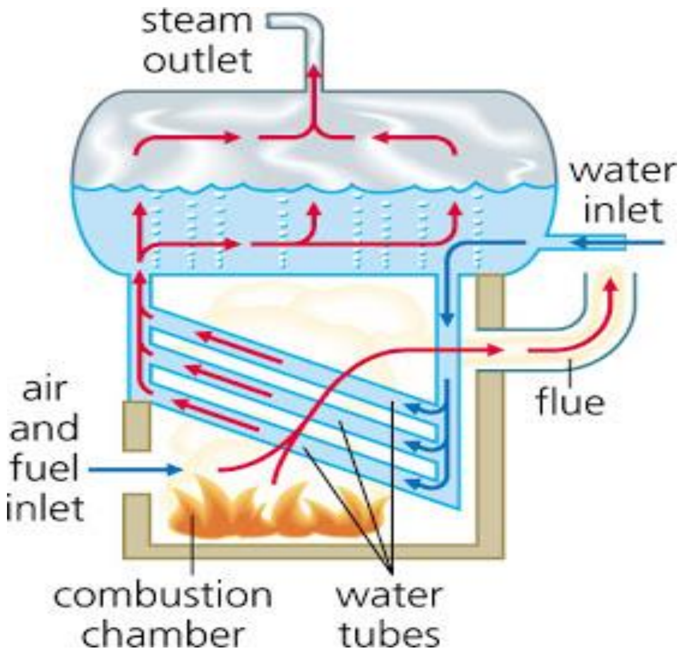


Figure 63: Water tube boiler (Source: BEE)

Packaged Boiler: The packaged boiler is so called because it comes as a complete package. Once delivered to site, it requires only the steam, water pipe work, fuel supply and electrical connections to be made for it to become operational. Package boilers are generally of shell type with fire tube design so as to achieve high heat transfer rates by both radiation and convection. See **Figure 64**

The features of package boilers are:

- Small combustion space and high heat release rate resulting in faster evaporation.
- Large number of small diameter tubes leading to good convective heat transfer.
- Forced or induced draft systems resulting in good combustion efficiency.
- Number of passes resulting in better overall heat transfer.
- Higher thermal efficiency levels compared with other boilers.

These boilers are classified based on the number of passes - the number of times the hot combustion gases pass through the boiler. The combustion chamber is taken, as the first pass after which there may be one, two or three sets of fire-tubes. The most common boiler of this class is a three-pass unit with two sets of fire-tubes and with the exhaust gases exiting through the rear of the boiler.

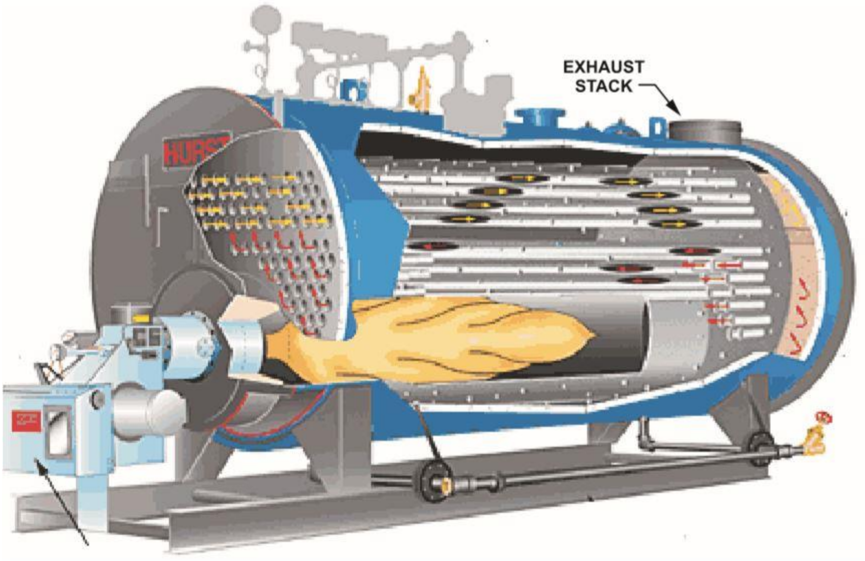


Figure 64: Packaged Boiler (Source: BEE)

5.10.4. Data collection

Following data shall be collected during audit from Boiler name plate and by interviewing the Boiler operator or plant supervisor:

- Type of Boiler
- Make and year of manufacturing
- Rated efficiency of Boiler
- Operating hours
- Operating parameters of Boiler like
  - Operating pressure
  - Operating load or steam required
  - Operating temperature
- Average fuel consumption from operator logbook
- Gross calorific vale (GCV) of fuel
- Feed water and inlet air temperature
- Amount and temperature of Condensate recovery if applicable
- Details of equipment/process where steam is used

While collecting information, it should also be checked, whether the Boiler are installed with Economiser, Air preheater, variable speed drive on FD or ID fan, Condensate recovery, excess air controller and any other energy saving retrofits.

In addition to above collect the following data through measurements:

- Thermal images of Boiler surface and steam pipeline (with focus on potential heat losses)
- Flue gas analysis data (applicable for fuel fired boiler only)
- Electricity consumption of FD and ID fan
- Flow measurement of Feed water

- Temperature measurement of feed water to Boiler, Air inlet and condensate recovered

5.10.5. Instruments required

For fuel fired boiler:

- Flue gas analyser
- Thermal imaging camera
- IR thermometer
- Sling psychrometer or digital thermometer
- TDS-Conductivity meter

For ID & FD fan of fuel fired boiler:

- Three-phase power analyser
- Manometer with pitot tube
- Anemometer
- Measuring tape

For Electric Boiler:

- Three-phase power analyser
- Thermal imaging camera
- IR thermometer

5.10.6. Performance terms and definitions

The performance parameters of boiler, like efficiency and evaporation ratio reduces with time due to poor combustion, heat transfer surface fouling and poor operation and maintenance. Even for a new boiler, reasons such as deteriorating fuel quality, water quality etc. can result in poor boiler performance. Boiler efficiency tests help us to find out the deviation of boiler efficiency from the best efficiency and target problem area for corrective action.

Boiler evaporation ratio, also known as steam to fuel ratio is a common and simple indicator for boiler performance. Evaporation ratio monitoring is best suited for any boiler when its own performance is compared on day to day basis as a performance indicator, given that enthalpy gain in steam and fuel calorific value remain constant. A drop in evaporation ratio indicates a drop in Boiler efficiency.

Boiler efficiency: Thermal efficiency of boiler is defined as the percentage of heat input that is effectively utilised to generate steam.

5.10.7. Performance evaluation of Boilers

There are two methods of assessing boiler efficiency.

1. Direct Method

This is also known as ‘input-output method’ since it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula:

$$Boiler\ efficiency\ (\eta) = \frac{Heat\ output}{Heat\ input} \times 100$$

Measurement required for direct method testing
Both heat input and heat output must be measured:

Heat input
The measurement of heat input requires knowledge of the calorific value of the fuel and its flow rate in terms of mass or volume, according to the nature of the fuel.

- **For gaseous fuel**: A gas meter of the approved type can be used, and measured volume should be corrected for temperature and pressure.
- **For liquid fuel**: Heavy fuel oil is very viscous, and this property varies sharply with temperature. A calibrated meter for the particular oil is to be used and over realistic range of temperature should be installed. Even better is the use of an accurately calibrated day tank.
- **For solid fuel**: The accurate measurement of the flow of coal or other solid fuel is difficult. The measurement must be based on mass, which means that bulky apparatus must be set up on the boiler house floor.
- **For electricity**: Using a hand-held clamp meter or three-phase power analyser measure the power consumption of the boiler at full load and convert the kWh into kcal (1 kWh = 860 kcal). Measure the power consumption of boiler at full load.

Heat output
With steam boilers, an installed steam meter can be used for measuring flow rate, but this must be corrected for temperature and pressure. In earlier days, this approach was not favoured due to the change in accuracy of orifice or venturi meter with flow rate. It is now viable with modern flow meters of the variable-orifice or vortex-shedding types.

The alternative with small boiler is to measure feed water, and this can be done by previously calibrating the feed tank and noting down the levels of water during the beginning and end of trial. Care should be taken not to pump water during this period.

In case of boiler with intermittent blowdown, blowdown should be avoided during the trial period. In case of continuous blowdown, the heat loss due to blowdown should be calculated and added to the heat in the steam.

$$Boiler\ efficiency(\eta) = \frac{Q \times (h_g - h_f)}{q \times GCV\ of\ fuel} \times 100$$

$$Boiler\ efficiency\ for\ electrical\ boiler\ (\eta) = \frac{Q \times (h_g - h_f)}{Electricity\ consumed\ (kcal)} \times 100$$

Where,
Q= Quantity of steam generated per hour in kg/hr
q= Quantity of fuel used per hour in kg/hr
h_g=Enthalpy of saturated steam in kcal/kg

h_f=Enthalpy of feed water in kcal/kg

Example:

- Type of boiler: Coal fired
- Quantity of steam (dry) generated: 8 TPH
- Steam pressure (gauge) / temp: 10 kg/cm^2, 180°C
- Quantity of coal consumed: 1.8 TPH
- Feed water temperature: 85° C
- GCV of coal: 3200 kcal/kg
- Enthalpy of steam at 10 kg/cm^2 pressure: 665 kcal/kg (saturated)
- Enthalpy of feed water: 85 kcal/kg

$$\text{Boiler efficiency}(\eta) = \frac{8 \times (665 - 85) \times 1000}{1.8 \times 3200 \times 1000} \times 100 = 80\%$$

Merits and demerits of direct method is given below:

Merits of direct method	Demerits of direct method
Plant people can quickly evaluate the efficiency of boilers	Does not give clues to the operator as to why efficiency of system is lower
Requires few parameters for computation	Does not calculate various losses accountable for various efficiency levels
Needs few instruments for monitoring	Evaporation ration and efficiency may mislead if the steam is highly wet due to water carryover

2. Indirect method (for fuel fired Boiler only)

Indirect method is also called as heat loss method. The efficiency can be measured easily by measuring all the losses occurring in the boiler using the principle described as below. The disadvantage of direct method can be overcome by this method, which calculates the various heat losses associated with boiler. The efficiency can be arrived at, by subtracting the heat losses fractions from 100. An important advantage of this method is that the errors in measurement do not make significant change in efficiency.

Thus, if boiler efficiency is 90%, an error of 1% in direct method will result in significant change in efficiency. i.e. 90$\pm$0.9=89.1 to 90.1. In indirect method, 1% error in measurement of loss will result in:
Efficiency= 100-(10$\pm$0.1) =90$\pm$0.1= 89.9 to 90.1. The various heat loss occurring in boiler are shown in **Figure 65**.

The following heat losses are applicable to liquid, gas and solid fired Boiler:

- L1- Loss of heat due to dry flue gas
- L2- Loss of heat due to hydrogen in fuel and combustion air
- L3- Loss of heat due to combustion of moisture in fuel Loss of heat due to radiation
- L4- Loss of heat due to combustion of moisture in Air
- L5- Loss of heat due to carbon monoxide
- L6- Loss of heat due to surface radiation, convection and other unaccounted[5]

The following losses are applicable to solid fuel fired boiler in addition to above

- L7- Unburnt losses in fly ash (carbon)
- L8- Unburnt losses in bottom ash (carbon)

Boiler Efficiency by indirect method= 100 - (L1+L2+L3+L4+L5+L6+L7+L8)

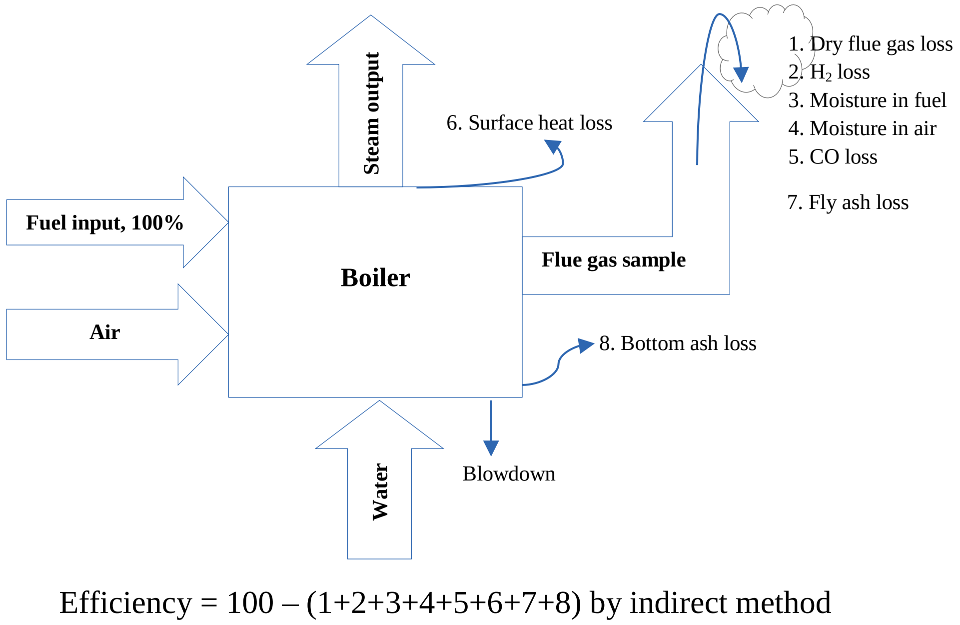


Figure 65: Various heat losses in fuel fired Boiler

In the above, loss due to moisture in fuel and the loss due to combustion of hydrogen are dependent on the fuel and cannot be controlled by design.

[5] Losses which are insignificant and difficult to measure

Measurement required for performance assessment testing:

The following parameters need to be measured, as applicable for the computation of boiler efficiency and performance:

a) Flue gas analysis
   - Percentage of O_2 and CO_2 in flue gas
   - Percentage of CO in flue gas
   - Temperature of flue gas

b) Flow measurement for
   - Fuel
   - Steam
   - Feed Water
   - Condensate water
   - Combustion air

c) Temperature measurement for
   - Flue gas
   - Steam
   - Makeup water
   - Condensate return
   - Combustion air
   - Fuel
   - Boiler feed water

d) Pressure measurement for
   - Steam
   - Combustion air both primary and secondary
   - Draft

e) Water condition
   - Total dissolved solid (TDS)
   - pH
   - Blow down rate and quantity

The parameter listed above can be measured with the instrument that are given in below table:

Table 30: Typical instrument used for Boiler performance assessment

Instrument	Type	Measurement
Flue gas analyser	Portable or fixed	%CO_2, O_2 and CO
Temperature indicator	Thermocouple, liquid in glass	Flue gas temperature, Combustion air temperature, boiler surface, steam temperature
Draft gauge	Manometer, differential pressure	Amount of draft used or available
TDS meter	Conductivity	Boiler water TDS, feed water TDS, make-up water TDS.
Flow meter	As applicable	Steam flow, water flow, fuel flow, air flow

Test conditions and precautions for indirect method testing

The efficiency test does not account for:

- Blow down loss, the amount of energy wasted by blow down varies over a wide range.
- Soot blower steam, the amount of steam used by soot blowers is variable that depends on the type of fuel.
- Auxiliary equipment energy consumption, the combustion efficiency test does not account for the energy usage by auxiliary equipment, such as burners, fans, and pumps.

Preparations and pre-conditions for testing

- Conduct the tests while the boiler is under steady load. Avoid testing during warming up of boilers from a cold condition
- Ensure the Boiler is running as per daily routine operation.
- Ensure the accuracy of fuel and ash analysis in the laboratory.
- Check the type of blow down and method of measurement
- Ensure proper operation of all measuring instruments.
- Check for any air infiltration in the combustion zone.

Options of flue gas analysis: Check the oxygen test with the carbon dioxide test

If continuous-reading oxygen test equipment is installed in boiler plant, use oxygen reading. Occasionally use portable test equipment that checks for both oxygen and carbon dioxide. If the carbon dioxide test does not give the same results as the oxygen test, something is wrong. One (or both) of the tests could be erroneous, perhaps because of stale chemicals or drifting instrument calibration. Another possibility is that outside air is being picked up along with the flue gas. This occurs if the combustion gas area operates under negative pressure and there are leaks in the boiler casing.

Carbon monoxide test

The carbon monoxide content of flue gas is a good indicator of incomplete combustion with all types of fuels, as long as they contain carbon. Carbon monoxide in the flue gas is minimal with ordinary amounts of excess air, but it rises abruptly as soon as fuel combustion starts to be incomplete.

Planning for the testing

- Advanced planning is essential for the resource arrangement of manpower, fuel, water, and instrument check etc and the same to be communicated to the boiler Supervisor and Production Department.
- Sufficient quantity of fuel stock and water storage required for the test duration should be arranged so that a test is not disrupted due to non-availability of fuel and water.
- Necessary sampling point and instruments are to be made available with working condition.
- Lab analysis should be carried out for fuel, flue gas and water in coordination with lab personnel.
- The steam table, psychometric chart, calculators are to be arranged for computation of boiler efficiency.

Boiler efficiency by indirect method: Calculation procedure and formula

In order to calculate the boiler efficiency by indirect method, all the losses that occur in the boiler must be established. These losses are conveniently related to the amount of fuel burnt. In this way it is easy to compare the performance of various boilers with different ratings.

However, it is suggested to get an ultimate analysis of the fuel periodically from a reputed laboratory.

Theoretical (stoichiometric) air fuel ratio and excess air supplied are to be determined first for computing the boiler losses. The formula is given below for the same.

Formulae for computing theoretical air fuel ratio and excess air supplied for combustion	
Theoretical air required for combustion	$[(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)] / 100$ kg/kg of fuel from fuel analysis: Where C, H_2, O_2, and S are the percentage of carbon, hydrogen, oxygen and sulphur present in the fuel.
% Excess air supplied (EA)	$= \frac{O_2\%}{21 - O_2\%} \times 100$ O_2% to be obtained from flue gas analysis Usually, O_2 measurement is recommended, if O_2 measurement is not available, use CO_2 measurement and below formula to obtain excess air $= \frac{7900 \times [(CO_2\%)_t - (CO_2\%)_a]}{(CO_2\%)_a \times [100 - (CO_2\%)_t]}$ $(CO2\%)_t$ is theoretical CO_2 $(CO2\%)_a$ is actual CO_2% measured in flue gas
$(CO_2)_t$	$= \frac{\text{Moles of C}}{(\text{Moles } N_2 + \text{Moles of C} + \text{Moles of S})}$
Moles of N_2	$= \frac{(\text{Weight of } N_2 \text{ in theoretical air})}{(\text{Molecular Weight of } N_2)} + \frac{\text{Weight of } N_2 \text{ in fuel}}{\text{Molecular weight of } N_2}$
Moles of C	$= \frac{\text{Weight of C in fuel}}{\text{Molecular weight of C}}$
Moles of S	$= \frac{\text{Weight of S in fuel}}{\text{Molecular weight of S}}$

Formulae for computing theoretical air fuel ratio and excess air supplied for combustion	
Actual mass or air supplied/kg of fuel, AAS	$= \left(1 + \frac{EA}{100}\right) X\ theoretical\ air$

The various losses associated with the operation of a boiler are discussed below with required formula

Various losses associated with operation of Boiler	
Heat loss due to dry flue gas in % **(L1)**	$= \frac{m\ X\ C_P X\ (t_f - t_a)}{GCV\ of\ fuel}\ X\ 100$ Where, total mass of dry flue gas in (m)/kg of fuel = mass of CO_2 in flue gas + mass of SO_2 in flue gas + mass of N_2 content in fuel + mass of N_2 in the combustion air supplied + mass of O_2 in flue gas **OR** Total mass of dry flue gas (m)/kg of fuel = Mass of actual air supplied (AAS) + Mass of fuel supplied Cp=Specific heat of flue gas in kcal/kg°C t_f= Temperature of flue gas in °C t_a= Temperature of ambient air in °C
Heat loss due to formation of water from H_2 in fuel in % **(L2)**	$= \frac{9\ X\ H_2\ X\ (584 + C_P\ (T_f - Ta)}{GCV\ of\ fuel}\ X\ 100$ H_2 = Kg of Hydrogen present in 1 kg fuel C_p = Specific heat of superheated steam in kcal/kg°C T_f = Flue gas temperature in °C T_a = Ambient temperature in °C 584 = latent heat corresponding to the partial pressure of water vapour in kcal/kg "The combustion of hydrogen causes a heat loss because the product of combustion is water. This water is converted to steam and this carries away heat in the form of its latent heat".
Heat loss due to moisture present in fuel in % **(L3)**	$= \frac{M\ X\ (584 + C_P X\ (t_f - t_a)}{GCV\ of\ fuel}\ X\ 100$ M= Kg of moisture in 1 kg of fuel C_p=Specific heat of superheated steam in kcal/kg°C 584= latent heat corresponding to the partial pressure of water vapour in kcal/kg "Moisture entering the boiler with the fuel leaves as a superheated vapour".

Various losses associated with operation of Boiler	
Heat loss due to moisture present in air in % **(L4)**	$= \frac{AAS\ X\ humidity\ X\ C_P X\ (t_f - t_a)}{GCV\ of\ fuel}\ X\ 100$ AAS = Actual mass of air supplied per kg of fuel Humidity factor = kg of water/kg of dry air C_p = Specific heat of superheat steam in kcal/kg°C t_f = flue gas temperature in °C t_a =ambient temperature in °C (dry bulb) "Vapour in the form of humidity in the incoming air, is superheated as it passes through the boiler. Since this heat passes up the stack, it must be included as a boiler loss".
Heat loss due to partial conversion of C to CO or incomplete combustion in % **(L5)**	$= \frac{\%CO\ X\ C}{\%CO + \%\ CO_2}\ X\ \frac{5654}{GCV\ of\ fuel}\ X\ 100$ CO = Volume of CO in flue gas (%) (1% = 10,000 ppm) CO_2 = Actual volume of CO_2 in flue gas C = Carbon content kg/kg of fuel "Carbon monoxide (CO) is the only gas whose concentration can be determined conveniently in a boiler plant test".
Heat loss due to radiation and convection in W/m^2 **(L6)**	$= 0.548 \times [(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957\ X\ (T_s - T_a)^{1.25}\ X\ \sqrt{[(1.968V_m + 68.9) / 68.9]}$ V_m = wind velocity in m/s T_s = Surface temperature T_a = Ambient temperature Normally surface loss and other unaccounted losses is assumed based on the type and size of the boiler as given below For industrial fire tube/packaged boiler = 1.5% to 2.5% For industrial water tube boiler = 2 to 3% For power station boiler = 0.4 to 1% "The other heat losses from a boiler consist of the loss of heat by radiation and convection from the boiler casting into the surrounding boiler house".
Heat loss due to unburnt in fly ash in % **(L7)**	$= \frac{Total\ ash\ coected\ per\ kg\ of\ fuel\ burnt\ X\ GCV\ of\ fly\ ash}{GCV\ of\ fuel}\ X\ 100$
Heat loss due to unburnt in bottom ash in % **(L8)**	$= \frac{Total\ ash\ collected\ per\ kg\ of\ fuel\ burnt\ X\ GCV\ of\ bottom\ ash}{GCV\ of\ fuel}\ X\ 100$

Example:

The following are the data collected for a boiler using coal as the fuel. Find out the boiler efficiency by indirect method.

Table 31: Measured and collected parameter from a plant

Parameter	Values
Fuel firing rate	5600 kg/hr
Steam generation rate	21940 kg/hr
Steam pressure	43 kg/cm^2
Steam temperature	377°C
Feed water temperature	96°C
$\%O_2$ in flue gas	2.75%
Average flue gas temperature	190°C
Ambient temperature	31°C
Humidity in ambient air	0.0204 kg/kg dry air
Surface temperature of boiler	70°C
Wind velocity around boiler	3.5 m/s
Total surface area of boiler	90 m^2
GCV of bottom ash	800 kcal/kg
GCV of fly ash	450 kcal/kg
Ratio of bottom ash to fly ash	90:10
Fuel analysis in %	
Ash	48%
Moisture	4.4%
Carbon	36%
Hydrogen	2.6%
Nitrogen	1.1%
Oxygen	7.3%
Sulphur	0.6
GCV	3501 kcal/kg

Solution: Boiler efficiency by indirect method

Steps for calculating Boiler efficiency by indirect method	
Step-1 Find theoretical air requirement for complete combustion	
Theoretical air required for combustion	$[(11.6 X C) + \{34.8 X (H_2 – O_2/8)\} + (4.35 X S)] / 100$ kg/kg of fuel = [(11.6 X 36) + {34.8 X (2.6 – 7.3/8)} + (4.35 X 0.6)] / 100 = **4.79 kg/kg of coal**
Step-2 Find CO_2% at theoretical condition, $(CO_2)_t$	
$(CO_2)_t$	=Moles of C/ (Moles N_2+Moles of C+ Moles of S)
Moles of N_2	= (Weight of N_2 in theoretical air/ Mol. Weight of N_2) + (Weight of N_2 in fuel / Mol Weight of N_2) = (4.79× (77/100)/28) +(0.011/28) =0.1321
Moles of C	= 0.36/12= 0.03

Steps for calculating Boiler efficiency by indirect method	
Moles of S	= 0.006/32= 0.0001875
$(CO_2)_t$	= 0.03/ (0.03+0.1321+0.0001875) = **18.48 %**
Step 3- To find Excess air supplied	
Actual O_2 measured in flue gas	=2.75%
% Excess air supplied (EA)	$= \frac{O_2\%}{21 - O_2\%} X\ 100$ $= \frac{2.75\%}{21-2.75\%} X\ 100$ = **15%**
Step 4- To find actual mass of air supplied, AAS	
AAS	$= \left(1 + \frac{EA}{100}\right) X\ theoretical\ air$ $= \left(1 + \frac{15}{100}\right) X\ 4.79$ = **5.51 kg/kg of coal**
Step 5- To find actual mass of dry flue gas	
Actual mass of dry flue gas	= Mass of actual air supplied + Mass of fuel supplied = 5.51+1 **=6.51 kg/kg of coal**
Step 6- To find all the losses	
Heat loss in dry flue gas **(L1)**	$= \frac{m\ X\ C_P X\ (t_f - t_a)}{GCV\ of\ fuel} X\ 100$ $= \frac{6.51\ X\ 0.24\ X\ (190 - 31)}{3501} X\ 100$ **= 7.1%** Cp =Specific heat of flue gas = 0.24 kcal/kg°C
% Heat loss due to formation of water from H_2 in fuel **(L2)**	$= \frac{9\ X\ H_2\ X\ (584 + C_P\ (T_f - Ta)}{GCV\ of\ fuel} X\ 100$ $= \frac{9\ X\ 0.026\ X\ (584 + 0.45\ (190 - 31)}{3501} X\ 100$ **= 4.36%** C_p = Specific heat of superheated steam =0.45 kcal/kg°C

Steps for calculating Boiler efficiency by indirect method	
Heat loss due to moisture in fuel **(L3)**	$= \frac{M\ X\ (584 +\ C_P X\ (t_f -\ t_a)}{GCV\ of\ fuel}\ X\ 100$ $= \frac{0.044\ X\ (584 + 0.43\ X\ (190 -\ 31)}{3501}\ X\ 100$ = **0.83%**
Heat loss due to moisture in air **(L4)**	$= \frac{AAS\ X\ humidity\ X\ C_P X\ (t_f -\ t_a)}{GCV\ of\ fuel}\ X\ 100$ $= \frac{5.51\ X\ 0.0204\ X\ 0.43\ (190 - 31)}{3501}\ X\ 100$ = **0.21%**
Heat loss due to partial conversion of C to CO **(L5)**	$= \frac{\%CO\ X\ C}{\%CO + \%\ CO_2}\ X\ \frac{5654}{GCV\ of\ fuel}\ X\ 100$ $= \frac{0.55\ X\ 0.36}{0.55\ + 14}\ X\ \frac{5654}{3501}\ X\ 100$ = **2.2%**
Heat loss due to radiation and convection in W/m^2 **(L6)**	= 0.548 × [(Ts / 55.55)4 - (Ta / 55.55)4] + 1.957 X (Ts - Ta)1.25 X √[(1.968Vm + 68.9) /68.9] = 0.548 × [(343/55.55)^4-(304/55.55)^4] + 1.957 X (343-304)$^{1.25}$ X √[(196.85 X 3.5 + 68.9)/68.9) = 937.62 W/m^2 *(1 W = 0.86 kcal)* = 937.67×0.86 = 806.35 kcal/m^2
Total radiation and convection loss per hour	= Heat loss due to radiation and convection X total surface area of boiler = 806.35 X 90 = 72,571.6 kcal/hr
Heat loss due radiation and convection loss in % **(L6)**	= (total radiation and convection loss per hour) / (GCV of fuel X Fuel firing rate) = (72,571.6) / (3501 X 5600) = 0.0037 = 0.0037 X 100 **= 0.37%**
Heat loss due to unburnt in fly ash **(L7)**	
% ash in coal	= 48
Ratio of bottom ash to fly ash	= 90:10
GCV of fly ash	= 450 kcal/kg
Amount of fly ash in 1 kg of coal	= 0.1 × 0.48 = 0.048 kg

Steps for calculating Boiler efficiency by indirect method	
Heat loss in fly ash	= 0.048 × 450 = 21.6 kcal / kg of coal
Heat loss in fly ash in % **(L7)**	= 21.6 × 100 /3501 **= 0.62%**
Heat loss due to unburnt in bottom ash **(L8)**	
GCV of bottom ash	= 800 kcal/kg
Amount of bottom in 1 kg of coal	= 0.9 × 0.48 = 0.432 kg
Heat loss in bottom ash	= 0.432 × 800 = 345.6 kcal/kg of coal
Heat loss in bottom ash in % **(L8)**	= 345.6 × 100/3501 **= 9.87 %**
Boiler efficiency	
Boiler efficiency by indirect method	= 100-(L1+L2+L3+L4+L5+L6+L7+L8) =100 - (7.1+4.36+0.83+0.21+2.2+0.37+0.62+9.87) = 100 – 25.6 **= 74.4%**

5.10.8. Boiler Blowdown

When water is boiled and steam is generated, any dissolved solids contained in the water remain in the boiler. If more solids are put in with the feed water, they will concentrate and may eventually reach a level where their solubility in the water is exceeded and they deposit from the solution. Above a certain level of concentration, these solids encourage foaming and cause carryover of water into the steam. The deposits also lead to scale formation inside the boiler, resulting in localized overheating and finally causing boiler tube failure.

It is, therefore, necessary to control the level of concentration of the solids and this is achieved by the process of 'blowing down', where a certain volume of water is blown off and is automatically replaced by feed water - thus maintaining the optimum level of total dissolved solids (TDS) in the boiler water. Blow down is necessary to protect the surfaces of the heat exchanger in the boiler. However, blow down can be a significant source of heat loss, if improperly carried out. The maximum amount of total dissolved solids (TDS) concentration permissible in various types of boilers is given in below table.

Table 32: Recommended TDS levels for various industrial process Boilers

Boiler Type	Maximum TDS (ppm)[6]
Lancashire	10,000
Smoke and water tube boilers	5,000
Low pressure water tube boiler	2000-3000
High pressure water tube boiler	3,000-3,500
Package and economic boiler	3,000

[6] parts per million

Conductivity as indicator of Boiler water quality

Since it is tedious and time consuming to measure total dissolved solids (TDS) in boiler water system, conductivity measurement is used for monitoring the overall TDS present in the boiler. A rise in conductivity indicates a rise in the "contamination" of the boiler water.

Conventional methods for blowing down the boiler depend on two kinds of blowdown - intermittent and continuous.

Intermittent Blowdown

The intermittent blown down is given by manually operating a valve fitted to discharge pipe at the lowest point of boiler shell to reduce parameters (TDS or conductivity, pH, Silica and Phosphates concentration) within prescribed limits so that steam quality is not likely to be affected. In intermittent blowdown, a large diameter line is opened for a short period of time, the time being based on a thumb rule such as “once in a shift for 2 minutes”.

Intermittent blowdown requires l*arge* short-term increases in the amount of feed water put into the boiler, and hence may necessitate larger feed water pumps than if continuous blow down is used. Also, TDS level will be varying, thereby causing fluctuations of the water level in the boiler due to changes in steam bubble size and distribution which accompany changes in concentration of solids. Also, substantial amount of heat energy is lost with intermittent blowdown.

Continuous Blowdown

There is a steady and constant dispatch of small stream of concentrated boiler water, and replacement by steady and constant inflow of feed water. This ensures constant TDS and steam purity at given steam load. Once blow down valve is set for a given conditions, there is no need for regular operator intervention.

Even though large quantities of heat are wasted, opportunity exists for recovering this heat by blowing into a flash tank and generating flash steam. This flash steam can be used for pre-heating boiler feed water or for any other purpose. This type of blow down is common in high-pressure boilers.

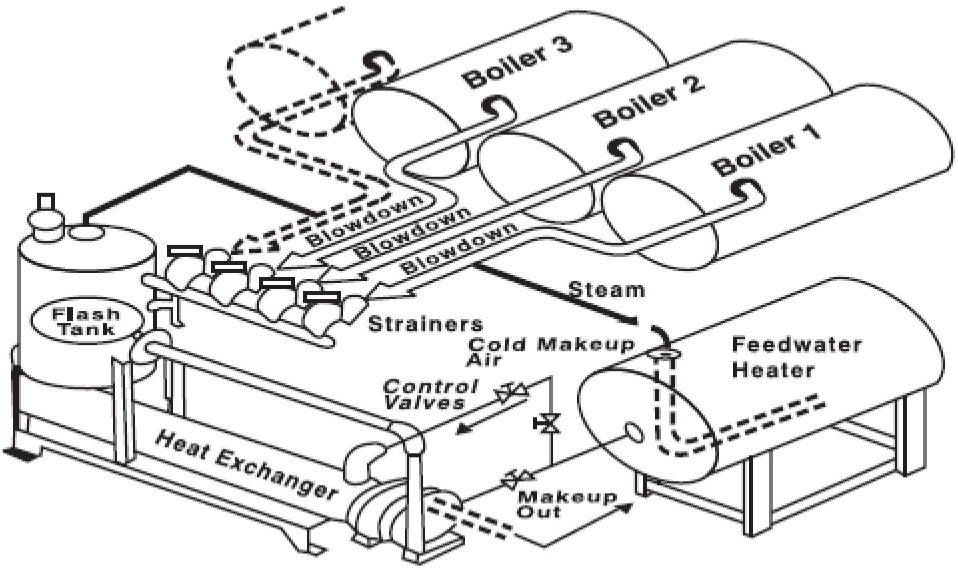


Figure 66: Blowdown heat recovery system

Blowdown calculations

The quantity of blowdown required to control boiler water solids concentration is calculated by using the following formula:

$$\text{Blow down (\%)} = \frac{\text{Feed water TDS X Make up water \%}}{\text{Maximum permissible TDS in Boiler water} - \text{Feed water TDS}} \text{ X 100}$$

If maximum permissible limit of TDS as in a package boiler is 3000 ppm, percentage make up water is 10% and TDS in feed water is 300 ppm, then the percentage blow down is given as:

$$\text{Blow down (\%)} = \frac{300 \text{ X } 10\%}{3000 - 300} \text{ X } 100 = 1.11\%$$

If boiler evaporation rate is 3000 kg/hr then required blow down rate is:
3000 X 1.11 % = 33.3 kg/hr

Benefits of Blowdown

Good boiler blow down control can significantly reduce treatment and operational costs that include:

- Lower pre-treatment costs
- Less make-up water consumption
- Reduced maintenance downtime
- Increased boiler life
- Lower consumption of treatment chemicals

5.10.9. Energy savings opportunities in Boiler

The various energy efficiency opportunities in boiler system can be related to combustion, heat transfer, avoidable losses, high auxiliary power consumption, water quality and blowdown.

Examining the following factors can indicate if a boiler is being run to maximize its efficiency:

1. Stack temperature

The stack temperature should be as low as possible. However, it should not be so low that water vapour in the exhaust condenses on the stack walls. This is important in fuels containing significant sulphur as low temperature can lead to sulphur dew point corrosion. Stack temperatures greater than 200°C indicates potential for recovery of waste heat. It also indicates the scaling of heat transfer/recovery equipment and hence the urgency of taking an early shut down for water / flue side cleaning.

2. Feed water preheating using economiser

Typically, the flue gases leaving a modern 3-pass shell boiler are at temperatures of 200 to 300°C. Thus, there is a potential to recover heat from these gases. The flue gas exit temperature from a boiler is usually maintained at a minimum of 200°C, so that the sulphur oxides in the flue gas do not condense and cause corrosion in heat transfer surfaces. When a clean fuel such as natural gas, LPG or gas oil is used, the economy of heat recovery must be worked out, as the flue gas temperature may be well below 200°C.

The potential for energy saving depends on the type of boiler installed and the fuel used. For a typically older model shell boiler, with a flue gas exit temperature of 260°C, an economizer could be used to reduce it to 200°C, increasing the feed water temperature by 15°C. Increase in overall thermal efficiency would be in the order of 3%. For a modern 3-pass shell boiler firing natural gas with a flue gas exit temperature of 140°C. A condensing economizer would reduce the exit temperature to 65°C increasing thermal efficiency by 5%.

3. Combustion air preheat

Combustion air preheating is an alternative to feedwater heating. In order to improve thermal efficiency by 1%, the combustion air temperature must be raised by 20°C. Most gas and oil burners used in a boiler plant are not designed for high air preheat temperatures.

Modern burners can withstand much higher combustion air preheat, so it is possible to consider such units as heat exchangers in the exit flue as an alternative to an economizer, when either space or a high feed water return temperature make it viable.

4. Incomplete combustion

Incomplete combustion can arise from a shortage of air or surplus of fuel or poor distribution of fuel. It is usually obvious from the colour or smoke and must be corrected immediately.

In the case of oil and gas fired systems, CO, or smoke (for oil fired systems only) with normal or high excess air indicates burner system problems. A more frequent cause of incomplete combustion is the poor mixing of fuel and air at the burner. Poor oil fires can result from improper viscosity, worn tips, carbonization on tips and deterioration of diffusers or spinner plates.

With coal firing, unburned carbon can comprise a big loss. It occurs as grit carry-over or carbon-in-ash and may amount to more than 2% of the heat supplied to the boiler. Non uniform fuel size could be one of the reasons for incomplete combustion. In chain grate stokers, large lumps will not burn out completely, while small pieces and fines may block the air passage, thus causing poor air distribution. In sprinkler stokers, stoker grate condition, fuel distributors, wind box air regulation and over-fire systems can affect carbon loss. Increase in the fines in pulverized coal also increases carbon loss.

5. Excess air control

The **Table 33** gives the theoretical amount of air required for combustion of various types of fuel. Excess air is required in all practical cases to ensure complete combustion, to allow for the normal variations in combustion and to ensure satisfactory stack conditions for some fuels.

Table 33: Theoretical combustion data - common Boiler fuel (Source: BEE)

Fuel	kg of air required/kg of fuel	kg of flue gas/kg of fuel	m^3 of flue/kg of fuel	Theoretical CO_2 % in dry flue gas	CO_2 % in flue gas achieved in practice
Bagasse	3.2	3.43	2.61	20.65	10-12
Coal (bituminous)	10.8	11.7	9.40	18.70	10-13
Lignite	8.4	9.10	6.97	19.40	9-13
Paddy Husk	4.6	5.63	4.58	19.8	14-15
Wood	5.8	6.4	4.79	20.3	11.13
Furnace Oil	13.90	14.30	11.50	15.0	9-14
LSHS	14.04	14.63	10.79	15.5	9-14

The optimum excess air level for maximum boiler efficiency occurs when the sum of the losses due to incomplete combustion and loss due to heat in flue gases is minimum. This level varies with furnace design, type of burner, fuel and process variables. It can be determined by conducting tests with different air fuel ratios. Typical values of excess air supplied for various fuels are given in **Table 34**

Table 34: Excess air levels for different fuels (Source: BEE)

Fuel	Type of Furnace or Burners	Excess Air (% by weight)
Pulverized coal	Completely water-cooled furnace for slag tap or dry ash removal	15-20
	Partially water-cooled furnace for dry-ash removal	15-40

Fuel	Type of Furnace or Burners	Excess Air (% by weight)
Coal	Spreader stoker	30-60
	Water-cooler vibrating-grate stokers	30-60
	Chain-grate and traveling-gate stokers	15-50
	Underfeed stoker	20-50
Fuel oil	Oil burners register type	15-20
	Multi-fuel burners and flat flame	20-30
Natural gas	High pressure burner	5-7
Wood	Dutch over (10-23%through grates) and Hofft type	20-25
Bagasse	All furnaces	25-35
Black liquor	Recovery furnaces for draft and soda-pulping processes	30-40

Controlling excess air to an optimum level always results in reduction in flue gas losses; for every 1% reduction in excess air there is approximately 0.6% rise in efficiency.

Various methods are available to control the excess air:

- Portable oxygen analysers and draft gauges can be used to make periodic readings to guide the operator to manually adjust the flow of air for optimum operation. Excess air reduction up to 20% is feasible.
- The most common method is the continuous oxygen analyser with a local readout mounted draft gauge, by which the operator can adjust air flow. A further reduction of 10-15% can be achieved over the previous system.
- The same continuous oxygen analyser can have a remote controlled pneumatic damper positioner, by which the readouts are available in a control room. This enables an operator to remotely control a number of firing systems simultaneously.
- The most sophisticated system is the automatic stack damper control, whose cost is really justified only for large systems.

6. Radiation and convection heat Loss

The external surfaces of a shell boiler are hotter than the surroundings. The surfaces thus lose heat to the surroundings depending on the surface area and the difference in temperature between the surface and the surroundings.

The heat loss from the boiler shell is normally a fixed energy loss, irrespective of the boiler output. With modern boiler designs, this may represent only 1.5% on the gross calorific value at full rating, but will increase to around 6%, if the boiler operates at only 25 percent output. Repairing or augmenting insulation can reduce heat loss through boiler walls and piping.

7. Automatic blowdown control

Uncontrolled continuous blowdown is very wasteful. Automatic blowdown controls can be installed that sense and respond to boiler water conductivity and pH. A 10% blow down operating at 15 kg/cm^2 pressure in a boiler will result in 3% efficiency loss.

8. Reduction of scaling and soot losses

In oil and coal-fired boilers, soot build-up on tubes acts as an insulator against heat transfer. Any such deposits should be removed on a regular basis. Elevated stack temperatures may indicate excessive soot build-up. Also, same result will occur due to scaling on the water side. High exit gas temperatures at normal excess air indicate poor heat transfer performance. This condition can result from a gradual build-up of gas-side or waterside deposits. Waterside deposits require a review of water treatment procedures and tube cleaning to remove deposits. An estimated 1% efficiency loss occurs with every 22°C increase in stack temperature.

Stack temperature should be checked and recorded regularly as an indicator of soot deposits. When the flue gas temperature rises about 20°C above the temperature for a newly cleaned boiler, it is time to remove the soot deposits. It is, therefore, recommended to install a dial type thermometer at the base of the stack to monitor the exhaust flue gas temperature.

It is estimated that 3 mm of soot can cause an increase in fuel consumption by 2.5% due to increased flue gas temperatures. Periodic off-line cleaning of radiant furnace surfaces, boiler tube banks, economizers and air heaters may be necessary to remove stubborn deposits.

9. Reduction of Boiler steam pressure

This is an effective means of reducing fuel consumption, if permissible, by as much as 1 to 2%. Lower steam pressure gives a lower saturated steam temperature and without stack heat recovery, a similar reduction in the temperature of the flue gas temperature results.

Steam is generated at pressures normally dictated by the highest pressure / temperature requirements for a particular process. In some cases, the process does not operate all the time, and there are periods when the boiler pressure could be reduced. The energy manager should consider pressure reduction carefully, before recommending it. Adverse effects, such as an increase in water carryover from the boiler owing to pressure reduction, may negate any potential saving. Pressure should be reduced in stages, and no more than a 20 percent reduction should be considered.

10. Variable speed control for Fans, Blowers and Pumps

Variable speed control is an important means of achieving energy savings. Generally, combustion air control is affected by throttling dampers fitted at forced and induced draft fans. Though dampers are simple means of control, they lack accuracy, giving poor control characteristics at the top and bottom of the operating range. In general, if the load characteristic of the boiler is variable, the possibility of replacing the dampers by a VSD should be evaluated.

11. Effect of Boiler loading on efficiency

The maximum efficiency of the boiler does not occur at full load, but at about two-thirds of the full load. If the load on the boiler decreases further, efficiency also tends to decrease. At zero output, the efficiency of the boiler is zero, and any fuel fired is used only to supply the losses. The factors affecting boiler efficiency are:

- As the load falls, so does the value of the mass flow rate of the flue gases through the tubes. This reduction in flow rate for the same heat transfer area, reduced the exit flue gas temperatures by a small extent, reducing the sensible heat loss.

- Below half load, most combustion appliances need more excess air to burn the fuel completely. This increases the sensible heat loss.

In general, efficiency of the boiler reduces significantly below 25% of the rated load and as far as possible, operation of boilers below this level should be avoided.

12. Proper Boiler scheduling

Since, the optimum efficiency of boilers occurs at 65-85% of full load, it is usually more efficient, overall, to operate a fewer number of boilers at higher loads, than to operate a large number at low loads.

13. Boiler replacement

The potential savings from replacing a boiler depend on the anticipated change in overall efficiency. A change in a boiler can be financially attractive if the existing boiler is:

- old and inefficient
- not capable of firing cheaper substitution fuel
- over or under-sized for present requirements
- not designed for ideal loading conditions

The feasibility study should examine all implications of long-term fuel availability and company growth plans. All financial and engineering factors should be considered. Since boiler plants traditionally have a useful life of well over 25 years, replacement must be carefully studied.

5.11. Furnaces & Ovens – energy performance assessment

5.11.1. Furnace

A furnace is an equipment to melt metals for casting or heat materials for change of shape (rolling, forging, etc.) or for change of properties (heat treatment).

5.11.2. Type and classification of difference furnaces

Based on the method of generating heat, furnaces are broadly classified into two types namely combustion type (using fuels) and electric type. The combustion type furnace can be broadly classified as oil fired, coal fired, or gas fired, depending upon the kind of combustion.

- Based on the mode of charging of material furnaces can be classified as (a) Intermittent or Batch type furnace or Periodical furnace and (b) Continuous furnace.
- Based on mode of waste heat recovery as recuperative and regenerative furnaces.
- Another type of furnace classification is made based on mode of heat transfer, mode of charging and mode of heat recovery.

The electric furnaces can be broadly classified as resistance type for heating and induction arc for melting of metals.

5.11.3. Characteristics of an efficient furnace

A furnace should be designed so that in a given time, as much of material as possible can be heated to a uniform temperature as possible with the least possible fuel and labour. To achieve this end, the following parameters can be considered.

- Determination of the quantity of heat to be imparted to the material or charge.
- Liberation of sufficient heat within the furnace to heat the stock and overcome all heat losses.
- Transfer of available part of that heat from the furnace gases to the surface of the heating stock.
- Equalisation of the temperature within the stock.
- Reduction of heat losses from the furnace to the minimum possible extent.

5.11.4. Furnace energy supply

Since the products of flue gases directly contact the stock, type of fuel chosen is of importance. For example, some materials will not tolerate sulphur in the fuel. Also use of solid fuels will generate particulate matter, which will interfere with the stock place inside the furnace. Hence, vast majority of the furnaces use liquid fuel, gaseous fuel or electricity as energy input. Electricity is used in induction and arc furnaces for melting steel and cast iron. Non-ferrous melting utilizes oil as fuel.

5.11.5. Data collection (for any type of furnace)

Following data shall be collected through observation and by interviewing furnace operator or supervisor:

- Furnace capacity

- Furnace batch cycle time (material processed (t) per batch)
- Rated parameters
- Type of raw material
- Energy supply (fuel fired or electric)
- Operating hours
- All other general operating details of furnace

In addition to above collect the following data through measurements:

- Thermal images of furnaces (with focus on potential heat losses)
- Flue gas analysis data (for fuel fired furnace only)
- Electricity consumption per batch cycle (for electrical furnaces only)

5.11.6. Instruments required (for Induction furnace)

- Three-phase power analyser
- Thermal imaging camera
- IR thermometer
- Sling psychrometer or digital thermometers

5.11.7. Performance terms and definition

$$Furnace\ efficiency, \eta = \frac{Heat\ output}{Heat\ input}\ X\ 100$$

OR

$$Furnace\ efficiency, \eta = \frac{Heat\ in\ stock\ (material), kcal}{Heat\ in\ fuel\ or\ electricity, kcal}\ X\ 100$$

$$Specific\ energy\ consumption = \frac{Amount\ of\ energy\ consumed, kcal/hr}{Quality\ of\ material\ processed, t/hr}$$

5.11.8. Induction Furnaces

Induction furnaces are ideal for melting and alloying a wide variety of metals with minimum melt losses. However, little refining of the metal is possible. There are two main types of induction furnace: coreless and channel the principle of operation of which are the same.

Coreless Induction Furnace consist of a water-cooled helical coil made of a copper tube, a crucible installed within the coil and supporting shell equipped with trunnions on which the furnace may tilt. Alternating current (AC) passing through the coil induces alternating current in the metals charge loaded to the crucible. This induced current heat the charge. When the charge is molten, electromagnetic field produced by the coil interacts with the electromagnetic field produced by the induced current. The resulted force causes stirring effect helping to homogenize the melt composition and the temperature. The frequency of the alternating current used in induction furnaces may vary from the line frequency (50 Hz or 60 Hz) to high frequency 10,000 Hz

The total absolute energy required to melt one tonne of different metals at different molten temperature is given in below table:

The induction furnace has mainly three phases of operation per batch processed. These are: melting phase, de-slagging phase, and pouring phase. The power requirement varies with each phase as shown in **Figure 67**

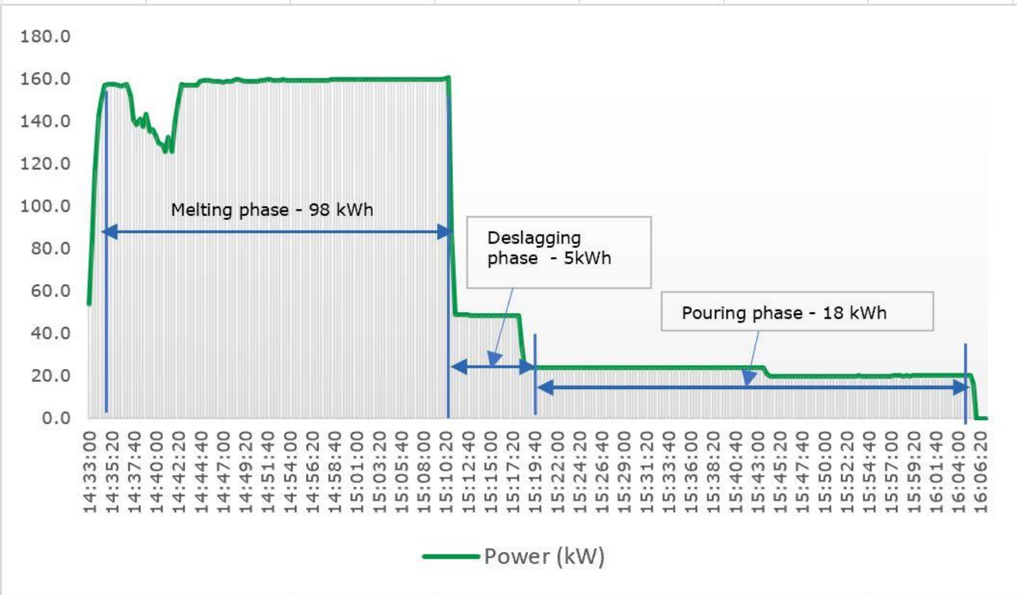


Figure 67: Different phases of induction furnace batch process – an example (Source: STENUM Asia)

5.11.9. Induction Furnace (IF) efficiency

$$IF\ efficiency\ (\%), \eta = \frac{Theoretical\ total\ heat\ required\ for\ melting, kWh}{Actual\ electricity\ consumed\ for\ melting,\ kWh}\ X\ 100$$

5.11.10. Theoretical heat required for melting

$$Heat\ required\ for\ melting\ metal, kWh\ = \frac{W_m\ X\ (C_P\ X\ (T_2 - T_1) + h)}{3600}$$

3600 kJ = 1 kWh

$$\text{Heat required for melting slag, , kWh} = \frac{1.65\ X\ W_s}{3.6}$$

3.6 MJ = 1 kWh

Where,
W_m – Weight of the metal, kg
W_s – Weight of the slag, kg
C_p – Specific heat of metal, kJ/kg°C
T_2 – Final melting temperature of the metal
T_1 – Initial or charge temperature of the metal
h – latent heat of metal

5.11.11. Determine Induction furnace efficiency

To determine the induction furnace efficiency, follow the below steps:

Step-1: Using a three-phase power analyser, record the power consumption of induction furnace over a full batch cycle as shown in **Figure 67**

Step-2: With the help of furnace operator or shift engineer, determine the weight of the molten metal and the slag. This may be estimated using best efforts, if exact measured values are not available.

Step-3: Measure the ambient temperature and Note the melting temperature of molten metal

Step4: Use the induction furnace efficiency formula to calculate the efficiency

Example: Calculate the induction furnace efficiency of a Brass melting process from the data given below:

Specific heat of Brass metal: 0.38 kJ/kg°C
Latent heat: 168 kJ/kg
Melting temperature: 1000°C
Metal temperature at ambient: 30°C
Quantity of metal: 250 kg
Quantity of slag: 15 kg
Electricity consumed for melting: 98 kWh

Solution: Using the below formula

$$Heat\ required\ for\ melting\ metal, HT, kWh\ = \frac{W_m\ X\ (C_P\ X\ (T_2 - T_1) + h)}{3600}$$

$$Heat\ required\ for\ melting\ metal = \frac{250\ X\ (0.38\ X\ (1000 - 30) +\ 168)}{3600}$$

$$Heat\ required\ for\ melting\ metal =\ 37\ kWh$$

$$Heat\ required\ for\ melting\ slag,\ kWh = \frac{1.65\ X\ 15}{3.6} = 7\ kWh$$

Total theoretical heat required for melting 250 kg of Brass = 37 + 7 = 44 kWh

$$Efficiency(\%), \eta = \frac{Theoretical\ total\ heat\ required\ for\ melting, kWh}{Actual\ electricity\ consumed\ for\ melting, kWh}\ X\ 100$$

$$Efficiency(\%), \eta = \frac{44\ kWh}{98\ kWh}\ X\ 100$$

$$Efficiency\ (\%), \eta = \mathbf{45}\%$$

5.11.12. Energy savings opportunities in Induction furnaces

1. Charge preparation and charging

- Weigh and arrange raw material on melt floor near to furnace before starting the melting procedure.
- Keep record of charging time to each crucible heat wise. This will help to compare charging time shift wise and thus finding opportunity to reduce charging time.
- Charge must be free from sand, dirt and oil/grease. Rusty scrap not only takes more time to melt but also contains less metal per charging. For every 1% slag formed at 1500°C, energy loss is 10 kWh per ton.
- The maximum size of single piece of metal/scrap should not be more than 1/3 of diameter of furnace crucible. It avoids problem of bridging. Moreover, each charge at a time should be about 10% of crucible volume
- Charge the scrap continuously as the melt in proceeds. Continuous charging helps in preheating the scrap at the top. Do not charge furnace beyond the coil level.
- First Charge should be smaller pieces having high density or thin and compact scrap. Larger scrap pieces should be added once there is a molten pool available inside the crucible
- Install automatic vibratory feeder for faster and continuous feeding of material.

2. Melting and making the melt ready

- Run the furnace at maximum power since beginning. Maximum power input increases rate of melting and hence reduces cycle time of a heat.
- Use lid mechanism or ceramic blanket cover for furnace crucible, radiation heat loss accounts for 4 – 6 % input energy. A 500 kg crucible melting at 1450°C with no lid or cover has radiation heat loss of up to 25 kWh/t
- Do not super heat the metal. Install pyrometer to measure and monitor molten metal temperature. "Superheating by 50°C can increase furnace specific energy consumption by 25 kWh/t"

3. Emptying the furnace

- Plan melting according to moulding capacity. Metal should never wait for mould rather mould should be ready before metal.
- Keep record of waiting time caused due to non-readiness of the moulding line.
- Insulate the ladle; the surface temperature should not be greater than 80ºC. This will also reduce the additional time taken by the induction furnace to reheat the molten metal to attain desired temperature.
- Use ladle pre-heater. Using molten metal to pre-heat ladle is quite energy intensive and expensive.
- Glass-wool or ceramic-wool covers for pouring ladle to minimize temperature drop between tapping and pouring.
- Do not delay moulding process once melt is ready and ensure quantity of liquid metal returned to furnace must be as low as possible

4. Other best practices

- Installing separate energy meters for each crucible.
- Monitoring energy consumption on heat by heat basis. Analyse them in correlation with production data to arrive at specific energy consumption of each crucible on daily basis.
- Keep storage of scrap dust and moisture free. Separate covered, raised concrete storage platform can be provided to keep stored scrap material dust and moisture free.
- Keep all the slag removing tools near to furnace prior to de-slagging. Completely remove the slag to avoid slag deposition on furnace lining. Slag deposition on furnace lining reduces furnace volume and hence the metal output.

5.11.13. Electric Arc Furnace (EAF)

The alternating current (AC) electric arc furnace (EAF) melts the charged material using an electric arc. The energy required for producing the melt is provided by the electric arc between each of the three electrodes and the metallic charge as shown in **Figure 68**. Through the EAF route it is possible to produce steel using 100% scrap mix, which would reduce the energy consumption for making steel as compared to primary steelmaking through the blast furnace route. The construction of EAF encompasses an outer cylindrical steel shell internally lined with several layers of designated refractory materials, with the whole system mounted on a motorized tilting mechanism. The three electrodes enter the furnace from the roof through three cylindrical openings at an angle of 120°. The roof is made of refractory brick, usually of high alumina. The vertical movement of electrodes is generally controlled automatically with a thyristor-based system. The crucible, roof, and electrodes are water cooled to maintain the temperature and improve the service life. EAFs are generally provided with a door at the back to carry out alloying, oxygen lancing, and de-slagging. A pouring spout is present at the front in case of a launder pouring system and an opening is present at the bottom in case of an 'Eccentric Bottom Tapping' (EBT) which leads to slag-free tapping and shorter tap-to-tap times.

The steps involved in EAF operations include: (i) charging (ii) complete meltdown (iii) oxidation and refining (iv) de-oxidation, and (v) tapping into ladle.

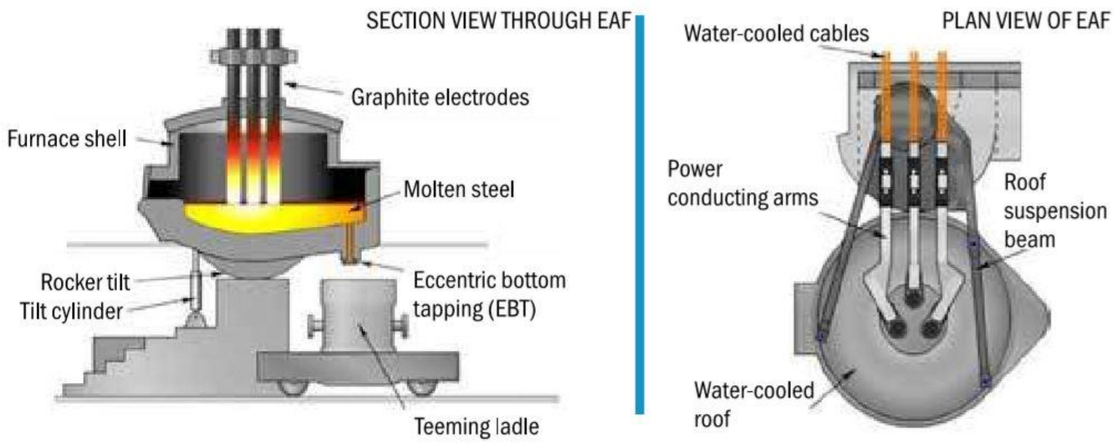


Figure 68: Electric arc furnace - section and plan view (source: steeluniversity.org)

5.11.14. Instruments required (for EAF)

- Three-phase power analyser
- Ultrasonic water flow meter
- Flue gas analyser
- Thermal imaging camera
- Pyrometer
- Differential pressure meter

5.11.15. Performance terms and definitions of EAF

1. Capacity utilisation

The performance of the EAF is dependent on the overall utilisation of the capacity of EAF. The capacity utilisation is the ratio of utilised capacity to installed capacity in percentage.

2. Yield

The yield of an EAF unit is defined as the share in percent of liquid metal with reference to the quantity of raw materials charged. Higher the ratio of liquid metal, higher will be the yield and vice versa. The yield of an EAF is primarily dependent on the quality of scrap and share of input raw materials, such as direct reduced iron, scrap, pig iron, and returns. The degree of metallisation of the raw materials varies, thus the ratio of different raw materials is an important parameter in deciding the net yield of EAFs. The yield can vary significantly based on grades of steel produced in the EAF. The typical yield of the EAF was found to vary from 85% to 92%. The yield of the EAF plant generally increases with furnace capacities.

$$Yield\ (\%) = \frac{Quantity\ of\ liquid\ metal\ (tonne\ per\ heat)}{Total\ quantity\ of\ raw\ materials\ added\ in\ the\ furnace\ (tonne\ per\ heat)}\ X\ 100$$

3. Specific energy consumption of EAF

The major energy form used in an EAF unit is electricity followed by chemical energy. The Specific Energy Consumption (SEC) of the EAF is defined as the ratio of the total energy consumed by the furnace to the production of liquid steel. The SEC level is an important indicator of the EAF that shows how effectively the furnace is performing. The energy consumption in an EAF is monitored for each heat on a tap-to-tap basis. A few EAF units have installed oxy-fuel burner systems which provide additional thermal energy through gas firing along with electrical energy input. In this case, the overall SEC of the EAF would include both electricity and fuel consumption.

$$SEC\ of\ EAF = \frac{Energy\ input\ (kWh\ per\ heat)}{Total\ quantity\ of\ raw\ materials\ added\ in\ the\ furnace\ (tonne\ per\ heat)}$$

Wide variations have been observed in the SEC levels of the EAF units. The SEC of the electric arc furnaces was observed to be in the range of 420 to 775 kWh per tonne of liquid steel. Large variations in the SEC level may be attributed to numerous factors, such as the grade of steel produced, composition of raw materials, size of the furnace, capacity utilization, temperature of liquid metal, and operating practices. The SECs of the furnaces have a tendency to decrease with an increase in capacities and vice versa. Moreover, any deviations of tapping temperature from set temperatures can lead to a substantial increase in SEC levels for the same product. On-line measurements and the control of key operating parameters and associated control systems are important to optimise SEC levels in EAFs.

4. Material balance

The input of the material balance are three fold: firstly, the metallic raw materials comprising pig iron, direct reduced iron (DRI), light and heavy scrap and plant returns; secondly, additives such as limestone, dolomite, coke, CPC, ferroalloys, aluminium ingots and deoxidizers; finally, the electrode consumed during the EAF operation. The world average use of pig iron in EAF is about 5%, which may go up to 60% with scarce availability of scrap. The pig iron usage in the EAF typically varies between 5%–30% depending on the grade of steel produced, cost of pig iron and scrap, etc. The quality of scrap used is one of the important factors in the overall yield (liquid metal) of the furnace. The output predominantly includes liquid metal (85%–92%), slag (6%–11%) and off-gases (1%–2%) generated through chemical reactions

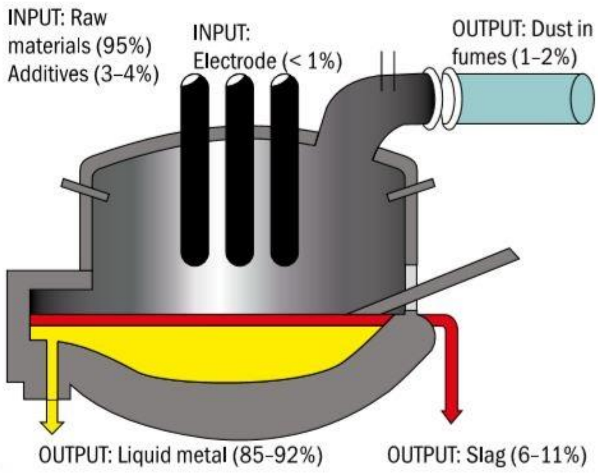


Figure 69: Material balance of EAF

5. **Energy balance**

The energy balance of the EAF is a method to evaluate the efficiency of the system and compare relative energy losses. It is based on the total energy inputs and outputs to the EAF over the entire tap-to-tap cycle. The energy distribution in an EAF is mainly dependent on the raw material quality, its costs and is unique to the specific unit operation. The oxygen provided to the EAF will react with a number of elements in the bath, such as aluminium, silicon, manganese, phosphorus, carbon and iron, and forming oxides of respective elements. These reactions are exothermic providing additional heat.

The major heat losses include sensible heat in off gases (15%–20%) which are generated during various reactions occurring inside the furnace during operation. Another significant heat loss in an EAF is heat carried by cooling water (8%–14%). The quantum of heat losses in EAF clearly shows that there exists a significant potential to reduce energy consumption by reducing various heat losses. In addition to the EAF, the other energy-consuming areas include cooling water systems (pumps and cooling tower) and fumes extraction system (primary-and secondary-induced draft fans). There is a significant potential for energy saving through the adoption of energy-efficient technologies and practices in these areas as well.

5.11.16. Measurements in EAF

The assessment of the energy balance is based on measurements and analysis of the data collated during energy audits. The portable instruments used for measuring key operating parameters are as shown in table:

Instruments	Application
Three-phase power analyser	Record the power consumption of EAF over a complete cycle
Ultrasonic water flow meter	Measure the cooling water flow rate
Flue gas analyser	Conduct flue gas analysis to measure the CO & O_2 content in flue gas
Thermal imaging camera	Measure the surface temperatures of the EAF
Pyrometer	Measure the temperature of EAF and openings
Differential pressure meter	Measure off-gases velocity

5.11.17. Performance assessment of EAF

This section describes the basic methods for quantification of energy losses and performance assessment of the EAFs. The assessment of furnace and its associated auxiliaries should be conducted at normal plant-load operation. Ideally, all heat inputs to the furnace should be utilised towards the melting of metal; however, in practice, a number of energy losses occur within the system, leading to deviations in system performance. These losses are summarised below.

Heat loss in off-gases: The off-gases resulting from various chemical reactions occurring inside the furnace exit at quite high temperatures (900 -1100°C), which account for major heat loss in an electric arc furnace.

Heat loss in off-gases =m ×Cp ×(Tg-Ta)

m: Quantity of off-gases (kg/heat)
Cp: Specific heat of gases (kcal/kg °C)
Tg: Temperature of off-gases (°C)
Ta: Ambient temperature (°C)

Heat loss in cooling water: The furnace needs to be cooled continuously during the operation in order to maintain the sidewall and roof temperatures within the permissible limits. Any increase in the temperature of furnace walls can lead to refractories being damaged. Further, the temperature of off-gas needs to be brought down using cooling water before entering into bag filters, where temperature is a limiting factor.

Heat loss in cooling water=m × (Tout – Tin)

m: Quantity of cooling water (kg/heat)
Tout: Outlet temperature of cooling water (°C)
Tin: Inlet temperature of cooling water (°C)

Heat in slag: The melting operation forms a sizeable quantity of slag. The slag comprises oxides of Si, Mn, Ca, Fe, and Al along with other impurities present in charge material. This slag is removed at very high temperatures leading to substantial heat losses.

Heat loss in slag = [m×Cp×L×(Tm-Ta)] +(m×L) + [m×Cp×L×(Ts-Tm)]

m: Quantity of slag (kg/heat)
Cps: Specific heat of solid slag (kcal/kg °C)
CpL: Specific heat of liquid slag (kcal/kg °C)
Tm: Melting point of slag
Ts: Temperature of slag (°C)
Ta: Ambient temperature (°C)
L: Heat required for phase transition (kCal/kg)

Heat losses through openings: Radiation and convection heat losses occur from openings present in the furnace and through air infiltration due to furnace draft. The main opening in furnace is slag door, which is kept open throughout the heat in most units.

Heat loss through opening =Fb ×E ×F ×A

E: Emissivity of the surface
Fb: Black body radiation at furnace temperature (kcal/kg/cm^2/hr)
F: Factor of radiation
A: Area of opening (cm^2)

Surface heat loss: The heat from furnace surfaces, such as sidewalls, roof, etc. are radiated to the atmosphere. The quantum of surface heat losses are dependent on the type and quality of insulation used in furnace construction. The surface heat loss per m2 area can be estimated using:

$$\mathbf{Q = [a \times (Ts - Ta)^{5/4}] + [4.88 \times E \times \{(T_s/100)^4 - (T_a/100)^4\}]}$$

a: Factor for direction of the surface of natural convection ceiling
T_S: Surface temperature (K)
Ta: Ambient temperature (K)
E: Emissivity of external wall surface of the furnace
The total energy losses are the sum of all the losses occurring in the furnace.

Furnace efficiency: The efficiency of furnace is evaluated by subtracting various energy losses from the total heat input. For this, various operating parameters pertaining to different heat losses must be measured, for example, the energy consumption rate, heat generated from chemical reactions, temperature of off-gases, surface temperatures, etc. Data for some of these parameters can be obtained from production records while others must be measured with special monitoring instruments.

Furnace efficiency = Total heat input – Total energy losses

5.11.18. Energy savings opportunities in EAF

1. Replacement of old and inefficient power transformers in EAF units

The old (more than 20 years) and inefficient transformers with up to maximum power rating of 500 kVA per tonne can be replaced with Ultra-high-power transformers (UHP) in EAF units, which will help in reducing energy losses and shorter tap-to-tap time. This would help reduce fixed losses of the EAF. By definition, in EAFs, if the input power is above 700 kVA per tonne, the transformer is termed as UHP. Although UHPs are typically available in the range 700–1,500 kVA.

2. Aluminium electrode arm

The electrode current-conducting arm carries power from the transformers to the electrodes. A mild steel support with water-cooled copper cables is the standard material used in EAFs. A copper clad, that is, steel arm with copper bus tubes, is also being used in the furnaces. The copper system (Cu-system) has high strength and conductivity. The overall weight of the Cu-system is quite high; the electromagnetic forces around the copper bus and electrode clamping heads affect the system performance. This increases the system resistance leading to a drop in the power fed to the furnace. The maintenance requirement for a Cu-system is also high.

The shortcomings in EAF operations with Cu-system can be overcome with 'aluminium electrode arm'. The aluminium system (Al-system) is lighter than the Cu-system which is also a non-magnetic material. The Al-system comprises aluminium current conducting electrode arms and columns with guide roll assemblies. The average energy savings with aluminium electrode arm is estimated to be about 0.7%. The advantages of an Al-system include the following:

- High-arc power
- Increased productivity
- Reduction in maintenance downtime
- Lower weight
- Less mechanical vibrations

3. Improved regulation control

One of the major issues with a conventional regulation system is that it is a complex-structure contact on-load changer, which increases the switching time (3–5 seconds). Further, the on-load changers operate in a high-intensity mode (frequent changes ~500–800 per day) leading to high wear and tear thereby, decreasing the operational reliability.

The shortcomings in conventional regulation systems (analog/electro-hydraulic) can be addressed with "high pressure hydraulic digital regulation". The digital system would allow minimum delays for switching from one melting stage to another. This system can be linked with 'Level-2 or 3'automation for dynamic production control. The main advantages of digital based regulation system are the following:

- Reduction in tap-to-tap time
- Increase in productivity
- Increase in operational reliability

4. Bottom stirring – inert gas purging

The molten metal in the arc furnace may not be of homogenous mass or uniform quality across the cross section. This may result in increased tap-to-tap time and energy consumption. Moreover, it can lead to a high rejection level. Homogenisation of the liquid metal bath is required to overcome the issues and enhance productivity.

The bottom stirring of liquid bath in an EAF is a potential solution for better homogenisation and ensures uniform quality. The mechanism used at present for bottom stirring is inert gas injection, mostly used in developed countries. In an inert gas-stirring system, the stirring of liquid metal is accomplished using inert gases such as argon or nitrogen. Bottom-stirring systems based on inert gas injection are available either as a single tube or multi-hole plugs. These plugs are either buried in the furnace hearth ramming mix or 'indirect purging' or in contact with steel melt or 'direct purging'. Indirect purging arrangement offers improved stirring arrangement due to better distribution of inert gases.

The bottom stirring using inert gases are more suitable for smaller furnaces. Bottom stirring further accelerates chemical reactions between steel and slag. The stirring helps in an increased heat transfer with an estimated energy saving of 12–24 kWh per tonne liquid steel. It further leads to increased metal yield of about 0.5%. However, the use of inert gas would require significant maintenance after every heat. The advantages of inert gas-based bottom stirrer include the following:

- Improved control of the temperature and chemical composition
- Lower consumption of refractory and electrode
- Shorter TTT times
- Improvement in liquid metal yield

5. Mist cooling for electrodes

Typically, graphite electrodes are used in EAFs. The electrodes are clamped by an electrode holder and inserted in the furnace. The electric arc is generated between the tip of the electrodes which produces heat to melt the material in the furnace. The side surface of the electrodes is oxidised and consumed due to the high temperature. During the operation of the furnace, the shape of electrodes changes and at the tip it decreases to as low as 70% of the original electrode diameter.

The oxidation loss of the side surface of the electrodes can be reduced by coating the outer surface or by reducing the outer surface temperature of the electrode. A jacket of water mist is created over the outer surface of the electrodes which forms a coating over the electrodes surface, thereby reducing the temperature of the side surface.

5.11.19. Fuel Fired Furnace

Furnace oil is the major fuel used in oil fired furnaces, especially for reheating and heat treatment of materials. Light diesel oil (LDO) is used in furnaces where presence of sulphur is undesirable. The key to efficient furnace operation lies in complete combustion of fuel with minimum excess air.

Furnaces operate with efficiencies as low as 7% as against up to 90% achievable in other combustion equipment such as boiler. This is because of the high temperature at which the furnaces have to operate to meet the required demand. For example, a furnace heating the stock to 1200°C will have its exhaust gases leaving at least at 1200 °C resulting in a huge heat loss through the stack.

However, improvements in efficiencies have been brought by methods such as preheating of stock, preheating of combustion air and other waste heat recovery systems.

5.11.20. Instrument required (for fuel fired furnace)

- Flue gas analyser
- Thermal imaging camera
- IR thermometer
- Three-phase power analyser
- Digital distance operator

5.11.21. Performance terms for fuel fired furnace

$$Thermal\ efficiency\ of\ the\ furnace = \frac{Heat\ in\ the\ stock}{Heat\ in\ the\ fuel\ consumed\ for\ heating\ the\ stock}\ X\ 100$$

5.11.22. Performance evaluation of a typical fuel fired furnace

Thermal efficiency of process heating equipment, such as furnaces, ovens, heaters, or kilns is the ratio of useful heat output to heat input.

In the context of performance assessment of furnaces, the concepts of excess air and computation of various heat losses, as in case of boilers, could be applied, but there exist several additionalities and features, that differentiate furnace efficiency from boiler efficiency. Whereas boiler efficiency of 70-90% is achievable, furnace efficiencies at times are as low as 7%, while with favourable condition, like good design, appropriate loading, waste heat recovery practices, efficiencies of up to 60% & higher can be achieved. The reasons for low furnace efficiency include:

- High stack temperature and excess air levels.
- Low capacity utilization/ hearth loading.
- Radiation losses due to opening.
- Surface heat losses.
- Batch operation involving heating, cooling and soaking cycles.

The purpose of a heating process is to introduce a certain amount of thermal energy into a product, raising it to a certain temperature to prepare it for additional processing or change its properties. To carry this out, the product is heated in a furnace. This results in energy losses in different areas and forms as shown in Sankey diagram **Figure 70** For most heating equipment, a large amount of the heat supplied is wasted in the form of exhaust gases.

These furnace losses include:

- Heat storage loss in the furnace structure
- Losses from the furnace outside walls or structure
- Heat transported out of the furnace by the load conveyors, fixtures, trays, etc. called material handling losses.
- Radiation losses from openings, hot exposed parts, etc.
- Heat carried by the cold air infiltration into the furnace
- Heat carried by the excess air used in the burners.

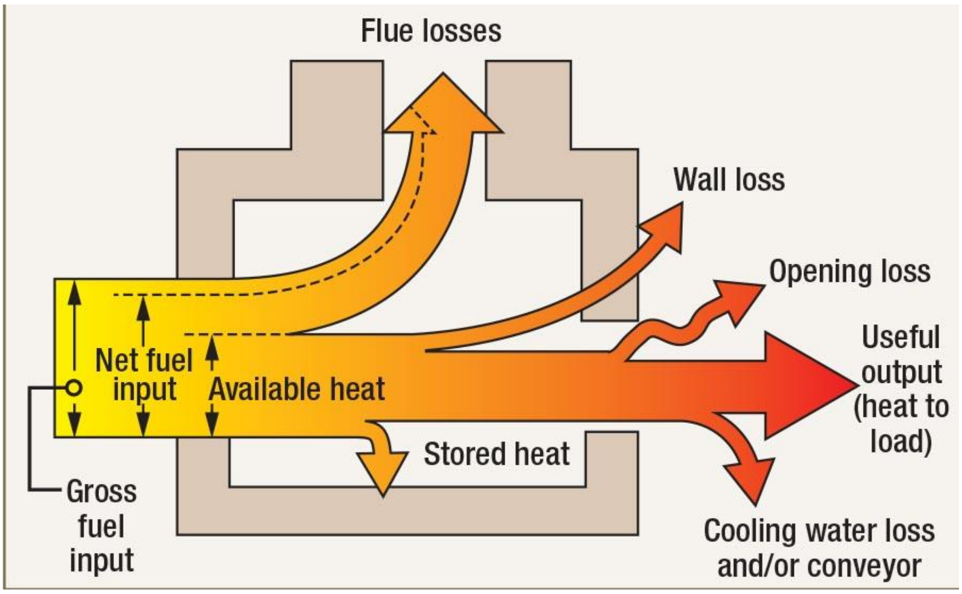


Figure 70: Furnace losses

Heat storage loss in the furnace structure: First, the metal structure and insulation of the furnace must be heated so their interior surfaces are about the same temperature as the product they contain. This stored heat is held in the structure until the furnace shuts down, then it leaks out into the surrounding area. The more frequently the furnace is cycled from cold to hot and back to cold again, the more frequently this stored heat must be replaced. Fuel is consumed with no useful output.

Furnace wall losses: Wall or transmission losses are caused by the conduction of heat through the walls, roof, and floor of the heating device, as shown in **Figure 71** The wall losses continue as long as the furnace is operating.

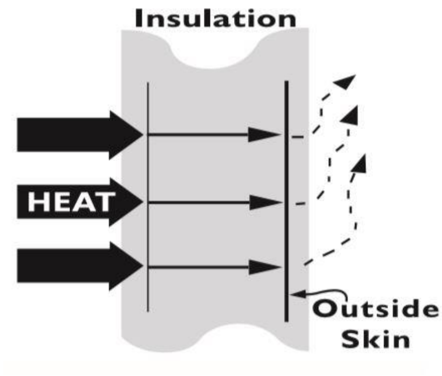


Figure 71: Furnace wall losses

Radiation losses or opening losses: Furnaces and oven operating at temperatures above 540°C might have significant radiation losses, as shown in **Figure 72.** Hot surfaces radiate energy to nearby colder surfaces, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. If there are any openings, damaged roof/wall or open inspection windows, there will be heat loss by radiation.

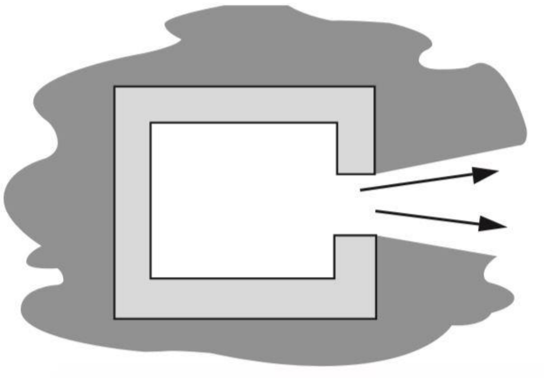


Figure 72: Furnace opening losses

Material handling losses: Many furnaces use equipment to convey the work into and out of the heating chamber, and this can also lead to heat losses. Conveyor belts or product hangers that enter the heating chamber cold and leave it at higher temperature drain energy from the combustion gases. In car bottom furnaces, the hot car structure gives off heat to the room each time it rolls out of the furnace to load or remove work. This lost energy must be replaced when the car is returned to the furnace.

Air infiltration: Excess air does not necessarily enter the furnace as part of the combustion air supply. It can also infiltrate from the surrounding room if there is negative pressure in the furnace. Because of the draft effect of hot furnace stacks, negative pressures are fairly common, and cold air slips past leaky door seals, cracks and other openings in the furnace. **Figure 73** illustrates air infiltration from outside the furnace. Every time the door is opened, considerable amount of heat is lost. Economy in fuel can be achieved if the total heat that can be passed on to the stock is as large as possible.

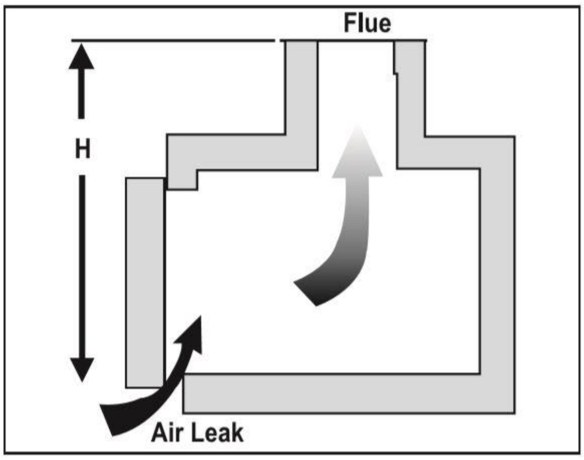


Figure 73: Air infiltration in furnace

Waste-gas losses: Waste gas loss, also known as flue gas or stack loss, is made up of the heat that cannot be removed from the combustion gases inside the furnace. The reason is the heat flows from the higher temperature to the lower temperature heat receiver.

5.11.23. Furnace heat balance method

Heat balance helps us to numerically understand the present heat loss and efficiency and improve the furnace operation using these data. Thus, preparation of heat balance is a pre-requirement for assessing energy conservation potential. The methodology of a typical furnace heat balance is given simultaneously along with an example in **5.11.26**

The total heat input is provided in the form of fuel or power. The desired output is the heat supplied for heating the material or process. Other heat outputs in the furnaces are undesirable heat losses. The inputs and outputs are calculated on the basis of per tonne of stock/charge.

Similar to the method of evaluating boiler efficiency by indirect method, furnace efficiency can also be calculated from heat balance. Furnace efficiency is calculated after subtracting

- sensible heat loss in flue gas
- loss due to moisture in flue gas
- heat loss due to openings in furnace
- heat loss through furnace skin and
- other unaccounted losses from the heat input to the furnace.

In order to carry out a heat balance, various parameters that are required are hourly oil consumption, material output, excess air quantity, temperature of flue gas, temperature of furnace at various zones, skin temperatures and hot combustion air temperature.

The energy absorbed by the material requires the use of specific heat which can be obtained from reference manual/data book.

If the process requires a change in state, from solid to liquid, or liquid to gas, then in addition to sensible heat, an additional quantity of energy is required called the latent heat of fusion or latent heat of evaporation and this quantity of energy needs to be added to the total energy requirement.

5.11.24. Measurement parameters in fuel fired furnace

The following are some of the key measurements to be carried out for the heat balance method in reheating furnaces

- **Weight of stock/billets heated**, with the help of furnace operator obtain the weight of stock or billets to be heated per batch.
- Using thermal imager camera or IR thermometer measure the initial and final temperature of the stock/billets in °C
- Using thermal imager camera or IR thermometer measure temperature of the furnace walls and roofs
- Using furnace engineering drawing which is usually available with engineering team, find the area of furnace walls and roof
- Using flue gas analyser, measure the flue gas temperature
- Using the flue gas analyser, measure the O_2, CO_2, CO (and other gas) parameters
- Measure or collect from industry measured values of the fuel consumption of furnace per batch
- Reference manual shall be referred for certain data like specific heat and humidity, etc.

5.11.25. Determine fuel fire furnace efficiency by direct method

The direct determination of furnace efficiency is carried out as follows:

$$Thermal\ efficiency\ of\ the\ furnace = \frac{Heat\ in\ the\ stock}{Heat\ in\ the\ fuel\ consumed\ for\ heating\ the\ stock}\ X\ 100$$

Heat in the stock can be found by following formula:

$Q_s = m \text{ X } Cp \text{ X } (t_2 - t_1)$

Where,

m = weight of the stock in kg

C_p = Specific heat of stock in kcal/kg°C

t_1 = final temperature of stock desired in °C

t_2 = Initial temperature of stock before it enters the furnace in °C

And, Heat in the fuel consumed for heating the stock can be found by following formula:

Heat in Fuel = Quantity of fuel X gross calorific value (GCV) of fuel

Example: the following are the operating parameters of rerolling mill furnace
Weight of input material – 10 t/hr
Furnace oil consumption – 600 l/hr
Specific gravity of oil – 0.92
Final material temperature - 1200°C
Initial material temperature - 40°C
Specific heat of the material – 0.12 kcal/kg/°C
GCV of oil – 10,000 kcal/kg
Yield percentage of furnace – 92%

a. Calculate furnace efficiency by direct method
b. Calculate specific fuel consumption on finished based basis

Solution:

a. Furnace efficiency by direct method

Heat input = 600 l/hr X 0.92 X 10,000 = 55,20,000 kcal/hr
Heat output = 10,000 X 0.12 X (1200 – 40) = 13,92,000 kcal/hr
Efficiency = 13,92,000 / 55,20,000 = **25.2%**

b. Specific fuel consumption of finished basis

Weight of finished products = 10 X 0.92 = 9.2 t/hr
Furnace oil consumption = 600 l/hr
Specific fuel consumption = 660/9.2 = **65.2 l/t**

5.11.26. Example: Heat balance of furnace

An oil-fired reheating furnace has an operating temperature of 1340°C. Average fuel consumption is 400 l/hr. The flue gas exit temperature after air pre-heater is 655°C. Air is pre-heated from ambient temperature of 40°C to 190°C through an air pre-heater. The furnace has 460 mm thick wall on the billet extraction outlet side, which is 1mm high (D) and 1 m wide. Draw a heat balance to identify losses, efficiency and specific fuel consumption. The other data are as follows:

Parameter	Value
Flue gas temperature after air pre-heater	655°C
Ambient temperature	40°C
Absolute humidity	0.03437 kg/kg dry air
Pre-heated air temperature	190°C
Specific gravity of oil	0.92
Average fuel oil consumption (l/hr)	400 l/hr
Average fuel oil consumption (kg/hr)	= 400 X 0.92 = 368 kg/hr
O_2 in flue gas	12%
CO_2 in flue gas	6.5%
CO in flue gas	50 ppm
Weight of stock	6,000 kg/hr
Specific heat of billet	0.12 kcal/kg°C
Surface temperature of ceiling	85°C
Surface temperature of side walls	100°C
Surface temperature of flue duct	64°C
Area of ceiling	15 m^2
Area of side walls	36 m^2
Area of flue duct	10.3 m^2
Diameter of flue duct	0.4 m

Furnace oil constituents (% by weight)

Carbon: 85.9%, Hydrogen: 12%, Oxygen: 0.7%, Nitrogen: 0.5%, Sulphur: 0.5%, H_2O: 0.35%, Ash: 0.05%, GCV: 10,000 kcal/kg

Solution:

1.Calculation of air quantity and specific fuel consumption	
Theoretical air required for combustion	[(11.6 X C) + {34.8 X (H_2 – O_2/8)} + (4.35 X S)] / 100 kg/kg of fuel (from fuel analysis) = [(11.6 X 85.9) + {34.8 x (12-0.7/8)} + (4.35 X 0.5)] /100 = **14.12 kg of air/kg of fuel**
% excess air supplied (EA)	$= \frac{O_2\%}{21 - O_2\%} X\ 100 = \frac{12}{21-12} X\ 100 = \mathbf{133.3}\%$
Actual mass of air supplied / kg of fuel (AAS)	$= \left(1 + \frac{EA}{100}\right) X\ theoretical\ air$ $= \left(1 + \frac{133.3}{100}\right) X\ 14.12 = \mathbf{32.94\ kg\ of air/kg\ of\ fuel}$
Mass of dry flue gas (m_d)	= Mass of CO_2 + Mass of N_2 content in the fuel + Mass of sulphur dioxide + Mass of N_2 in the combustion air supplied + Mass of oxygen in flue gas $= \frac{0.859\ X\ 44}{12} + 0.005 + \frac{0.005\ X\ 64}{32} + \frac{32.94\ X\ 77}{100} + \frac{(32.94 - 141.12)\ X\ 23}{100}$ = **32.86 kg/kg of coal**
Amount of wet flue gas	= AAS +1 = 32.94 + 1 = **33.94 kg of flue gas / kg of fuel**
Amount of water vapor in flue gas (m_w)	= M + 9 H_2 (M - % moisture in fuel, H_2 - % hydrogen in fuel) = (0.35/100) + 9 x (12/100) = **1.084 kg of H_2O/kg of fuel**
Amount of dry flue gas	Amount of wet flue gas -Amount of water vapour in flue gas = 33.94-1.084 = **32.86 kg /kg of fuel**
Specific fuel consumption	= Amount of fuel consumed (kg/hr) / Amount of billet (t/hr) = 368 /6 = **61.33 kg of fuel / t of billet**

2. Calculation of heat input	
Combustion heat of fuel (Q_1)	= Amount of fuel consumed per t of billet X GCV of fuel = 61.33 X 10,000 = **613,300 kcal/t of billet**
Sensible heat of fuel (Q_2)	= F X C_{pfuel} (t_f – t_a) = 61.33 X 0.5 X (100 – 40) = **1840 kcal/t of billet** Where, F = Amount of fuel consumed per t of billet (kg/t) C_{pfuel} = Average specific heat of fuel (kcal/kg°C) t_f = Fuel temperature before fed into the burner °C = 100°C t_a = Ambient temperature °C = 40°C
Total heat input	= Q1 + Q2 = 613,300 + 1840 = **615,140 kcal/t of billet**

3. Calculation of heat output	
Heat carried away by 1 t of billet, Q_3	= 1000 kg/t X C_p X (T_0 – T_i) = 1000 X 0.12 X (1340 – 40) = **156,000 kcal/t of billet** Where, C_p = specific heat of billet in kcal/kg°C = 0.12 T_0 = Temperature of billet at furnace exit in °C = 1340°C T_i = Temperature of billet at furnace entrance in °C = 40°C
Heat loss in dry flue gas per t of billet (Q_4)	= F X m X $C_{p\ fg}$ X (t_1 – t_a) = 61.33 X 32.86 X 0.26 X (655 – 40) = **322,247 kcal/t of billet** Where, F = Amount of fuel consumed in kg per t of billet m = Actual mass of dry flue gas in kg/kg of fuel $C_{p\ fg}$ = Mean specific heat of flue gas in kcal/kg°C = 0.26 kcal/kg°C (calculated in **5.11.27**) t_1 = Temperature of flue gas after air pre-heater = 655°C t_a = ambient temperature = 40°C

3. Calculation of heat output	
Heat loss due to formation of water vapour from fuel per t of billet (Q_5)	= F X m_w X (584 + $C_{p\ of\ super\text{-}heated\ vapor}$ X ($t_1 - t_a$)) = 61.33 X 1.084 X (584 + 0.47 X (655 – 40) = **58,042 kcal/t of billet** Where, m_w = amount of water vapour in flue gas $C_{p\ of\ super\text{-}heated\ vapor}$ (for specific heat value refer **Table 36**)
Heat loss due to moisture in combustion air (Q_6)	= F X AAS X humidity of air X $C_{p\ of\ super\text{-}heated\ vapor}$ X ($t_1 - t_a$)) = 61.33 X 32.94 X 0.03437 X 0.47 X (655 – 40) = **20,070 kcal/t of billet**
Heat loss due to partial conversion of C to CO (Q_7)	$= F\ X\ \frac{\%CO\ X\ C}{\%CO+\%CO_2}\ X\ 5654$ $= 61.33X\ \frac{0.005\ \ X\ 0.859}{0.005+6.5}\ X\ 5654$ = **229 kcal/t of billet**
Amount of heat loss from the furnace body and other sections (Q8) **Where,**	= (q_1 +q_2 + q_3 + q_4), kcal/hr / amount of billet (t/hr) Where, q_1 = Heat loss from the furnace body ceiling surface (horizontal surface facing upward) q_2 = Heat loss from the furnace body sidewall surface (vertical surfacing sideways) q_3 = Bottom (horizontal surface facing downward) q_4 = Heat loss from the flue gas duct between the furnace exit and air pre-heater (including heat loss from the external surface of the air pre-heater)
q_1	$= [h\ X\ A\ X\ (t_1 - t_2)^{1.25}] + [4.88\ X\ E\ X\ \left(\frac{t_1+273}{100}\right)^4 - \left(\frac{t_2+273}{100}\right)^4\ X\ A]$ $= [2.8\ X\ 15\ X\ (85-40)^{1.25}] +$ $[4.88\ X\ 0.75\ X\ \left(\frac{85+273}{100}\right)^4 - \left(\frac{40+273}{100}\right)^4\ X\ 15]$ = [2.8 X 15 X $45^{1.25}$] + [4.88 X 0.75 X $(3.58)^4$ – $(3.13)^4$ X 15 = **8,644 kcal/hr** Where,

3. Calculation of heat output	
	h = heat rate, natural convection factor, (for ceiling = 2.8 kcal/m2h°C) A = ceiling surface area (m^2) = 15 m^2 t_1 = External temperature of ceiling = 85°C t_2 = Ambient temperature around furnace = 40°C E = Emissivity of the furnace body surface = 0.75
q_2	= $[h\,X\,A\,X\,(t_1-t_2)^{1.25}] + [4.88\,X\,E\,X\,\left(\frac{t_1+273}{100}\right)^4 - \left(\frac{t_2+273}{100}\right)^4 X\,A]$ = $[2.2\,X\,36\,X\,(100-40)^{1.25}] +$ $[4.88\,X\,0.75\,X\,\left(\frac{100+273}{100}\right)^4 - \left(\frac{40+273}{100}\right)^4 X\,36]$ = $[2.2 \text{ X } 36 \text{ X } 60^{1.25}] + [4.88 \text{ X } 0.75 \text{ X } (3.73)^4 - (3.13)^4 \text{ X } 36]$ = **26,084 kcal/hr** Where, h = heat rate, natural convection factor, (for sidewall = 2.2 kcal/m2h°C) A = side wall surface area (m^2) = 36 m^2 t_1 = External temperature of sidewall = 100°C t_2 = Ambient temperature around furnace = 40°C E = Emissivity of the furnace body surface = 0.75
q_3	= Bottom (horizontal surface facing downward) As the bottom surface is not exposed to the atmosphere **q3 is ignored** in this calculation
q_4	= $[\,h\,X\,A\,X\,\frac{(t_1-t_2)^{1.25}}{D^{0.25}}] + [4.88\,X\,E\,X\,\left(\frac{t_1+273}{100}\right)^4 - \left(\frac{t_2+273}{100}\right)^4 X\,A]$ = $[\,1.1\,X\,10.3\,X\,\frac{(64-40)^{1.25}}{0.4^{0.25}}] +$ $[4.88\,X\,0.75\,X\,\left(\frac{64+273}{100}\right)^4 - \left(\frac{40+273}{100}\right)^4 X\,10.3]$ = $[1.1 \text{ X } 10.3 \text{ X } (4^{1.25}/0.4^{0.25})] + [4.88 \text{ X } 0.75 \text{ X } (3.37)^4 - (3.13)^4 \text{ X } 10.3]$ = **2,001 kcal/hr** h = heat rate, natural convection factor, (for flue gas duct = 1.1 kcal/m^2h°C)

3. Calculation of heat output	
	A = External surface area of flue gas duct (m^2) =10.3 m^2 D = Outside diameter of the flue gas duct in m = 0.4 m t_1 = External temperature of flue gas duct = 64°C t_2 = Ambient temperature around furnace = 40°C E = Emissivity of the furnace body surface = 0.75
Q8	= (q1 + q2 +q3 +q4) / amount of billet (t/hr) = 8,644 + 26,084 +0 + 2,001 = **6,122 kcal/t**

Radiation heat loss through furnace openings (Q_9)	$= hr\ X\ A\ X\ \Phi\ X\ 4.88\ \ X\left[\left(\frac{t_1+273}{100}\right)^4 - \left(\frac{t_2+273}{100}\right)^4\right]$ / amount of billet (t/hr) $= 1\ X\ 1\ X\ 0.70\ X\ 4.88\ \ X\left[\left(\frac{1613}{100}\right)^4 - \left(\frac{313}{100}\right)^4\right]/6$ = **38,485 kcal/t** Where, hr = open time during the period of heat balancing =1 hr A = Area of an opening in m^2 = 1 m^2 Φ = Co-efficient based on the profile of furnace openings (from **Table 35**) = Diameter (or) the shortest side / wall thickness = 1/0.46 = 2.17 = 0.70 (value corresponding to 2.17 and square shape from **Table 35**) t_1= furnace temperature = 1340°C t_2= ambient temperature around furnace = 40°C Amount of billet (t/hr) = 6

Other types of heat loss / unaccounted losses (Q_{10})	other types of heat loss will include the following, • Heat carried away cooling water in the flue damper • Heat carried away by cooling water at the furnace access door • Radiation from the furnace bottom • Heat accumulated by refractory • Instrumental error and measuring error • Others
Q_{10}	= $Q_1+Q_2 - (Q_3+Q_4+Q_5+Q_6+Q_7+Q_8+Q_9)$ = (6,13,300 + 1,840) – (1,56,000 + 3,22,247 + 58,042 + 20,070 +229 + 6,122 + 38,485) = **13,945 kcal/t**

Total heat output	= $Q_3+Q_4+Q_5+Q_6+Q_7+Q_8+Q_9$ = 1,56,000 + 3,22,247 + 58,042 + 20,070 +229 + 6,122 + 38,485 = **615,140 kcal/t**

4. Heat balance table					
Heat Input			**Heat Output**		
Item	**kcal/t**	**%**	**Item**	**kcal/t**	**%**
Q_1	613,300	99.7	**Q_3**	156,000	25.4
Q_2	1,840	0.3	**Q_4**	322,247	52.4
			Q_5	58,042	9.4
			Q_6	20,070	3.3
			Q_7	229	0.04
			Q_8	6,122	1.0
			Q_9	38,485	6.2
			Q_{10}	13,945	2.3
Total	**615,140**	**100**		**615,140**	**100**

5. Efficiency of Furnace

$$Furnace\ efficiency\ (\%), \eta = \frac{Heat\ carried\ away\ by\ billet\ in\ kcal/t}{Combustion\ heat\ of\ fuel\ in\ kcal/t}\ X\ 100$$

$$Furnace\ efficiency\ (\%), \eta = \frac{156{,}000}{613{,}300}\ X\ 100 = \mathbf{25.4}\%$$

Data Tables

Table 35: Coefficient based on the profile of furnace openings (Φ)

Shape of opening	Diameter (or) the shortest sided divided (÷) by wall thickness							
	0.01	**0.1**	**0.2**	**0.5**	**1.0**	**2.0**	**4.0**	**6.0**
Circular	0.02	0.10	0.18	0.35	0.52	0.67	0.80	0.86
Square	0.02	0.11	0.20	0.36	0.53	0.69	0.82	0.87
Rectangular (2:1)	0.03	0.13	0.24	0.43	0.60	0.75	0.86	0.90
Very long and very narrow	0.05	0.22	0.34	0.54	0.68	0.81	0.89	0.92

Table 36: Specific heat of gases at constant pressure

Temperature (°C)	**Specific heat in kcal/Nm^3°C**						
	N_2	**CO_2**	**O_2**	**H_2O**	**H_2**	**SO_2**	**Air**
0	0.311	0.388	0.312	0.341	0.306	0.425	0.311
100	0.311	0.413	0.316	0.344	0.307	0.446	0.311
200	0.312	0.433	0.321	0.349	0.309	0.465	0.312
300	0.313	0.451	0.325	0.352	0.310	0.482	0.316
400	0.317	0.467	0.330	0.357	0.311	0.495	0.318
500	0.319	0.481	0.334	0.364	0.311	0.508	0.322
600	0.322	0.494	0.339	0.370	0.312	0.519	0.324
700	0.325	0.505	0.344	0.376	0.313	0.528	0.328
800	0.329	0.516	0.348	0.382	0.314	0.536	0.332
900	0.332	0.524	0.351	0.388	0.317	0.543	0.334
1000	0.334	0.533	0.355	0.394	0.317	0.549	0.339
1100	0.339	0.541	0.356	0.400	0.319	*0.555*	0.340
1200	0.340	0.548	0.360	0.407	0.322	0.560	0.344
1300	0.343	0.554	0.362	0.411	0.323	0.564	0.345
1400	0.345	0.560	0.365	0.419	0.325	0.568	0.349
1500	0.348	0.566	0.367	0.424	0.327	0.571	0.350
1600	0.350	0.571	0.368	0.429	0.328	0.574	0.354
1700	0.351	0.576	0.371	0.434	0.330	0.578	0.355
1800	0.354	0.580	0.372	0.440	0.333	0.580	0.356
1900	0.355	0.584	0.375	0.444	0.334	0.582	0.359
2000	0.356	0.588	0.377	0.449	0.337	0.584	0.360

5.11.27. Calculation of mean specific heat

Composition of dry flue gas	Mass of gas/kg of fuel	Mass fraction	Specific heat (kcal/Nm^3 °C @ 655°C)	Partial specific heat (kcal/Nm^3 °C) @655°C	Partial specific heat (kcal/kg°C) @655°C
CO_2	3.15	0.096	0.4995	0.0479	0.0244
SO_2	0.01	0.0003	0.5235	0.0002	0.0001
O_2	4.33	0.132	0.3415	0.0450	0.0315
N_2	25.37	0.772	0.3235	0.2498	0.1998
Total	**32.86**				**0.26**

Specific heat of dry flue gas at 655°C = 0.26 kcal/kg°C

Specific heat of dry flue gas at 40°C = 0.24 kcal/kg°C
(calculated in the same way as for 655°C)

$$Mean\ specific\ heat\ of\ dry\ flue\ gas, kcal\ /kg°C = \frac{(0.26\ X\ 655) - (0.24\ X\ 40)}{655 - 40} = 0.26$$

Sample calculation for CO_2 in the above table

$$Mass\ of\ \mathrm{CO_2}\ per\ kg\ of\ fuel\ firing = \frac{\%\ carbon\ in\ fuel\ X\ Molecular\ weight\ of\ \mathrm{CO_2}}{100\ X\ Molecular\ weight\ of\ carbon}$$

$$Mass\ of\ \mathrm{CO_2}\ per\ kg\ of\ fuel, kg/kg = \frac{85.9\ X\ 44}{100\ X\ 12} = 3.15$$

$$Mass\ fraction\ of\ \mathrm{CO_2}\ in\ dry\ flue\ gas = \frac{Mass\ of\ \mathrm{CO_2}\ per\ kg\ of\ fuel}{Mass\ of\ dry\ flue\ gas\ per\ kg\ of\ fuel}$$

$$Mass\ fraction\ of\ \mathrm{CO_2}\ in\ dry\ flue\ gas = \frac{3.15}{32.86} = 0.096$$

$$Partial\ specific\ heat\ kcal\ per\ kg°C = \frac{Mas\ fraction\ X\ specific\ heat\ X\ 22.4}{Molecular\ weight}$$

$$Partial\ specific\ heat\ kcal\ per\ kg°C = \frac{0.096\ X\ 0.4995\ X\ 22.4}{44} = 0.0244$$

Specific heat of dry flue gas, kcal/kg°C = ∑Partial specific heat

Specific heat of dry flue gas, kcal/kg°C = 0.26

5.11.28. Energy savings opportunities in fuel fired furnaces

1. Excess air optimization

The quantum of waste heat generation is directly proportional to the quantity of air used for combustion of fuel. Air, slightly in excess of ideal stoichiometric (or theoretical) is required (air ratio) for complete combustion. However, excess air beyond optimum range may substantially decrease combustion efficiency as it leads to generation of excessive hot waste gases. On the other hand, if the excess air is less, then unburnt components in flue gases will increase and would be carried away in the flue gases through stack. The optimization of combustion air is the most attractive and economical measure for energy conservation. The impact of this measure is higher when the temperature of furnace is high.

Air Ratio is defined as the ratio of "actual air supplied" (AAS) to theoretical air requirement. The following formula shall be used for calculating the air ratio (value rounded to two digits). The air ratio is considered based on steady state operation at constant load conditions and can be measured and verified at specific measurement points while maintaining maximum permissible limit for carbon monoxide (CO) level to 200 ppm.

$$Air\ ratio = \frac{21}{21 - Oxygen\ \%\ in\ flue\ gas}$$

- *Using a flue gas analyser, measure the oxygen % in flue gas*
- *Maintain the air ratio for industrial fuel fired furnaces as per below* **Table 37**

Table 37: Air ratio for fuel fired furnaces

Kiln type	Air ratio for oil fired furnaces	Oxygen% in flue gas
Oil heating (thermal fluid heater)	1.18 – 1.22	3.2% - 3.7%
Reheating Furnace	1.15 – 1.20	2.73% - 3.5%

2. Air ratio control by VFD

Controlling oxygen levels and using Variable frequency Drives (VFDs) on combustion air fans associated with reheating furnaces help in optimizing combustion in the furnace. The use of VFDs on combustion air fans in reheating furnace also helps to control oxygen levels, especially during variation in furnace production rate. The fuel and electricity savings in reheating furnace through optimization of excess air level depend on load factor of the furnace and the control strategies applied. The estimated energy saving is 4%–9% of thermal energy.

3. Air ratio control by damper

If a reheating furnace is not equipped with an automatic air ratio fuel controller, it is necessary to periodically sample gas in the furnace and measure its oxygen contents by a flue gas analyser and accordingly adjust the damper to control and maintain the target air fuel ratio.

4. Uniform heat distribution

Furnace design should be such that in a given time, as much of the stock could be heated uniformly to a desired temperature with minimum fuel firing rate.

Following points shall be examined during audit for furnace burners:

- The flame should not touch any solid object and should propagate clear of any solid object. Any obstruction will atomise the fuel particles thus affecting combustion and create black smoke. If flame impinges on the stock, there would be increase in scale losses. (Refer **Figure 74 to Figure 77**)
- If the flames impinge on refractories, the incomplete combustion products can settle and react with refractory constituents at high flame temperatures.
- The flames of different burners in a furnace should stay clear of each other. If they intersect, inefficient combustion will occur. It is recommended to stagger the burners on the opposite sides.
- The burner flame tends to travel freely in the combustion space just above the material. In small furnaces, the axis of the burner is never placed parallel to the hearth but always at an upward angle. Flame should not hit the roof.

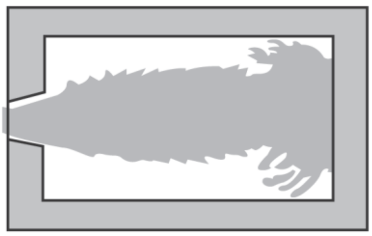


Figure 74: Wrong Correct heat distribution in furnace

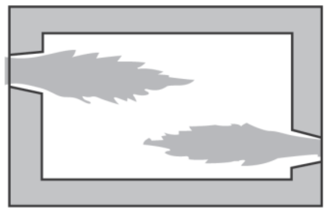


Figure 75: Correct heat distribution in furnace

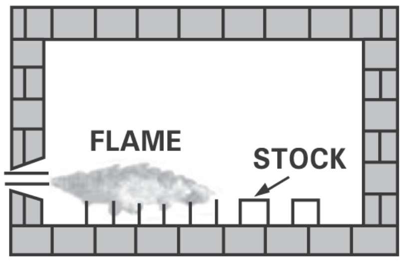


Figure 76: Wrong alignment of burners

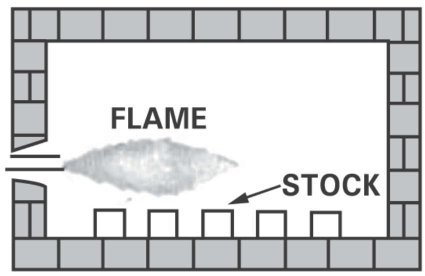


Figure 77: Correct alignment of burners

- The larger burners produce a long flame, which may be difficult to contain within the furnace walls. More burners of less capacity give better heat distribution in the furnace and also increase furnace life.
- For small furnaces, it is desirable to have a long flame with golden yellow colour while firing furnace oil for uniform heating. The flame should not be too long that it enters the chimney or comes out through the furnace top or through doors. In such cases, major portion of additional fuel is carried away from the furnace.

5. Maintaining optimum operating temperature of furnace

It is important to operate the furnace at optimum temperature. The operating temperature of various furnaces are given in below **Table 38**

Table 38: Operating temperature of various furnaces

Operating temperature of various furnaces	
Slab reheating furnaces	1200°C
Rolling mill furnaces	1200°C
Bar furnace for sheet mill	800°C
Bogey type annealing furnace	650 - 750°C

Operating at too high temperatures than optimum causes heat loss, excessive oxidation, decarbonisation as well as over stressing of the refractories. These controls are normally left to operator judgement, which is not desirable. To avoid human error, on/off controls should be provided.

6. Prevention of heat loss through openings

Heat loss through openings consists of, the heat loss by direct radiation through openings plus(+) the heat loss caused by combustion gas that leaks through openings, If the furnace pressure is slightly higher than outside air pressure (as in case of reheating furnace) during its operation, the combustion gas inside may blow off through openings and results in heat loss. But it is more detrimental, if outside air intrudes into the furnace, creating uneven temperature distribution inside the furnace and in process also oxidizing billets.

7. Control of furnace draft

If negative pressures exist in the furnace, air infiltration is liable to occur through the cracks and openings thereby affecting air- fuel ratio control. Tests conducted on apparently airtight furnaces have shown air infiltration up to the extent of 40%. Neglecting furnaces pressure could mean problems of cold metal and non-uniform metal temperatures, which could affect subsequent operations like forging and rolling and result in increased fuel consumption. For optimum fuel consumption, slight positive pressure should be maintained in the furnace as shown in **Figure 78** Exfiltration is less serious than infiltration. Some of the associated problems with exfiltration are leaping out of flames, overheating of the furnace refractories leading to reduced brick life, increased furnace maintenance, burning out of ducts and equipment attached to the furnace.

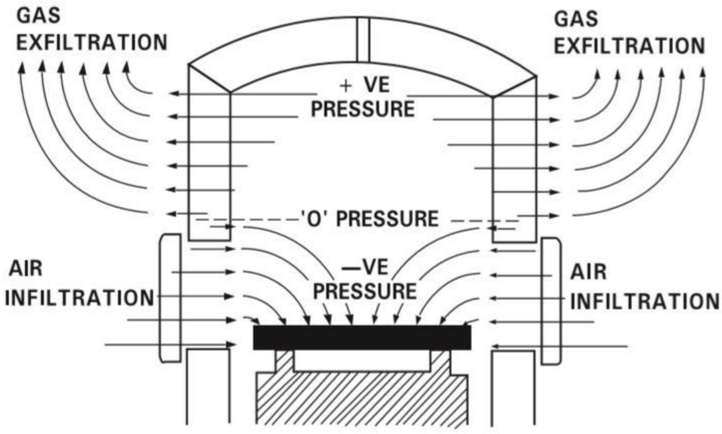


Figure 78: Effect of pressure on the location of zero level and infiltration of air (Source: BEE)

In addition to the proper control on furnace pressure, it is important to keep the openings as small as possible and to seal them in order to prevent the release of high temperature gas and intrusion of outside air through openings such as the charging inlet, extracting outlet and peephole on furnace walls or the ceiling.

8. Optimum capacity utilisation

One of the most vital factors affecting efficiency is loading. There is a specific loading at which the furnace will operate at maximum thermal efficiency. If the furnace is under loaded a smaller fraction of the available heat in the working chamber will be taken up by the load and therefore efficiency will be low.

The best method of loading is generally obtained by trial; note the weight of material put in at each charge, the time it takes to reach the desired temperature and the amount of fuel used. Every endeavour should be made to load a furnace at the rate associated with optimum efficiency although it must be realised that limitations to achieving this are sometimes imposed by work availability or other factors beyond control.

The loading of the charge on the furnace hearth should be arranged so that

- It receives the maximum amount of radiation from the hot surfaces of the heating chambers and the flames produced.
- The hot gases are efficiently circulated around the heat receiving surfaces

Stock should not be placed in the following position

- In the direct path of the burners or where flame impingement is likely to occur
- In an area which is likely to cause a blockage or restriction of the flue system of the furnace.
- Close to any door openings where cold spots are likely to develop.

In the interests of economy and work quality the materials comprising the load should only remain in the furnace for the minimum time to obtain the required physical and metallurgical requirements. When the materials attain these properties, they should be removed from the furnace to avoid damage and fuel wastage. The higher the working temperature, higher is the loss per unit time. The effect on the materials by excessive residence time will be an increase in surface defects due to oxidation. The rate of oxidation is dependent upon time, temperature, as well as free oxygen content. The possible increase in surface defects can lead to rejection of the product. It is therefore essential that coordination between the furnace operator, production and planning personnel be maintained. One of the reasons for not operating the furnace at optimum loading is the mismatching of furnace dimension with respect to charge and production schedule.

9. Waste heat recovery from furnace flue gases

In any industrial furnace the products of combustion leave the furnace at a temperature higher than the stock temperature. Sensible heat losses in the flue gases, while leaving the chimney carry 35 to 55% of the heat input to the furnace. The higher the quantum of excess air and flue gas temperature, the higher would be the waste heat availability. Waste heat recovery should be considered after all other energy conservations measures have been taken. Minimising the generation of waste heat should be the primary objective.

The sensible heat in flue gases can be generally recovered by the following methods:

- Charge (stock) preheating
- Preheating of combustion air
- Utilising waste heat for other process (to generate steam or hot water by a waste heat boiler)

Charge pre-heating

When raw materials are preheated by exhaust gases before being placed in a heating furnace, the amount of fuel necessary to heat them in the furnace is reduced. Since raw materials are usually at room temperature, they can be heated sufficiently using high temperature to reduce fuel consumption.

Preheating of combustion air

The energy contained in the exhaust gases can be recycled by using it to pre-heat the combustion air. A variety of equipment is available to preheat the combustion air such as:

Radiation recuperators generally, take the form of concentric cylinders, in which the combustion air passes through the annulus and the exhaust gases from the furnace pass through the centre, see **Figure 79 (a)**. The simple construction means that such recuperators are suitable for use with dirty gases, have a negligible resistance to flow, and can replace the flue or chimney if space is limited. The annulus can be replaced by a ring of vertical tubes, but this design is more difficult to install and maintain. Radiation recuperators rely on radiation from high temperature exhaust gases and should not be employed with exhaust gases at less than about 800°C.

Convection recuperators consist essentially of bundles of drawn or cast tubes; see **Figure 79 (b)** Internal and/or external fins can be added to assist heat transfer. The combustion air normally passes through the tubes and the exhaust gases outside the tubes, but there are some applications where this is reversed. For example, with dirty gases, it is easier to keep the tubes clean if the air flows on the outside. Design variations include 'U' tube and double pass systems. Convection recuperators are more suitable for exhaust gas temperatures of less than about 900°C.

Self-Recuperative burners are based on traditional heat recovery techniques in that the products of combustion are drawn through a concentric tube recuperator around the burner body and used to pre-heat the combustion air. A major advantage of this type of system is that it can be retrofitted an existing furnace structure to increase production capability without having to alter the existing exhaust gas ducting arrangements. Self-recuperative burners are generally more suited to heat treatment furnaces where exhaust gas temperatures are lower and there are no stock recuperation facilities.

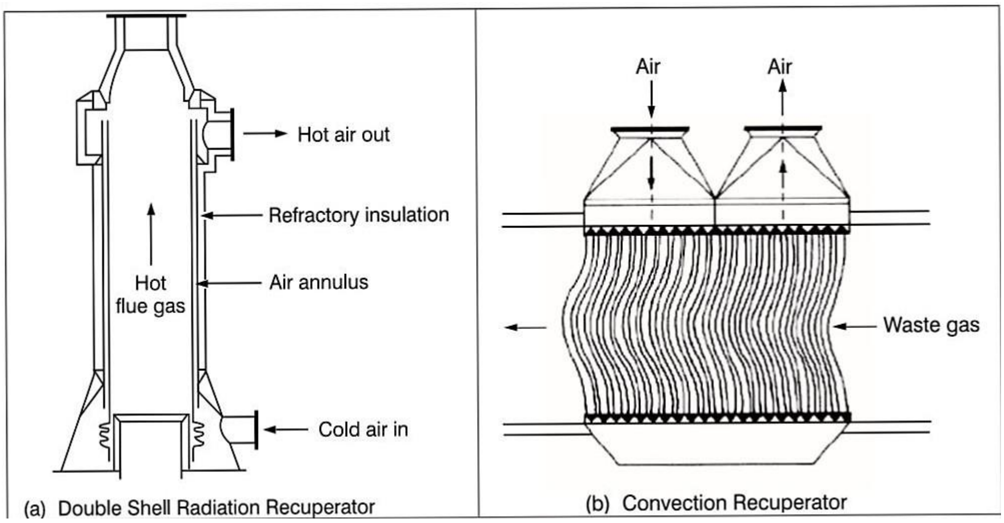


Figure 79: Recuperators

Estimation of fuel savings by pre-heating combustion air: By using preheated air for combustion, fuel can be saved. The fuel saving rate is given by the following formula:

$$S = \frac{P}{F + P - Q} X\,100$$

Where, S: Fuel saving rate (%)

F: Calorific value of fuel (kcal/kg fuel)
P: Quantity of heat brought in by preheated air (kcal/kg fuel)
Q: Quantity of heat taken away by exhaust gas (kcal/kg)

By this formula, fuel savings rates for heavy oil were calculated for various temperatures of exhaust gas and preheated air. The results are shown in the following **Figure 80**

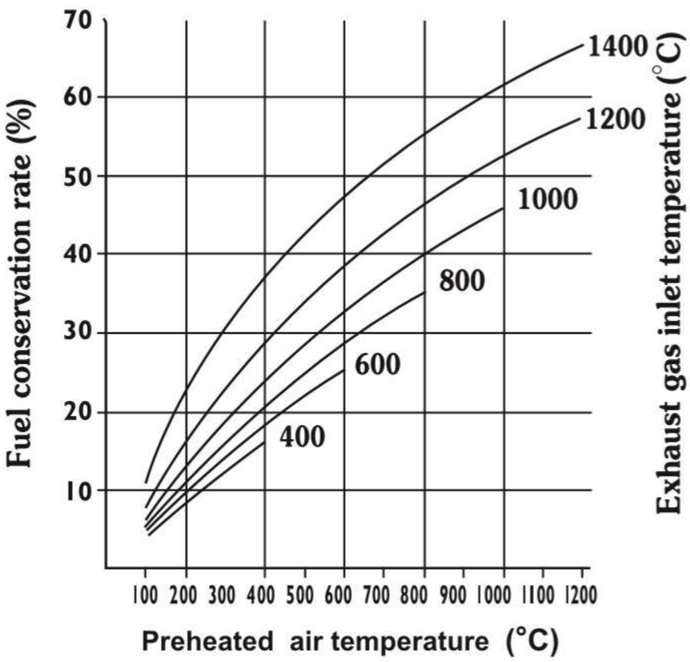


Figure 80: Fuel savings rate by preheated air temperature (Source: BEE)

For example, when combustion air for heavy oil is preheated to 400°C by a heat exchanger with an inlet temperature of 800 °C, the fuel conservation rate is estimated to be about 20 percent. When installing a recuperator in a continuous steel reheating furnace, it is important to choose a preheated air temperature that will balance the fuel saving effect and the invested cost for the equipment.

Also, the following points should be checked:

Draft of exhaust gas: When exhaust gas goes through a recuperator, its draft resistance usually causes a pressure loss of 5-10 mm H_2O.Thus, the draft of stack should be checked.

Air blower for combustion air: While the air for combustion goes through a recuperator, usually 100-200 mm H_2O pressure is lost. Thus, the discharge pressure of air blower should be checked, and the necessary pressure should be provided by burners.

Since the volume of air is increased owing to its preheating, it is necessary to be careful about the modification of air-duct diameters and blowers. As for the use of combustion gases resulting from high-density oils with a high sulphur content, care must be taken to avoid problems such as clogging with dust or sulphides, corrosion or increases in nitrogen oxides.

Utilizing waste heat as a heat source for other processes

The temperature of heating-furnace exhaust gas can be as high as 400- 600 °C, even after heat has been recovered from it.

When a large amount of steam or hot water is needed in a plant, installing a waste heat boiler to produce the steam or hot water using the exhaust gas heat is preferred. If the exhaust gas heat is suitable for equipment in terms of heat quantity, temperature range, operation time etc., the fuel consumption can be greatly reduced. In one case, exhaust gas from a quenching furnace was used as a heat source in a tempering furnace so as to obviate the need to use fuel for the tempering furnace itself.

10. Minimizing wall losses

About 30-40% of the fuel input to the furnace generally goes to make up for heat losses in intermittent or continuous furnaces. The appropriate choice of refractory and insulation materials goes a long way in achieving fairly high fuel savings in industrial furnaces. The heat losses from furnace walls affect the fuel economy considerably. The extent of wall losses depends on emissivity of wall, thermal conductivity of refractories, wall thickness, whether furnace is operated continuously or intermittently.

Heat losses can be reduced by increasing the wall thickness, or through the application of insulating bricks. Outside wall temperatures and heat losses of a composite wall of a certain thickness of firebrick and insulation brick are much lower, due to lesser conductivity of insulating brick as compared to a refractory brick of similar thickness. In the actual operation in most of the small furnaces the operating periods alternate with the idle periods. During the off period, the heat stored in the refractories during the on period is gradually dissipated, mainly through radiation and convection from the cold face. In addition, some heat is abstracted by air flowing through the furnace. Dissipation of stored heat is a loss because the lost heat is again imparted to the refractories during the heat "on" period, thus consuming extra fuel to generate that heat. If a furnace is operated 24 hours, every third day, practically all the heat stored in the refractories is lost. But if the furnace is operated 8 hours per day all the heat stored in the refractories is not dissipated. Furnace walls built of insulating refractories and cased in a shell reduce the flow of heat to the surroundings.

Prevention of radiation heat loss from surface of furnace

The quantity of heat release from surface of furnace body is the sum of natural convection and thermal radiation. This quantity can be calculated from surface temperatures of furnace. The temperatures on furnace surface should be measured at as many points as possible, and their average should be used. If the number of measuring points is too small, the error becomes large.

The quantity (Q) of heat release from a reheating furnace surface is calculated with the following formula:

$$Q \ = \{h\ X\ A\ X\ (t_1 - t_2)^{1.25}\} + \{4.88\ X\ E\ X\ \left(\frac{t_1+273}{100}\right)^4 - \ \left(\frac{t_2+273}{100}\right)^4 X\ A\}$$

Where, Q = quantity of heat released (kcal/hr)

h: heat rate, natural convection factor,
(for ceiling = 2.8, side walls = 2.2, and hearth = 1.5)
A: surface area (m^2)
t_1: temperature of the external wall surface of the furnace (°C)

t_2: temperature of air around the furnace (°C)
E: Emissivity of external wall surface of the furnace (assume = 0.75)

Use thermal imaging camera or Infra-red (IR) thermometer to measure the surface temperature of furnace walls

Example: There is a reheating furnace whose ceiling surface has 20 m^2 of surface area. The average surface temperature is measured to be 80°C and ambient temperature is 30°C. Evaluate the quantity of heat release from the ceiling.

$$Q = \{2.8\, X\, 20\, X\, (80 - 30)^{5/4}\} + \{4.88\, X\, 0.75\, X\, \left(\frac{80 + 273}{100}\right)^4 - \left(\frac{30 + 273}{100}\right)^4 X\, 20\}$$

Q = 7448 + 5202 = 12,650 kcal/hr

11. Use of ceramic coatings

Ceramic coatings in furnace chamber promote rapid and efficient transfer of heat, uniform heating, and extended life of refractories. The emissivity of conventional refractories decreases with increase in temperature whereas for ceramic coatings it increases. This outstanding property has been exploited for use in hot face insulation. Ceramic coatings are high emissivity coatings which when applied has a long life at temperatures up to 1350°C. The coatings fall into two general categories-those used for coating metal substrates, and those used for coating refractory substrates. The coatings are non-toxic, non-flammable and water based. Applied at room temperatures, they are sprayed and air dried in less than five minutes. The coatings allow the substrate to maintain its designed metallurgical properties and mechanical strength. Installation is quick and can be completed during shut down. Energy savings of the order of 8-20% have been reported depending on the type of furnace and operating conditions.

12. Summary of measures for energy conservation in fuel fired furnaces

All the possible measures discussed above can be incorporated in furnace design and operation. The **Figure 81** shows characteristic diagram of energy conservation for a fuel fired furnace

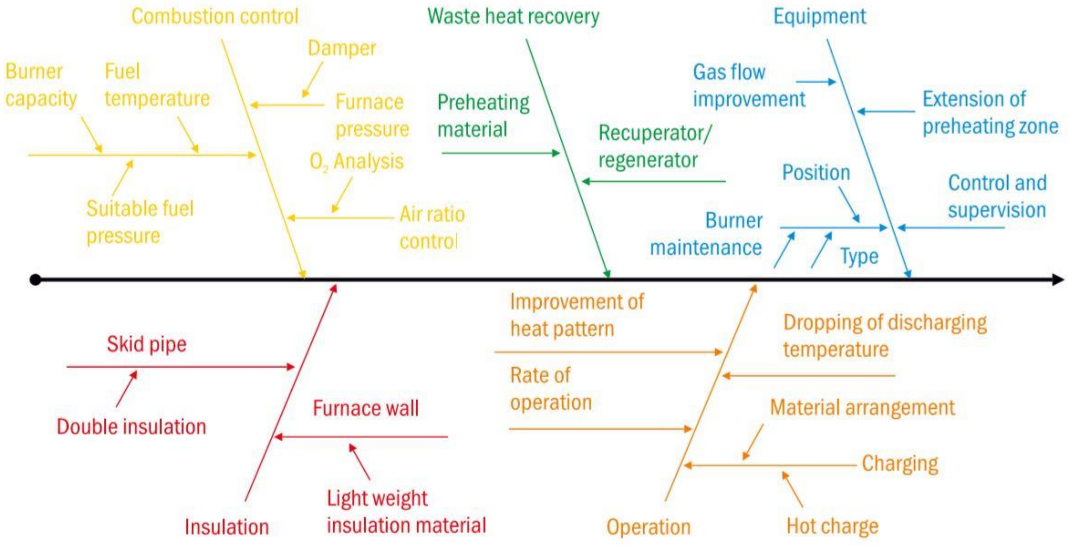


Figure 81: Fishbone diagram of fuel fired furnace for energy optimisation and control system improvement (Source: adapted from TERI)

5.11.29. Industrial Oven

An industrial oven is a heated chamber that is designed to heat to less than 600 ºC and can be used for many process heating applications. Industrial ovens have a wide range of applications in countless industries, such as: manufacturing, electronics, food and beverage, medicine and healthcare, pharmaceuticals, chemical, research and development, plastics, aerospace, automotive and metal forming. The Oven heats up the material to a specified temperature and holds the temperature for a specified amount of time to achieve a change in the material's properties or state.

Industrial ovens work using heat and mass transfer, which is achieved by conduction, convection, infrared radiant heat generation or combination of these. Infrared radiation is the most efficient heat transfer method used by industrial ovens. Whereas Convection uses gases including natural gas and propane gas. Conduction is also available in industrial ovens, but they are not very efficient and are less frequently used.

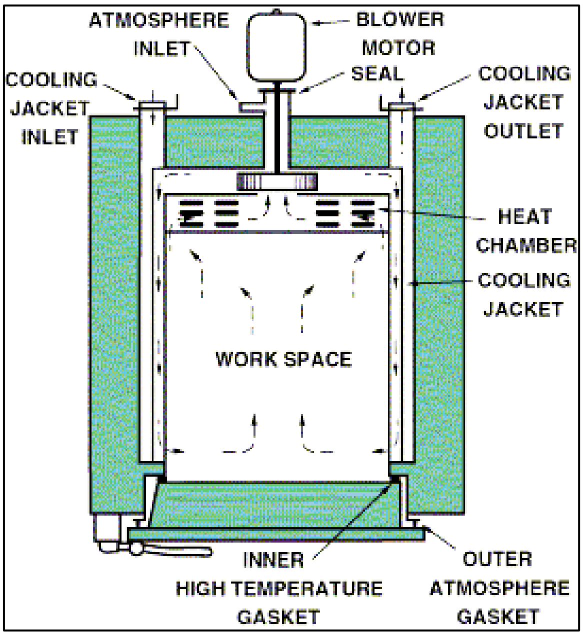


Figure 82: Typical industrial oven

5.11.30. Difference between oven and furnace

Industrial ovens and industrial furnaces are usually similar as far as the basic functioning is concern. They both are fireproof and insulated boxes in which controlled heat treatment processes is performed. The differences between these two technologies can be categories based on the following parameters that is described below.

Temperature

The temperature range is the main difference between an industrial oven and industrial furnace. Ovens usually operates between the temperatures from 125ºC – 550 ºC, while furnaces operate between temperatures of up to 1200 ºC or higher.

Atmosphere

Ovens operate in either an air or inert-gas atmosphere. While furnaces are designed to operate in air, an inert atmosphere, or a combustible atmosphere (e.g. hydrogen, exothermic or endothermic gas).

Heat distribution

In an Oven the air flows in a circular motion. After getting heated, the air becomes lighter and collides with the ceiling, it again comes back down after cooling. The amount of air required is high, in order to successfully transfer the heat from the source to the sample under heat treatment. Whereas in an industrial furnace the heat is introduced directly onto the sample to be heated. Depending on the heat source, the heat source can be placed in various configurations in order to provide the most uniform heating.

5.11.31. Data collection

The energy auditor shall collect the following data by interviewing the oven operator or supervisor.

- Batch operation time
- Application of oven
- Type of fuel or electricity
- Annual running hours
- All other rated and operational parameters of oven

In addition to above, the following data shall be collected through observations & measurements.

- Electricity consumption per batch cycle (for electrical ovens)
- Fuel consumption per batch cycle (for fuel fired ovens)
- Flue gas analysis data (for fuel fired ovens)
- Thermal images of ovens
- Ambient air temperature across ovens

5.11.32. Instruments required

- Thermal imaging camera
- IR thermometer
- Three-phase power analyser (for electric ovens)
- Flue gas analyser (for fuel fired oven)
- Sling psychrometer

5.11.33. Performance terms

$$Oven\ efficiency, \eta = \frac{Heat\ in\ stock\ (material), kcal}{Heat\ in\ fuel\ or\ electricity, kcal}\ X\ 100$$

Heat in the stock can be found by following formula:

$Q = m X Cp X (t_2 – t_1)$

Where,

m = weight of the stock in kg

C_p = Specific heat of stock in kcal/kg°C

t1 = final temperature of stock desired in °C

t2 = Initial temperature of stock before it enters the oven in °C

And, Heat in the fuel consumed for heating the stock can be found by following formula:

Heat in Fuel = Quantity of fuel X gross calorific value (GCV) of fuel

or

For electrical oven, measure electricity consumption using three-phase power analyser for one complete batch operation. Convert kWh into kcal (1 kWh = 860 kcal)

5.11.34. Performance assessment

The following are some of the key measurements to be carried out to obtain oven efficiency

- **Weight of stock/billets heated**, with the help of oven operator obtain the weight of stock or material to be heated per batch.
- Using thermal imager camera or IR thermometer measure the initial and final temperature of the stock/billets in °C
- Using thermal imager camera or IR thermometer measure temperature of the oven walls and roofs
- Using oven engineering drawing which is usually available with engineering team, find the area of furnace walls and roof

For fuel fired ovens

- Using flue gas analyser, measure the flue gas temperature
- Using the flue gas analyser, measure the O_2, CO_2, CO (and other gas) parameters
- Measure or collect from industry, measured values of the fuel consumption of oven per batch

For electric ovens

- Measure the electricity consumption of oven per batch cycle
- Convert the electricity consumption, kWh into kcal (1 kWh = 860 kcal)

5.11.35. Energy savings opportunities in Ovens

Energy efficient features on your industrial oven can drastically reduce energy use and operating costs. Few of the energy savings opportunities are mentioned below:

1. **Adjustable Exhaust Rate:** Industrial oven exhaust fan removes solvent vapours, moisture, or combustion by-products. Adjusting the exhaust fans with a manual damper or variable frequency drive results in reduction in energy consumption.

2. **Heat Recovery System**: Exhaust air from oven carries heat energy with itself. A heat recovery system can be deployed to capture this waste heat energy and can be utilized in different applications.

3. **Humidity Control System:** A humidity control system senses oven humidity and varies the exhaust rate of your oven as per requirement. It results in lower energy consumption.

4. **Optimising the insulation:** Use of thicker or more effective insulation wherever possible while customization of the oven can save heat loss from the system.

5. **Seal Oven Openings:** Seal the area from where the parts enter and exits from an oven. Use of high temperature curtains, powered air seals, or unheated vestibules help retain heat and can save energy.

6. **Variable Speed Recirculation Fan:** Use of a variable frequency drive with the recirculation fan can save energy wastage.

7. **Idle Mode**: Use idle mode when there is a pause in the treatment cycle, for tooling changing, or when there is a break from the operator side. During idle mode, the temperature is temporarily reduced so that it uses less energy.

8. **Maintenance:** Proper maintenance of the oven which includes regular cleaning of filters and blowers can save a lot of wastage of energy. Proper following up of burner gas pressure and combustion airflow rates also saves a lot of fuel.

9. **Energy Saving Mode:** Industrial ovens come with energy saving mode which uses lower energy for different applications. It also reduces the peak load and therefore the peak demand charge and save energy bill.

10. **Proper Scheduling:** Shifting the usage of ovens during non-peak hours can save a lot of unnecessary high peak rate electricity charges that would have been charged otherwise.

5.12. Waste heat recovery

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then "dumped" into the environment even though it could still be reused for some useful and economic purpose. The essential quality of heat is not the amount but rather its "value". The strategy of how to recover this heat depends in part on the temperature of the waste heat gases and the economics involved.

Large quantity of hot flue gases is generated from Boilers, Kilns, Ovens and Furnaces. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. The energy lost in waste gases cannot be fully recovered. However, much of the heat could be recovered and loss minimized by adopting following measures as outlined in this chapter.

5.12.1. Heat losses -quality

Depending upon the type of process, waste heat can be rejected at virtually any temperature from that of chilled cooling water to high temperature waste gases from an industrial furnace or kiln. Usually higher the temperature, higher the quality and more cost effective is the heat recovery. In any study of waste heat recovery, it is necessary that there should be some use for the recovered heat.

Typical examples of use would be preheating of combustion air, space heating, or pre-heating boiler feed water or process water. With high temperature heat recovery, a cascade system of waste heat recovery may be practiced ensuring that the maximum amount of heat is recovered at the highest potential. An example of this technique of waste heat recovery would be where the high temperature stage was used for air pre-heating and the low temperature stage used for process feed water heating or steam raising.

5.12.2. Heat losses - quantity

In any heat recovery situation, it is essential to know the amount of heat recoverable and also how it can be used. An example of the availability of waste heat is given below:

Example: In a heat treatment furnace, the exhaust gases are leaving the furnace at 900°C at the rate of 2100 m^3 /hour. The total heat recoverable at 180°C final exhaust can be calculated as

$Q = V \times \rho \times C_p \times \Delta T$

Where,
Q is the heat content in kcal
V is the flow rate of the substance in m^3/hr
ρ is density of the flue gas in kg/m^3
C_p is the specific heat of the substance in kcal/kg°C
ΔT is the temperature difference in °C
C_p (Specific heat of flue gas) = 0.24 kcal/kg°C

Heat available (Q) = 2100 x 1.19 x 0.24 x (900-180) = 4,31,827 kcal/hr

By installing a recuperator, this heat can be recovered to pre-heat the combustion air. The fuel savings would be 33% (@ 1% fuel reduction for every 22°C reduction in temperature of flue gas).

5.12.3. Classification and application

In considering the potential for heat recovery, it is useful to note all the possibilities, and grade the waste heat in terms of potential value as shown in the following **Table 39**

Table 39: Waste source and quality

Waste Source and Quality		
S. No.	Source	Quality
1	Heat in flue gases	Higher the temperature of flue gas, greater the potential value for heat recovery
2	Heat in vapour streams	Higher the temperature of vapor, greater the potential value for heat recovery but when condensed latent heat is also recoverable
3	Convective and radiant heat lost from exterior of equipment	Low grade – if collected may be used for space heating or air preheat
4	Heat losses in cooling water	Low grade – useful gains if heat is exchanged with incoming fresh water
5	Heat losses in providing chilled water or in the disposal of chilled water	High grade if it can be utilised to reduce demand for refrigeration Low grade if refrigeration unit used as a form of heat pump
6	Heat stored in products leaving the process	Quality depends upon temperature
7	Heat in gaseous and liquid effluents leaving process	Poor, if heavily contaminated and thus requiring alloy heat exchanger

5.12.4. Benefits of waste heat recovery

Benefits of 'waste heat recovery' can be broadly classified in two categories:

Direct Benefits: Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.
Indirect Benefits: Reduction in pollution, a number of toxic combustible wastes such as carbon monoxide gas, sour gas, carbon black off gases, oil sludge, Acrylonitrile and other plastic chemicals etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.

Reduction in equipment sizes: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gas handling equipment such as fans, stacks, ducts, burners, etc.

Reduction in auxiliary energy consumption: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption like electricity for fans, pumps etc.

5.12.5. Development of a waste heat recovery systems

Understanding the process

Understanding the process is essential for development of Waste Heat Recovery system. This can be accomplished by reviewing the process flow sheets, layout diagrams, piping isometrics, electrical and instrumentation cable ducting etc. Detail review of these documents will help in identifying:

- Sources and uses of waste heat
- Upset conditions occurring in the plant due to heat recovery
- Any other constraint such as dew point occurring in an equipment
- Availability of space

After identifying source of waste heat and the possible use of it, the next step is to select suitable heat recovery system and equipment to recover and utilise the same.

Economic evaluation of Waste Heat Recovery System

It is necessary to evaluate the selected waste heat recovery system on the basis of financial analysis such as investment, depreciation, payback period, rate of return etc. In addition, the advice of experienced consultants and suppliers must be obtained for rational decision. A brief description of common heat recovery devices which are commercially available is given in next section.

5.12.6. Commercial waste heat recovery devices

Recuperators

In a recuperator, heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Duct or tubes carry the air for combustion to be pre-heated, the other side contains the waste heat stream. A recuperator for recovering waste heat from flue gases is shown in **Figure 83**

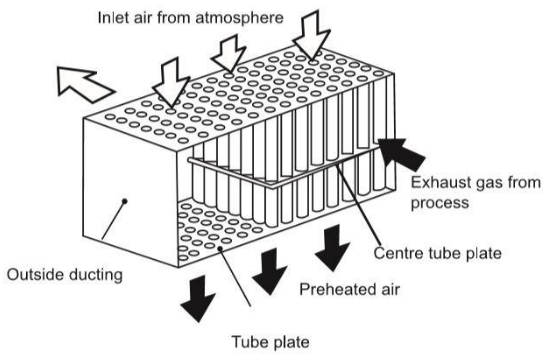


Figure 83: Recuperator configuration

The simplest configuration for a recuperator is the metallic radiation recuperator, which consists of two concentric lengths of metal tubing as shown in **Figure 84.** The inner tube carries the hot exhaust gases while the external annulus carries the combustion air from the atmosphere to the air inlets of the furnace burners. The hot gases are cooled by the incoming combustion air which now carries additional energy into the combustion chamber. This is energy which does not have to be supplied by the fuel. Consequently, less fuel is burned for a given furnace loading. The saving in fuel also means a decrease in combustion air and therefore stack losses are decreased not only by lowering the stack gas temperatures but also by discharging smaller quantities of exhaust gas. The radiation recuperator gets its name from the fact that a substantial portion of the heat transfer from the hot gases to the surface of the inner tube takes place by radiative heat transfer. The cold air in the annulus, however, is almost transparent to infrared radiation so that only convection heat transfer takes place to the incoming air. As shown in the **Figure 84,** the two gas flows are usually parallel, although the configuration would be simpler and the heat transfer more efficient if the flows were opposed in direction (or counterflow).

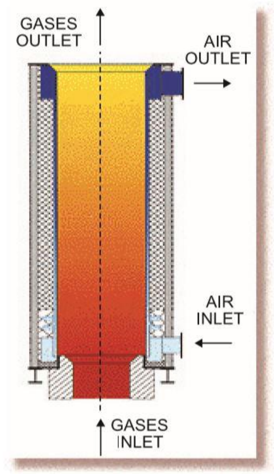


Figure 84: Metallic radiation recuperator

The reason for the use of parallel flow is that the recuperators frequently serve the additional function of cooling the duct carrying away the exhaust gases and consequently extending its service life.

A second common configuration for recuperators is called the tube type or convective recuperator. As seen in **Figure 85** the hot gases are carried through a number of parallel small diameter tubes, while the incoming air to be heated enters a shell surrounding the tubes and passes over the hot tubes one or more times in a direction normal to their axes.

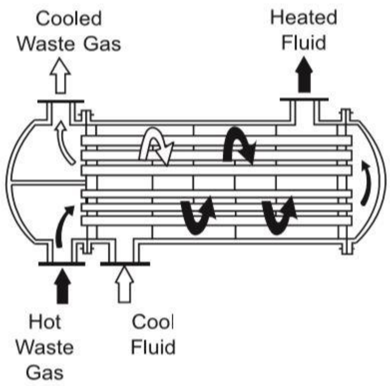


Figure 85: Tube type recuperator

If the tubes are baffled to allow the gas to pass over them twice, the heat exchanger is termed as two-pass recuperator, if two baffles are used, a three-pass recuperator, etc.

Although baffling increases both the cost of the exchanger and the pressure drop in the combustion air path, it increases the effectiveness of heat exchange. Convective recuperators are generally more compact and have a higher effectiveness than radiation recuperators because of larger heat transfer area made possible through use of multiple tubes and multiple passes of the gases.

Example: In oil fired furnace following are the operating parameters:

Capacity of furnace	10 t/hr
Daily production operating at 10 hours a day	100 t/day
Specific fuel consumption	65 l/t of finished products
Flue gas temperature at the exit of furnace	600°C
Ambient temperature	30°C
GCV of oil	10,000 kcal/kg
Theoretical air required for combustion	14 kg of air/ kg of fuel
Specific heat of flue gas	0.26 kcal/kg°C
Specific heat of air	0.24 kcal/kg°C
Oxygen in flue gas	8%
Furnace yield without the recuperator	90%
Furnace yield after installing the recuperator	95%

The management is planning to install a recuperator to pre-heat the combustion air up to 200°C. Calculate:

1. the percentage heat reduction in flue gas after installation of recuperator
2. the increase in daily production due to yield improvement
3. specific fuel consumption after installing the heat recovery recuperator (assuming 1 % fuel saving for every 20°C rise in combustion air temperature)

Solution:

1. Percentage heat reduction in flue gas after installation of recuperator	
% excess air supplied (EA)	$= \frac{O_2\%}{21 - O_2\%} X\ 100 = \frac{8}{21-8} X\ 100 = 61.5\%$
Actual mass of air supplied / kg of fuel (AAS)	$= \left(1 + \frac{EA}{100}\right) X\ theoretical\ air$ $= \left(1 + \frac{61.5}{100}\right) X\ 14.12 = \mathbf{22.61\ kg\ of air\ per\ kg\ of\ fuel}$
Daily fuel consumption	= 65 X 1000 = 6500 kg/day
Total mass, m	= mass of fuel + (mass of fuel X AAS) = 6500 + (6500 X 22.61) = 153,465 kg/day
Heat in flue gas	= m X $C_{p\ fg}$ X (t_1 – t_a) = 153,465 X 0.26 X (600 – 30) = **22,743,513 kcal/day** m = total mass of fuel and AAS $C_{p\ fg}$ = Specific heat of flue gas = 0.26 t_1 = Flue gas temperature at exit of furnace t_a = Ambient temperature
Heat in preheated combustion air	= m X C_p X (t_1-t_a) = (6500 X 22.61) X 0.24 X (200-30) = **5,996,172 kcal/day** m = mass of fuel X AAS C_p = specific heat of air t_1 = temperature of pre-heated combustion air t_a = Ambient temperature
Heat reduction in flue gas in percentage (%)	= (5,996,172 / 22,743,513) = **26.4%**

2. The increase in daily production due to yield improvement	
Daily additional production due to yield improvement	= 100 X (95/90) = 105.5 t/day = 105.5 – 100 = **5.5 t/day**

3. specific fuel consumption after installing the heat recovery recuperator	
Combustion air temperature raise after installing recuperator	= expected temperature – existing temperature = (200 – 30) = 170°C
Reduction in fuel consumption (assuming 1 % fuel saving for every 20°C rise in combustion air temperature, thumb rule)	= 170 / 20 = **8.5%**
Fuel consumption after waste heat recovery	= 6500 – (6500 X 8.5%) = 5,947.5 kg/day
Production after installing recuperator	= 105.5 t/day
Specific fuel consumption	= 5947.5 / 105.5 = **56.37 kg/t**

5.12.7. Heat Wheel

A heat wheel is finding increasing applications in low to medium temperature waste heat recovery systems. **Figure 86** is a sketch illustrating the application of a heat wheel.

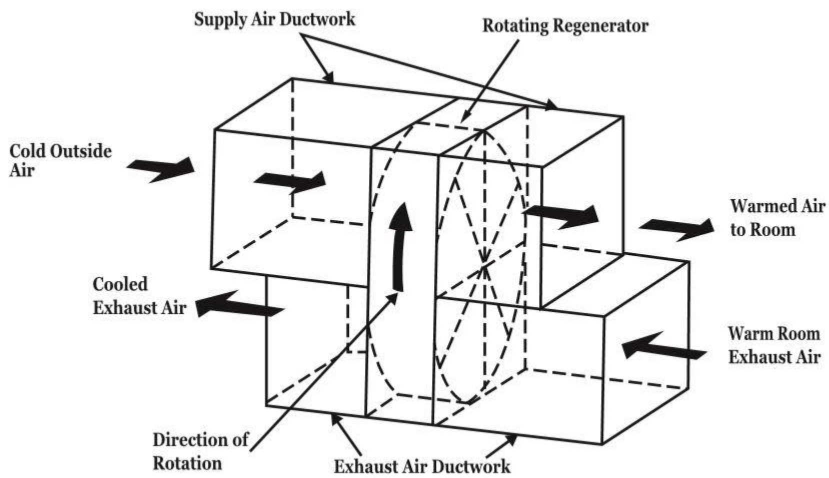


Figure 86: Sketch of heat wheel

It is a sizable porous disk, fabricated with material having a fairly high heat capacity, which rotates between two side-by-side ducts: one a cold gas duct, the other a hot gas duct. The axis of the disk is located parallel to, and on the partition between, the two ducts. As the disk slowly rotates, sensible heat (moisture that contains latent heat) is transferred to the disk by the hot air and, as the disk rotates, from the disk to the cold air. The overall efficiency of sensible heat transfer for this kind of regenerator can be as high as 85 percent. Heat wheels have been built as large as 21 metres in diameter with air capacities up to 1130 m^3/min. A variation of the Heat Wheel is the rotary regenerator where the matrix is in a cylinder rotating across the waste gas and air streams. The heat or energy recovery wheel is a rotary gas heat regenerator, which can transfer heat from exhaust to incoming gases. Its main area of application is where heat exchange between large masses of air having small temperature differences is required. Heating and ventilation systems and recovery of heat from dryer exhaust air are typical applications.

5.12.8. Economiser

In case of boiler system, economizer can be provided to utilize the flue gas heat for pre-heating the boiler feed water. On the other hand, in an air pre-heater, the waste heat is used to heat combustion air. In both the cases, there is a corresponding reduction in the fuel requirements of the boiler. An economizer is shown in **Figure 87**

For every 22°C reduction in flue gas temperature by passing through an economiser or a pre-heater, there is 1% saving of fuel in the boiler. In other words, for every 6°C rise in feed water temperature through an economiser, or 20°C rise in combustion air temperature through an air pre-heater, there is 1% saving of fuel in the boiler.

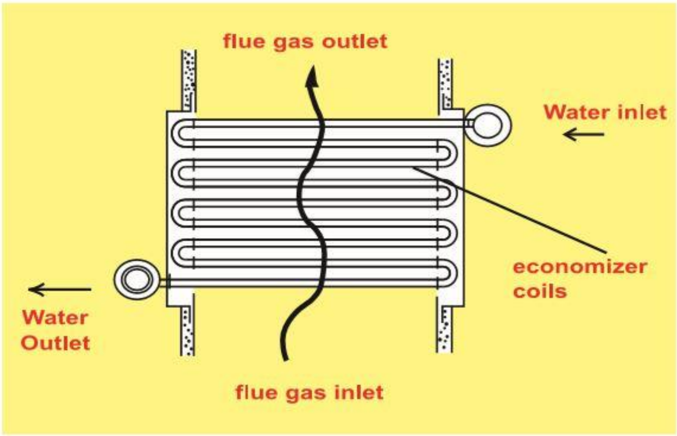


Figure 87: Economiser

5.13. Insulation & refractories

5.13.1. Introduction

Detailed study of thermal insulation for consideration of energy loss is a part of any energy audit, since thermal insulation condition is an indicative parameter for the potential thermal energy savings. The study aims at judging the potential thermal energy saving by insulation up gradation but also for planning proper maintenance schedule keeping in view equipment and personnel safety. In addition, periodic insulation survey should be carried out to initiate measures by maintenance personnel to prevent heat losses due to poor insulation.

The instruments required for conduction energy audit of thermal insulation are Thermal imaging camera and non-contact type IR thermometer

The scope of insulation study includes:

- Temperature profile survey of insulated surfaces in areas of boiler, steam pipes, ducts and turbine etc. / thorough thermal scanning of all related surfaces for identifying hot spots with poor insulation.
- Identification of areas of poor / damaged insulation, contributing to excessive heat losses.
- Estimation of extra heat loss/ revenue loss due to the hot spots because of damaged or poor insulation.

5.13.2. Measurements and observation to be made

Before start of temperature measurement, the auditor should ensure from that unit (Boiler, furnace, ovens or any other heating equipment) is running around base load.

1. Scan and record the temperatures at various locations of the insulated surface at intervals of 1-2 meters with the help of non-contact type IR thermometer or thermal imaging camera.
2. Carryout physical survey and make a list of defective insulation areas indicating type of defect i.e. insulation damaged / poor insulation / cladding missing / cladding loose/ uninsulated or any other along with description of location and approximate area of defect.
3. Record external factors responsible for increase of insulation surface temperature (if any), e.g. leakages of flue gas, steam, hot air etc. along with locations.
4. After recording the temperature and tabulating, highlight the measurements where temperatures are above acceptable level. While reporting, enclosed the thermal images taken from thermal camera highlighting the heat losses as shown in **Figure 88**

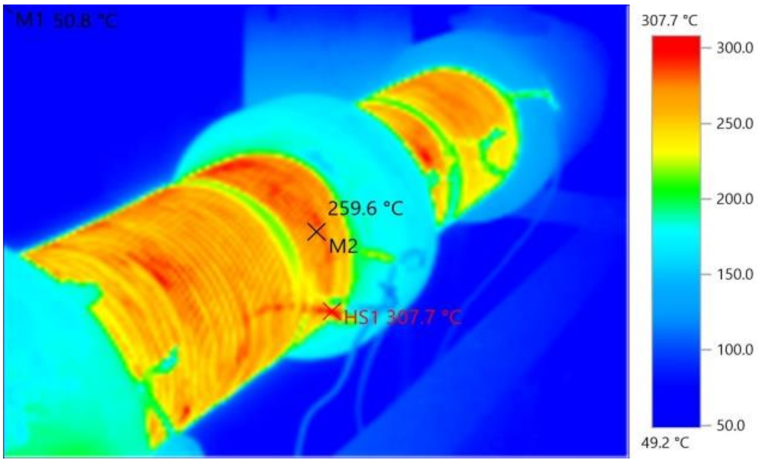


Figure 88: An example of thermal image taken from thermal camera

5.13.3. Purpose of Insulation

A thermal insulator is a poor conductor of heat and has a low thermal conductivity. Insulation is used in buildings and in manufacturing processes to prevent heat loss or heat gain. Although its primary purpose is an economic one, it also provides more accurate control of process temperatures and protection of personnel. It prevents condensation on cold surfaces and the resulting corrosion. Such materials are porous, containing large number of dormant air cells. Thermal insulation delivers the following benefits:

- Reduces over-all energy consumption
- Offers better process control by maintaining process temperature.
- Prevents corrosion by keeping the exposed surface of a refrigerated system above dew point
- Provides fire protection to equipment
- Absorbs vibration

5.13.4. Types and application

The Insulation can be classified into three groups according to the temperature ranges for which they are used.

Low Temperature Insulations (up to 90°C)

This range covers insulating materials for refrigerators, cold and hot water systems, storage tanks, etc. The commonly used materials are Cork, Wood, 85% magnesia, Mineral Fibres, Polyurethane, and expanded Polystyrene, etc

Medium Temperature Insulations (90 - 325°C)

Insulators in this range are used in low temperature, heating and steam raising equipment, steam lines, flue ducts etc. The types of materials used in this temperatures range include 85% Magnesia, Asbestos, Calcium Silicate and Mineral Fibres etc.

High Temperature Insulations (325°C- above)
Typical uses of such materials are super-heated steam system, oven dryer and furnaces etc. The most extensively used materials in this range are Asbestos, Calcium Silicate, Mineral Fibre, Mica and Vermiculite based insulation, Fireclay or Silica based insulation and Ceramic Fibre.

5.13.5. Classification of insulation material

Insulation materials can also be classified into organic and inorganic types.

1. Organic insulations are based on hydrocarbon polymers, which can be expanded to obtain high void structures. For example, Thermocol (Expanded Polystyrene) and Polyurethane foam (PUF).
2. Inorganic insulation is based on Siliceous/Aluminous/Calcium materials in fibrous, granular or powder forms. For example, Mineral wool, Calcium silicate etc.

Properties of common insulating materials are as under:

Calcium Silicate: Used in industrial process plant piping where high service temperature and compressive strength are needed. Temperature ranges varies from 40°C to 950°C.

Glass mineral wool: These are available in flexible forms, rigid slabs, and preformed pipe work sections. Good for thermal and acoustic insulation for heating and chilling system pipelines. Temperature range of application is -10 to 500°C.

Thermocol: These are mainly used as cold insulation for piping and cold storage construction.

Expanded nitrite rubber: This is a flexible material that forms a closed cell integral vapour barrier. Originally developed for condensation control in refrigeration pipe work and chilled water lines; now- a-days also used for ducting insulation for air conditioning.

Rock mineral wool: This is available in a range of forms from light weight rolled products to heavy rigid slabs including preformed pipe sections. In addition to good thermal insulation properties, it can also provide acoustic insulation and is fire retardant.

5.13.6. Thermal conductivity

The thermal conductivity of a material is the heat loss per unit area per unit insulation thickness per unit temperature difference. The unit of measurement is W/m°C. The thermal conductivity of material increases with temperature. So, thermal conductivity is always specified at the mean temperature (mean of hot and cold face temperatures) of the insulation material.

Thermal conductivities of typical hot insulation materials are given in **Table 40**

Table 40: Thermal conductivities of typical hot insulation materials (Source: BEE)

Mean temperature °C	Calcium silicate	Resin bonded mineral wool	Ceramic fiber blankets
100	-	0.04	-
200	0.07	0.06	0.06
300	0.08	0.08	0.07

Mean temperature °C	Calcium silicate	Resin bonded mineral wool	Ceramic fiber blankets
400	0.08	0.11	0.09
700	-	-	0.17
1000	-	-	0.26
specific heat (kJ/kg/°C)	0.96	0.921	1.07
	at 40°C	at 20°C	at 980°C
Service temperature (°C)	950	700	1425
Density kg/m^3	260	48 to 144	64 to 128

5.13.7. Economic thickness of insulation

Insulation of any system means capital expenditure. Hence the most important factor in any insulation system is to analyse the thermal insulation with respect to cost. The effectiveness of insulation follows the law of decreasing returns. Hence, there is a definite economic limit to the amount of insulation, which is justified. An increased thickness is uneconomical and cannot recovered through small heat savings. This limiting value is termed as economic thickness of insulation. An illustrative case is given in **Figure 89**

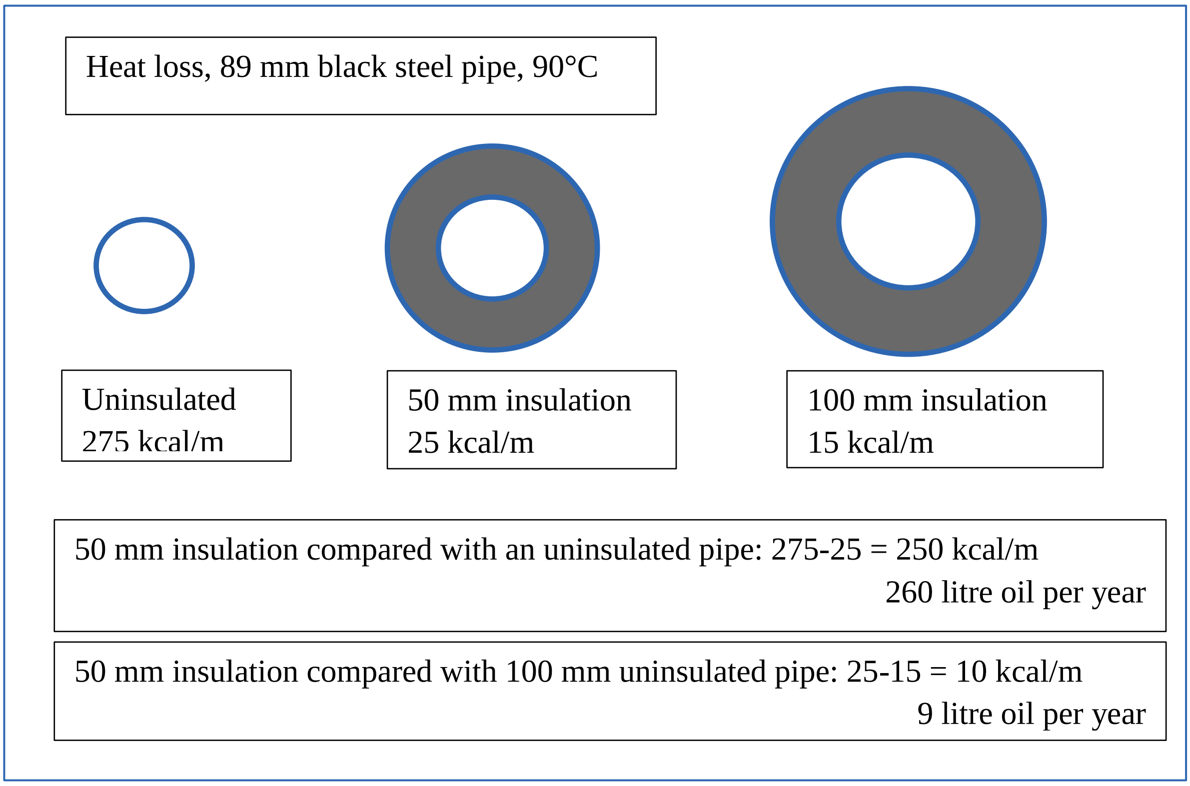


Figure 89: Illustration of optimal insulation

Each industry has different fuel cost and boiler efficiency. These values can be used for calculating economic thickness of insulation. This shows that thickness for a given set of circumstances results in the lowest overall cost of insulation and heat loss combined over a given period of time. The **Figure 90** illustrates the principle of economic thickness of insulation.

The simplest method of analysing whether to use 1” (inch), 2” or 3” insulation is by comparing the cost of energy losses with the cost of insulating the pipe. The insulation thickness for which the total cost is minimum is termed as economic thickness. Refer **Figure 90** the curve representing the total cost reduces initially and after reaching the economic thickness corresponding to the minimum cost, it increases.

The determination of economic thickness requires the attention to the following factors:

- Cost of fuel
- Annual hours of operation
- Heat content of fuel
- Boiler efficiency
- Operating surface temperature
- Pipe diameter/thickness of surface
- Estimated cost of insulation
- Average exposure ambient air temperature

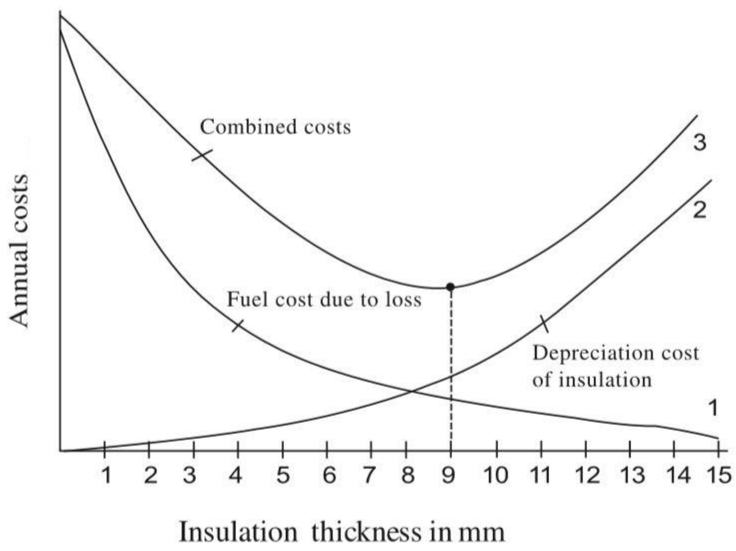
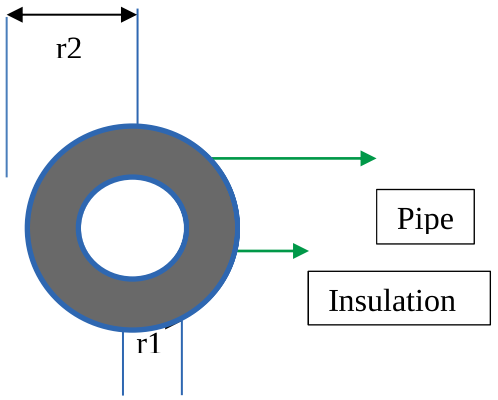


Figure 90: Determination of economic thickness of insulation (Source: BEE)

5.13.8. Formulae and method for calculating economic thickness of insulation

The most basic model for insulation on a pipe is shown in below figure



r1 shows the outside radius of the pipe
r2 shows the radius of pipe + insulation
Heat loss from a surface is expressed as:

$Q = h \times A \times (T_h - T_a)$

Where,
Q = heat loss, W
h = Heat transfer coefficient, W/m^2-K
T_a = Average ambient temperature °C
T_h = Surface temperature °C
T_s = Desired actual insulation surface temperature °C

heat transfer coefficient, h can be calculated by:
For horizontal pipes,
$h = (A + 0.005 (T_h - T_a) \times 10)\ W/m^2\text{-K}$

For vertical pipes,
$h = (B + 0.009 (T_h - T_a) \times 10)\ W/m^2\text{-K}$

Using the coefficients, A & B as given below:

Surface	ε	A	B
Aluminium, bright rolled	0.05	0.25	0.27
Aluminium oxidised	0.13	0.13	0.33
Steel	0.15	0.32	0.34
Galvanised sheet metal, dusty	0.44	0.53	0.55
Non-metallic surfaces	0.95	0.85	0.87

Mean temperature formula

$$Tm = \frac{Th+Ts}{2}$$

Where,
Tm – Mean temperature
Th – Bare pipe surface temperature
Ts – Desired or expected wall temperature with insulation

The heat flow from the pipe surface and the ambient can be expressed as follows:

$$Heat\ flow, H\ (W) = \frac{Th - Ta}{Ri + Rs} = \frac{Ts - Ta}{Rs}$$

Where,
Rs = Surface thermal resistance = (1/h) °Cm^2/W
Ri = Thermal resistance of insulation = (tk/k) °Cm^2/W

Where,
k = Thermal conductivity of insulation at mean temperature of Tm, W/m°C
tk = thickness of insulation, mm

5.13.9. Simplified formula for heat loss calculation

Various charts, graphs and references are available for heat loss computation. The surface heat loss can be computed with the help of a simple relation as given below. **This equation can be used up to 200°C surface temperature**. Factors like wind velocities, conductivity of insulating material etc has not been considered in the equation.

$$S = \left[10 + \frac{(Ts - Ta)}{20}\right] X\ (Ts - Ta)$$

Where,
S = surface heat loss in kcal/hr m^2
Ts = Hot surface temperature in °C
Ta = Ambient temperature in °C

Total heat loss/hr = S X A
Where,
A is the surface area in m^2
Based on the cost of heat energy, the quantification of heat loss in Nu. can be calculated as follows:

$$Equivalent\ fuel\ loss, kg/year = \frac{\text{Total heat loss per hour X annual hours of operation}}{GCV\ X\ Boiler\ efficiency}$$

Case Example
Steam pipeline 100 mm diameter is not insulated for 100 metre length supplying steam at 10 kg/cm^2 to the equipment. Find out the fuel savings if it is insulated with 65 mm insulating material.

Given:
Boiler efficiency = 80%
Fuel oil cost = Nu. 15,000/t
Surface temperature without insulation, Ts = 170°C
Surface temperature after insulation, = 65°C
Ambient temperature, Ta = 25°C

Solutions:
Calculating Existing heat loss

$$S = \left[10 + \frac{(170\ - 25)}{20}\right] X\ (170 - 20) = \ 2500\ \text{kcal/hr} - \text{m}^2$$

Modified system
After insulating with 65 mm glass wool with aluminium cladding, the expected hot face temperature will be 65°C
Ts = 65°C
Ta = 25°C
Substituting these values

$$S = \left[10 + \frac{(65\ - 25)}{20}\right] X\ (65 - 20) = \ 480\ \text{kcal/hr} - \text{m}^2$$

Table 41: Fuel savings calculation

Pipe dimension	= 100 mm diameter & 100 m length
Surface area existing	= 3.14 X 0.1 X 100 = 31.4 m^2
Surface area after insulation	= 3.14 X 0.23 X 100 = 72.2 m^2
Total heat loss in existing system	= 2500 X 31.4 = 78,500 kcal/hr
Total heat loss in modified system	= 480 X 72.2 = 34,656 kcal/hr
Reduction in heat loss	78500 – 34656 = 43,844 kcal/hr
No. of hours operation in a year	8400
Total heat loss (kcal/year)	43844 X 8400 = 3,682,89,600
GCV of fuel oil	10,300 kcal/kg
Boiler efficiency	80%
Price of fuel oil	Nu. 35000/t
Yearly fuel oil savings	= (3,682,89,600 / 10,300) X 0.8 = **44,695 kg/year**

5.13.10. Cold insulation

Cold Insulation should be considered and where operating temperature are below ambient where protection is required against heat gain, condensation or freezing. Condensation will occur whenever moist air comes into contact with the surface that is at a temperature lower than the dew point of the vapour. In addition, heat gained by uninsulated chilled water lines can adversely affect the efficiency of the cooling system.

The most important characteristics of a suitable Cold insulation material have following features:

- Low thermal conductivity
- High water resistance, and
- Durability at low temperature

Other properties like easy workability, negligible capillary absorption should also be taken into consideration while making a selection. The insulation system is only as good as its vapour barrier and the care with which it is installed.

5.13.11. Material selection for cold insulation

Selection of insulation materials should be carefully considered where the possibility of steam purging of the equipment is required or for other reasons which may cause the temperature to be increased to a level that exceeds the maximum limiting temperature of the insulation materials, i.e., material then deteriorate. Examples of cold insulation include Urethane Foam, Expanded Polystyrene, Resin bonded glass wool, Resin Bonded Glass wool, and Phenolic Foam.

5.13.12. Economics of cold insulation

Unlike hot insulation system, the concern area in Cold Insulation is the heat gain into the refrigerated space, which leads to increase in the refrigeration load (TR) & energy consumption as a consequence. The cost of heat gain can thus be assessed & evaluated against cost of additional cold insulation thickness, to optimize overall energy consumption & cost in refrigeration system.

5.13.13. Refractories

Any material can be described as 'refractory,' if it can withstand the action of abrasive or corrosive solids, liquids or gases at high temperatures. For example, fireclay, alumina, magnesite, chrome magnesite, dolomite etc. Refractory materials are made in varying combinations and shapes and for different requirements of high temperature processes carried out in metal extraction, cement, glassmaking, manufacturing, ceramic etc.

The general requirements of a refractory material can be summed up as:

- Ability to withstand high temperatures.
- Ability to withstand sudden changes of temperatures.
- Ability to withstand action of molten metal slag, glass, hot gases, etc.
- Ability to withstand load at service conditions.
- Ability to withstand load and abrasive forces.
- Low coefficient of thermal expansion.
- Should be able to conserve heat.
- Should not contaminate the material with which it comes into contact.

5.13.14. Some useful insulating materials to minimise heat losses

Insulating materials greatly reduce the heat losses through walls. Insulation is done by providing a layer of material having a low heat conductivity between the internal hot surface of a furnace and the external surface, thus causing the temperature of the external surface reduced. Insulating materials owe their low conductivity to their pores while their heat capacity depends on the bulk density and specific heat. Structure of air insulating material consists of minute pores filled with air which have in themselves very low thermal conductivity, excessive heat affects all insulation material adversely, but the temperatures to which the various materials can be heated before this adverse effect occurs differ widely. Clearly, therefore, the choice of an insulating material must depend upon its effectiveness to resist heat conductivity and upon the temperature that it will withstand.

Ceramic Fibre

Ceramic fibre is a low thermal mass insulation material, which has revolutionised the furnace design lining systems. Ceramic fibre is an alumina silicate material manufactured by blending and melting alumina and silica at temperature of 1800-2000°C and breaking the molten stream by blowing compressed air or dropping the melt on spinning disc to form loose or bulk ceramic fibre. The bulk fibre is converted to various products including blanket, strips, veneering and anchored modules, paper, vacuum formed boards and shapes, rope, wet felt, mastic cement etc. for insulation applications.

These fibres are generally produced in bulk wool form and needled into blanket mass of various densities ranging from 64 to 190 kg/m^3 Converted products and over 40 different forms are made from blankets to suit various requirements.

High Emissivity Coatings

Emissivity, the measure of a material's ability to both absorb and radiate heat, has been considered by engineers as being an inherent physical property which like density, specific heat and thermal conductivity, is not readily amenable to change. However, the development of high emissivity coatings now allows the surface emissivity of materials to be increased, with resultant benefits in heat transfer efficiency and in the service life of heat transfer components. High emissivity coatings are applied in the interior surface of furnaces. High emissivity coating shows a constant value over varying process temperatures.

The application of high-emissivity coatings in furnace chambers promotes rapid and efficient transfer of heat, uniform heating, and extended life of refractories and metallic components such as radiant tubes and heating elements. For intermittent furnaces or where rapid heating is required, use of such coatings was found to reduce fuel or power to tune of 25-45%. Other benefits are temperature uniformity and increased refractory life. Furnaces, which are operate at high temperatures have emissivity's of 0.3. By using high emissivity coatings this can go up to 0.8 thus effectively increasing the radiative heat transfer. The **Figure 91** below shows high emissivity of various insulating materials including high emissivity coatings.

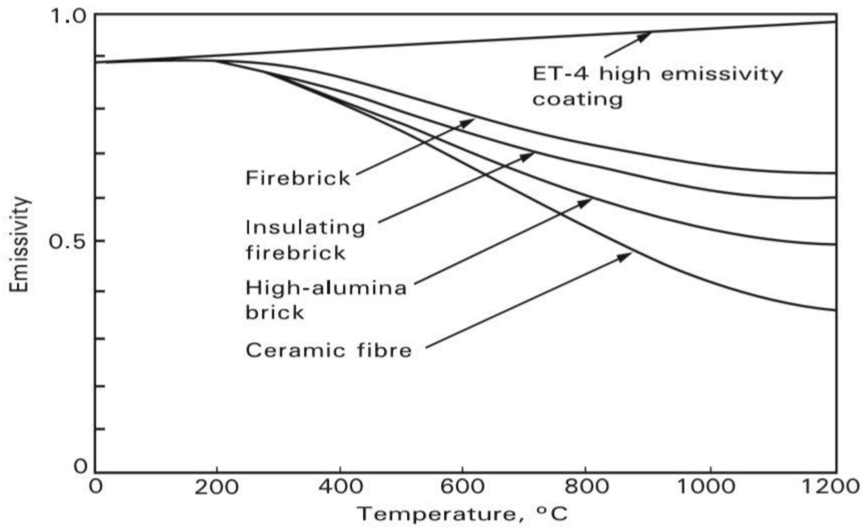


Figure 91: High emissivity coatings of various insulating materials

Castable and Concretes

Monolithic linings and furnace sections can be built up by casting refractory insulating concretes, and by stamping into place certain light weight aggregates suitably bonded. Other applications include the formation of the bases of tunnel kiln cars used in the ceramic industry. The ingredients are similar to those used for making piece refractories, except that concretes contain some kind of cement, either Portland or high-alumina cement.

5.14. Renewable energy systems

5.14.1. Scope in energy audit

The inclusion of Renewable energy in energy audits depends upon the focus of the audit and the objectives of the client organization management team. If the organisational goal is to reduce the overall carbon footprint, then it will come under renewable energy focused areas. Whereas if the organisation's goal is to reduce the energy, this will come under the scope of energy audit. Also, it should be noted that low-cost or no-cost opportunities should be of prime focus. Principle which focusses on reducing the size of the renewable system required or to save the energy wastage should be followed under renewable energy audits.

The solar systems are available in various sizes depending upon the application. Over the years as the technology has improved the efficiency of these solar energy collector has improved and there are a lot of varieties available. The amount of electricity generated is dependent on several factors: the size and arrangement of the system, module type, the available sunlight, and the efficiency of the electrical components used to covert solar energy into electricity.

5.14.2. Stand-alone PV System

A free standing or Stand-alone PV System is made up of a number of individual photovoltaic modules (or panels) usually of 12 volts with power outputs of between 50 and 100+ watts each. These PV modules are then combined into a single array to give the desired power output. A simple *standalone PV system* is an automatic solar system that produces electrical power to charge banks of batteries during the day for use at night when the suns energy is unavailable. A stand-alone small-scale PV system employs rechargeable batteries to store the electrical energy supplied by a PV panels or array.

Stand-alone PV systems are ideal for remote rural areas and applications where other power sources are either impractical or are unavailable to provide power for lighting, appliances, and other uses. In these cases, it is more cost effective to install a single stand-alone PV system than pay the costs of having the local electricity company extend their power lines and cables directly to the home.

A stand-alone photovoltaic (PV) system is an electrical system consisting of and array of one or more PV modules, conductors, electrical components, and one or more loads. But a small-scale PV system does not have to be attached to a roof top or building structures for domestic applications, they can be used for camper vans, RV's, boats, tents, camping and any other remote location. Many companies now offer portable solar kits that allow you to provide your own reliable and free solar electricity anywhere you go even in hard to reach locations.

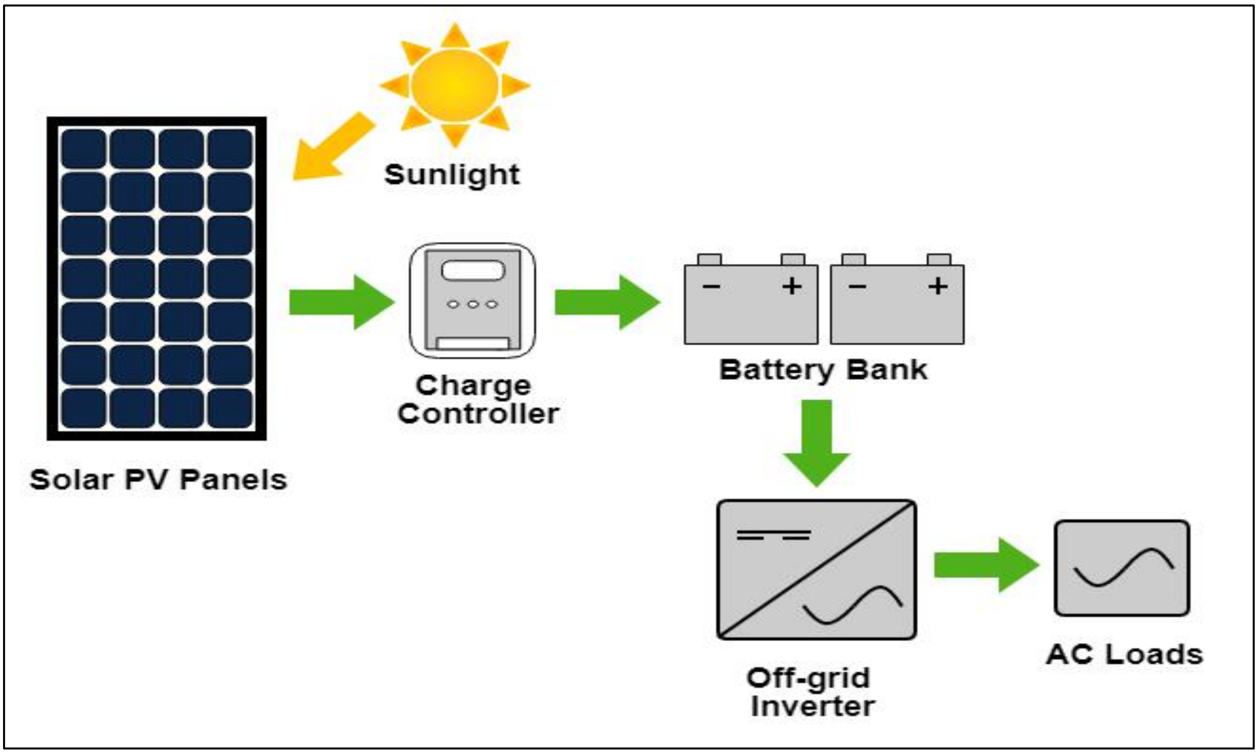


Figure 92: Stand-alone PV system (Source: Apricus solar)

5.14.3. Solar potential in Bhutan

According to International Renewable Energy Agency (IRENA), Bhutan has the potential of 12 GW of solar generation capacity. The solar resource data show that Bhutan has an adequate resource for flat-plate collectors, with annual average values of global horizontal solar radiation ranging from 4.0 to 5.5 kWh/m^2 per day (4.0 to 5.5 peak sun hours per day). Various other parameters related to the solar energy are mentioned below.

Direct Normal Solar Radiation: **Figure 93** shows the annual average direct normal radiation which are important for solar thermal system. The DNI varies between 2.5 and 5.0 kWh/m^2 per day. The best DNI resource is in some of the high-altitude areas in the far north of the country. Average DNI estimate of less than 6.0 or 7.0 kWh/m^2 per day is insufficient for concentrating solar power systems.

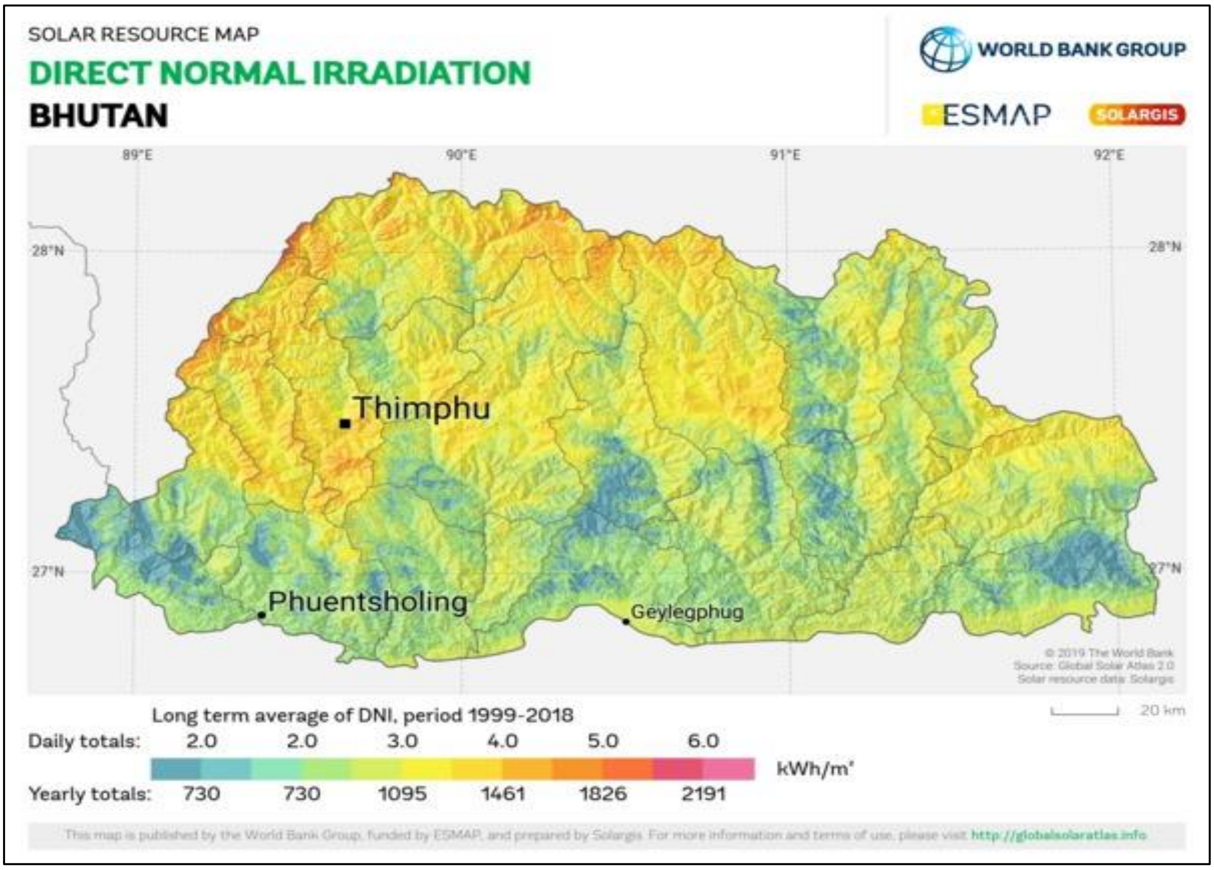


Figure 93: Direct Normal Irradiation map of Bhutan (Source: World bank group)

Global Horizontal Solar Radiation: **Figure 94** shows the annual average GHI, which is considered for flat plate solar collector applications. The values range from 4.0 to 5.5 kWh/m^2 per day. From the figure it is clear that the solar resource for flat-plate collectors is available for Bhutan. The best resource is in the northern part of the country with a few in the central-west portion near Paro and just north of Wangdue. In Bhutan's rural electrification program, estimations of solar home system production use an annual average GHI value of 4.4 kWh/m^2 per day (NREL).

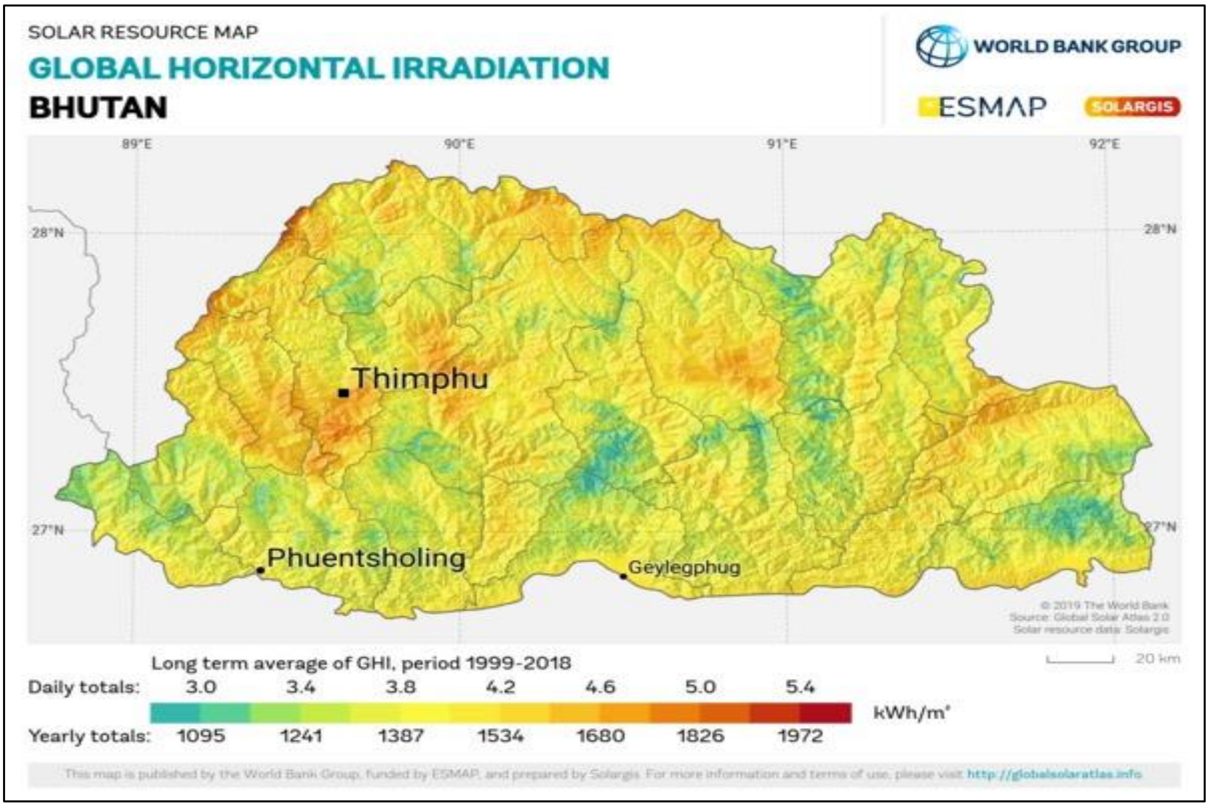


Figure 94: Global Horizontal Irradiation (Source: World bank group)

5.14.4. Data collection to estimate solar PV potential

If a solar PV is not installed, following data shall be collected from site for solar potential estimate

- Connected load (kW)
- Actual average load (kW)
- Average monthly electricity consumption (kWh)
- Critical load (needs to ON most of the time)
- Annual working days
- Available area, rooftop or ground in m^2
- If available area is rooftop than find type of rooftop (tiles/corrugated metals/others)

5.14.5. Data collection for solar PV audit

If a solar PV is already installed, following data shall be collected during audit:

- Average electricity generation by solar plant per month and year (kWh/month, kWh/year)
- DC power output from PV module (kW) or DC power input to inverter (kW)
- AC power input from inverter (kW)
- Array area (m^2)
- GPS location of solar plant

5.14.6. Instruments required

- Measuring tape or Distance meter
- Hand-held clamp meter
- Compass

5.14.7. Performance terms

- Performance ratio
- Solar PV module efficiency
- Inverter efficiency
- System efficiency
- Capacity utilisation factor

5.14.8. Performance assessment of the PV system

The performance of solar photovoltaic power plant work can be done manually as well as automatically using various software's or tools. The tools imports meteorological data from many different sources and help to predict the performance of the system. Software can evaluate the performance of grid-connected, stand-alone and pumping systems based on the specified module selection. The program accurately predicts the system yields computed using detailed hourly simulation data. Solar GIS is a geographic information system designed to meet the needs of the solar energy industry. The application combines solar resource data and meteorological data with a web-based application system to support planning, development, and operation of solar energy systems.

While in order to evaluate the performance of SPV plant manually, it required to understand various parameters. These parameters are the indicators of the performance of the plant and can be used by the auditor for evaluating the plant performance.

Performance Ratio

The performance ratio (PR) indicates the overall effect of losses on a PV array's normal power output depending on array temperature and incomplete utilization of incident solar radiation and system component inefficiencies or failures. Also defined as a ratio of the final yield divided by the reference yield and it represents the total losses in the PV system when converting from DC to AC. It indicates how close it approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation, and their nominal rated power capacity. Performance ratio will also consider the availability of the grid, minimum level of irradiation needed to generate electrical energy.

Performance ratio is defined by the following equations as

$$PR\ (\%) = \frac{Total\ AC\ Energy\ Output(kWh)}{Global\ Irradiation,(kWh/m^2)\ X\ Array\ Plane\ Area(m^2)\ X\ Panel\ Efficiency}\ X\ 100$$

5.14.9. Solar PV module efficiency

Solar panel efficiency is a measurement of a solar panel's ability to convert sunlight into usable electricity. The efficiency is the most used parameter to compare the performance of one solar cell to another. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Different types of materials used in manufacturing of solar panel yields possess different efficiencies. Today, most solar panels have efficiencies between 15% and 20%. The instantaneous PV module conversion efficiency is calculated in the equation.

$$P_{max} = V_{OC}\ X\ I_{SC}$$

Where,
Voc is the open-circuit voltage
Isc is the short-circuit current

$$\eta_{PV} = \frac{DC\ power\ output\ from\ the\ PV\ module\ (kW)}{Global\ Irradiation\ kW/m^2\ \ X\ Array\ area(m^2)}\ X\ 100$$

5.14.10. Inverter efficiency

It is the comparison of the amount of the total AC power obtained after the inverter with the DC power generated by the solar panel. In order to maintain a good overall system efficiency, it is required that an appropriate inverter is selected for the system. The instantaneous PV module conversion efficiency is calculated in the equation.

$$\eta_{inv} = \frac{AC\ power\ output\ from\ the\ inverter\ (kW)}{DC\ power\ input\ to\ the\ inverter\ (kW)}\ X\ 100$$

5.14.11. System efficiency

System efficiency is a collective term that include efficiencies of various electrical equipment present in the system along with various other efficiencies that affects the system. The instantaneous PV module conversion efficiency is calculated in the equation.

$$\eta_{PV} = \frac{AC\ power\ output\ from\ the\ system\ (kW)}{Global\ Irradiation\ kW/m^2\ \ X\ Array\ area(m^2)}\ X\ 100$$

5.14.12. Capacity Utilisation Factor (CUF)

It is the ratio of the actual output from a solar plant over the year to the maximum possible output from it for a year under ideal conditions. If the system delivers full rated power continuously, its CF would be unity. It is dependent on the location, orientation, tilt angle unlike the Performance ratio.

$$CUF(\%) = \frac{Energy\ output\ (kWh)}{Total\ Installed\ Capacity\ (kW)\ X\ time\ period\ (hrs)}\ X\ 100$$

5.14.13. Specific plant losses

Energy losses occur in various components in a SPV Power plant under real operating conditions. These losses are evaluated using the monitored data.

There exist a variety of sources through which energy losses occur in PV systems. These losses affect the performance of PV systems thereby justifying why, it is necessary to evaluate these losses using detailed performance monitoring data. Prominent among these losses are array capture losses, shading losses, system losses, cell temperature losses, soiling and degradation. Soiling and degradation losses are more difficult to evaluate because they are small effects that occur over large fluctuations in operating conditions.

The International Electrotechnical Commission (IEC) prepares and publishes international standards for photovoltaic systems that convert solar energy into electrical energy, as well as for all the elements in the entire photovoltaic energy system. In case of detail specific or performance monitoring these testing, procedures needs to be followed. The standards are used for testing and monitoring the module performance. Some of them are mentioned below:

IEC 60891 Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics

IEC 61853-2: Scope of work in progress includes spectral response, incidence angle and module operating temperature measurements for PV module performance testing and energy rating.

IEC 61683 Power conditioners – Procedure for measuring efficiency

5.14.14. Effect of temperature on solar efficiency

The power generation from the PV plant is greatly affected by the temperature. If the temperature of the module goes beyond the rated module temperature, the power generated is much less when compared to the power generated when the temperature equals or is marginally greater than the rated temperature. This effect appears on the output voltage of the cell, where the voltage is indirectly proportional to the temperature, i.e. the decrease in voltage is caused by an increase in the cell temperature.

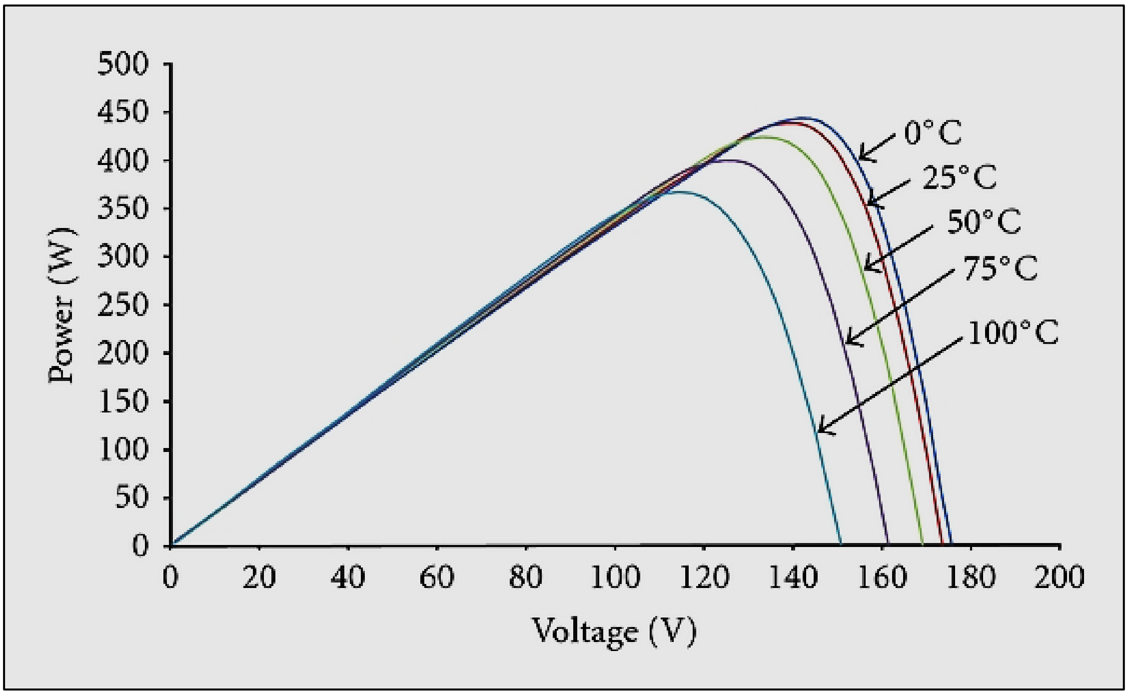


Figure 95: Effect of temperature change on power and voltage

5.14.15. Solar PV facts

- The area required to install 1 kWp capacity solar PV system is approx. 8 to 10 m^2.
- Solar panels produce approx. 10 kWh of electricity per square foot.
- It is possible to install a solar PV system without battery to reduce installation cost.
- The orientation of solar panels (solar angles) are best aligned according to the latitude of location.
- Solar PV also produces electricity during cloudy days, but in lesser amount.
- Most solar panels come with a 25-year warranty. Solar energy is a completely free source of energy and is found in abundance. Solar energy can also be used to generate hot water or steam for process applications in industries.

5.14.16. Solar water heating system

Solar water heating system is a device that uses solar energy to heat water for domestic, commercial, and industrial needs. Water is heated during the daytime and is stored in a tank which makes it available throughout the day as well night due to insulation provided over the tank. The system is generally installed on the roof or open ground, with the collector facing the sun and connected to a continuous water supply. The sun rays have heats up the water up to 55°C to 70°C which is more than enough for various applications. The water remains at required temperature for a duration of approximately two days.

For use in cloudy days, as a backup the system is consist of an electrical heating system. The estimated life of a solar water heater is 15 to 20 years. A typical solar water heating system roughly can save up to 1500 units of electricity every year, for every 100 litres per day of solar water heating capacity.

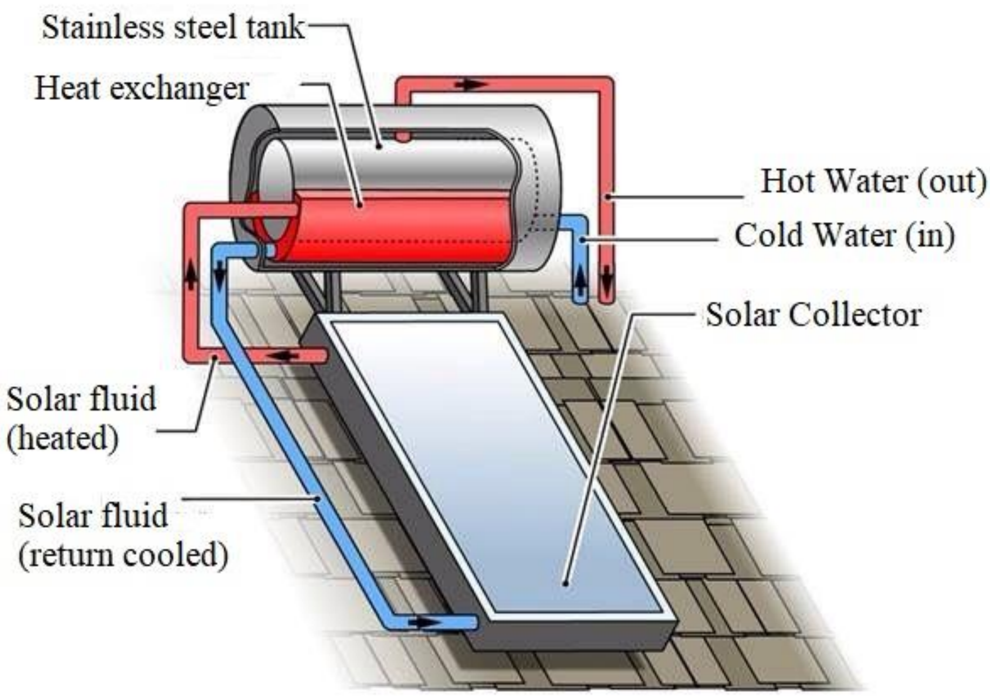


Figure 96: Solar water heater

5.14.17. Data collection to estimate solar water heating potential

If a solar thermal system is not installed, following data shall be collected to estimate solar water heating potential:

- Amount of hot water required per day (kl/day)
- Available roof top or ground area (m^2)
- Existing system of water heating
- Existing energy usage for water heating
- Type of process and other relevant details

5.14.18. Selection of a solar water system

The following factors are considered while selecting an appropriate solar water heating system for any facility.

1. Types of panels

There are basically two types of solar panel commonly available are:

Flat plate collector

Flat plate solar panels are commonly used collectors that has a metal plate with a dark-coloured coating to absorb heat. Pipes under the plate contain water or some other fluid such as glycol, which absorbs heat and carries it to the water in the storage cylinder. A transparent cover, usually glass, admits solar radiation but stops it from escaping. The construction is simple, with no moving parts, which means they are easily repaired. They are relatively low cost and can supply water at temperatures up to 95ºC, though efficiency diminishes rapidly above 70ºC, so systems should be sized to avoid these sorts of temperatures.

Evacuated glass tube collector

Evacuated glass tube solar panels are made up of several glass tubes, typically 20 or more. Each tube has a vacuum to reduce convection and conduction heat losses. Evacuated tubes may contain an absorber plate connected to pipes through which a heat-absorbing fluid circulates or a heat pipe that contains an evaporating/condensing fluid to transfer heat.
Individual tubes sometimes fail but can be replaced at relatively low cost.

2. Sizing the panels

The size of the panel depends on the water storage capacity available and is typically based on a ratio of about 1 square meter of panel for each 50–70 litres of cylinder volume. Most panels commercially available are in the 3–8 m² range.

3. Positioning to maximize solar heat absorption

The heating capacity of a solar water heating system is directly proportional to the amount of solar radiation absorbed, which depends on the following factors:

- Solar intensity: That is the available solar radiation energy (kWh/m²) at a location.
- Solar panel area: The larger the area, the more heat can be produced.
- Solar panel tilt angle: The optimum installed angle for solar absorption is perpendicular to the sun. But due to the continuous change in sun's position an optimal angle is chosen to maximize the utilization.
- Solar panel orientation: The positioning of the panel to maximize the solar energy considering the suns movement.

5.14.19. Efficiency of collector

The efficiency and effectiveness of a solar water heating system depends on the size, type of panels used, and on positioning them to maximize absorption of solar radiation. Although for basic evaluation of performance of solar water heater, the efficiency of the system needs to be monitored. Collector efficiency can be given as the ratio between the solar energy incident on the panel to the available thermal energy at the application site.

Efficiency can be shown in the equation as follows:

$$\eta = \frac{Heat\ energy\ available}{Incident\ Solar\ energy} = \frac{Q_{out}}{Q_{in}}$$

Where,

$$Q_{in} = A_c\ X\ G_t$$

$$Q_{out} = m\ X\ C_p\ X\ (T_{out} - T_{in})$$

$$\eta = \frac{m\ X\ C_p\ X\ F_R\ X\ (T_{out} - T_a)}{A_c\ X\ G_t}$$

Where,

Q_{out} = the energy absorbed by the collector (W/m^2)
m = mass of water going into the collector (kg/s)
C_p = specific heat capacity of water
A_C = the size of the collector (m^2)
F_R = collector heat loss factor
G_t = total solar radiation intensity (W/m^2)
T_{in} = temperature of incoming water
T_{out} = temperature of the outgoing water
T_a = ambient temperature

6 Analysis of Energy Use and Material Balance

6.1. Introduction

A material balance in its most broad definition is the application of the law of conservation of mass, which states matter is neither created nor destroyed. Matter may flow through a control volume and may be reacted to form another species, however, no matter is ever lost or gained. The same is true for energy. As with material balances, we can apply the law that energy is neither created nor destroyed, it is simply converted into another form of energy. The law of conservation of mass and energy leads to what is called a mass (material) and energy balance.

Material balances, as they pass through processing operations, can describe material quantities. If there is no accumulation, what goes into a process must come out. This is true for batch operation. It is equally true for continuous operation over any chosen time interval.

Material balances are fundamental to the control of processing, particularly in the control of yields of the products. Material balance can be determined from conceptual stage to final production stage. Initially, material balance is estimated during the planning stage of a new process or equipment. This estimate is improved while carrying out pilot scale tests related to the new process. This material balance is verified during commissioning stage and finally used as a control measure during actual production stage.

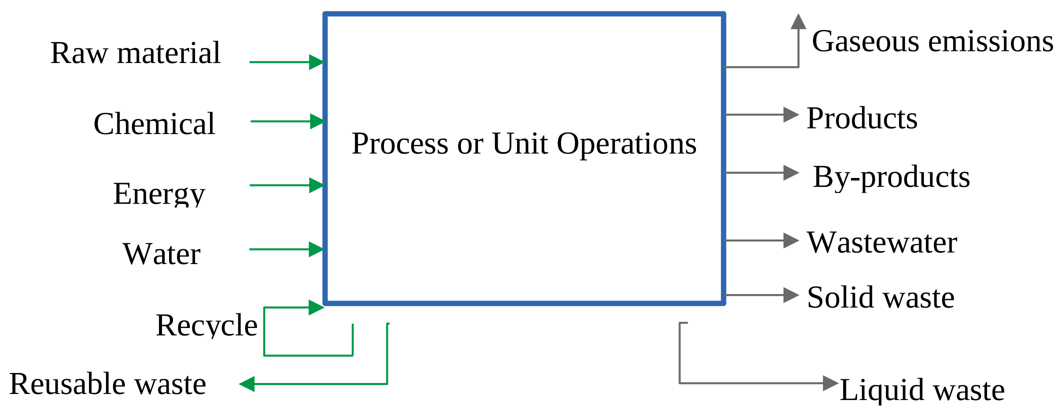
Energy balances are means for industry to examine ways of reducing energy consumption in processing because of increasing energy cost. Energy balances are used in the examination of the various stages of a process, over the whole process and even extending over total production system from the raw material to the finished product.

6.2. Purpose of energy and material balance

- To assess the input, conversion efficiency, output and losses
- To quantify all material, energy and waste streams in a process or a system
- Powerful tool for establishing basis for improvement and potential savings

6.3. Component of energy and material balance

Typical components of material and energy balance for a process or unit operation is shown in below figure It may be noted that recycle stream is shown along with input side.



6.4. Basic principles of energy and material balance

If the industry operation, whatever its nature is seen as a whole it may be represented diagrammatically as a box as shown in **Figure 97** The mass and energy going into the box must balance with the mass and energy coming out.

The law of conservation of mass leads to what is called a mass or material balance.

Mass in = Mass Out + Mass stored

∑Raw materials = ∑Products + ∑Wastes + ∑Stored materials

$m = p + w + s$

If there are no chemical changes occurring in the plant, the law of conservation of mass will apply also to each component. For example, in a plant that is producing sugar, if the total quantity of sugar (m) going into the plant is not equalled by the total of the purified sugar (p) and the sugar in the waste liquors (w) and accumulated in the process (s), then there is something wrong. Sugar is either being burned (chemically changed) or else it is going unnoticed down the drain somewhere. In this case:

$m = p + w + s + l$

where, l is the unknown loss and needs to be identified so, the material balance is now:

Raw materials = Products + waste products + stored products + Losses

Where, losses are the unidentified materials.

Just as mass is conserved, energy is conserved in process operations. The energy coming into a unit operation can be balanced with the energy coming out and the energy stored.

∑Energy in = ∑Energy out + ∑Energy stored

$\sum E_m = \sum E_p + \sum E_w + \sum E_s + \sum E_l$

Where,

$\sum E_m$ = Total energy entering with raw materials
$\sum E_p$ = Total energy leaving with products
$\sum E_w$ = Total energy leaving with waste materials
$\sum E_s$ = Total energy stored
$\sum E_l$ = Total energy lost to surroundings

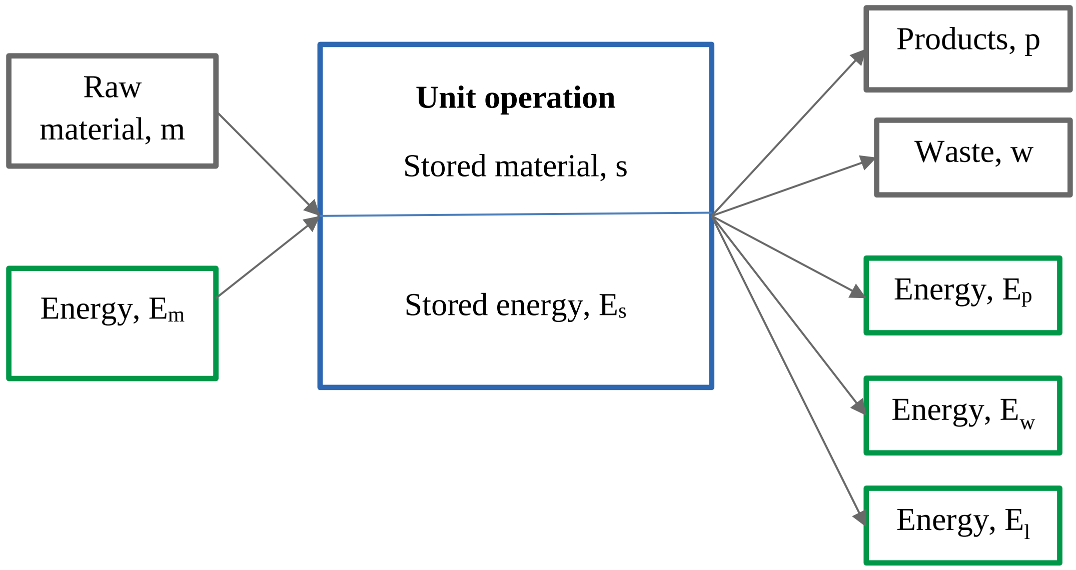


Figure 97: Energy and material balance representation

Energy balances are often complicated because forms of energy can be inter-converted, for example mechanical energy to heat energy, but overall, the quantities must balance.

6.5. Classification of process

Process can be viewed overall or as a series of units. Each unit is a unit operation that can be represented by a box as shown in **Figure 98** Raw materials and energy go into the box and desired products, by-products, wastes and energy come out of the box. The mass in and out of a control box must be equal. The equipment within the box will make the required changes with little waste and energy as possible. There are different types of process.

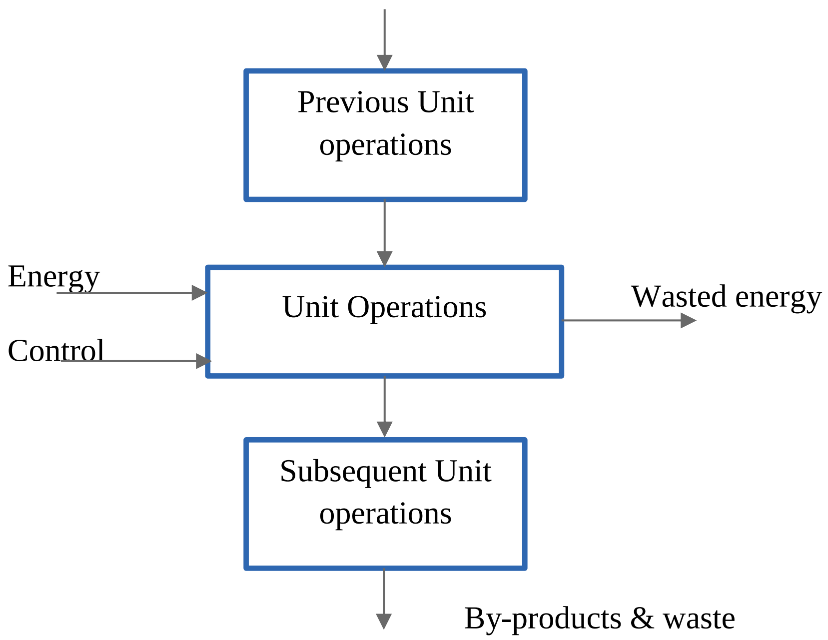


Figure 98: Classification of process

A) Based on how the process varies with time

Steady-state process is one where none of the process variables change with time Unsteady-state process is one where the process variables change with time

B) Based on how the process was built to operate

A continuous process is one that has the feed streams and product streams moving into and out of the process all the time. Examples are oil refinery, distillation process etc.

A batch process is one where the feed streams are fed to the process to get it started. The feed material is then processed through various process steps and finished products are taken out at specific times.

Steps:

- Feed is charged into vessel
- Process is started
- No mass is added or removed from vessel (process parameters are usually monitored and controlled)
- At some conditions or after fixed time, products are removed

Material Balance

Levels of Material Balance

The material balances can be developed at various levels:

Overall Material balance: This involves input and output steams for complete plant

Section wise Material balances: This involves M&E balances to be made for each section/department/cost centre. This would help to prioritise focus areas for efficiency improvement

Equipment-wise Material balances: Material balances for key equipment would help assess performance of equipment, which would in turn help identify energy and material losses.

The choice among the types of material balance depends on the reasons for making the balance. The major factor is the cost of the materials and so costly materials are more likely consider than cheaper ones and products more than waste materials

6.5.1. Material balance procedure

First step is to identify materials in, materials out and material stored. Next step is to consider whether materials in each category have to be treated as whole (gross material balance) or whether individual constituents in the material should be treated separately. For example, we can do material balance for dry solids alone as opposed to total material. This means separating the material into two constituents' non-water and water.

Typical steps are as follows:

a) Define basis & units: Choose a basis of calculations on quantity (mass for batch process) or flow rate (mass per hour for continuous process) of one of the process streams. Convenient Units are then chosen as mass can be expressed in various ways: weight/weight (wlw)weight/volume (wlv)molar concentration (M), mole fraction.

- The weight/weight concentration is the weight of the solute divided by the total weight of the solution and is the fractional form of the percentage composition by weight.
- The weight volume concentration is the weight of solute in the total volume of the solution with gases concentrations are primarily measured in weight concentrations per unit volume, or as partial pressures.
- The molar concentration is the number of molecular weights of the solute expressed in kg in 1 m^3 of the solution.
- The mole fraction is the ratio of the number of moles of the solute to the total number of moles of all species present in the solution.

b) Draw a flow chart: Establish a boundary so that the flow streams in and out can be identified. The identification and drawing up a unit operation/process is prerequisite for energy and material balance. Flow charts are schematic representation of the production process involving various input resources conversion steps and output and recycle streams. The process flow may be constructed stepwise i.e. by identifying the inputs ***I*** output ***I*** wastes at each stage of the process, as shown in the refer **Figure 2 of Chapter 4.1**

Inputs of the process could include raw materials, water, steam, energy (electricity, etc.)

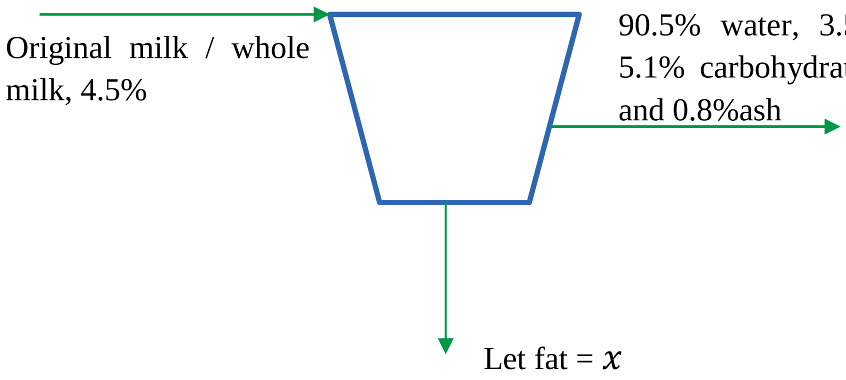
Process Steps should be sequentially drawn from raw material to finished product. Intermediates and any other by-product should also be represented. The operating process parameters such as temperature, pressure, % concentration, etc. should be represented.

The flow rate of various streams should also be represented in appropriate units like m^3/h or kg/h. In case of batch process, the total cycle-time should be included.

Wastes by-products could include solids, water, chemicals, energy etc. For each process steps (unit operation) as well as for an entire plant, energy and mass balance diagram should be drawn. Output of the process is the final product produced in the plan

c) Write material balance equations: The following examples are illustration for writing the material balance equations

Example: Skim milk is prepared by the removal of some of the fat from whole milk. This skim milk is found to contain 90.5% water, 3.5% protein, 5.1% carbohydrate, 0.1% fat and 0.8% ash. If the original milk contained 4.5% fat, calculate its composition assuming that fat only was removed to make the skim milk and that there are no losses in processing.



Basis: 100 kg of skim milk.

This contains, therefore, 0.1 kg of fat. Let the fat which was removed from it to make skim milk be x kg.

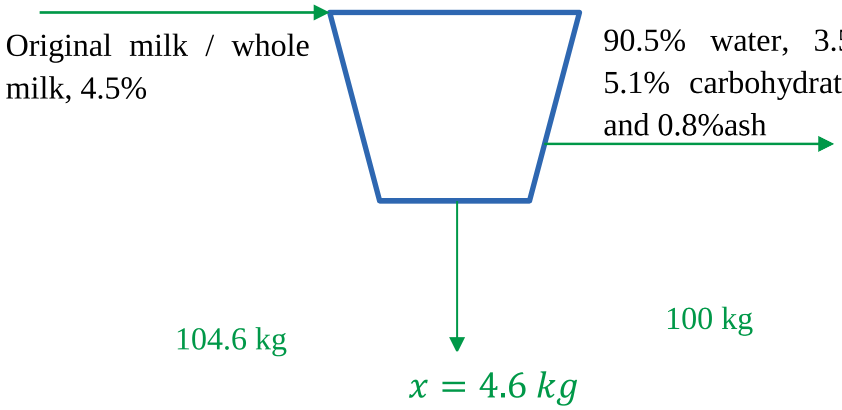
Total original fat = $(x + 0.1)$ kg
Total original mass= $(100 + x)$ kg

and as it is known that the original fat content was 4.5% so

$$\frac{(x+0.1)}{(100+x)} = 0.45$$

$$x + 0.1 = 0.45\,(100 + x)$$
$$x = 4.6\ kg$$

So, the composition of the whole milk is then fat = 4.5%, water = 90.5/104.6 = 86.5 %, protein = 3.5/104.6 = 3.3 %, carbohydrate= 5.1/104.6 = 4.9% and ash= 0.8%



Example: A bag filter is used to remove the dust from the inlet gas stream to meet the emission standards in cement, fertilizer and other chemical industries.

Inlet gas to a bag filter is 1,69,920 m^3/hr and the dust loading is 4577 mg/m^3
Outlet gas from the bag filter is 1,85,040 m^3/hr and the dust loading is 57 mg/m^3
What is the maximum quantity of ash that will have to be removed per hour from the bag filter hopper based on test results?

Solution:
Dust balance, mass in = mass out
Inlet gas duct = outlet gas duct + hopper ash

Inlet dust quantity	= 1,69,920 (m^3/hr) X 4,577 (mg/m^3) X (1/10,00,000) kg/mg = 777.7 kg/hr
Outlet dust quantity	= 1,85,040 (m^3/hr) X 57 (mg/m^3) X (1/10,00,000) kg/mg = 10.6 kg/hr
Hopper ash	= Inlet quantity – Outlet dust quantity = 777.7 kg/hr – 10.6kg/hr **= 767.1 kg/hr**

6.6. Energy balance

Energy is the capacity to do work or to transfer heat. The law of conservation of energy states that energy can neither be created nor destroyed. The total energy in the materials entering the processing plant, plus the energy added in the plant must equal the total energy leaving the plant. This is a more complex concept than the conservation of mass, as energy can take various forms such as kinetic energy, Potential energy, heat energy, chemical energy, electrical energy and so on. During processing, some of these forms of energy can be converted from one to another; say for instance mechanical energy in a fluid can be converted through friction into heat energy. It is the sum total of all these forms of energy that is conserved.

For example, in the pasteurizing process for milk, the milk is pumped through a heat exchanger and is first heated and then cooled. The energy affecting the product is the heat energy in the milk. Heat energy is added to the milk by the pump and by the hot water passing through the heat exchanger. Cooling water then removes part of the heat energy and some of the heat energy is also lost to the surroundings. The heat energy leaving in the milk must equal the heat energy in the milk entering the pasteurizer plus or minus any heat added or taken away in the plant.

Heat energy leaving in milk = initial heat energy + heat energy added by pump + heat energy added in heating section - heat energy taken out in cooling section - heat energy lost to surroundings.

The law of conservation of energy can also apply to part of a process. For example, considering only the heating section of the heat exchanger in the pasteurizer, the heat lost by the hot water must be equal to the sum of the heat gained by the milk and the heat lost from the heat exchanger to its surroundings.

6.6.1. Conservation of energy

In a system, if the storage does not change, the ingoing and outgoing energy must be equal **Figure 99 a**

If the storage changes, this must be reflected in the energy balance and the energy input to a system might not balance the energy that goes out. For instance, as in **Figure 99 b**, the input is 75 units of energy but only 60 units go out. Since the first law requires that the energy be conserved, system had to gain 15 units of energy. In the **Figure 99 c** the input is short by 15 units of energy so it can be inferred that the system must have lost 15 units.

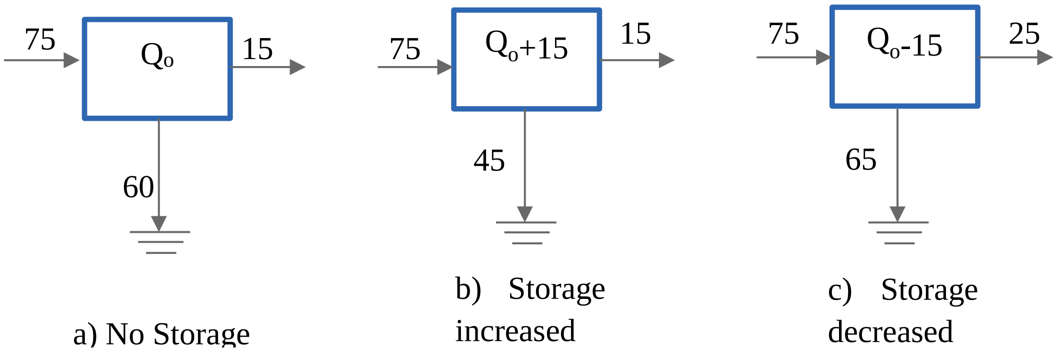
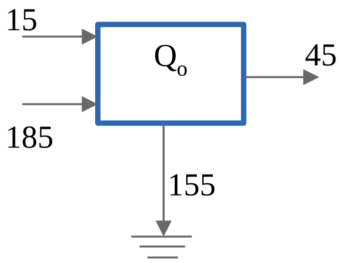


Figure 99: Conservation of energy

The sinks are depositories of leakage or rejected energy. It is usually low-grade heat, as in, radiation losses from boilers or heat carried away by cooling water. The outputs represent useful work.

Efficiency

The (thermodynamic) efficiency of a process is the ratio of useful output to input and is always less than 100%. In the energy balance shown in **Figure 100**, there is no internal storage, so the sum of the inputs must equal the outgoing energy. The efficiency of the process is 22.5% and the energy lost in the system is 100 - 22.5 = 77.5%.



Input = 15 + 185
Output + Sink = 45 + 155
Efficiency = Output/Input
$\eta = 45 / (15+185) = .225$ or 22.5%

Figure 100: Efficiency and losses

6.6.2. Energy analysis and Sankey diagram

The basic data needed for an energy analysis is an energy balance of each process section. The objective is to define in detail the energy input, energy utilized, and the energy dissipated or wasted. This is best represented by a Sankey diagram.

The Sankey diagram is very useful tool to represent an entire input and output energy flow in any energy equipment or system such as boiler generation, fired heaters, furnaces after carrying out energy balance calculation. Usually the flows are represented by arrows. The width of the arrows is proportional to the size of the actual flow. Better than numbers, tables or descriptions, this diagram represents visually various outputs (benefits) and losses so that energy managers can focus on finding improvements in a prioritized manner. For example, the **Figure 101** shows a Sankey diagram for Boiler fuel input to heat output.

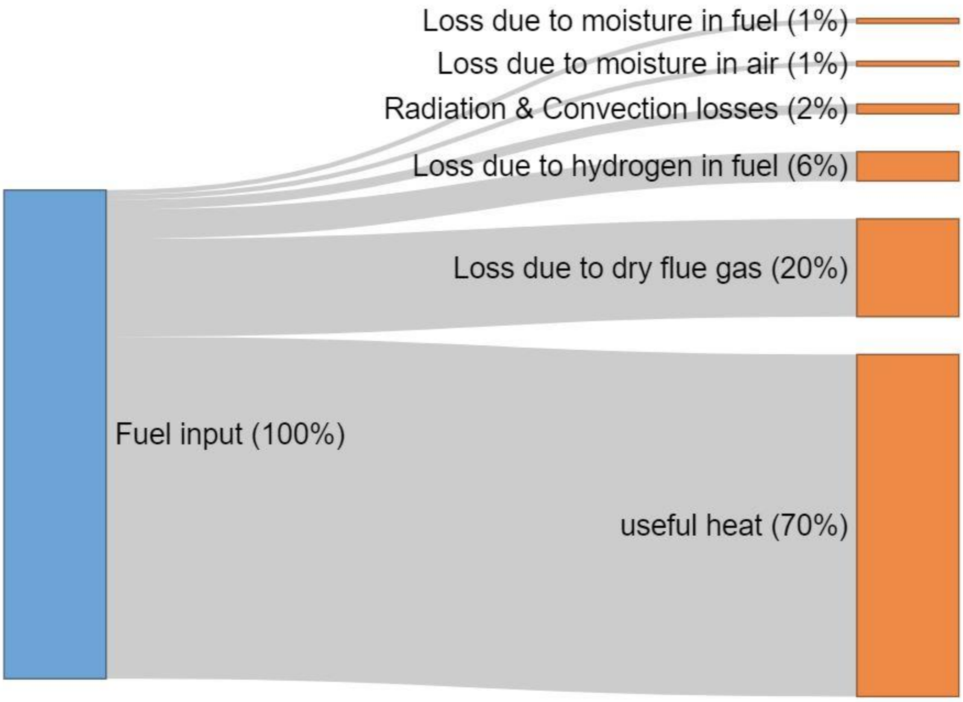


Figure 101: Sankey diagram for Boiler fuel input to heat output

7 Benchmarking

Benchmarking can be a useful tool for understanding energy consumption patterns in an industrial sector and for taking measures to improve energy efficiency. Energy benchmarking for industry is a process in which the energy performance of an individual plant or an entire sector of similar plants is compared against a common metric that represents 'standard' or 'optimal' performance. It may also entail comparing the energy performance of a number of plants against each other.

Since benchmark tool is used for comparison across a number of plants or sectors, there are two important features they should have. First, because they are applied to plants or sectors of different sizes and outputs, the metric used should be common irrespective of plant size. The most common metric used therefore is energy intensity which measures 'energy use per unit of output'. Second, the tool should be used in a wide range of facilities so as to compensate for differences in production at similar facilities.

7.1. Industrial benchmarking programs

Benchmarking energy performance of a facility enables energy auditors and managers to identify best practices that can be replicated. It establishes reference points for managers for measuring and rewarding good performance. It identifies high-performing facilities for recognition and prioritizes poor performing facilities for immediate improvement

There are three approaches for energy benchmarking.

1. The **first approach** is to evaluate an entire industrial sector, such as steel, ferro and alloy, cement, etc. This evaluation is used to answer the following questions:
    - How well is this sector performing compared to how it would perform using the best available technologies?
    - Has the sector been improving over time?
2. The **second approach** is the comparison of individual plants within a sector. A benchmark-type indicator is calculated for all the facilities within a sector so that they can be compared on even terms. This evaluation can answer the following questions: What is the state- of-the-art performance in this given sector? How does my plant compare against the state-of-the-art? How does it compare against the majority of other plants in the sector? In developing benchmarks at the level of individual plants the issue of proprietary data becomes important. Individual companies are very reluctant to disclose information about their production processes, particularly if it will be released to their competitors. It is important that the indicators developed are general enough not to reveal any proprietary information and that a credible system is established that encourages plants to trust the process.
3. The **third approach** for energy benchmarking that has been seen widely in recent years is for large industries to set themselves energy efficiency goals by using historical best performance as benchmark. Industries use this approach to set targets for reducing energy use by certain percentages over given time frames. Companies do not need to reveal any proprietary information, since the benchmarking is done internally.

The key steps in benchmarking include:

1. Determine the level of benchmarking (for example, at equipment level, process line level, or industry level). In simple terms, setting up the boundary for benchmarking.
2. Develop metrics: select units of measurements that effectively and appropriately express energy performance of the plant (e.g. kWh/t product, MTOE/ton product, kg/t product, etc.)
3. Conduct comparisons to determine the performance of the plant or system being studied compare to the benchmark.
4. Track performance over time to determine if energy performance being improved or worsening over time in order to take the appropriate actions

While conducting benchmarking, the key drivers of energy use should be identified and the benchmarking metrics might be adjusted or normalized, for instance, based on the weather, production levels, or product characteristics that affect energy use. Normalizing data ensures a meaningful comparison and avoids comparing "apples to oranges." Evaluating and acting on benchmarking results are as important as undertaking the benchmarking activity. Below are some examples of benchmarking parameters for various industries:

Table 42: Benchmarking parameters for various industries

Industry	Benchmarking parameter or specific energy consumption (SEC)	Process parameters need to be stated for meaningful comparison among similar industries
Cement Industry	kWh/t of cement produced	type of cement, blaine number (cement fineness) i.e. Portland and process used (wet/dry) are to be reported alongside kWh/t or in terms of tons of oil equivalent toe/t
Foundry	kWh/t of molten metal output	Furnace type, composition (mild steel, high carbon steel/cast iron etc.) raw material mix, number of power trips could be some useful operating parameters to be reported while mentioning specific energy consumption data.
Beverages	kWh/l of beverage produced	type of beverage, type of technology used
Food and agro products	kWh/kg of food and agro product	type of product, type of technology

It is evident from above **Table 42** that it is not feasible to define a single norms/standard unless there is significant homogeneity amongst units in a sector. Therefore, it is preferable to fix the energy efficiency improvements targets as "unit specific" (approach 3).

As per the BEE studies, the wide bandwidth of specific energy consumption (SEC) within an industrial sector is indicative of the large energy-savings potential in the sector. The wide bandwidth is also a reflection of the differences in the energy-saving possibilities amongst plants because of their varying technologies deployed, vintage, production capacity, raw material quality, and product-mix. Such wide variation also makes it difficult to specify a single benchmark SEC for the sector as a whole: older plants will find the benchmark impossibly high if it is set at the level of newer plants; newer plants will find it trivial if it is set at the level of older plants. The broad bandwidth of SEC within a sector, and the inability of all plants to achieve a sectoral benchmark SEC, suggests that SEC improvement norms need to be set for individual plants.

7.2. Plant Energy Performance (PEP)

Industry energy performance is the measure of whether a plant is using more or less energy to manufacture its products than it did in the past, a measure of how well the energy management program is doing.

Plant energy performance monitoring compares Plant energy use of a reference year and the subsequent years considering product output to determine the improvement (or deterioration) that has been made.

However, since the Plant production output varies from year to year it has significant impact on Plant’s energy use. For a meaningful comparison it is necessary to determine the energy that would have been required to produce current year’s production output had the plant operated in the same way as it did during the reference year. This calculated value can then be compared with the actual value to determine the improvement or deterioration that has taken place since the reference year.

7.3. Production factor

Production factor is the ratio of production in the current year to that in the reference year.

$$Production\ factor = \frac{Current\ year's\ production}{Reference\ year's\ production}$$

Production factor is used to determine the energy that would have been required to produce this year's production output if the plant had operated in the same way as it did in the reference year.

Reference Year Equivalent Energy Use

The reference years equivalent energy use (or reference year equivalent) is the energy that would have been used to produce the current year's production output.

The reference year equivalent is obtained by multiplying the reference year energy use by the production factor (obtained above)

Reference year equivalent = Reference year energy use x Production factor

Plant Energy Performance is the improvement or deterioration from the reference year. It is a measure of Plant energy progress.

$$\text{Plant energy performance} = \frac{\text{Reference year equivalent} - \text{Current year's energy use}}{\text{Reference year equivalent}} \; X\ 100$$

The energy performance is the measure of energy saved at the current rate of use compared to the reference year rate of use. The greater the improvement; the higher the number will be.

Plant energy performance is the starting point for evaluating energy performance. It does not require detailed calculations of the energy used by every piece of equipment, or the energy use of every process. It utilizes the most effective measure of energy savings, the actual measurement of energy consumption compared to production output. Yearly comparisons minimize seasonal effects. Once a plant has started measuring yearly energy performance, management wants more frequent performance information in order to monitor and control energy use on an on-going basis. In such cases Plant energy performance can just as easily be used for monthly reporting as yearly reporting.

8 Cost Benefit Analysis

After identifying the list of energy-efficiency measures applicable to the facility, the auditor shall also conduct cost benefit analysis for the measures and make recommendations for their implementation. Step-by-step guidance for energy auditors on payback period, return of investment, net present value, and internal rate of return, in order to conduct the common economic analysis for the assessment of financial viability of the energy efficiency measures is presented below.

8.1. Payback period

Payback period refers to the amount of time (number of years) it takes to recover the capital cost of an investment. Shorter payback period means more attractive investments while longer paybacks are less desirable. It is a simple term to determine whether to go through with an investment or not.

Simply put, the payback period is the cost of the investment divided by the annual cash flow or annual net savings and can be calculated using the following equation:

$$Simple\ payback\ period = \frac{Capital\ cost}{Annual\ net\ savings}$$

Annual net savings is the cost savings achieved after all the operational costs have been met. The word 'Simple' is used as a prefix to the term 'payback period' to denote that time value of money is not considered in its calculation.

Example: A new waste heat recovery system (WHR) installed in a facility is expected to reduced energy bill by Nu. 400,000. If the capital cost of investment of the new WHR is Nu. 500,000. What will be the expected payback period for the project?

$$Simple\ payback\ period = \frac{500{,}000}{400{,}000} = 1.25\ years, or\ 15\ months$$

8.2. Return on Investment (ROI)

Return on Investment (ROI) is a performance measure used to evaluate the efficiency of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost. To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment. The result is expressed as a percentage or a ratio.

$$ROI = \frac{Annual\ net\ cash\ flow}{Capital\ cost}\ X\ 100$$

Example: An investment of Nu. 100,000 for equipment is expected to provide an after-tax cash flow of Nu. 25,000 over a period of six years, without significant annual fluctuations. What is the return of investment?

$$ROI = \frac{25{,}000}{100{,}000} X\, 100 = 25\%$$

8.3. Net Present Value (NPV)

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project.

The net present value method considers the time value of money. This is done by equating future cash flow to its current value today, or in other words by determining the present value of any future cash flow. The present value is determined by using an assumed interest rate, usually referred to as a discount rate. Discounting is the opposite process to compounding. Compounding determines the future value of present cash flows, whereas discounting determines the present value of future cash flows.

The net present value method calculates the present value of all the yearly cash flows (i.e. capital costs and net savings) incurred or accrued throughout the life of a project and summates them. As a matter of convention, costs are represented as negative values and savings as positive values. The sum of all the present values is known as the net present value (NPV). The higher the net present value, the more attractive is the proposed project.

The following formula is used to calculate NPV:

$$NPV = -\frac{CF_0}{(1+i)^0} + \frac{CF_1}{(1+i)^1} + \dots\dots\dots + \frac{CF_n}{(1+i)^n} = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t}$$

Where,

CF_t = Cash flow occurring at the end of year ‘t’ (t =0,1…n) (As per our convention, net savings or inflows are represented by (+) sign and net costs or outflow are represented by (-) sign. Since capital investment is an outflow, it will be treated as negative (-) as per our convention)
i = Discount rate
n = Life of the project

The discount rate (i) employed for evaluating the present value of the expected future cash flows should reflect the risk of the project. Hence the decision rule associated with the net present value criterion is: "Accept the project if the net present values is positive and reject the project if the net present value is negative". A negative net present value indicates that the project is not achieving the return standard and thus will cause an economic loss if implemented. A zero NPV is value neutral.

The net present value takes into account the time value of money and it considers the cash flow stream in entire project life.

Example: Using the net present value analysis technique, evaluate the financial merits of the two proposed projects shown in the table. The annual discount rate is 8% for each of the project.

Projects	Project 1	Project2
Capital Cost (Nu.)	30,000	30,000
Year	**Net annual savings (Nu.)**	**Net annual savings (Nu.)**
1	+6,000	+6,600
2	+6,000	+6,600
3	+6,000	+6,300
4	+6,000	+6,300
5	+6,000	+6,000
6	+6,000	+6,000
7	+6,000	+5,700
8	+6,000	+5,700
9	+6,000	+5,400
10	+6,000	+5,400
Total net savings at the end of 10^{th} year	**+60,000**	**+60,000**

For Project 1:

$$NPV = -\frac{30000}{(1+0.08)^0} + \frac{6000}{(1+0.08)^1} + \frac{6000}{(1+0.08)^2} + \frac{6000}{(1+0.08)^3} + \frac{6000}{(1+0.08)^4} + \frac{6000}{(1+0.08)^5} + \frac{6000}{(1+0.08)^6} + \frac{6000}{(1+0.08)^7} + \frac{6000}{(1+0.08)^8} + \frac{6000}{(1+0.08)^9} + \frac{6000}{(1+0.08)^{10}}$$

NPV = +10,254

For Project 2:

$$NPV = -\frac{30000}{(1+0.08)^0} + \frac{6600}{(1+0.08)^1} + \frac{6600}{(1+0.08)^2} + \frac{6300}{(1+0.08)^3} + \frac{6300}{(1+0.08)^4} + \frac{6000}{(1+0.08)^5} + \frac{6000}{(1+0.08)^6} + \frac{5700}{(1+0.08)^7} + \frac{5700}{(1+0.08)^8} + \frac{5400}{(1+0.08)^9} + \frac{5400}{(1+0.08)^{10}}$$

NPV = +10,867

For a 10-year lifespan, the net present value for project 1 is Nu. 10,254, while for project 2 it is Nu. 10,867. Therefore project 2 is preferred.

The whole credibility of the net present value depends on a realistic prediction of discount rate which could often be unpredictable. prudent to set the discount rate slightly above the interest rate at which the capital for the project is borrowed.

8.4. Internal Rate of Return (IRR)

By setting the net present value of an investment to zero (the minimum value that would make the investment worthwhile), the discount rate can be computed. The internal rate of return (IRR) of a project is the discount rate, which makes its net present value (NPV) equal to zero. It is the discount rate of equation:

$$0 = -\frac{CF_0}{(1+i)^0} + \frac{CF_1}{(1+i)^1} + \ldots\ldots\ldots + \frac{CF_n}{(1+i)^n} = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t}$$

Where,

CF_t = Cash flow occurring at the end of year 't'
i = Discount rate
n = Life of the project

CF_t value will be negative if it is expenditure and positive if it is savings.

If this discount rate is greater than current interest rate, the investment is sound.

This procedure, like net present value, can also be used to compare alternatives. The criterion for selection among alternatives is to choose the investment with the highest rate of return. The calculation procedure for determining IRR is tedious and usually requires a computer spreadsheet. The IRR function formula is available in Excel and can be used in practice. However, it is important to get acquainted with the fundamental procedure of determining the IRR. Determining IRR is an iterative process requiring guesses and approximations until a satisfactory answer is derived.

8.5. Capital investment considerations

To judge the attractiveness of any investment, we must consider the following four elements involved in the decision:

- Initial capital cost or net investment
- Net operating cash inflows (the potential benefits)
- Economic life (time span of benefits)
- Salvage value (any final recovery of capital)

8.5.1. Initial capital cost or net investment

When companies spend money, the outlay of cash can be broadly categorized into one of two classifications: expenses or capital investments. Expenses are generally those cash expenditures that are routine, ongoing, and necessary for the ordinary operation of the business. Capital investments, on the other hand, are generally more strategic and have long term effects. Decisions made regarding capital investments are usually made by senior management and carry with them additional tax consequences as compared to expenses.

The capital investments usually require a relatively large initial cost. The initial cost may occur as a single expenditure or occur over a period of several years. Generally, the funds available for capital investments projects are limited.

Initial capital costs include all costs associated with preparing the investment for service. This includes purchase cost as well as installation and preparation costs. Initial costs are usually non-recurring during the life of an investment.

8.5.2. Net operating cash inflows

The benefits (revenues or savings) resulting from the initial cost for a capital investment occur in the future, normally over a period of years. As a rule, the cash flows which occur during a year are generally summed and regarded as a single end-of-year cash flow. Annual expenses and revenues are the recurring costs and benefits generated throughout the life of the investment after adjusting for applicable taxes and effects of depreciation. Periodic replacement and maintenance costs are similar to annual expenses except that they do not occur annually.

8.5.3. Economic life

The period between the initial cost and the last future cash flow is the life cycle or life of the investment.

8.5.4. Salvage value

The salvage (or terminal) value of an investment is the revenue (or expense) attributed to disposing of the investment at the end of its useful life. If substantial recovery of capital from eventual disposal of assets at the end of the economic life, these estimated amounts must be made part of the analysis. Such recoveries can be proceeds from the sale of facilities and equipment (beyond the minor scrap value), as well as the release of any working capital associated with the investment.

9 Detailed Energy Audit Reporting

After finishing the energy audit, the audit team should write an energy audit report. In the report, the auditors should explain their work and the results in a well-structured format. The energy audit report should be concise and precise and should be written in a way that is easy for the target audience to comprehend. Some key issues that should be kept in mind while writing an audit report are:

- The audit report should be written in a way that provides suitable information to the potential readers of the report which could be the CEO or plant manager, the supervisor of engineering or maintenance, and the plant shift supervisor.
- The audit report should be concise and precise and use direct language that is easy to understand.
- Use more graphs rather than tables for the presentation of data, results, and trends.
- The recommendation section should be specific, clear and with adequate detail.
- Assumptions made in the analysis should be explained clearly (If any). How changes in the key assumptions can influence the results should also be explained.
- The auditors should do their best to avoid mistakes and errors in the report, especially in the results. Even a few errors could damage the credibility of the audit.
- The energy audit report should be consistent in structure and terminology used.
- The calculations made in the analysis work should be explained clearly.

Typical energy audit report contents and format are shown below. The following format is applicable for detailed energy audit of a facility in most industries. However, the format can also be modified for targeted energy audit.

9.1. Typical contents of the report

1. Title page
2. Table of contents
3. Acknowledgement
4. Auditor firm and audit team details and declaration
5. Executive summary
6. Audit objectives, scope, and methodology
7. Plant overview
8. Energy and utility system description
9. Energy performance assessment
    - Summary of recommendations and action plan
10. List of suppliers of retrofits / vendors.
11. Annexures / references, software tools used

The details pertaining to each content are given in the following sections.

9.1.1. Title page of the report

The title page of the report may contain:

Audit report title, for example if the detailed energy audit is carried out for industry "XYZ", then the title could be "Energy Audit Report of XYZ".

Similarly, if the audit covers one system or equipment (e.g. Boiler) of industry "XYZ" then the title can be "Energy Audit Report of Boiler of XYZ".

Name of the facility and location: The title sheet may also include the name along with and identification code (if there is any identification code for industries issued by government) and category. The location of industry shall also be mentioned.

Date of report (month and year)

Auditor name: The name of the auditor may be written on the title sheet.

Mandatory audit details: If the energy audit is carried out as a part of mandatory requirement, it may be mentioned.

9.1.2. Table of contents

A table of contents sometimes also refer as simply "Contents". The contents usually include the titles or descriptions such as chapter titles and in longer reports second level (section level) and third level (subsections level) as applicable.

Like any engineering report, table of contents should be very comprehensive and include:

- Sections and subsections along with page numbers in main content sheet
- List of tables along with the table number and corresponding page number
- List of figures and graphs including diagrams and flow charts along with number and corresponding page number
- Abbreviations used in the report

All chapters, sections and subsections of the chapters, tables, figures, graphs, flow charts and diagrams should be numbered for easy identification and references.

9.1.3. Acknowledgement

The basic purpose to include acknowledgement page is just to give a thankful note for all those plant personnel who have supported you in carrying out your audit. It is advisable to include people in the proper order according to the importance of their provided support. However, acknowledgment should be concise not more than 1 or 2 paragraphs.

9.1.4. Audit firm and team details and declaration

The report shall contain the energy auditor details (such as name, address, phone, fax, e-mail address etc.). The details shall also include energy auditor registration number as and when such a registration system is instituted by DRE in Bhutan.

A declaration such as shown here may be used:

The data collection has been carried out diligently and truthfully. All data measuring devices used by the auditor are in good working condition, have been calibrated and have valid certificate from the authorized approved agencies and no tampering of such devices has occurred. All reasonable professional skill, care and diligence had been taken in preparing the energy audit report and the contents thereof are a true representation of the facts. The energy audit has been carried out in accordance with the Energy Auditing and Reporting Guidelines issued by the Department of Renewable Energy, Ministry of Economic Affairs, Royal Government of Bhutan, 2020".

The energy auditor shall sign the energy audit report under the seal of the firm below the declaration.

9.1.5. Executive Summary

An executive summary provides management of the audited facility with brief overview of the total savings and highlight of each energy saving measure. The purpose of an executive summary is to summarize the key points of the energy audit study such as energy saving potential, recommendations, cost savings, investment requirement etc, for each sub system for which energy audit done. Executive summary should be tailored to non-technical personnel.

The executive summary shall draw the entire information from the main report. The executive summary shall contain:

- Summary of energy savings potentials
- Recommended energy-efficiency measures (with a brief explanation of each)
- Implementation costs, savings, and payback period for the recommended measures, A typical format is shown in **Table 43**

Table 43: Summary of energy savings recommendation format

Sl. No.	Brief description of Energy saving recommendation	Annual energy savings (kWh/year)	Annual fuel savings (kl/year)	Annual cost savings (Nu.)	Investment (Nu.)	Simple Payback period in months

- Highlight the impact of implementation of energy savings measures in energy savings and cost savings,
- Summary list of energy saving measures along with classification shall be given. A typical format is shown in **Table 44**

Table 44: Types and priority for energy savings measure format

Sl. No.	Type of energy savings recommendations	Annual electricity (kWh) or fuel savings (kl/kg)	Annual Savings (Nu.)	Priority
A	No/low cost measure • Operational improvement Housekeeping			
B	Medium term measure • Controls • Equipment Process change			
C	Long term measure • Energy efficiency devices • Product modification Technology change			

9.1.6. Audit objective, scope, and methodology

- Audit objectives and purpose of energy audit.
- Scope of work: Brief description of scope of work can be given in this section while detailed scope can be enclosed as annexure.
- Methodology and approach followed for the audit (i.e. inspection, measurements, calculations, analysis, and assumptions).
- Time schedule for conducting the energy audit – field study and report preparation.
- Instruments used: Details of portable energy audit instruments and specific online instruments used during the audit (such as make, model, type, parameters measured, calibration details, etc.)

Industry overview

Under the overview of the Industry, energy audit report shall include the information pertaining to:

- General plant details and description
- Process description – brief description of plant process with process flow diagram.

9.1.7. Energy consumption profile

The section shall include the following:

- Energy consumption pattern: The audit report shall contain data for one year preceding the year for which energy audit report is being prepared giving details of energy consumed and specific energy consumption of plant.
- Desegregations of the energy consumption data and identification of major energy consuming equipment /section /process
- Mention unit cost (Nu./kWh) for electricity and Nu./kl or Nu./kg for fuel considered for techno-economic evaluation.

9.1.8. Equipment and utility system description

This section shall include all major energy consumer of plant (any or all of the following that are applicable):

- Motors
- Compressors
- Boilers
- Furnaces
- Chillers
- Water pumping systems

9.1.9. Energy performance assessment

There may be some other sections /equipment in addition to those mentioned above which may need to be added. Each item of the above list shall be treated in a separate chapter while preparing the report. Under each equipment/ section the following may be given (refer relevant sections pertaining to the equipment)

- Introduction and description of the equipment and process
- Specifications / design parameter / PG test values
- Energy consumption pattern and specific energy consumption
- Observations, analysis, and findings:
    - General condition of the plant and equipment
    - Operation and operating parameters
    - Surveys conducted
    - Test and trial runs
    - Performance analysis / efficiency evaluation
- Energy saving recommendations
- Summary list of energy saving measures and classification as per suggested implementation schedule (short term, medium term and long term)
- Impact of implementation of energy saving recommendations (pre and post scenario) in terms of specific energy consumption /specific energy cost.

Energy savings recommendations

All energy conservation measures suggested during the audit study shall include:

1. A suitable title of recommendation (for easy identification)
2. A brief description of present practice/ system/ equipment shall be given, its background and its impact on energy efficiency or energy consumption should be provided. The technical estimations on energy loss/wastage due to the present system can be included. A brief process flow / line diagram can help in easy explanation of present system
3. Description of recommendation: Details pertaining to the recommendation regarding its technical and operational features, benefits expected and any known risk, etc
4. If the recommendation pertains to replacement, retrofitting, or resizing, the auditor shall give the key technical specifications along with energy performance parameters (efficiency / specific energy consumption, etc).

5. Detailed estimation of energy savings and energy cost reduction over a reasonable technical or economic life of the measure
6. Detailed techno-economic evaluation
7. Preliminary assessment of the financial attractiveness or assessment of maximum investment based on the estimated energy cost and saving potential over the life of the measure
8. Where different alternatives are available, all options may be compared, and better options suggested.
9. Where the installation or implementation of any recommended energy saving measure affects the procedure of operation and maintenance, staff deployment and the budget, the recommendation shall include discussion of such impacts including their solution.
10. List of Suppliers / vendors /contractors details for implementation

Table 45: Energy savings recommendation format

Reporting format for energy savings recommendation	
Title of recommendation	Replace high wattage 40 W fluorescent tube lights with energy efficient 18 W LED tube light
Description of existing system	150 High wattage fluorescent tube lights (40 W each) are installed for lighting the shop floor, electrical control room and office. (Average use 12 hours per day)
Description of proposed system	• Replace fluorescent tube lights with energy efficient LED tube lights • The replacement of tube lights may be done in phase wise manner. Such as if any or couple of lights are fused or damaged replace those with LED lights
Energy savings Calculations	
Existing system	
No. of fluorescent tube lights	= 150
Power consumption of each fluorescent tube lights	= 40 W = 0.04 kW
Average use per day	= 12 hours
Annual running of plant	= 250 days
Annual energy consumption of tube lights	= 150 X 0.04 X 12 X 250 = 18,000 kWh
Proposed system	
No. of LED tube lights	= 150

Reporting format for energy savings recommendation	
Power consumption of each LED tube lights	= 18 W = 0.018 kW
Average use per day	= 12 hours
Annual running of plant	= 250 days
Annual energy consumption of tube lights	= 150 X 0.018 X 12 X 250 = 8,100 kWh
Net energy savings	= 18,000 – 8,100 = **9,900 kWh**
Cost benefits	
Annual monetary savings (@ 3 Nu./kWh)	= **Nu. 29,700**
Investment (@ Nu. 330 per LED tube light)	= 150 X 330 = Nu. 49,500
Payback	= 49,500 / 29,700 = **20 months**

9.1.10. Action plan

The auditor shall summarise all recommendations and provide action plan for implementation in which the recommendations are prioritised. This shall be discussed with the energy manager / concerned plant personnel.

The action plan shall include:

- Preparation of detailed techno-economics of the selected measures in consultation with energy manager / plant personnel
- A monitoring and verification protocol to quantify on annual basis the impact of each measure with respect to energy conservation and cost reduction for reporting to top management of the industry.
- A time schedule agreed upon by the plant management of selected measures taking into consideration constraints such as availability of finance, resources, and availability of proposed equipment.

9.1.11. List of suppliers, vendors, and contractors

The energy audit report shall provide the information for supporting the industry to implement proposed recommendations. Such information may include list of suppliers / vendors and local contractors who would be able to provide the technology or services to the industry for effective implementation of recommended measures. The details shall include name and address, contact person, contact details such as phone, fax, email etc.

The energy auditor's role is not to promote specific supplier / vendor and hence it is important to provide details of various options and to let the industry choose the vendor of their choice using their own criteria. It strongly recommended that the list of vendors may be accompanied by a disclaimer, that the energy auditor does not recommend or endorse any supplier.

9.1.12. Appendices

Appendices shall include background material that is essential for understanding the calculations and recommendations and may include:

- Plant layout diagrams
- Process diagrams
- Reference graphs used in calculations, such as motor efficiency curves, pump performance curves etc.
- Data sets that are large enough to clutter the text of the report.
- Detailed specifications, design details, test certificates, performance covers.

9.1.13. References, software used

The audit report shall include the references utilized for technical inputs such as papers, journals, handbooks, publications etc. In addition, if the auditor used any software for the analysis, the details of such software shall be given in the report.

10 Post Audit Activities

In practice there are often barriers that prevent the successful implementation of energy efficiency measures recommended in an energy audit report. Therefore, it is helpful to establish a clear procedure to ensure the successful realization of recommended improvements. An implementation action plan should be described in a simple way with clear goals, saving targets, and definitions of roles and responsibilities for its execution

A detailed action plan helps to ensure a systematic process to implement energy-efficiency measures. The action plan can be updated regularly, most often on an annual basis, to reflect recent achievements, changes in performance, and shifting priorities. While the scope and scale of the action plan is often dependent on the organization, the steps below outline a basic starting point for creating a plan:

1. Define technical steps and targets
2. Determine roles and resources

Before finalizing the action plan, it is better to consult with plant managers and key engineers to get their input on the action plan.

10.1. Define technical Steps and targets

The energy audit results can provide an indication of the technical performance of the plant and its gap with the efficient performance. Based on this, opportunities for energy-efficiency improvement can be identified and prioritized.

Three key steps are:

1. Create performance targets for each industrial process, department, and operation of the organization to track progress towards achieving the goals.
2. Set timelines for actions, including regular meetings among key personnel to evaluate progress, completion dates, milestones and expected outcomes.
3. Establish a monitoring system to track and monitor the progress of actions taken. This system should track and measure energy use and project/program activities.

10.2. Determine roles and resources

10.2.1. Identify internal roles

The action plan should determine who is involved in the energy-efficiency program and what their responsibilities are. Depending on the organization and action plan, this might include departments such as:

- Plant and operations management
- Financial management - capital investments, budget planning
- Human resources - staffing, training, and performance standards
- Maintenance

- Supply management - procurement procedures, energy purchasing and equipment and materials
- Building and plant design
- Engineering
- New product/process development teams
- Communications Marketing
- Environmental, Health, and Safety

10.2.2. Identify external roles

The action plan should determine the degree to which consultants, service providers, vendors, and other product providers will be used. Some organizations may choose to outsource entire aspects of their action plan while others may only want to contract with specific vendors for limited projects. If contractors will be used, the action plan should determine what standards will be used to evaluate bids and incorporated these metrics into agreements with contractors.

10.2.3. Determine resources

For each project or program in the action plan, estimate the cost for each item in terms of both human resources and capital/expense. Then, develop the business case for justifying and gaining funding approval for action plan projects and resources need.

10.2.4. Implement the action plan

To successfully implement the action plan, it is vital to gain support from the personnel within the plant involved in the energy-efficiency improvement programs. To implement the action plan, the following steps should be considered:

1. Create a communication plan: Develop targeted information for key audiences about the energy efficiency action plan

2. Raise awareness: Build support for all levels of the organization for energy efficiency initiatives and goals.

3. Build capacity: Through training, access to information, and transfer of successful practices, and procedures to expand the capacity of the plant staff.

4. Motivate: Create incentives that encourage staff to improve energy performance to achieve goals.

5. Track and monitor: Use the tracking system developed as part of the action plan to track and monitor progress regularly.

10.2.5. Evaluate progress:

Plant managers can evaluate the progress of their activities using energy data and a review of the activities taken as part of the action plan, comparing them to the established goals. This review can be used to revise the action plan and see the lessons learned. Regular evaluation of energy performance and the effectiveness of energy-efficiency initiatives also allows energy managers to:

- Measure the effectiveness of projects and programs implemented
- Make informed decisions about future energy projects
- Reward individuals and teams for accomplishments
- Document additional savings opportunities as well as non-quantifiable benefits that can be leveraged for future initiatives

It's worth highlighting the fact that a company needs to have an energy management program to be able to fully benefit from the energy audit results and to have sustainable energy efficiency improvement. If it does not have an energy management program, the audit will likely be a one-time event, and the implementation rate of the audit recommendations will be low.

11 Energy Audit Instruments

Description of instruments	Image representation (for visual purpose only)
Hand-held Clamp meter Used for measurement of voltage, current, power factor and power without interrupting the connections or routine operation of plant for quick and instantaneous measurements.	
Three-phase power analyser Used for measurement of various parameters such as voltage, current, power factor, power, harmonics, frequency, reactive power, and all other electrical parameters. This instrument is applied online without interrupting the routine operation of plants and can measure and record all electrical parameters for long duration (more than 24 hours). The recorded data can easily be transported in computer/laptop for further analysis and identification of energy savings opportunity.	
Thermal imaging camera This is a non-contact type infra-red thermal monitoring and imaging device for measuring thermal energy radiation from hot or cold surfaces of an object. The thermal camera unit converts electromagnetic thermal energy (IR) radiated from an object into electronic video signals. These signals are amplified and transmitted via interconnected cable to a display monitor where the resulting image is analysed and interpreted for hot/cold spots	

Description of instruments	Image representation (for visual purpose only)
Infra-red (IR) thermometer This is a non-contact device, used for measuring temperatures from a distance using infrared technology – helpful in determining heat loss. This is also helpful in determination of temperature of objects placed in hazardous or hard-to-reach places.	
Sling Psychrometer A type of hygrometer used to measure the relative humidity in the atmosphere with the help a dry bulb and a wet bulb thermometer mounted on it. A dry bulb thermometer measured the dry air temperature while the wet bulb thermometer dipped in a wet cloth measure the wet bulb temperature.	
Pen-type thermometer This is a contact-type device used for measurement of surface or water temperatures. This is helpful in HVAC system to measure the temperatures of chilled water and cooling water.	
Hygrometer This is used to measure dry bulb temperatures, wet bulb temperatures, humidity, and dew point of ambient air. This is an especially useful device in assessing HVAC system. (Image source: Extech)	

Description of instruments	Image representation (for visual purpose only)
Flue gas analyser This instrument has in-built chemical cells which measure various gases such as O_2, CO_2, CO, NO_x, SO_x, etc. This is mainly used to monitor the exhaust flue gases coming out of boiler or fuel fired furnace stacks. It is portable, lighter, and easier to operate. (Image source: Testo)	
Ultrasonic water flow meter Used for measurement of flow of liquids through pipelines of various sizes through ultrasonic sensors mounted on the pipelines – helpful in determining pumping and cooling system efficiencies. This is a non-invasive technique to measure the water flow. This is mainly used to assess performance of pumps by measuring water flow.	
Lux meter Used for measurement of illumination level – helpful in optimising lighting loads. This is also known as light meter. (Image source: Extech)	

Description of instruments	Image representation (for visual purpose only)
Anemometer Used for measurement of air flow, this is useful in assessing the performance of cooling tower and air handling unit fans. (Image source: Extech)	
Manometer with pitot tube Used for measurement of pressures in air duct carrying exhaust gases or air from fans and blowers. To measure pressure in air pipe, manometers must be used in combination with a pitot tube. (Image source: Extech)	
Tachometer Used for measurement of motor speed in RPM (revolutions per minutes). This can be used either in contact type method or non-contact method to measure the rotation of motor shaft and determine the belt slip.	

<table>
<tr><th>Description of instruments</th><th>Image representation (for visual purpose only)</th></tr>
<tr><td>Smart energy meters
Used for measurement of voltage, current and power in single phase. This is mainly used to measure and monitor the single-phase electronic equipment’s energy consumption. This can also record the energy consumption data.</td><td>
</td></tr>
<tr><td>Ultrasonic leak detector
Used for detection of compressed air leakages in plant. This detects almost any leaks because short distance/access and high air pressure is not needed, sensitive to sound and filters background noises. This instrument does not measure the size of leak that energy auditor has to assess.</td><td></td></tr>
<tr><td>TDS Conductivity meter
Used for spot measurement of TDS (total dissolved solids) and conductivity of water especially in boiler blowdown. This is also useful during performance assessment of cooling tower.</td><td>
</td></tr>
</table>

12 List of Simulation Software

Software Name	Software application and brief description
Pump System Improvement Modeling tool (PSIM)	PSIM 2 is a free educational tool that allows engineers to build models of pump systems and simulate hydraulic behaviour. PSIM 2 will model pump system behaviour and demonstrate the impact of operational and design trade-offs on system performance and energy usage for centrifugal and positive displacement pumping systems.
Pump system assessment tool (PSAT)	The **Pumping System Assessment Tool (PSAT)** is a free online software tool to help industrial users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.
Thermoflex	This is referred to as "heat balance software". It is a fully flexible program with a graphic user interface in which the user creates a thermal system network by selecting, dragging, dropping and connecting icons representing over two hundred different components. The program covers both design and off-design simulation, and models all types of power plants, including combined cycles, conventional steam cycles, and repowering, as well as a wide range of renewable energy plants and systems. It can also model general thermal power systems and network. Software for purchase: https://www.thermoflow.com
TRNSYS	It is an extremely flexible graphically based software environment used to simulate the behaviour of transient systems. The vast majority of simulations are focused on assessing the performance of thermal and electrical energy systems TRNSYS is made up of two parts. The first part is an engine (called the kernel) that reads and processes the input file, iteratively solves, determines convergence, and plots system

Software Name	Software application and brief description
	variables. The kernel also provides utilities that determine thermo-physical properties, invert matrices, perform linear regressions, and interpolate external data files. The second part of TRNSYS is an extensive library of components, each of which models the performance of one part of the system. The standard library includes approximately 150 models ranging from pumps to multi-zone buildings, wind turbines to electrolysers, weather data processors to economics routines, and basic HVAC equipment to cutting edge emerging technologies. Models are constructed in such a way that users can modify existing components or write their own, extending the capabilities of the environment. Applications • Central plant modeling • Building simulation (including LEED Energy Modeling) • Solar thermal processes • Ground coupled heat transfer • High temperature solar applications • Geothermal heat pump systems • Coupled multi-zone thermal/airflow modeling Optimization • Energy system research • Emerging technology assessment • Power plants (Biomass, Cogeneration) • Hydrogen fuel cell systems • Wind and Photovoltaic Systems • Data and simulation calibration Reference website for purchase: http://www.trnsys.com/
AirSim	AirSim is a compressed air simulation software tool, which is useful for estimating savings from various energy efficiency upgrades and control changes. AirSim is designed so that simulation outputs can be visually calibrated to measured energy consumption and pressure data. Once calibrated, system parameters can be changed to simulate expected compressor and system performance under various conditions.

Software Name	**Software application and brief description**
	The AirSim sequence of operation begins by opening the program file. The user can choose to run a simulation on a compressed air system with one air compressor or multiple air compressors. Free Website for download: https://www.airbestpractices.com/
LightSim	This software uses TMY (Typical Meteorological Year) or EPW (Energy Plus weather data) weather files as input. The hourly illuminance incident on windows and skylights is computed assuming that natural daylight has luminous efficacy of 110 lm/W. The hourly illuminance on the work plane of an interior space is computed using the IES method. The fraction of time that daylighting meets a target illuminance, and hence the fraction of time that electric lights can be turned off, is computed. These results support the design and economic evaluation of daylighting projects. After each simulation, LightSim reports input data and annual simulation results. It reports the fraction of hours that illumination from daylighting meets or exceeds the target illumination on a monthly basis. LightSim also reports the "fraction electrical power reduction" if sophisticated controls were able to turn off or dim a portion of the lights, to meet the target illumination. Reference website for purchase: https://syngient.in

13 Annexures

13.1. Compilation of audit checklist and energy savings tips

These are generic checklists and improvement options for guidance of energy auditors. This list is not a substitute for a detail assessment carried out by an energy auditor. Care must be exercised in matching an improvement option for a particular industry

Boiler

- Fireside surfaces, waterside surfaces, the burner assembly and the stack should be regularly maintained. This includes visual inspection, and cleaning, if necessary.
- Seals, feed water pumps and safety valves should be checked for leaks and repaired, if necessary
- Minimise idle time at low fire. Try to operate one boiler at full load instead of two boilers at half load.
- Optimise blow down by measuring conductivity of the boiler water and automatically controlling blow down.
- Recover heat from flash steam (forming from blow down or returning condensate). The flash tank acts as a separator allowing the remaining liquid to separate from flash steam. The low-pressure steam can then be used for process applications.
- Use warmest air as combustion intake. As a rule of thumb, an increase in boiler efficiency of approximately 1% is possible for each 20°C increase in intake combustion air temperature. Generally, the area just below the roof will be warmer due to temperature stratification of air.
- Recover stack gas loss. The energy loss through the stack is a function of flue gas temperature and the excess air. Typically, this contributes to about 15% energy loss. Energy from stack can be recovered for preheating combustion intake air or preheating water.
- Adjust air to fuel ratio. Best performance is obtained by the installation of an automatic air control system that will adjust the supplied air volume depending on the residual oxygen content in the exhaust gas.
- Eliminate steam leaks. Significant savings can be realised by locating and repairing leaks in live steam lines and in condensate return lines. Leaks in the steam lines allow steam to be wasted, resulting in higher steam production requirements from the boiler to meet the system needs. Additional feed water is required to make up for condensate losses and more energy is expended to heat the cooler feed water than to heat the warmer condensate. Water treatment would also increase as the top-up water quantity increased. Leaks most often occur at the fittings in the steam and condensate pipe systems. Savings for this measure depend on the boiler efficiency, the annual hours during which the leaks occur, the boiler operating pressure and the enthalpies of the steam and boiler feed water (where enthalpy is a measure of the energy content of the steam and feed water).

Compressed air system

- Recover waste heat from an air compressor. More than 80% of the electricity supplied to the compressor can be recovered as heat from cooling the compressor. In air cooled machines, the hot air can be used directly for room heating (where applicable). Water cooled compressors can provide hot water at about 75°C.
- Use outside air for compressor intake, as compressors require less energy to compress cooler and denser air. Typical results are savings of about 5%, with payback periods of less than a year for compressors with continuous operation. Every 4°C rise in inlet air temperature results in a higher energy consumption of 1%.
- Repair compressed air leaks. In a typical industrial plant without a leak detection and repair programme, air leaks contribute to about 25 – 40% of the air demand. A leak detection and repair programme can reduce leaks to about 10% of compressor air demand. Air leaks occur mainly in the following areas:
  - Couplings, flexible hoses, rubber and plastic tubes, and fittings
  - Pressure regulators
  - Pipe joints and thread sealants
- Reduce line pressure to the minimum required. As a rule of thumb, 1% savings can be achieved with every 0.1 bar reduction in pressure for screw compressors.
- Segregate high and low-pressure requirements. If several appliances require higher pressure air, consider using a smaller separate high-pressure compressor
- Design for a minimum pressure drop in the distribution line. A properly designed system should have a pressure loss of much less than 10% of the compressor's discharge pressure, measured from the receiver tank output to the point-of-use.

Air conditioning

- Mount blinds outside the window or in addition to inside the window
- Turn off unused devices (they produce additional heat)
- Close doors in air-conditioned rooms
- Turn off air conditioning when no cold air is needed
- Increase room temperature on the air conditioner to not less than 25°C; every degree or higher room temperature saves up to 6% electricity in air conditioning
- Maintain air conditioning devices according to manufacturers' information
- Cold air should be blown where used (flapper position)
- Select an air conditioning unit appropriate for the room size and heat sources

Ventilation, exhaust system

- Install occupancy sensors or timers for restrooms and offices that are not used 24 hours a day so that the fans are used only when they are needed.
- Switch off fans/blowers if not needed (e.g. during break time).
- Install variable frequency drives (VFDs) on all air handlers that have to cope with a range of operating conditions – savings of up to 40% of electricity are reported if the required air volume is 50% for 50% of the operation time.

Motors

- Make a list with your electric drives including rated power, hours of operation, age.
- Meter the actual load to identify the percentage of actual to rated power.
- Size motors for efficient operation: motors should be sized to operate within a load window of between 65% and 100% of the rated load. The common practice of over sizing results in less efficient motor operation. For example, a motor operating at a 35% load is less efficient than a smaller motor that is matched to the same load.
- Rewinding reduces the motor efficiency by 1 to 3%. Therefore, rewinding more than 3 times is not considered economical across world.
- Install Variable Frequency Drives (VFDs) on fans and pumps which have to operate over a range of operating conditions and are controlled by valves. An exact analysis of the economics can be done knowing the frequency of operating conditions. As a rule of thumb: supplying an air flow of 50% with a VFD reduces electricity consumption by 70% as compared to control with a valve.

Belts

- Use energy efficient V-belt. V-belts have a trapezoidal cross section to create a wedging action on pulleys to increase friction and power transfer capacity. V-belt drives can reach a nominal efficiency of 93%. Regularly check the tension of the belts.

Pumps

- Operate pumps near their best efficiency point (BEP)
- Ensure adequate NPSH at site of installation
- Modify pumping system and pumps losses to minimize throttling.
- Ensure availability of basic instruments at pumps like pressure gauges, flow meters
- Adapt to wide load variation with variable speed drives or sequenced control of multiple units
- Avoid operating more than one pump for the same application
- Use booster pumps for small loads requiring higher pressures
- To improve the performance of heat exchangers, reduce the difference in temperature between the inlet and outlet rather than increasing the flow rate
- Repair seals and packing to minimize water loss by dripping
- Balance the system to minimize flows and reduce pump power requirements
- Avoid pumping head with a free-fall return (gravity), and use the siphon effect
- Conduct a water balance to minimize water consumption, thus optimum pump
- operation
- Avoid cooling water re-circulation in DG sets, air compressors, refrigeration systems,
- cooling towers feed water pumps, condenser pumps and process pumps
- In multiple pump operations, carefully combine the operation of pumps to avoid
- throttling
- Replace old pumps with energy efficient pumps

- To improve the efficiency of oversized pumps, install variable speed drive, downsize /replace impeller, or replace with a smaller pump
- Optimize the number of stages in multi-stage pump if margins in pressure exist
- Reduce the system resistance by pressure drop assessment and pipe size optimization
- Regularly check for vibration to predict bearing damage, misalignments, unbalance, foundation looseness etc.

Renewable energy

- Use solar heating to generate hot water for sanitary purposes or for cleaning
- Use (waste) biomass as fuel (e.g. bagasse in the sugar industry, rice husk or wood waste)
- Use biogas (e.g. from the treatment of organically concentrated wastewater in dairies or breweries)

Furnace

- Load residence time
- Furnace loading
- Control of furnace draught
- Minimizing wall losses
- Reducing heat losses from furnace openings
- Operating at the desired temperature
- Complete combustion with minimum excess air

Lighting

- Make the most of daylight, e.g. by putting translucent tiles into the roof.
- Paint ceilings and walls white.
- Use light-coloured flooring materials.
- Install occupancy sensors for restrooms, offices, etc. Determining which lights are most appropriate candidates for an occupancy sensor depends on how much electricity the light uses, the traffic of the area and how often lights are left on. Occupancy sensors can conserve more than 20% of the annual energy usage of an individual lighting system, depending upon the area.
- Use light timers and photo sensors. Install photo sensor devices to allow control of artificial (electrical) lighting during periods when natural sunlight from exterior windows (or skylights) is adequate.

13.2. List of excel forms

These forms are available in “soft” format (MS excel files) for the reader of the EARG. Some of these sheets are reproduced as tables in section 13.3 of these guidelines as a reference. The data collection sheet has been prepared for the following equipment and utilities.

1. Electricity bills
2. Transformer
3. Motor
4. Compressor
5. Evaporator
6. Condenser
7. Cooling towers
8. Air handling units (AHU)
9. Pumps
10. Boilers
11. Electric Furnaces
12. Fuel fired furnaces
13. Lighting
14. Solar PV

13.3. Sample excel forms

Electricity Bill									
Months	Contract Demand (kVA)	Actual Maximum Demand (kVA)	Power Factor (PF)	Energy Consumption (kWh)	Demand charges	Energy charges	PF Penalty/incentive	Total Bill	Effective Rate (Nu./kWh)

Cooling Tower										
S.No.	Identification	Rated Capacity (TR)	Cooling water inlet temperature °C	Cooling water outlet temperature °C	Ambient air wet bulb temp. °C	Ambient air dry bulb temp. °C	Measured cooling water flow (m^3/hr)	Measured Fan Power (kW)	Measured Air flow (m^3/hr)	Cooling water (TDS)

14 References

- Guidebook for energy auditors and energy managers by Bureau of Energy Efficiency (BEE), India
- Energy Audit handbook by Sustainable energy authority of Ireland (SEAI)
- Industrial energy audit guidebook by Ali Hasanbeigi, Lynn Price, Berkeley National Laboratory
- Energy Audit manual and tool by Canadian industry Program for Energy conservation (CIPEC)
- Best practices guide for MSME clusters by TERI and Shakti Sustainable Energy Foundation, India.
- Descriptive Manual on Energy Efficiency by STENUM Asia and ACMA supported by UNIDO, Vienna.
- International standard on energy management system, ISO 50001.
- International standard on energy audits, ISO 50002.