

Electrical Energy Efficiency

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ABOUT THIS BOOK

- The cost of electricity per year can be far more than the original cost of the equipment using it.
- Reducing the running costs of equipment is a major preoccupation in many organisations. This helps to increase profits.
- Too often, this consideration only starts once the equipment is commissioned.
- This publication shows how electrical equipment can be specified to optimum energy efficiency to help maximise profits.
- The combination of financial appraisals, electrical theory and common sense can achieve much together, especially when built in to Company policy.
- This book shows you how.

Preface for Financial Decision Makers

***Section 1* Introduction**

This section introduces the reader to the concepts of financial appraisal and power losses in inefficient electrical installations and provides information on the scale of these losses and the sums of money they are costing industry.

***Section 2* Energy-Efficient Motors**

The importance of considering running costs as well as capital costs before specifying new plant is emphasised here. The different types of power losses in motors are discussed and comparisons of losses between standard and high-efficiency motors are made. Economic justification for selection of high-efficiency motors is illustrated with actual case histories.

***Section 3* Transformers**

The magnitude and nature of transformer losses is given along with methods of evaluation of these losses to industry.

***Section 4* Power Cables**

Energy losses in undersized power cables are often ignored. This section gives the reasons for selecting power cables larger than the minimum safe size recommended in the IEE regulations, which not only reduces power losses but also improves power quality.

***Section 5* A Systems Approach to Calculating Energy Saving**

The previous sections have looked at individual components of an electrical installation. Here, the complete installation from transformer through cable to motor is considered with a worked example showing the total savings to be made by specifying energy-efficient options throughout the system.

Appendices Background information, theory and worked examples are given for calculating energy losses, their costs and economic evaluation.

Preface for Financial Decision Makers

In the current economic climate financial decision makers need to be aware of every cost saving opportunity. Paring of capital budget by buying the cheapest possible equipment can result in very high running costs throughout the lifetime of the equipment. **Lowest first cost is false economy.** This book outlines the savings to be made by replacing standard electrical equipment with high-efficiency alternatives or by specifying high-efficiency equipment in a new installation. Savings on running costs, which can be made throughout the lifetime of the installation, can be as high as 40%, with no detrimental effect on circuit performance.

The book describes examples on the savings to be made by selecting energy-efficient motors, transformers and cables by giving straightforward cost comparisons between the capital and running costs of standard and high-efficiency components. Financial appraisal of these savings is first considered in terms of the simplified 'payback period' but also by the calculation of capitalisation values for these savings, in terms of Net Present Values and Test Discount Rates. The latter method is of course more subjective and depends upon the financial policies of individual organisations and the importance they place on energy efficiency. **Company procurement policy should be to evaluate the cost savings by energy efficiency as well as capital costs.**

Listed below are the areas of the book which will be of the most interest to you.

Financial appraisal and *The cost of the energy losses to industry* are discussed in Section 1 along with an example illustrating the potential savings to be made by specifying a high-efficiency installation. Further examples are given in Section 5.

Methods of appraisal of capital expenditure are discussed in Appendix 5.

Economic justification for purchasing high-efficiency motors is given in Section 2.3 and actual case histories detailing the savings made can be found in Section 2.4.

Evaluation of transformer losses is covered in Section 3.2 with a typical example of the cost of these losses to industry given in Appendix 2 K.

Cost considerations of cable selection can be found in Section 4.2.1 with a detailed worked example of total installation costs given in Appendix 3 C.

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Electrical Energy Efficiency

by Vin Callcut, David Chapman, Martin Heathcote and Richard Parr.

1. Introduction

Did you Know?

- £ More than 8% of the electricity you buy is probably wasted due to the design of your equipment and the way it has been installed! This is in addition to the energy wasted by running equipment for longer than necessary.
- \$ Electricity is the most expensive form of energy available - about 8 times the cost of coal and six times the cost of gas - this expensive fuel must be used wisely!
- ¥ The average cost of industrial electricity in the UK has risen by 13% in the last five years despite the very strict regulatory environment. In future, it may rise even faster.
- £ Motors use 64% of industry's electricity in the UK - worth around £4 billion per year. Using high-efficiency motors, properly selected and installed, could save industry up to **£300 million** per year.
- \$ A motor consumes electricity to the equivalent of its *capital cost in just three weeks* of continuous use - high efficiency motors save money over the whole of their long life.
- ¥ Energy is lost in all cables. Using the minimum regulation size means greater losses and hotter running. Using larger sizes saves energy and costs less over the lifetime of the installation - the energy saved is worth many times the slightly increased cost of larger cables.

This book provides you with the information you need to identify and financially appraise electrical energy saving opportunities in your organisation. It will help you to identify where money can be saved, how to select new and replacement equipment and help you ensure that your installer meets your needs by following best practice rather than minimum requirements.

Throughout the book there are examples and case studies which clearly demonstrate that the lowest first cost approach leads to higher running costs and higher overall costs. In every case, spending just a little more capital yields large savings in running costs leading to an improved competitive position and higher profit margins.

*This book **is not about** turning off the lights, re-setting the thermostats and using time switches - these measures are well covered elsewhere.*

*This book **is about** real, identifiable, quantifiable and manageable initiatives which will bring substantial savings in surprisingly short timescales - and continue to accrue savings over many years.*

1.1. Financial Appraisal

No organisation, whatever its size, can afford to overlook the improvement in profit and competitive position which can be achieved from the careful and thorough application of energy saving initiatives.

When investment opportunities are being assessed and compared by management, energy saving initiatives are too often given a much lower priority than production and development projects. This is despite the fact that energy saving initiatives can reduce revenue expenditure over the whole organisation with very low capital investment requirements, and can continue to do so over a very long period. Among the reasons given for this have been shortage of capital to invest and short term Company policies, and it has been difficult for Energy Managers to gain the necessary support for energy saving projects. This section examines the underlying issues, and demonstrates how financial and energy managers can co-operate in identifying and appraising projects and bringing the consequent benefits to their organisation.

Sometimes the method of appraisal employed does not fully identify all the revenue savings arising from the initiative, or has a bias which undervalues, say, longer term savings. Financial managers will already understand the need to test their appraisal methods to ensure that a balanced judgement is being made, and to apply the same fair assessment criteria to all potential investments; now they must also ensure that their Energy Managers have identified the best energy saving initiatives available to the organisation and help them prepare sound financial justifications.

The technology exists to reduce the energy consumption of UK commercial buildings by 15%, even more where energy intensive processes are in use, with a financial return at least as good as commercial organisations and public sector bodies achieve in their mainstream activities. This is an opportunity which no responsible manager can afford to overlook.

A recently published Good Practice Guide¹ gives detailed advice for Energy Managers and Financial Managers to help them identify opportunities and justify programmes to improve energy efficiency. The remainder of this section presents a brief overview of the material covered by the guide and later sections deal in depth with the technical issues of Electrical Energy Efficiency for those responsible for identifying initiatives and implementing the solutions.

1.1.1. The purpose of financial appraisal

A process of financial appraisal is necessary so that an organisation can determine which of the many investment opportunities available will bring the greatest financial gain with the least risk. It also provides a basis to review the project once it is running and the experience gained can be used to refine future appraisals.

The result of an appraisal is a number of financial parameters (e.g. payback, accounting rates of return, net present value, internal rate of return), each of which gives emphasis to different aspects of the project or external influences, such as project lifetime and interest rates. In practice, these financial parameters are all derived by mathematical manipulation of the same basic information. Often, individual managers or complete organisations concentrate on only one indicator and this has the effect of bringing the bias inherent in the indicator to all decision making. The more fundamental problem is that these indicators merely express the financial meaning of the information which has been gathered and measured - they do not provide any information about how thoroughly the basic investigative work has been done. For example, there is no way of knowing that a better investment opportunity has not been overlooked, or that all the assumptions about costs and benefits are sound.

1.1.2. How can energy saving opportunities be identified?

Identification of Energy saving opportunities must be carried out in a systematic manner so that it can be shown that the initiatives proposed are those which will yield the greatest benefits.

Major opportunities will arise during the planning of new buildings and plant where the incremental cost of high efficiency equipment will be easy to determine, the lifetime will be longest and there will be no, or little, difference in installation costs. There will be many instances where the installation of more modern equipment will be so beneficial that the replacement of existing equipment before its normal end-of-life will be justified by savings on running costs. Experience gained by monitoring the performance of new plant and comparing with it older plant will provide useful data.

Careful and systematic monitoring will be required to identify energy saving opportunities. It is essential that the energy demands and costs of every aspect of the business are well understood, so that areas of greatest waste can be identified and tackled, and that solutions for one situation can be applied to similar areas. Full records should be maintained so that cost savings can be demonstrated, and so that previously identified opportunities can be re-visited as costs and engineering solutions change. An organised approach will help to show management that the best investments are being selected for further work.

1.1.3. Why are energy reduction initiatives assigned such a low priority for funds?

Businesses usually give lower priority to cost reduction from energy savings than they do to other business initiatives. A survey² concluded that expenditure on energy saving in normally classified as capital, rather than revenue expenditure and is further categorised as discretionary spending relating to the maintenance of the present business - in other words, it is assumed that failing to make the investment will not affect the ability of the enterprise to carry on its current business activities. Business expansion is usually given higher priority, but the capital for this has to be provided from the profit from the existing business. Thus the priority ought to be given to maximising the revenue from existing business, irrespective of the use to which the capital accrued will be ultimately put. Energy saving initiatives reduce operating costs and therefore increase the revenue available for investment and so deserve a very high priority.

Normal accounting practices measure real transfers of money into and out of the business and enable the performance of individual parts of the business to be measured. They do not enable savings to be measured directly, and so do not provide the information needed to provide evidence of performance of past or present cost-saving initiatives. This is one of the major reasons why investment in Energy efficiency is difficult to justify. The solution is to maintain a capital return budget, and this is discussed below. Where no energy efficiency projects are already in place, the case studies presented later in this document may help to support similar proposals.

Often, financial justifications are concerned with a relatively short time period, while the cost benefits accrue over a very much longer period - several decades for some large electrical equipment. This results in an underestimate of the return from the investment and a perfectly valid proposal being rejected.

1.1.4. How can this low priority be over come?

Every organisation can identify many more potential areas for investment than it has capital to invest, so decisions about which to pursue will need careful appraisal. This situation is usually described as a 'shortage of capital' while it is more properly described as an 'excess of opportunity'. The latter description is more appropriate to the Energy Manager. The level of investment required for Energy Efficiency initiatives is relatively small compared with that required for other business purposes, so it is not true that shortage of Capital prevents investment in it. Other projects may have more measurable returns, so that the justification for having proceeded with them is simple, before, during and after completion. The same cannot be said of Energy Efficiency initiatives; frequently there are very few measurements available to substantiate the claimed potential savings. Even if good records of existing energy costs, suitable sub-divided, are available, the potential savings will be based on calculation and

include a number of assumptions. It may be difficult to convince higher management that the assumptions and calculations are valid and that future costs can be monitored accurately enough to justify the investment decision.

It is most important that proposals are made at the most appropriate level of management in the organisation.

Energy Managers should expect and anticipate that some of their initiatives will be rejected, and must therefore ensure that the best possible case is always presented. This will require that a good energy cost monitoring scheme is in place, that deficiencies in present plant are identified and measured, and that they have in place a system to monitor future energy savings. Establishing a capital return budget, explained in detail in the 'Good Practice Guide 165' and described briefly below, allows the financial performance of energy saving initiatives to be tracked and the value of such investments to be demonstrated.

Case studies from similar industrial and commercial operations, such as those given later in this document, can also help to verify the size of the potential savings.

1.1.5. The Capital Return Budget

The Capital return budget is a simple statement of capital expenditure and revenue savings in each year and the difference between them. Because the capital spend usually takes place within one year while the savings accrue over many years, it is essential that the capital return budget is cumulative covering several years. Once established, the accumulated balance demonstrates the success of past initiatives and highlights the sum which is, or will be, retained in the business as a result. Although it is not normally possible to show the use to which this money has been put, the energy manager can show clearly that the energy saving initiatives have contributed to the health of the organisation either by making funds available for other purposes, by improving the competitive position of the organisation or by increasing profit.

Although this document is primarily concerned with savings achieved as a result of improving electrical plant and installation practice (which will always require investment) small housekeeping savings (requiring little or no investment) will quickly establish the budget.

For a worked example of a Capital return budget see 'Good Practice Guide 165'.

1.2. Technical Overview

Electricity is by far the most expensive form in which an organisation buys power. Figure 1-1 shows the relative costs of different fuels, in terms of price per kilowatt-hour.

Figure 1-1 Relative Fuel Costs per kWh (1994)

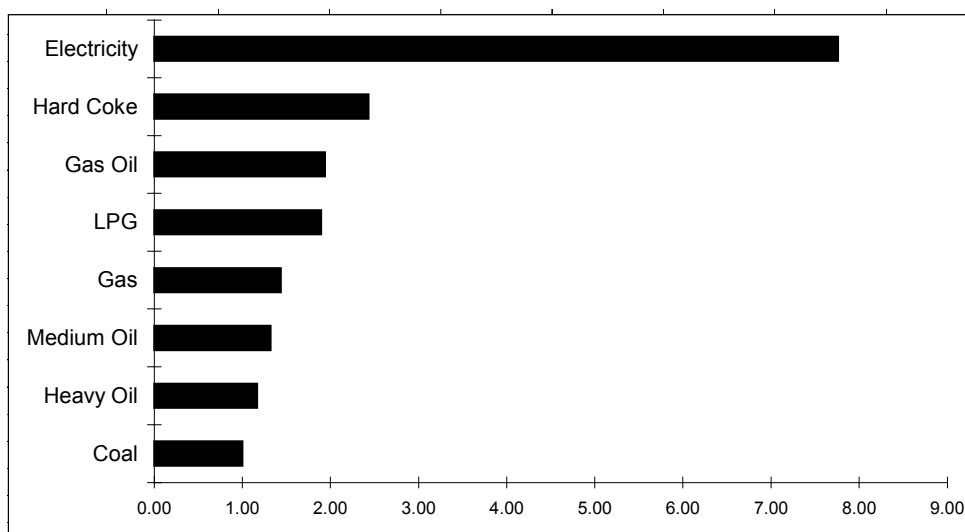
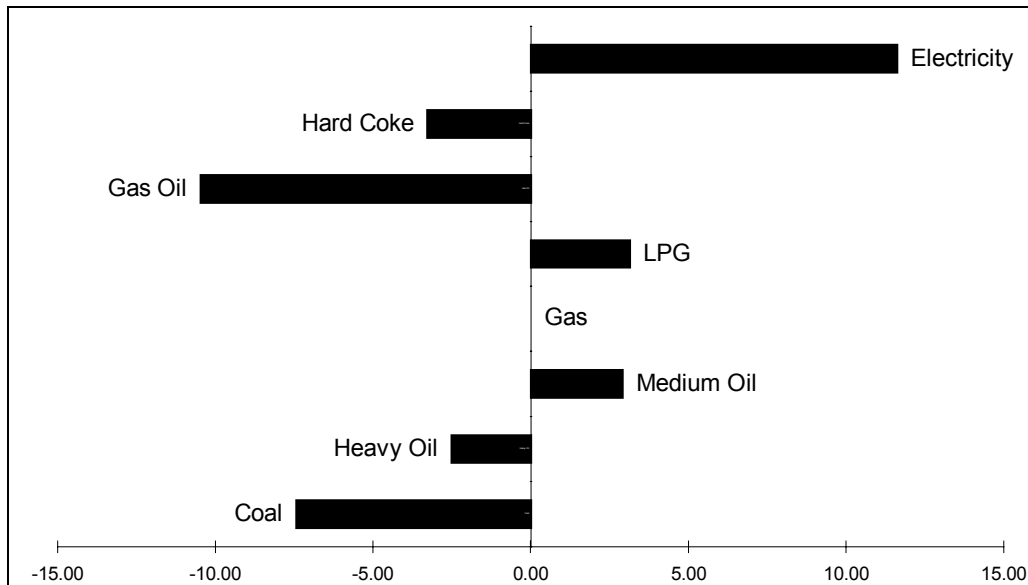


Figure 1-2 shows the change in costs between 1990 and 1994. Not only is electricity the most expensive, but it is also increasing in price while the prices of many other fuels are falling. The use of electricity is justified because it is often the only practical form of energy for many purposes, for example, for lighting and for the provision of local power for rotating machinery. It also has the advantage of being pollution-free at the point of use.

Figure 1-2 % Change in Energy Costs 1990 to 1994



The fact that electricity is the only practical form of energy does not mean that it should be used without proper consideration. The average industrial customer uses 350 MWh per year, at a cost of 4.43 p/kWh, resulting in an average bill for £15,500 (1994 figures). While thermal savings are keenly monitored and can readily be measured, much less attention has been paid to the money that can be saved by attention to the design, specification and installation of electrical plant and power systems. The efficiency of electrical equipment has always been assumed to be high and the amount of electrical energy that is wasted in commercial and industrial environments is usually greatly underestimated and is often assumed to be unavoidable. In fact, the efficiency of electrical equipment can be improved easily at low cost, and, because of the quantity of electrical energy used, this will yield substantial savings. Once high-efficiency equipment has been selected, it is equally important to ensure that it is correctly rated. For example, motor efficiency is highest *above* 75% of full load, so over generous rating will increase both capital and running costs. On the other hand, cables are *least* efficient when fully loaded, so generous rating of cables can substantially reduce running costs.

Power losses in electrical equipment are due to the electrical resistance in conductors and losses in the magnetic material and occur primarily in motors, transformers and in all cabling. The conductor losses are proportional to the resistance and the square of the current (I^2R losses) and can be minimised by using the optimum size of conductor for the application. Later sections of this document demonstrate that the lowest overall life cycle cost is achieved by specifying larger conductors than the safe thermal minimum, and a detailed design methodology is presented. Magnetic losses can be reduced by the use of better materials and production methods.

The available savings in energy costs are substantial and accrue over the whole of the life of the installation. Figure 1-3 shows the losses for a hypothetical installation using both typical standard efficiency and high-efficiency equipment. This is based on a 7.5 kW motor, operating for 5,600 hours per year (two-shift day) at 5.0 kW loading, with a cable run of 30 m. Because a transformer would supply many loads of this type, the illustrative losses shown here are scaled from a larger transformer. The figures are tabulated in Table 1-1 for reference.

Figure 1-3 Comparison of Losses for a Single Motor Installation

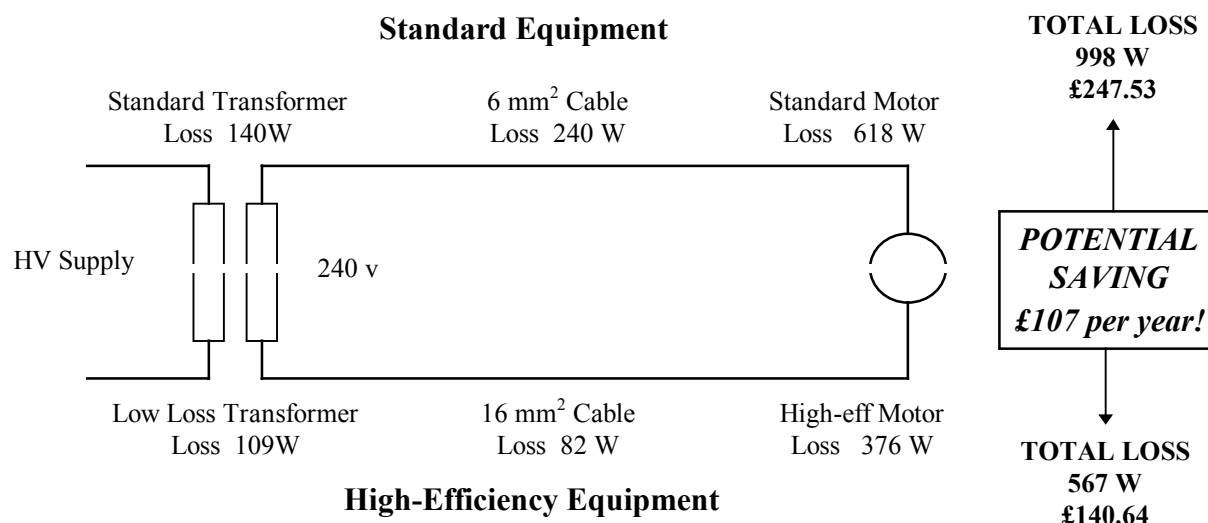


Table 1-1 Comparison between a Standard and High-efficiency Installation.

	Standard Equipment, 6 mm ² cable			High-efficiency equipment, 16 mm ² cable		
	Eff (%)	Loss (W)	Cost of loss/ annum (£)	Eff (%)	Loss (W)	Cost of loss/ annum (£)
Motor	89	618	153.30	93	376	93.28
Cable	96	240	59.50	98.5	82	20.34
Transformer	97.6	140	34.73	98	109	27.02
Totals	83.3	998	247.53	90	567	140.64
Total Bill		£1,488			£1,381	
<u>Saving</u>			<u>£107</u>			

The annual saving of £107, i.e. 7.2% of the bill, achieved on this small sample installation will payback the extra cost of high-efficiency equipment in about 18 months, and go on producing savings over the equipment life, on average 13 years for the motor, and 30 years for the cable and transformer - total life time savings of over £4,800, even assuming that the cost of electricity does not rise! The saving attributable to the use of a High-Efficiency motor is particularly significant since 64% of the electricity bought by industry in the UK is used to power motors. If this improvement were achieved over the whole of an average industrial user's motor load, electricity costs would fall by £700 pa, and for the whole of industry and commerce in the UK, total savings would amount to over £300 million pa.

1.2.1. Conductor Material

Copper is one of the key materials to be considered when work is being done to improve the energy efficiency of electrical equipment. High conductivity is one of its most important properties, and sixty per cent of the copper produced finds usage in electrical applications as is shown in Table 1-2

Table 1-2 Reasons for Using Copper

Primary Requirement	% used
Electrical conductivity	60.1
Corrosion resistance	21.1
Heat transfer	10.6
Structural capability	6.7
Aesthetics	1.5
	100

In 1993, CDA organised an international conference ‘EHC 9t3’, subtitled ‘Copper - Energy Efficiency, High Conductivity’ that drew twenty-three papers on the subject and delegates from all over the World. These described the many ways in which coppers and copper alloys are being tailored to suit new demands and the financial importance of energy-efficiency considerations in the design of all electrical equipment.

1.2.1.1. Interactive Software

Interactive software has been produced to facilitate the choice of the most cost-effective high-efficiency electric motors, optimum cable sizes and busbar designs.

The motor selection software³ allows the designer to compare the cost of operating both standard and high-efficiency motors, taking account of load factor, duty cycle and different energy tariffs. Overall savings and pay-back period are calculated.

The cable size optimisation software⁴ determines the most cost-effective size of power cable to install. Most popular types of cable and cable configuration are considered together with termination costs where appropriate. Calculations are based on varied utilisation at different tariffs by day and night and include allowances for electricity demand costs together with the variables mentioned above. This results in a significant simplification of the work needed to calculate the most economic size of conductor to specify.

Two programs have been developed to enable designers to specify busbars in the most cost-effective manner, one by CDA (UK)⁵ and the other by CDA Inc. (USA)⁶. The former enables designers to carry out many of the calculations included in the standard book on busbar design⁷, the latter enables designers to use a standard or variable set of costings to establish the most cost-effective installation design.

In co-operation with ETSU (Energy Technology Support Unit), two videos⁸ have been produced encouraging management to extend energy-efficient considerations to the purchase of electric motors and installation of power cables.

1.2.2. Electricity Generation in the UK

Since the oil crisis of the 1970’s, energy prices have risen dramatically and there has been increasing public awareness of the need to save energy in order to reduce both the consumption of fossil fuels and the environmental pollution which results from their use. There is increasing resistance to planning applications for large scale infrastructure projects including both conventional and nuclear power generation stations and distribution networks, and the opposition is becoming increasingly sophisticated. Although planning applications are normally allowed, the delay and expense involved have an impact on energy costs and availability. Effective management of the efficient use of energy has never been more important, from both an economic and a public relations standpoint.

The primary fuels used for the production of electricity in the UK are shown in Figure 1-4 and Figure 1-5 shows the percentages used by various market segments.

Figure 1-4 Primary Fuels used for Electricity Generation in the UK.

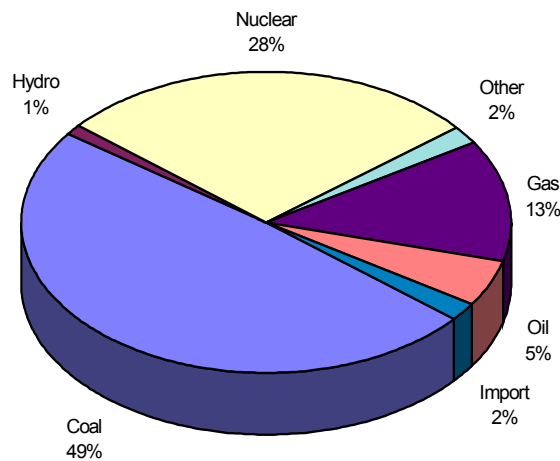
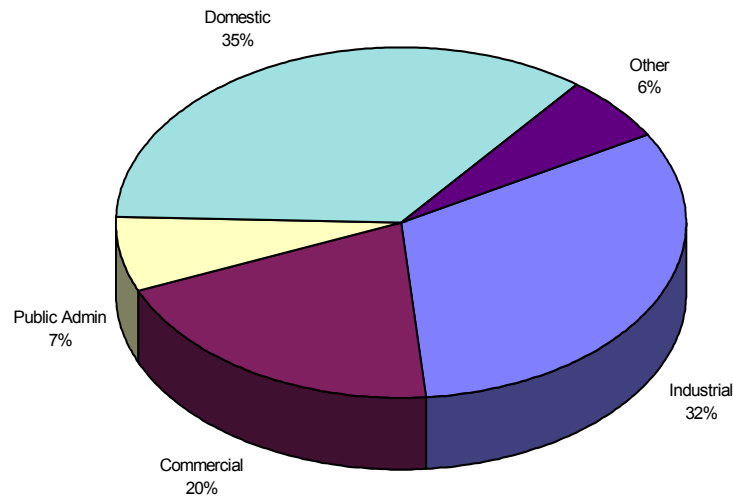


Figure 1-5 Electricity Consumption by Market Segment.



In the UK (in 1994), the total annual industrial and commercial usage was 160 TWh (1 TWh = 10^9 kWh). To help to put this enormous figure into perspective, it is equivalent to the continuous full load output of 15 power stations of the size of Sizewell B, or just over double the total UK nuclear capacity. The price industry pays for this energy is approximately £7 billion per annum, so an overall increase in efficiency of only 3% would reduce the cost by £220 million per annum and would save a great deal of pollution. Table 1-3 shows the total UK production of some pollutants and the amount attributable to electricity generation in 1992. An improvement in efficiency of 3% would reduce the carbon dioxide emission by 1.5 million tonnes - 60% of the UK's Rio Summit Meeting target.

Table 1-3 Annual Production of Pollutants in the UK (1992)

Pollutant	Total Annual Production	Contribution from Power Stations
Carbon dioxide	156 x 10 ⁶ tonnes	51 x 10 ⁶ tonnes
Sulphur dioxide	3.5 x 10 ⁶ tonnes	2.5 x 10 ⁶ tonnes
Oxides of Nitrogen	2.75 x 10 ⁶ tonnes	0.69 x 10 ⁶ tonnes

1.2.2.1. The Electricity Pool

The electricity industry in England and Wales is split into Generators and Suppliers (i.e. those who buy from the generators and supply to users), who trade electricity through the Electricity Pool. The Pool is regulated by its members and operated by the National Grid Company who also own and operate the distribution grid. Commercial contracts between the Generators and Suppliers are used to hedge against the uncertainty of future prices in the pool. Electricité de France (EdF), Scottish Power and Scottish Hydro Power are external members of the Pool and each of these has a number of commercially negotiated contracts to sell electricity to the suppliers in England and Wales. The Regional Electricity Companies (RECs) supply electricity to customers in their own area and may also compete to supply customers nation-wide. The main Generators also operate their own supply business, as do some other companies such as Scottish Power, Scottish Hydro Power, individual large users and trading companies.

Progressively since 1990, large customers, initially those with peak loads greater than 1 MW, and now those over 100 kW, have been able to select their supplier. By early 1995 75% of supplies to non-domestic customers were from a supplier other than the geographically appropriate REC.

Domestic and small industrial users buy their electricity from the local REC at controlled prices. By contrast, the Pool price is set half-hourly to reflect the supply situation prevailing at the time.

Although the average industrial price in 1994 was 4.43p per kWh, the actual Pool price varies greatly; on two occasions in December 1995 poor weather conditions caused abnormally high demand resulting in a Pool price of over £1 per kWh.

In 1994 7% of the generated energy, amounting to over 24 TWh - worth £1 billion, was attributed to transmission losses (including measurement errors), while electricity imported via the Anglo-French sub-channel link made up 2% of the total available power. Short-term non-availability of this link, together with the longer term failure of a relatively few items of equipment at UK power stations has threatened power blackouts on at least four occasions in the first half of 1996.

2. Energy-Efficient Motors

2.1. Introduction

The electric motor has a long history of development since its invention in 1887, with most early effort aimed at improving power and torque and reducing cost. The need for higher efficiency became apparent during the late 1970's and by the early 1980's at least one British manufacturer had started to market a premium range of motors with improved efficiency.⁹ Now the trend is towards marketing all motors with improved efficiency at little or no premium. However, because improved efficiency requires more careful manufacture, only the higher quality manufacturers are supplying high-efficiency units. There is therefore still a price difference, but one which applies between manufacturers rather than between ranges from the same manufacturer. There is still a choice to be made, and the following sections illustrate that paying for the high-quality high-efficiency motor is an excellent investment.

The UK industrial motor population¹⁰ is estimated at about 10 million units, while the new market is about 3,000 units per day, mostly rated at less than 150 kW. Of the electricity supplied to power industrial motors, one third is consumed by motors rated at 1.1 to 15 kW, and a further third by motors rated from 15 to 150 kW, suggesting that there are very large numbers of small motors among the installed base. Clearly, it is important to consider energy efficiency for all sizes.

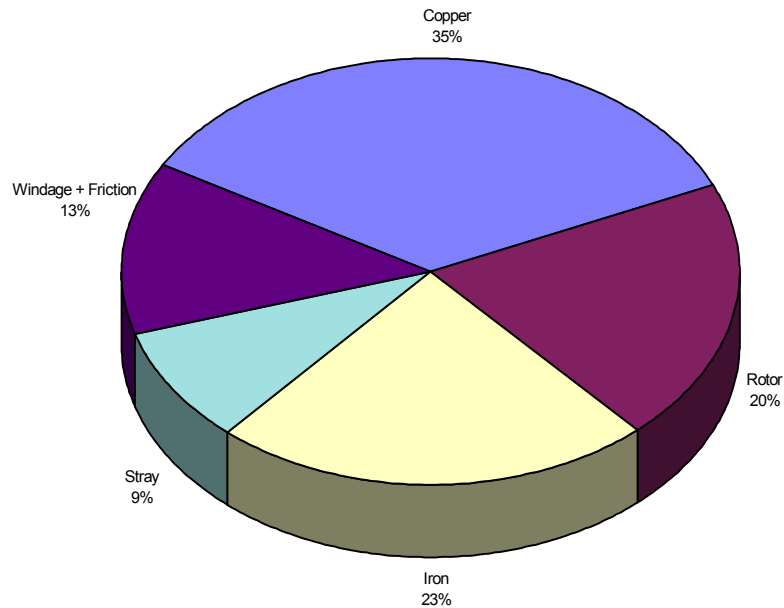
Most motors operate at less than their design loading. Safety margin, selection of preferred sizes, and starting torque requirements mean that most motors are operating at between 60% and 80% of full load, and many will run at very low load for a substantial part of their working life. It is important that high-efficiency motors retain their energy efficiency at these typical load factors and the leading manufacturers typically optimise efficiency at about 75% full load.

An electric motor can consume electricity to the equivalent of its capital cost within the first 500 hours of operation - a mere three weeks of continuous use, or three months of single shift working. Every year, the running cost of the motor will be from four to sixteen times its capital cost. Over its working life, an average of thirteen years, it may consume over 200 times its capital cost in energy. Clearly, the lowest overall cost will not be achieved unless both capital and running costs are considered together.

2.2. Energy Losses

It must be emphasised that the standard electric motor is already a very efficient device with efficiencies above 80% over most of the working range, rising to over 90% at full load. However, because of the high energy consumption, and the very large number of installed units, even a small increase in efficiency can have a major impact on costs. The efficiency of an electric motor depends on the choice of materials used for the core and windings, their physical arrangement and the care and precision with which they are handled and assembled.

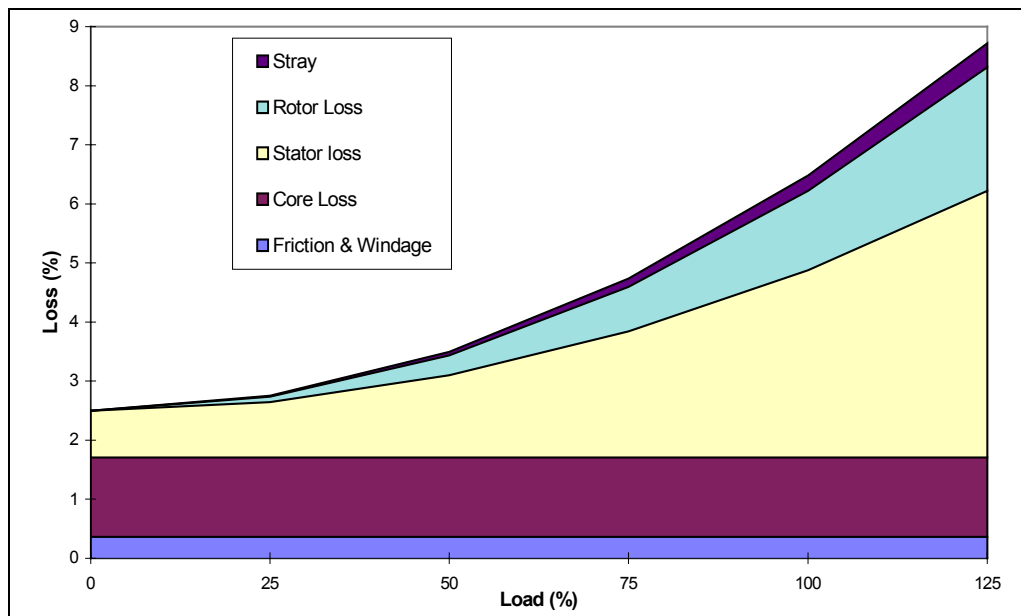
Figure 2-1 Distribution of Losses in a Standard 75 kW Induction Motor



Losses can be categorised into two groups; those which are relatively independent of load (constant losses), and those which increase with load (load dependent losses). The factors which affect efficiency are:

- | | |
|---------------------------------|-------------------------|
| Conductor content | (load dependent) |
| Magnetic steel | (mainly constant) |
| Thermal design | (mainly load dependent) |
| Aerodynamic design | (constant) |
| Manufacture and quality control | (constant) |

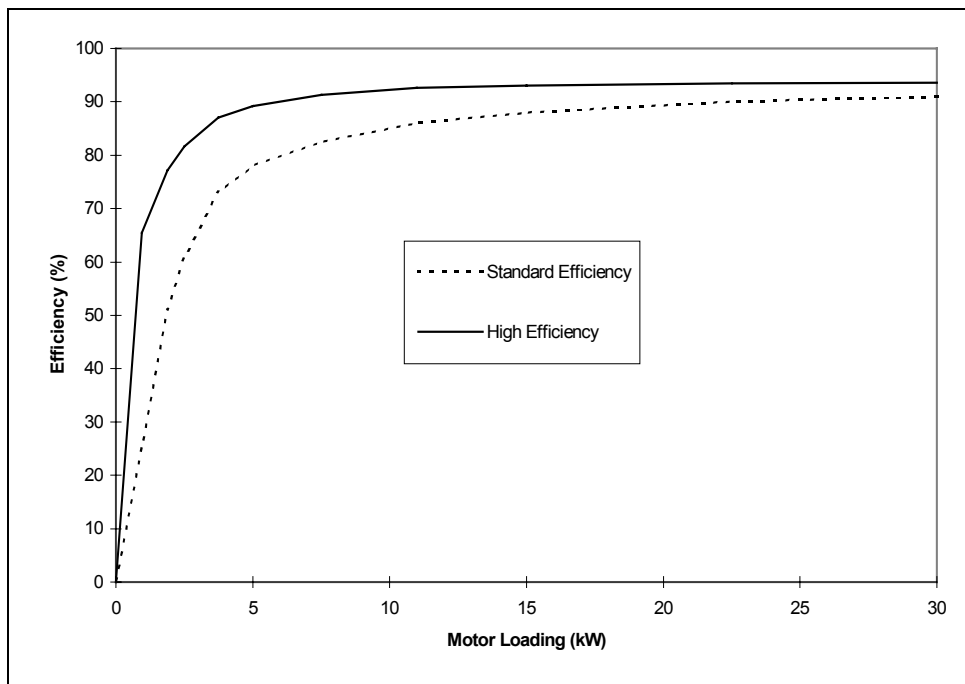
Figure 2-2 Loss Against Load for a Typical Standard Motor



Because many motors spend considerable time running at low loading or idling, designers of high-efficiency units have paid great attention to reduction of the constant losses. The result is a halving of losses at loadings less than 25% load and an efficiency improvement of 3 to 5% at full load, a reduction in losses of about 28%. This represents an impressive achievement. Figure 2-3 illustrates efficiency against loading for standard and high-efficiency 30 kW motors.

A detailed discussion of loss mechanisms is given in ‘*Design of Energy-efficient Motors*’ on Page 40.

Figure 2-3 Comparison of Efficiencies of Standard and High-Efficiency Motors



The increase in efficiency is accompanied by an increase in power factor. A poor power factor occurs when the load current is not in phase with the supply voltage, so that the *magnitude* of the current (a vector quantity) is increased. The Regional Electricity Companies (RECs) meter power in units of kWh, being the product of supply voltage, in-phase current and time. Additionally a charge is levied according to the maximum demand kVA, i.e. the product of supply voltage and the maximum *magnitude* of the current, and the customer is obliged to maintain a power factor greater than 0.92 lagging and 0.99 leading. In an induction motor, the no load current is mainly magnetisation current and so lags the supply voltage by nearly 90 degrees, i.e. a power factor of nearly zero. As the load increases, the power factor rises because the load component of the supply current is more or less in phase with the supply voltage. Although it might be expected that, since high-efficiency motors offer improved power factor, these issues will be less important, there are some points to be considered when replacing an existing unit. Firstly, the low power factor may not have been properly taken into account when the initial installation was carried out, and the required cable size should be re-assessed from an energy efficiency point of view as a matter of course. Secondly, there may have been some attempt to improve the power factor, either locally or centrally, and if so, this correction will have to be re-appraised since over compensation may result. Over compensation will result in a poor leading power factor instead of a poor lagging one, with the same penalties. ‘*Power Factor Correction*’ on Page 42 gives background on power factor.

2.3. Economic Justification for selecting High-Efficiency Motors

Justifying a capital purchase is probably one of the most difficult tasks faced by managers; in part this is because there are so many methods of calculation, and even more opinions about which is right! There is enormous pressure to minimise the cost of projects, and this means that decision makers tend to be looking for lowest first cost. However, this initial cost is only part of the story - as mentioned earlier, a motor may consume up to 200 times its capital cost in electricity, so a proper examination must include running costs.

Starting from the premise that the need for, and cost justification of, the purchase of a new motor has been made, how can the selection of a premium quality motor be justified? As with

any project, the capital outlay required, in this case the *difference* in cost between the high-efficiency motor and a standard unit, must be judged against the future cash, in this case the *savings* due to reduced energy consumption, generated in future years. Some of the popular methods of calculation are briefly defined in 'Methods of Financial Appraisal' on Page 111. The criteria by which the results are assessed will depend on the culture of the organisation, and may often involve comparison with other potential uses for the capital available. In the following section, several Case Histories are described, which demonstrate that, under a wide range of circumstances, the payback periods are typically around two years - short enough to be considered a good investment by most organisations. In order to assist managers to explore the savings available in their own circumstances CDA has made available a software package which enables users to enter motor utilisation characteristics, day and night electricity tariffs and demand charges and calculate the relevant costs. The program is easy to use, interactive, and produces prints of the results for distribution and easy future reference.

The economics of the installation of high-efficiency motors are best when new plant is being built. However, in certain circumstances, the cost of replacing an existing motor before the end of its serviceable life can be justified, but the economic considerations are complex. Consideration should be given either to comparing the additional cost of early replacement (for example the lost value of the residual life of the existing unit, the higher cost of immediate, rather than future, capital) with the future savings, or taking account of future energy savings to avoid or delay the expense of increasing the capacity of local supply transformers and circuits.

Another good time to consider the selection of high-efficiency motors is when an existing unit is being considered for rewinding. Approximately 300,000 motors are rewound in the UK every year, with an average rating of about 12 kW, so the efficiency of rewind motors is extremely important. The loss in efficiency on rewinding depends on the techniques, processes and skill used to perform the rewind, and is usually between 1 and 2%. The reasons for increased loss are discussed in Appendix 1 B. If the choice is between rewinding a standard efficiency motor or purchasing a new HE motor, the difference in efficiency will be 4 to 5% at full load in favour of the HE motor, which will also have a much longer service life. It will be found more cost effective in most cases to choose a high-efficiency unit. The rewinding of HE Motors has been studied with the objective of defining rewinding techniques which will limit the reduction in efficiency to 0.5%, so that the advantage of the HE motor can be preserved after rewinding¹¹.

Whenever a motor is to be newly installed or replaced, it should be standard practice to examine the cost benefits of selecting a high-efficiency type. The cost of running the plant can be estimated for both types of motors. If the equipment is going to be running for a significant proportion of each day, then it is very likely that it is worth paying a premium for a high-efficiency design. There is a need for a management policy commitment towards potential cost savings at the design and specification stages.

2.4. Case Histories

2.4.1. Brass Extrusion Mill

As part of the energy-efficiency project within the U.K., CDA sponsored the replacement of standard electric motors in several industrial locations. Performance, utilisation and power consumption were carefully monitored in conjunction with ETSU (Energy Technology Support Unit) before and after the installations so that consequent economics could be assessed. Payback periods varied very significantly from less than one year to three years, depending mainly on motor utilisation.

After examining the manufacturing site of a brass mill, five locations were selected for trials. These were mainly where motors were driving pumps, fans or other typical industrial equipment. The motors were rated at 1.1, 5.5, 7.5, 18.5 and 30.0 kW. Performance and efficiency were carefully monitored on the old motors before they were replaced, in order to give an accurate comparison that is not always possible in new installations. Since the changes

were well planned ahead, there was enough time for ETSU consultants to obtain accurate performance data. The results have been reported by ETSU¹² and are briefly summarised in Table 2-1.

Table 2-1 Cost Savings for Five Motors

Motor No.	Rating (kW)	Average load (%)	Running hours/year	Savings £/year	Premium £	Payback period (years)
1	30.0	49	7,704	80.67	271.60	3.37
2	18.5	27	4,704	110.38	179.90	1.63
3	7.5	87	8,760	76.65	94.50	1.23
4	5.5	60	8,760	110.38	85.40	0.77
5	1.1	77	8,760	30.66	36.89	1.20
	Totals			408.74	668.29	
	Average					1.64

It can be seen that the savings are significant and that the use of high-efficiency motors can be justified using most common standard criteria. Since the site was a large one and paid only £ 0.035 per kWh on average over the year, the savings were less than they would be on smaller sites on higher tariffs. Also, being a large user with a very high resistive demand, the effects of power factor improvements were not realisable. On a smaller site, extra savings of £ 380 per year would be made on these five motors alone. It is worth pointing out the very significant saving made by replacing Motor No 2, which is running for a little over half the time of motors 3 - 5, with a loading of only 27% and yet yields the greatest savings. This is a result of the large improvements in efficiency achieved by high-efficiency motors at low loadings, mainly due to the use of improved magnetic steels and careful production methods. This indicates that motors which are oversized with respect to their average load, but which need the capacity to handle higher loads intermittently, should be early targets for replacement with high-efficiency units. Motors which are merely oversized and do not need the extra capacity should, of course, be replaced with a high-efficiency motor of the optimum size for even greater savings. Other tests are yet to be reported.

2.4.2. Whisky Distillery

It has also been reported that, at a distillery in Scotland, the eight 110 kW motors driving the carbon dioxide gas compressors were replaced by high-efficiency motors showing savings of £1,577 per year each¹³.

2.4.3. Photographic Laboratory

In a photographic laboratory it was decided to replace eight 30 kW and eight 15 kW fan motors by high-efficiency designs. The result was a 20% reduction in maintenance costs and a 6dB(A) lower noise level. The total cost of replacing the motors was repaid in less than 2 years.

2.4.4. Copper Mine and Refinery

In a study of energy-efficiency applied to a copper mining company in Chile, Leibbrandt¹⁴ compared the losses in various sizes of NEMA design B drip-proof motors used in the plant. These are shown in Table 2-2, showing some variations of the effects of the individual factors through the size range, but a general increase in efficiency as the motor size increases.

Table 2-2 Motor Losses and Efficiencies

Motor HP	5	25	50	100	200
(kW)	3.7	18.7	37.5	75	150
Losses (%)					
Stator I ² R	40	42	38	28	30
Rotor I ² R	20	21	22	18	16
Magnetic Core	29	15	20	13	15
Friction and windage	4	7	8	14	10
Stray	7	15	12	27	29
Total	100	100	100	100	100
Efficiency					
Output, W	3,730	18,560	37,300	74,600	149,200
Input, W	4,491	20,946	41,217	81,530	160,432
Efficiency, %	83	89	90.5	91.5	93

Having studied the total number of motors installed in Chuquicamata refinery, it was found that the total heat loss due to motor inefficiency was 93.3 GWh/y (1 GWh = 10⁶ kWh). The installation of energy-efficient motors throughout would reduce electricity consumption by 54.6 GWh/y, a saving of \$3,000,000 per year. It has therefore been agreed that there should be a systematic programme of motor replacement giving due consideration to both capital, running and repair costs.

2.4.5. Heating, Ventilating and Air Conditioning Plant (HeVAC)

The BBC's Library and Archive premises uses a number of chillers and air conditioning units to maintain a constant cool environment for stored films and video tapes. A detailed study¹⁵ was undertaken on four motors so that the performance of high-efficiency motors could be compared directly. Table 2-3 gives details of the motors selected.

Table 2-3 Motor Details

Motor Application	Original Motor Details	Annual Operating Hours	Operating Load (%)	Cost Saving Opportunity
Fan No 1	4.0 kW, 4 pole	8,760	26.8	Use 2.7 kW HEM
Fan No 2	2.2 kW, 4 pole	8,760	48.6	Use 1.1 kW HEM
Fan No 3	2.2 kW, 4 pole	8,760	56.8	Use 2.2 kW HEM
Pump No 1	1.5 kW, 4 pole	8,760	39.3	Use 1.1 kW HEM

Table 2-4 shows the comparison between Standard and High-efficiency Motors in these four applications.

Table 2-4 Comparative Motor Performance

Motor Application	Operating Load (%)	Standard Motor Operation		High-efficiency Motor Operation		Power Saving (%)
		Efficiency (%)	Power Factor	Efficiency (%)	Power Factor	
Fan No 1	26.8	54.6	0.42	83.6	0.56	34.7
Fan No 2	48.6	79.3	0.56	82.9	0.56	4.40
Fan No 3	56.8	79.3	0.71	83.3	0.77	5.10
Pump No 1	39.3	73.0	0.45	86.0	0.53	14.8
Overall	42.9	71.6	0.54	84.0	0.61	14.8

The overall payback period on the replacement of these four motors was 1.1 years.

3. Transformers

As with electric motors, there is scope for improvement in the efficiency of power transformers and real economic benefits to be gained. Although all power transformers have a very high-efficiency - the largest are probably the most efficient machines devised by man - their throughput and the number of them installed means that the energy which they waste is indeed enormous.

The largest transformers operating in the UK have an efficiency of around 99.75% at full-load, but since full-load can be as high as 800 MVA, the lost 0.25% can amount to 2 megawatts. Large transformers have the highest efficiencies, of course, since in a transformer costing around two and a half million pounds it is economic to build-in the degree of sophistication necessary to reduce the losses to the minimum attainable level. At the opposite end of the scale small distribution transformers are less efficient, somewhere around 99.5%. Sophistication is costly; there is no room for this in a low cost unit. But there are so many more small distribution transformers than there are 800 MVA generator transformers that it is equally important in these, if not more so, to aim for the highest efficiency that can be practicably achieved. A recent survey commissioned by the Copper Development Association revealed that distribution transformer losses represent 23% of the network losses from the UK system. Under peak load conditions these amount to 1,300 MW, equivalent to the output of one large power station.

By the time it is received at most consumers' premises, at 415 V, three-phase, or 240 V single phase, most electrical energy has been through at least five transformations in voltage level; initially being stepped up to 400 kV by the generator transformer, then down to 132 kV via an interbus transformer, to 33 kV at an REC bulk-supply point, to 11 kV in a primary substation and finally to 415 V at a local distribution substation. All of these transformers are energised 24 hours per day, for almost twelve months of the year and are therefore consuming losses almost all of the time. It has been estimated that some five percent of all electricity generated is dissipated in iron losses in electrical equipment¹⁶. In the UK alone in the year 1987/88 the cost of these no-load losses in transformers was put at £110 million¹⁷. At that time around 10^9 units of electricity were estimated to be wasted in core-losses in distribution transformers each year, equivalent to seven million barrels of oil to produce it and releasing 35,000 tonnes of sulphur dioxide and four million tonnes of carbon dioxide into the atmosphere¹⁸.

3.1. The Nature of Transformer Losses

Transformer losses fall into three categories:

- No-load loss, or iron loss.
- Load-loss, or copper loss.
- Stray-loss, which is largely load related.

For some larger transformers there are also losses absorbed by fans and pumps providing forced cooling.

3.1.1. No-load Loss

Iron loss arises within the laminated steel core of the transformer and is due to the energy consumed in hysteresis and eddy-currents within the material as it is taken through its alternating cycles of magnetisation - in the UK fifty times per second. Iron loss has been regarded by electrical engineers as the major area for improvement in transformer efficiency since the earliest examples were built and tremendous strides have been made in reducing iron losses over the last century, mainly due to improvements in the core steel.

Efficient operation of a power transformer requires the greatest possible flux linkage between primary and secondary windings and, for the best use of the core material this requires that the core be operated at as high a flux density as possible whilst avoiding approaching too closely to

magnetic saturation. Flux density is measured in Tesla, T. Losses in the iron increase as flux density is increased, nevertheless modern core steels operating at 1.7 T can have losses only a little more than 10% of those associated with the steels of the 1920s at 1.5 T. In addition 1.7 T represents a normal working flux density for a modern steel, whereas those of the 1920s could really only operate at about 1.35 T because of the lower levels at which saturation occurred.

In addition to the above development of these so-called conventional core steels, there has, over the last few years, been a totally new electrical steel produced which has specific losses of only around one tenth of those of the best conventional steels. This is amorphous steel. There are, as yet, limitations in its manufacture and use; it is exceedingly thin, around 0.05 mm, can only be produced in sheets up to 200 mm wide and its saturation flux density at about 1.56 T is lower than that of modern conventional steels. It is additionally very brittle, making it difficult to handle and build into complete cores and the thickness tends to vary across the width of the sheet. Nevertheless these limitations can be overcome for smaller transformer cores so that amorphous steel can be of very real benefit in reducing the losses of distribution transformer cores.

3.1.2. Load Loss

Load loss, or copper loss, has tended to receive less attention than iron loss in the pursuit of energy-efficient transformers. One of the reasons is because the magnitude of the loss varies in accordance with the square of the load. Most transformers operate at less than half rated load for much of the time so that the actual value of the load loss might be less than one quarter of the nominal value at full rated load. Only in the case of generator transformers is it usual practice to cost load losses at the same value as no-load losses, since normally when a generator transformer is energised at all, it will be operating at or near to full load.

The placing of a lower value on load loss than that on no-load loss has tended to create the view that load loss is not important, but, of course, this is far from the case. Load losses are maximum at the time of maximum demand on the system and so place an extra drain on this at the very time when it is least able to meet it. At such times it is the most expensive generating plant which is called into operation and any savings in network losses that can be achieved will result in savings at an exceedingly high system marginal rate. As an indication of the effect that the placing of high demands on the system can have on the cost of electrical energy, it is of interest to note that in early December, 1995, the price for energy in the UK Electricity Pool rose to in excess of £1 per kilowatt hour.

Copper loss arises mainly as a result of the resistance of the transformer windings, that is it is the I^2R loss produced by the flow of the load current within the windings. There is however a significant additional component which is the eddy-current loss. Winding eddy-currents are produced as a result of the alternating leakage flux cutting the windings and these flow within the conductors at right angles to the load current path. For a particular winding the eddy-current losses are a fixed proportion of the load-losses. They do however vary as the square of the frequency so that the presence of any harmonics in the load current leads to significant additional eddy-current loss.

For many years eddy-current losses presented an obstacle to reduction of I^2R losses within transformer windings, since increasing the conductor cross-section with the object of reducing winding resistance had the effect of worsening the eddy-current component, so that little overall benefit was obtained. Since the mid 1960s continuously transposed conductor (CTC), which consists of a large number of individually enamel-insulated strands to increase the resistance of the eddy-current paths, has been available which has largely eliminated this problem. Its use, coupled with the use of flux shunts to control the distribution of leakage flux, means that eddy-current losses can now normally be contained within 10-15% of the I^2R loss so that reduction of load loss depends simply on the amount of materials, copper and iron, that it is considered economic to put into the transformer.

3.1.3. Stray Loss

So-called stray losses are those which occur in leads and tanks and other structural metalwork. Until the recent development of computer calculation techniques using finite element analysis, the magnitude of stray losses was usually determined empirically, with tolerances on guarantees taking care of instances where designs did not quite conform to previous experience. Modern computer programmes have not only removed the uncertainty from this aspect of design but have made possible improvements in the designs themselves by enabling designers to calculate and compare losses for differing arrangements as well as enabling the placing of suitable flux shields in critical areas. Stray loss, which is load dependent, has thus been reduced from perhaps 10% of the load losses to around half this value.

Figure 3-1 Relative Losses for Different Transformer Types

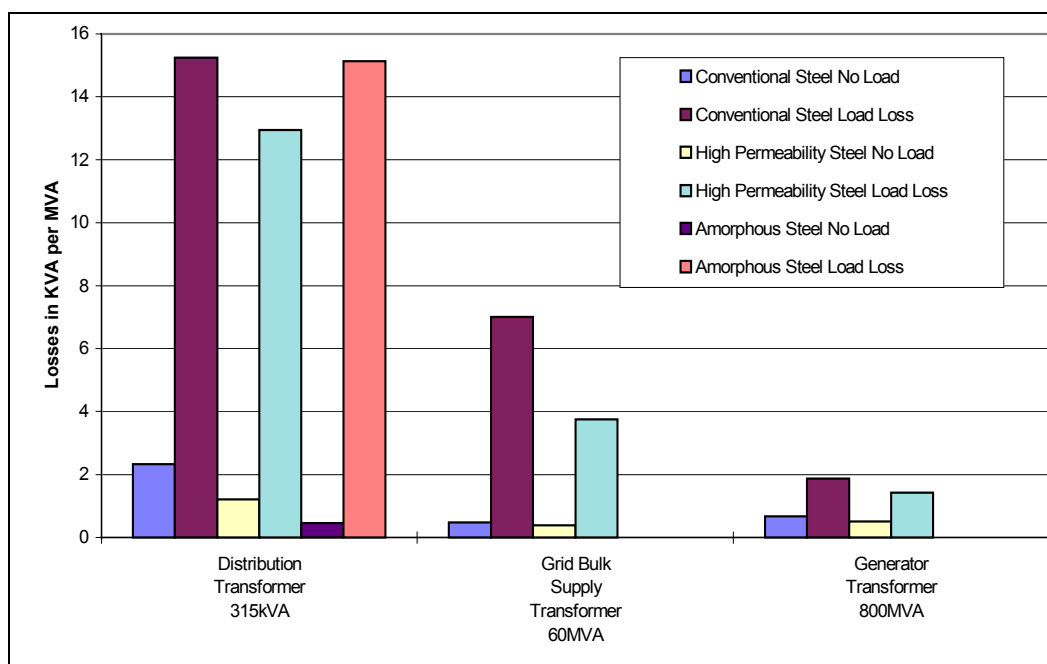


Figure 3-1 shows the very poor efficiencies of the smaller distribution transformers - even when supposedly of the low-loss types - compared to the larger sizes of transformers. As distribution transformers make up 23% of the total transformer population, considerable savings can be made by increasing their efficiency. Note that amorphous steel is not available for transformers larger than about 630 kVA. All loss values are typical only. The subject of transformer losses and the ways in which these can be reduced to improve energy efficiency is discussed in greater length in *'Energy-efficient Power Transformers'* on Page 47.

3.2. Loss Evaluation

In the power transformer business, standard designs are not common. Each design is tailored to the customer's technical requirements and to a level of losses which reflect the importance that the user places on energy efficiency. This is the case even for distribution transformers which might be manufactured in quite large quantities.

The different requirements and evaluation processes of the Regional Electricity Companies (RECs) and industrial users mean that the two groups are best served by different transformer types. Most utilities and a few industrial users quantify the value of energy efficiency when transformers are being procured by evaluating losses on the basis of marginal cost of producing or buying one extra kilowatt, amortised over a period of between 25 and 40 years, taking into account probable inflation and interest charges. In recent years utilities have become accustomed to weight this assessment in favour of minimising initial outlay by requiring that the

energy savings show a return of up to 10% on the additional capital employed. This they have done by applying a "test discount rate" (TDR) of up to 10% to the capitalised values of the losses at the time of carrying out their loss evaluation. However, this practice applies a very short term bias to the pursuit of energy efficiency and tends to steer utilities away from making savings in losses for which the payback period would be relatively short if the "true" cost of losses were put into the equation.

Regional Electricity Companies (RECs) typically apply capitalisation values of, say, £3,000 per kilowatt to no-load losses and £625 per kilowatt to load losses. These values will probably be derived using a test discount rate of between 8 and 10%. The lower value placed on load losses is because of the fact that most transformers operate at substantially less than full-load for most of the time, as explained above. If the test discount rate were reduced to just 5% this could increase the values placed on losses to about £3,750 per kilowatt for iron loss and around £780 per kilowatt for load loss. If the true cost of the units lost per year was totalled up this might give values of around £4,000 for iron loss and £800 for load loss. This process is explained in greater length by the inclusion of a worked example in *'Typical Cost of Losses to Industry'* on Page 56.

Table 3-1 shows typical distribution transformer variation of first cost with variation of losses enabling the effects of differing capitalisation rates to be seen.

Table 3-1 Typical First cost and Loss Data for Transformer types

Unit	Iron loss (Watts)	Copper loss (Watts)	Price £
315 kVA standard	735	4,800	5,000
315 kVA low loss	380	4,080	6,690
315 kVA amorphous	145	4,770	7,315

In the table the description 'standard' describes the loss values and price which might typically be offered by a manufacturer in response to an enquiry from an REC specifying typical loss capitalisation values as quoted above, i.e. £3,000 per kilowatt for no-load loss and £625 per kilowatt for load loss.

Table 3-2 shows the results of an evaluation exercise for each of the above alternative designs using three sets of loss values.

Table 3-2 Evaluation of Typical Transformers

	Typical REC (10% TDR)	Typical Industry User (see page 56)	Typical REC (5% TDR)
Loss capitalisation values per kilowatt	£3,000/£625	£3,988/£814	£3,750/£780
Standard loss alternative			
No-load loss 0.735 kW	£2,205.00	£2,931.18	£2,756.25
Load loss 4.8 kW	£3,000.00	£3,907.20	£3,744.00
Price	£5,000.00	£5,000.00	£5,000.00
Totals	£10,205.50	£11,838.38	£11,500.25
Low loss alternative			
No-load loss 0.38 kW	£1,140.00	£1,515.44	£1,425.00
Load loss 4.08 kW	£2,550.00	£3,321.12	£3,182.40
Price	£6,690.00	£6,690.00	£6,690.00
Totals	£10,380.00	£11,526.56	£11,297.40
Amorphous steel alternative			
No-load loss 0.145 kW	£435.00	£578.26	£543.75
Load loss 4.77 kW	£2,981.25	£3,882.78	£3,720.60
Price	£7,315.00	£7,315.00	£7,315.00
Totals	£10,731.25	£11,776.04	£11,579.35

It is clear from this exercise why manufacturers are driven to supply to RECs the low-first-cost option identified as the ‘standard loss’ alternative. The low loss alternative is however the most attractive option for the industrial user and this would also be the most attractive option for the ‘typical REC’ if they were to use a slightly lower test discount rate than that currently employed. The other interesting fact to emerge is that the amorphous steel core option is not attractive to any user who operates a ‘net present value’ type of assessment procedure as explained in ‘*Energy-efficient Power Transformers*’ on Page 47. Only if a ‘true cost’ system, as described in ‘*Energy-efficient Power Transformers*’, which costs a lifetime’s no-load loss at £10,550 per kilowatt and load loss at £2,152 per kilowatt, is used does the amorphous steel option appear to be the most attractive, as can be seen by reference to Table 3-3.

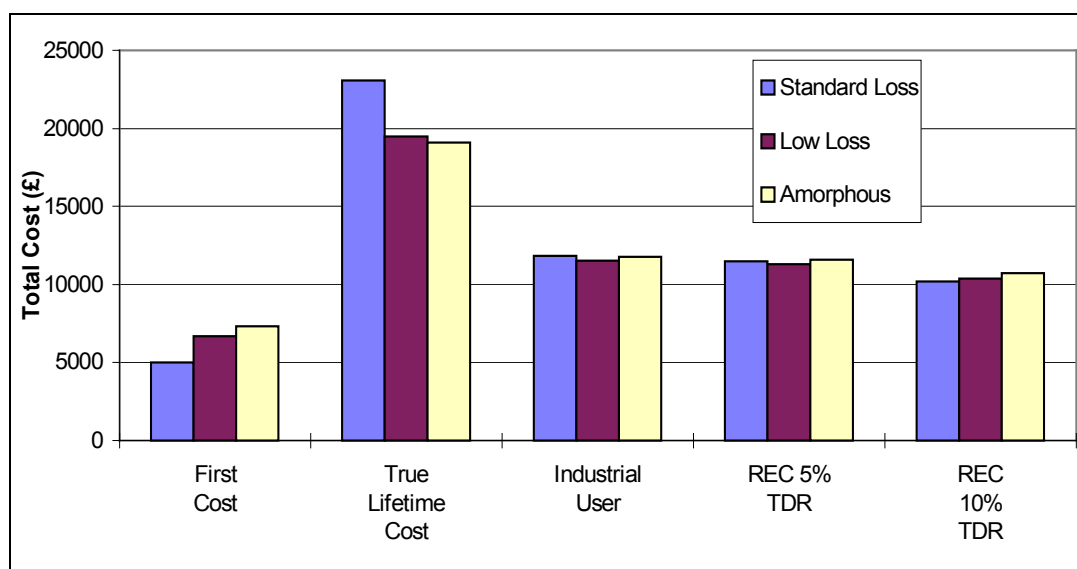
Table 3-3 Assessment Using True Lifetime Cost of Losses; no-load loss - £10550/kW, load loss - £2152/kW

	Standard loss		Low loss		Amorphous steel	
	loss	cost of loss (£)	loss	cost of loss (£)	Loss	cost of loss (£)
No-load loss kW	0.735	7,754.25	0.38	4,009.00	0.145	1,529.75
Load loss kW	4.8	10,329.60	4.08	8,780.16	4.77	10,265.04
Price £		5,000.00		6,690.00		7,315.00
Totals £		23,083.85		19,479.16		19,109.79

3.3. Industrial Users

Many industrial users do not evaluate losses at all when procuring transformers. They either consider transformers to be so efficient that the losses can be neglected or they take it that the manufacturer's design process will automatically provide them with the most appropriate value of losses. An industrial user's priorities are not necessarily the same as those of a REC so there is no reason why a design that a manufacturer has recently optimised for a REC should be the best for them. If an industrial user should decide to compute the cost of energy consumed by transformer losses the result can often lead to a decision to opt for lower losses than might otherwise have been the case. This will be made clearer by reference to the example set out in 'Typical Cost of Losses to Industry' on Page 56.

Figure 3-2 Evaluation of Typical Transformers



From Figure 3-2, it is clear that the most economical option depends on the loss capitalisation values chosen. If 'true cost' system values are used, amorphous steel appears to be the most attractive option. However, the low loss transformer appears to be the best option for both the industrial user and RECs using 5% TDR. Only in the case of a REC using 10% TDR - the typical case for RECs - does the standard transformer appear most attractive. Most manufacturers will use loss capitalisation values appropriate to a 10% TDR when quoting for supply, so it is important that customers specify their requirements carefully when requesting and comparing quotations.

3.4. Dry-Type Transformers

To many industrial and commercial organisations dry-type transformers are seen to be advantageous compared with oil-filled units. They avoid the perceived fire risk of oil-filled transformers and can thus be accommodated inside a building or even on the roof of an office block. Savings can be made on LV connections by installing the transformer integral with 415V switchgear. There is no need to house the transformers in banded enclosures or make any other provision for spillage as would be the case if a transformer filled with any type of liquid dielectric were installed.

All of these advantages as well as the apparent benefits of low maintenance and high reliability are energetically marketed by manufacturers and cast-resin insulated dry-types, in particular, are being installed in increasingly large quantities.

Most users of dry-type transformers are aware of the extra initial costs and accept these as the price to be paid for greater convenience. What users often do not realise, however, is that dry-type transformers are less energy-efficient and can involve significant increases in running

costs. Architects, in particular, may be very conscious of the benefits arising from the installation of dry-type transformers without having to live with the running costs and the potential user would do well to recognise this and examine available options with great care.

KVA for kVA a dry-type transformer will always be larger than its oil-filled counterpart. This is because larger electrical clearances are required when air is part of the insulation system. In addition air is less efficient than oil as a cooling medium, so that, although a higher temperature rise is usually permitted, larger cooling ducts will be required. Increased size means greater no-load loss and, because the transformer runs hotter, winding resistance will be increased, thus increasing I²R losses too. All of this is regardless of the class of dry-type transformer used. In addition cast resin transformers often use aluminium as a winding material because its coefficient of thermal expansion is closer to that of resin and this provides a better quality of encapsulation. This in turn leads to bulkier windings which have still higher losses.

Finally, of course, the additional burden placed on ventilation plant by the imposition of transformer losses must not be overlooked.

4. Power Cables

While the installation and use of much energy-efficient equipment is being well considered and actioned, the energy losses in undersized power cables are frequently ignored. If cables are installed with a conductor size that is the minimum allowed to avoid overheating, energy losses can be very significant. Mandatory regulations specify minimum conductor sizes for thermal safety but are not intended to be the most economical if energy losses throughout the life of the power cable are taken into consideration. Until the recent world-wide economic downturn, it was common practice to install cables that were two standard sizes larger than the minimum recommended simply in order to allow for increased demand. There was an immediate benefit from a reduction in I^2R losses and long, reliable lifetimes for the cables due to their running at less than their maximum rated temperature. Now, new costing policies may demand lowest first cost by installing the minimum permitted cable size *and result in these benefits being lost*.

It is therefore necessary to calculate running costs to ascertain the most economic size of cable to install. Where environments have to be controlled by ventilation or air conditioning, the extra cost of removing waste heat from inefficient cables must also be calculated. The cost of electricity is more likely to rise than fall; this too must be considered as far as is predictable.

If the energy demand of a system subsequently increases to a level above the safe cable rating, the installation of extra power cables can be a very significant extra expense. Initial specification of cables that are an optimum economic size is a recommended practice encouraged by a new British Standard.

4.1. Energy Costs

Energy lost in cables has to be generated. A reduction in losses brings about not only a reduction in fuel costs, but also in plant capacity needed to provide the losses at times of peak generation.

The cost of energy is generally increasing with inflation and the depletion of natural resources. Energy-efficient considerations are becoming increasingly important. The use of conductor cross-sections that have been chosen with the cost of energy losses in mind can be shown to save money now and will probably show increased savings with time.

4.2. IEE Regulations

Recommended procedures for choice of cable size are frequently followed without a full understanding of the implications. IEE regulations¹⁹, now BS 7671 (equivalent to IEC 364 and European Standard HD 384), can be used to ascertain the **minimum permissible safe conductor size**. These ensure that, when used at rated current flow, the cable does not overheat dangerously but **do not give the optimum size for lowest cost** over the life of the cable, nor even over a stipulated payback period.

As an example, a cable of 16 mm² section can be rated at 109 amps and run at 90° C but over a 100 metre run would drop over 30 volts and waste nearly 3.5 kW. This would cost over £1,500 per year if electricity is bought at £0.05 per unit. The use of 35 mm² section more than halves this wastage.

Cable sizes should be specified larger than the IEE Regulation minimum for any combination of a variety of reasons, including:

- Allowing cables to run cooler and save energy
- Nearest standard size up
- Standard fuse rating requiring larger cable for safety in overload conditions
- Allowing for future expansion in demand

4.2.1. Cost Considerations

In costing the installation, many factors have to be considered:

- Maximum rating when installed
- Resistance to possible short circuits
- Rate of growth of demand
- Cost of losses of power due to cable resistance
- Cost of removal of excess heat
- Installation cost
- Maintenance costs
- Cost of performance losses of equipment running at reduced voltage
- First cost of cable
- Future costs of energy
- Interest and discount rates

4.3. Optimum Cable Size

Cable installations should be specified according to the guidance of British Standard 7450:1991²⁰, equivalent to IEC 1059:1991, 'Economic Optimisation of Power Cable Size', which gives useful guidance on the optimum costing of cable installations. This standard needs to be a requirement of management procurement policy and included in contractual documents in order to avoid the false economy of 'lowest first cost' attitudes. The standard points out that:

'Rather than minimising the initial cost only, the sum of the initial cost and the cost of losses over the economic life of the cable should be minimised. For this latter condition a larger size of conductor than would be chosen based on minimum initial cost will lead to a lower power loss for the same current and will, when considered over its economic life, be much less expensive.'

For the values of the financial and electrical parameters used, the saving in the combined cost of purchase and operation is of the order of 50%. Calculations for much shorter financial periods can show a similar pattern.

It is difficult to give an accurate forecast of some of the time-dependent variables given above. However, the methods chosen have the result that the impact of errors in financial data, particularly those that determine future costs, is small. While it is advantageous to use data having the best possible accuracy, considerable savings can be made using data based on reasonable estimates.

The standard deals solely with the economic choice of conductor size based on joule losses. The effects of voltage-dependent losses may be significant but depend more on individual circumstances and have not been considered in the standard.

Laying cost for cables does not increase proportionately to cable size since most of the operations are common. For conductor sizes up to 100 mm², the laying cost for buried cables is higher than the cable cost.

In another example, a design study for a 10 kV cable required to carry 160 amps showed that a 240 mm² section was the most economic although on IEE thermal safety rules a 70 mm² section would be adequate.

The cost of waste heat removal can more than double the cost of I²R losses in cable ducts. In modern office and industrial buildings with a heavy demand for power, air conditioning plant has to be used to export surplus heat for much of the year. This cost must be taken in to account.

While cables are now being made with insulation that can withstand regular running at higher temperatures, it is false economy to save on conductor size and waste more energy throughout the lifetime of the cable. The benefits of modern high temperature cable materials are best realised in installations where space limitations, ambient temperatures and possible overcurrent conditions are such that a high conductor temperature cannot be avoided at any reasonable cost.

Upsizing of copper conductors can reduce energy losses significantly at a marginal premium cost. This can be evaluated using standard calculation techniques or software and can result in savings in energy losses of the order of 50%. Such calculations also add to the justification of upsizing cable sizes to allow for standard fuse ratings and the likelihood of increased future demand. Besides power cables in industry, consideration has also been given to optimum sizing of installations in commercial buildings such as offices and retail outlets.

In a paper published in 1989, Parr²¹ developed a list of sizes of cables that could be considered economic within given current ranges. This was a result of work done at ERA Technology and international co-operation leading to the IEC publication 1059:1991 'Economic Optimisation of Power Cable Size'. All of this work was based on the original rule formulated by Lord Kelvin in 1881²²: ***“The most economical size of conductor for a given load is one where the annual value of the interest and depreciation on the cost of the installed system is equal to the cost of the power losses”***, with the effects of variables fully considered.

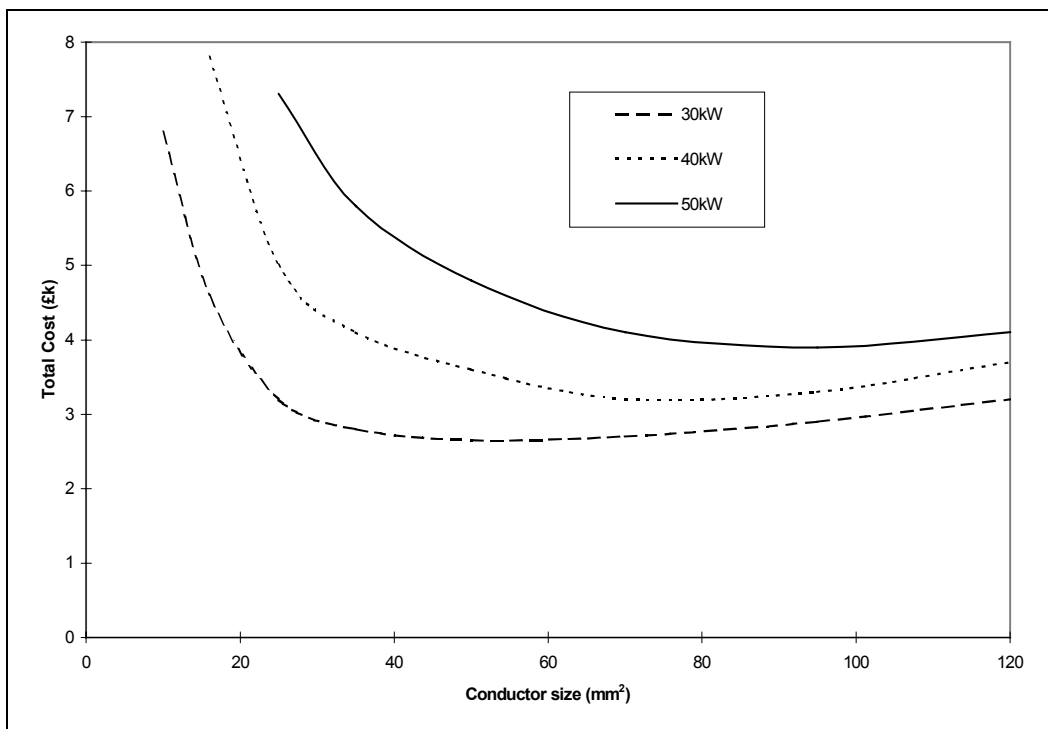
The standard sizes are shown in Table 4-1 and, as calculated, refer to the maximum current during the first year of a thirty-year expected lifetime. They are based on a 2% per annum load growth rate, a discount rate of 5% and an annual increase in energy costs of 2%. It shows the minimum and maximum economic current ratings for given sizes of cable, and it can be seen that even the maximum economic ratings are significantly less than the current permitted under IEE safety regulations.

In a more recent paper²³, Parr updates the information with graphs of cost/size curves for different loads, costs for different types of cable and a comparison of costs with regulation sizes. This paper has now been expanded and updated, and is included here as *'Economic Selection of Cables for Industry'*, beginning on Page 60. Formulae are given for carrying out calculations for the most economic sizes of conductors for variables such as the discount rate, load increase per year, energy cost increase per year, electricity costs and lifetime expectancy. The results of some of the basic calculations are shown in Figure 4-1. They show the total costs over the expected lifetime of a nominal 100 metre length of three-phase cable insulated with PVC and armoured with steel wire, installed with typical ventilation. The smallest size shown for each cable is that specified as a thermal limit, the second that normally required to meet typical overcurrent and earth fault contingencies. Even larger sizes of conductors can be seen to be the most cost-effective.

Table 4-1 Economic Current Ranges for Power Cables

Conductor size	Economical Current Range		Thermal Rating based on IEE Recommendations
	Lowest	Highest	
mm ²	A	A	A
25	-	15	91
35	15	23	112
50	23	29	133
70	29	40	163
95	40	55	194
120	55	71	224
150	71	82	250
185	82	106	286
240	106	141	332
300	141	191	372
400	191	-	423

Figure 4-1 Typical total cost / size curves showing cable costs in £k per 100m of three phase, insulated PVC/SWA



4.3.1. Best Conductor Material

The conductivity of copper is 65% higher than that of aluminium which means that the conductor size of similarly rated cables is proportionately smaller. Correspondingly less expense is then incurred in providing for insulation, shielding and armouring the cables themselves. Transport of the less-bulky cables is easier and so is installation. In limited spaces

in cable ducts, the smaller volume and better ductility of copper cables can have an even larger benefit.

Copper cables are easily jointed because copper does not form on its surface a tough, non-conducting oxide. The oxide film that does form is thin, strongly adherent and electrically conductive, causing few problems. Cleaning and protection of copper is easy and if joints are made as recommended they will not deteriorate to any great extent with age, which saves on maintenance costs.

For the same nominal current rating, the cable with the aluminium conductor is significantly larger in diameter, carries a proportionally greater volume of insulation and is not so easily installed because of being less flexible. Aluminium is notoriously difficult to joint reliably. Table 4-2 compares aluminium and copper conductors for equivalent current rating.

Table 4-2 Comparison between Copper and Aluminium Conductors in XLPE Insulated Steel-Wire Armoured Cables.

(Cable: to BS 5467 (& IEC 502) 4-core, stranded conductors, XLPE insulation, PVC bedding, steel wire armour, PVC oversheath, rated at 0.6/1.0 kV)

Characteristic	Copper	Aluminium
	300 mm ²	500 mm ²
Overall diameter (mm)	66.5	83.9
Minimum bending radius (mm)	550	700
Max dc resistance/km at 20° C (ohm)	0.0601	0.0617
Approx. voltage drop/A/m (mV)	0.190	0.188
Continuous current rating, drawn in to duct (amp)	496	501

These notes have largely been derived from reference to BS 7450:1991 which is identical to IEC 1059. Further detail and background information is included in 'Economic Selection of Cables for Industry', beginning on Page 60. Both of these give full details of the variables to be considered and the ways in which optimum cable size determinations can be made.

4.4. Power Quality

Power Quality problems are becoming increasingly common. Modern electronic office equipment - personal computers, printers, fax machines and photocopiers - all use switched mode power supplies (SMPS) which draw current in pulses, rather than continuously, from the supply. The result is that harmonics (mainly third and fifth) are generated in non-linear circuit elements in the equipment and in supply chain equipment - converting useful 50 Hz power to useless harmonic power. Two problems arise.

Firstly, the harmonic current flows around the phase/neutral loop so the neutral carries harmonics of each of the three phases. The predominant harmonic will be at three times the supply frequency, and the contribution from each phase will be displaced by one third of the supply cycle, so the harmonic content from each phase will be in phase and will add. This can give rise to very large neutral currents and in a recent site survey of a typical modern office, a 3 phase circuit supplying 100 amps was found to be carrying 150 amps of third harmonic in the neutral. It has been common practice to install half-sized neutrals on the assumption that neutral currents from a three phase supply cancel - true only for the fundamental - and this is no longer acceptable. Best practice is to use *double*-sized neutrals.

Secondly, the SMPS filter passes an earth leakage current at the supply frequency (not exceeding 3.5 mA) together with the high frequency noise current arising from the switching transients and a small fraction of the harmonic current. On an individual ring circuit the supply frequency leakage currents from individual loads will add and may reach quite high levels. As earth conductors from other rings on the other two phases are brought together, the currents will tend to cancel, but the harmonic and noise currents will add. The earth conductor on the supply

side of the distribution point is often provided by the cable armouring, which, being wound, has a significant inductive component to its impedance. The high frequency noise and harmonic currents generate noise voltages resulting in a noisy earth which can cause interference to other equipment. Worse still, on the 'consumer' side of the distribution point the earth conductor is usually a good low impedance copper conductor, so the noise arising from the feeder earth impedance is effectively distributed to every device connected to it.

Power quality problems can be very difficult to identify and solve; however, prevention is better than cure and the following good practice points should be applied during design and installation:

- Earth conductors should be well-rated **copper** conductors throughout so that the impedance is low at all frequencies.
- Neutral conductors should be generously rated, preferably at twice the cross-sectional area of the phase conductors. Phase conductors should be rated generously, taking into account the most *economical* size for the anticipated current.
- Provide a generous number of final circuits, carefully distributed among the phases, with dedicated circuits for problem loads - including laser printers.

Power Quality problems are dealt with in detail in CDA Publication No 111, 'Common Quality Problems and Best Practice Solutions'²⁴.

4.5. Busbars

Busbars normally carry very large and varying currents and are subject to large forces due to the magnetic effect of adjacent bars and to expansion and contraction as their temperature varies with load. They are usually uninsulated and are therefore subject to corona discharge if operated at high voltage. Considerations for economic sizing of busbars are similar to those for cables.

Design criteria for busbars are dealt with in detail in another CDA publication²⁵ which gives formulae for calculating the appropriate current rating for various busbar arrangements, taking account of resistance, inductance, skin effect and heat loss mechanisms. Performance under short circuit fault conditions is also discussed. Mechanical properties, including the ability to withstand thermally and electromagnetically induced stress, are fully considered.

5. A Systems Approach to Calculating Energy Saving

Various parts of this document have encouraged specifiers and engineers to look closely at the savings which can be made by specifying an energy-efficient version of a particular component. This section presents the case for taking the next step and looking at the overall benefit of specifying energy-efficient options throughout the system, looking at the motor and cabling together, and if appropriate, the local power transformer.

As an example, consider a ventilation fan motor, working full time, at 100 metres from the distribution panel.

The Motor.

Taking as an example Motor No 3 from the Brass Extrusion Mill example on Page 21.

Rating kW	% Load	Output Power kW	Duty hrs/yr.
7.5	87	6.525	8,760

Typical Motor parameters:

	Efficiency (%)	Output Power (kW)	Input Power (kW)	Annual Consumption (kWh)	Current per phase (A)
Standard	87	6.525	7.50	65,700	9.84
Energy-efficient	90	6.525	7.25	63,510	9.51

Annual Saving 2,190

(The input power is given by $\frac{\text{motor rating} \times \text{load}}{\text{efficiency}}$)

At a unit cost of £0.0443 per unit, the annual saving is £97.02, while the incremental cost of the energy-efficient motor would be about £95.

The Cable.

A conductor cross-section of 1.5 mm² would be considered adequate - from a thermal rating point of view - to carry this current (< 10A). Such a cable would have a resistance of 25 milliohms per metre. The power loss in the cable is:

$$p_L = I^2 \times R$$

The *reduction* in power loss in the cable due to the use of an energy-efficient motor is:

$$\begin{aligned} p_D &= (I_1^2 - I_2^2) \times R \\ &= (9.84^2 - 9.51^2) \times 25 \times 10^{-3} \times 100 \\ &= 5.796 \times 2.5 = 14.49 \text{ W} \end{aligned}$$

Energy saved per year = 127 kWh

But, if the cable size is chosen for energy efficiency, rather than the minimum safe size, much greater savings can be made.

For a 1.5 mm² cable supplying an energy-efficient motor the power loss is:

$$= 9.51^2 \times 25 \times 10^{-3} \times 100 = 226.1 \text{ W per phase, or } 678.3 \text{ W total for all three phases.}$$

Methods for determining the most economical cable size are fully explored in '*Economic Selection of Cables for Industry*' on Page 60, and these should be applied using cost figures relevant to the site.

Using, say, 10 mm² cable would reduce the total loss to 103.1 W, giving an annual saving of

$$575.2 \times 8,760 = \mathbf{5,037 \text{ kWh}}$$

At a unit price of £0.0443 per unit, the annual saving would be £223.14. Since the cost of installation will not be significantly higher than for the smaller cable, the only additional cost is the purchase cost of the cable.

This table shows the power saving achieved so far:

For 6.525 kW output power	Standard Motor, 1.5 mm ² cable (kW)	Energy-efficient Motor, 10 mm ² cable (kW)
Input Power	8.178	7.353
Overall Efficiency (%)	80	89

The overall annual power saving is 7,227 kWh, or £320.16

The Transformer.

'The Nature of Transformer Losses' on Page 47 details the factors which should be considered when selecting local transformers. By careful selection of the motor and cabling we have already reduced the input power by 10%, and consequently the attributable transformer load loss by 21%.

Selecting a low loss transformer would reduce the loss further. Transformer load loss is proportional to the square of the load current, so the loss associated with an incremental load depends on the degree of loading. Using the standard and low loss transformers from

Table 3-2 on page 29 and assuming that it is running at 80% load, the incremental loss associated with a 1 kW load for each transformer can be estimated at 24.4 W and 21.25 W respectively. For the incremental load of the motor, the additional losses are 195.2 W for the standard and 170 W for the low loss transformer, so that the low loss transformer saves a further 221 kWh per annum.

The additional cost of selecting a low loss transformer is equivalent to £5.37 per kW of rating (based on a 315 kW unit), so that attributable to the motor load (remembering that the overall loading is 80%) is £53.60.

For 6.525 kW output power	Input Power (kW)	
	Standard motor 1.5 mm ² cable standard transformer (kW)	Energy-efficient motor 10 mm ² cable low loss transformer (kW)
Input power to motor	7.500	7.250
Input power to cable	8.178	7.353
- plus incremental transformer loss	8.373	7.523
Annual Consumption	73,347 kWh	65,901 kWh

The overall saving is 7,446 kWh per year, equivalent to £329.85 per year (at £0.0443 per unit).

The payback period will be different for each element; in this example it is less than 1 year for the motor, and about 7 years for the transformer - a short time compared to the life expectancy of a transformer.

It must be remembered that the selection of more efficient downstream components, including cabling, reduces losses in other components upstream.

Appendices

1. Motors

A. Design of Energy-efficient Motors

Factors affecting the efficiency of Electric Motors

The efficiency of an electric motor depends on the choice of materials used for the core and windings, their physical arrangement and the care and precision with which they are handled and assembled. Losses fall into two categories; those which are load dependent, and those which are independent of load.

The factors which affect efficiency are:

Conductor content	(Load dependent)
Magnetic steel	(Mainly constant)
Thermal design	(Mainly load dependent)
Aerodynamic design	(Constant)
Manufacture and quality control	(Constant)

i. Conductor Content

Resistive losses in the windings increase with the square of the current (which increases with the load) and normally account for around 35% of the total losses. These resistive losses can be reduced by putting more copper into the windings - using a thicker gauge wire - and improving manufacturing techniques to shorten the end windings (which do not contribute to output power but do contribute to loss). Since more copper requires more space, both for the endwindings and in the stator slots, the volume of material in the magnetic circuit would be reduced, leading to earlier saturation and increased iron losses. As a result it is necessary to increase the length of the magnetic core, and sometimes the diameter as well. Normally, the increased length is accommodated by increasing the overhang at the non-drive end of the unit. Because copper losses are load-dependent, the benefit of increasing the copper content is most apparent at high loading. Since the coefficient of resistance of copper is positive, the losses increase as temperature rises.

ii. Magnetic Steel

Magnetic steel is the most expensive component of the motor, so any increase in the total amount used is undesirable on cost grounds. The iron losses are of two types - hysteresis loss and eddy-current loss. Hysteresis loss is due to the non-linearity of the flux density/magnetising force curve and is a property of the steel itself and to minimise it two properties are required - a low energy loss and good high field permeability, i.e. the steel must be easy to magnetise and must not saturate at high flux densities of up to 1.8 Tesla. This is the subject of on-going research which is making promising progress. Eddy-current losses are due to induced current in the stator laminations and are reduced by reducing the thickness of the laminations and by ensuring good insulation between adjacent laminations. Thinner laminations are, naturally much more expensive to produce and more difficult to handle, so the chosen thickness is always a compromise. The benefit of using improved magnetic steel is a reduction in loss across the whole of the working range, but, because it is not load dependent, it is particularly apparent at low loadings.

iii. Thermal Design

Good thermal design to eliminate local hot spots is a difficult matter because of the complex pattern of heat sources and the different thermal conductivity of the components of the assembly. New modelling techniques are now being used to gain a better understanding of the problem, allowing designers to predict operating temperatures accurately. As a result, motors can be produced which have an optimised cooling flow, reduced clearances (increasing the efficiency of the magnetic circuit) and lower copper losses. Lower losses and good thermal design result in lower operating temperatures and hence a longer service life.

iv. Aerodynamics

Most electric motors are cooled by drawing air through the windings by an integral fan and exhausting it over the externally ribbed casing. The air flow is complex and computer modelling has been used to optimise the design of the fan and cowling to produce more efficient cooling with a lower noise level. Windage losses can be reduced by careful design of the rotor.

v. Manufacture and Quality Control

Tests on existing motor designs in a variety of sizes and using a variety of magnetic steels revealed that the iron loss increased by approximately 50% as manufacture progressed. This obviously negated all the work being done to produce better steels, and was clearly unacceptable. The main cause was identified as physical stress, with the manner of fitting the core into the frame, and slight eccentricity between the stator and rotor (generating harmonic fluxes) also contributing. By considering assembly techniques at the design stage and by paying attention to handling techniques, the increase in iron loss during manufacture has been reduced to negligible proportions.

The overall result of these improvements is an increase in efficiency of 3% (corresponding to a reduction in loss of about 30%) at full load and a halving of losses at low loads.

B. Factors affecting the Efficiency of Rewound Motors. ²⁶

i. Increase in Iron Losses

An increase in the iron losses can be caused by :

- Mechanical damage to the core
- Thermal damage to the core
- Electromagnetic changes

Mechanical stress in the core will increase the hysteresis loss, as might happen if the core is fitted into a new frame with an undersized bore. The practice of hammering stator teeth back into place after stripping will result in increased hysteresis locally as a result of the residual stress. Eddy-current loss will increase if the insulation between adjacent laminations is damaged, for example by burring together by filing or by accidental impact. The stator tooth tips and rotor surface are the most vulnerable, since both carry high frequency harmonic fluxes. Skimming to remove damage is rarely acceptable because the air gap is increased and efficiency reduced.

Thermal damage to the oxide or varnish insulation between the laminations is normally regarded as the usual cause of increased iron loss following a rewind. New work in which the increased loss after rewind under carefully controlled conditions for a number of motors was measured has shown that for conventional steels the temperature should not exceed 380°C; losses increase very rapidly at higher temperatures. The very highest efficiency motors use thin laminations of high quality steel, coated with a microfilm of varnish and these were found to exhibit no increased loss over the test range of 350 - 400°C.

Most motors are designed to run with flux densities in the stator and rotor core just over the knee of the magnetisation curve. If the winding characteristics are changed after rewind, for example if the number of turns are reduced, the flux density and hence the loss will increase.

ii. Copper Loss

Stator copper loss is the largest loss (at full load) in most induction motors. The winding pattern may be changed during rewinding to simplify the process, and in doing so the repairer must consider the effect on flux density and resistance. The considerations are complex, and are beyond the scope of this document. Full details can be found in the reference.

iii. Mechanical Considerations

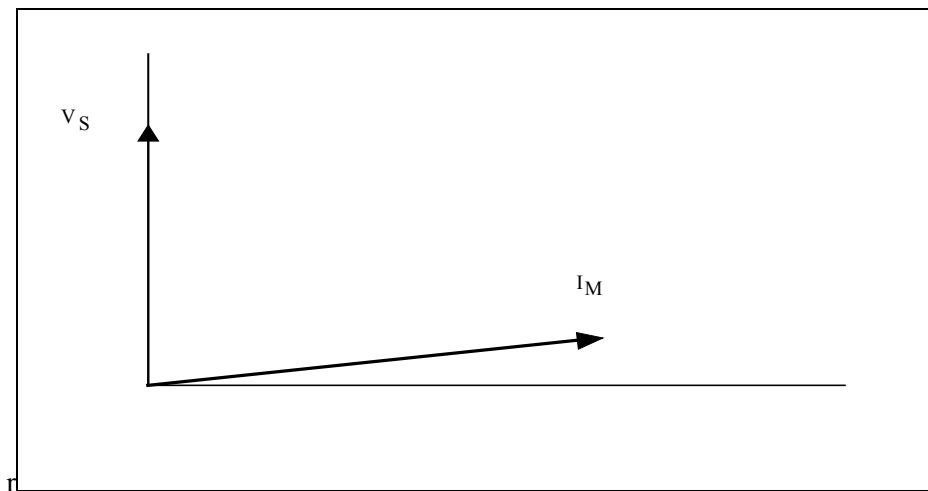
The concentricity of rotor and stator is very important. It is common practice to metal spray shafts or bearing housings which have been damaged in service. This is acceptable only if special care is taken to preserve concentricity - errors which result in a minimum to maximum gap ratio greater than 1:1.25 will adversely affect efficiency.

Replacement bearings (and lubricants) should be to the original specification, and repairers should be aware that HE motors are beginning to use newer, more sophisticated bearings.

C. Power Factor Correction

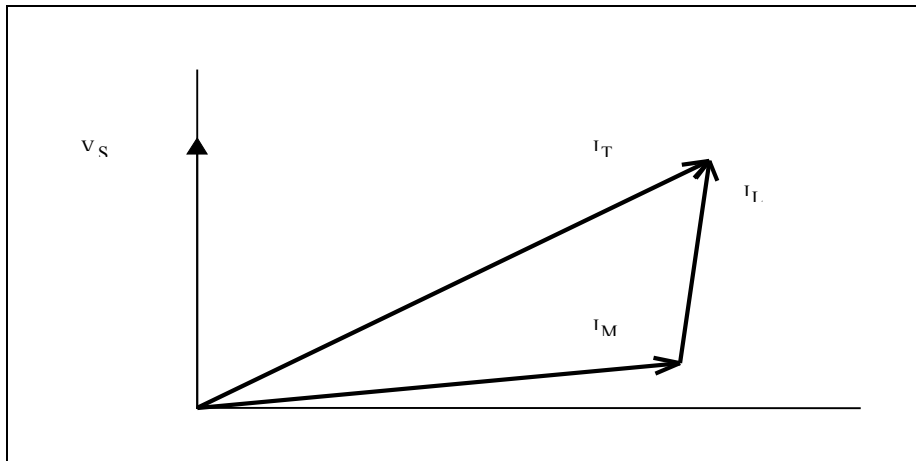
When an induction motor is idling or running at low loading most of the current consumed is used to magnetise the stator. As a result the motor equivalent circuit is effectively an inductor, so the magnetising current I_M , is nearly 90 degrees behind the phase of the supply voltage, as shown in Figure M C-1.

Figure M C-1 Phase Relationship in an Idling Induction Moto



When the motor is driving a load, the stator current increases by the addition of the “load component”, I_L , which, because it represents real work done, is nearly in phase with the supply voltage, V_S . The resultant total current is I_T . This situation is shown in Figure M C-2.

Figure M C-2 Phase Relationship for a Loaded Induction Motor



As the load increases the magnitude of I_L increases so that the total current I_T moves anticlockwise towards the phase of the supply voltage V_s , i.e. the power factor increases. Above full load as the slip starts to increase above its normal value the phase of the load component rotates clockwise, reducing the power factor.

Figure M C-3 Phase Relationship Between Supply Voltage and Current

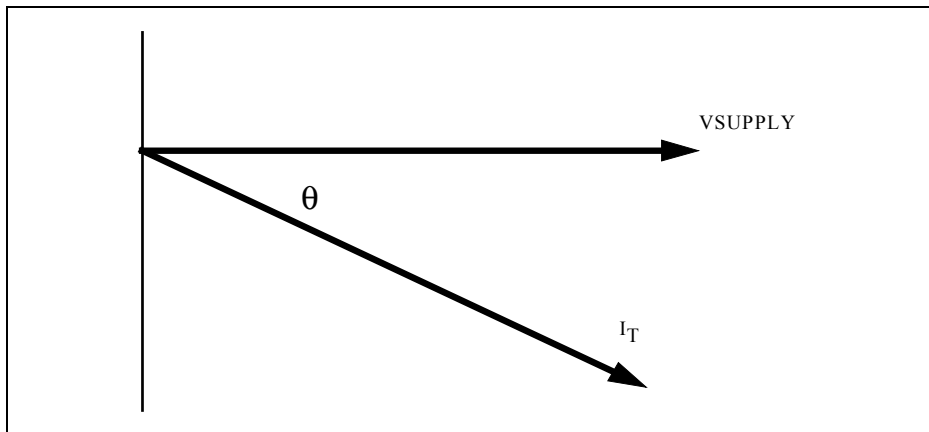
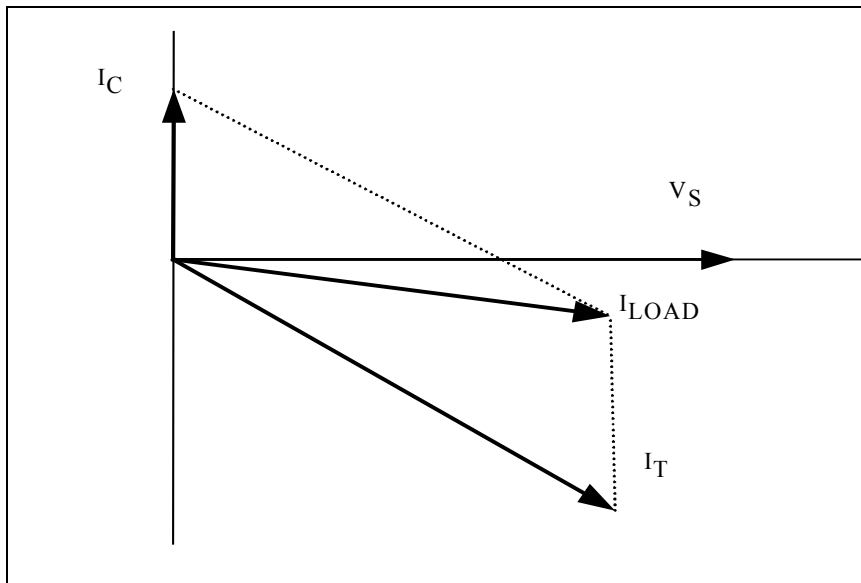


Figure M C-3 shows this relationship again, redrawn with the phase of the supply voltage rotated to 0 degrees.

The objective of Power Factor correction is to modify the equivalent circuit to reduce θ , i.e. to move the phase of the load current closer to the phase of the supply voltage. This is achieved, in the case of an inductive load, by adding a parallel capacitor. Figure M C-4 shows the effect of this. I_T is the motor load current, I_C is the current flowing in the capacitor, leading the phase of the supply voltage by 90° , and I_{LOAD} is the resulting supply current. Clearly, the magnitude of I_{LOAD} is significantly less than I_M , so that the losses in the supply circuit are also significantly reduced.

Figure M C-4 Power Factor Correction



RECs oblige their customers to maintain the overall power factor of the load between 0.92 lagging (i.e. inductive) and 0.99 leading (i.e. capacitive). While metering equipment measures only the in-phase component of the current, the overall demand tariff takes account of the magnitude of the current, so there is good economic sense in providing proper compensation. Most industrial loads, e.g. motors and fluorescent lighting, are lagging, few are naturally leading.

D. Example Calculations

i. Example 1

This example, although hypothetical, could be typical of many industrial drives. The performance data is from actual test figures of an energy saving motor and a standard motor, under identical test conditions. The electricity tariff charges are typical for a fairly large consumer, but will obviously vary with size of consumer and locality.

Motor rating: 30 kW @ 1,470 rev/min. frame D200L 4 pole.
 Actual motor load (average): 3/4 of rated load - 22.5 kW, at motor shaft.
 Motor running period: 2,000 hours/annum (approx 40 hours/week).

Table M D-1 Motor Performance Data

% of full load	Efficiency %				Power Factor			
	100	75	50	25	100	75	50	25
Motor type								
Energy-efficient Motor	93.4	93.9	94.0	91.7	0.882	0.866	0.840	0.693
Standard Motor	90.9	90.8	89.6	84.4	0.876	0.838	0.766	0.584

Table M D-2 Tariff Details:

Energy cost (including fuel adjustment)		£0.0403/kWh
Night unit cost		£0.0187/kWh
Maximum demand charges per month:	March to Oct	zero
	Nov and Feb	£1.90 per kVA
	Dec and Jan	£5.95 per kVA

∴ Maximum demand average charge per month, $\frac{£(1.9 \times 2) + (5.95 \times 2)}{12} = £1.308$ per kVA

Table M D-3 Comparison of Energy costs

	Standard Motor	Energy-efficient Motor
kW input to motor = $\frac{\text{kW output} \times 100}{\% \text{ efficiency}}$	24.78	23.96
Annual direct energy cost = kW input x hours x cost/kWh	£1,997.27	£1,931.18
Annual direct energy saving	-	£66.09
kVA input to motor = $\frac{\text{kW input}}{\text{Power factor}}$	29.57	27.66
Maximum demand charge = kVA input x charge/kVA x 12	£464.13	£434.15
*Annual max demand saving	-	£29.98
Total annual saving	-	£96.07

This is nearly 64% of the extra price of the Energy-efficient motor, and therefore represents a payback period of approximately 1.6 years.

*** Note:** To be strictly accurate, the saving in maximum demand should be adjusted according to the difference in power factor of the increased load, and that of the system. Unless this difference exceeds 10% the error is negligible.

ii. Example 2

This is a larger motor than in Example 1, and operating fully loaded.

Motor rating 185 kW @ 1,475 rev/min, frame D315L 4 pole.

Actual motor load 185 kW at motor shaft.

Motor running period 2,000 hours/annum (approx 40 hours/week).

Table M D-4 Motor Performance Data

Motor type	Efficiency %				Power Factor			
	100	75	50	25	100	75	50	25
Energy-efficient Motor	95.5	95.4	94.6	91.4	0.930	0.905	0.870	0.790
Standard Motor	94.1	93.9	92.9	88.5	0.924	0.906	0.856	0.780

Tariff details - as in Example 1.

Using the same method of calculation as before, the calculated total annual saving is £272. This is about 37% of the extra price of the Energy-efficient motor, and therefore represents a payback period of approximately 2.7 years.

iii. Process Applications

Examples 1 and 2 are both based on 2,000 hours/annum operation, which is typical of applications in single shift industrial plants.

However, process plants often involve continuous 24 hour/day operation for say 48 weeks per annum. To illustrate the effect of this higher level of utilisation on the annual savings and pay back periods, both the above examples have been calculated for 8000 hours/annum operation, the results being as follows:

The direct energy saving is increased, but not in direct proportion to the hours, as approximately 39% of the additional operating hours are on night unit tariff. The maximum demand charge is unaffected by the additional utilisation.

For Example 1: Total annual savings @ 8,000 hours per annum, £294.39

Payback period 7 months.

For Example 2: Total annual savings @ 8,000 hours per annum, £927

Payback period 10 months.

2. Energy-efficient Power Transformers

A. Introduction

The invention of the power transformer just over a hundred years ago made possible the development of the modern constant voltage AC supply system, with power stations often located many miles from centres of electrical load. Before that, in the early days of public electricity supplies, these were DC systems with the source of generation, of necessity, close to the point of loading.

Pioneers of the electricity supply industry were quick to recognise the benefits of a device which could take the high current relatively low voltage output of an electrical generator and transform this to a voltage level which would enable it to be transmitted in a cable of practical dimensions to consumers who might be a mile or more away and could do this with an efficiency which, by the standards of the time, was nothing less than phenomenal.

Modern transformers are, of course, vastly more efficient than those of a century ago. The largest modern generator transformers used in the UK transform a generator output current of up to 19,000 A at 23.5 kV and, by stepping this up to 400 kV, reduce it to a far more manageable 1,200 A or so. This is done with an efficiency of probably better than 99.7%, even so, the losses will be around 2 megawatts.

Of course, the voltage must be reduced again before the power can be used by electrical consumers. Some of the largest items of electrical plant might be operated at 11 kV; quite a few more at 3.3 kV; but the vast majority of consumers operate at 415 V, three-phase, or 240 V, single-phase to neutral.

There are thus many transformer substations involved between generator and consumer, as indicated in the body of the document probably five at least for users operating at 415V. Most of these substations will be part of the public supply network, that is they are owned and operated either by the National Grid Company or by a Regional Electricity Company (REC) and, being part of the electricity supply network, will remain energised twenty four hours per day, possibly 365 days of the year. Some large energy users take their supply at 33 kV or 11 kV, in which case they may well own the means of transforming down to the lowest voltage used. It is possible that some of their substations may be shut down overnight, or when the plant is shut down, but the majority of these are also likely to be energised for most of the time.

Hence, although because of their high-efficiency, transformer losses are small, they exist for most of the time and thus represent a constant drain on the system. Statistics quoted in the body of the document aim to provide some quantification of the waste of resources and the pollution resulting from no-load losses alone. Load losses are at least as great as no-load losses when averaged out over a year, but because by their nature they are very much larger than the average at the time of largest load they put an added burden on the system at the time of peak demand, increasing the required rating of cables and transmission lines and creating the need for least economic generating plant to be operated. These increased losses often bring into operation extra auxiliary cooling plant, further adding to the loading of the system at the time of peak demand.

B. The Nature of Transformer Losses

A power transformer normally consists of a pair of windings, primary and secondary, linked by a magnetic circuit or core. When an alternating voltage is applied to one of these windings, generally by definition the primary, a current will flow which sets up an alternating flux in the core. This alternating flux in linking both windings induces an electro-motive force (emf) in each of them. In the primary winding this is the "back-emf" and, if the transformer were perfect, it would oppose the primary applied voltage to the extent that no current would flow. In reality the current which flows is the transformer magnetising current. In the secondary winding the induced emf is the secondary open-circuit voltage. If a load is connected to the secondary

winding which permits the flow of secondary current, then this current creates a demagnetising flux thus destroying the balance between primary applied voltage and back-emf, so that an increased primary current is drawn from the supply. Equilibrium is once more established when this additional primary current creates ampere-turns balance with those of the secondary. Since there is no difference between the voltage induced in a single turn whether it is part of either the primary or the secondary winding, then the total voltage induced in each of the windings must be proportional to the number of turns. Thus the well known relationship is established that :

$$E_1/E_2 = T_1/T_2$$

and, in view of the need for ampere-turns balance :

$$I_1 T_1 = I_2 T_2$$

where E, I and T are the induced voltages, the currents and number of turns respectively in the windings identified by the appropriate subscripts. Hence, the voltage is transformed in proportion to the number of turns in the respective windings and the currents are in inverse proportion.

C. Core-loss

Mention has already been made, in passing, to the effect that the transformation is not perfect. That is, there must exist a magnetising current in the primary winding which is additional to that current which flows to balance the current in the secondary winding. The magnetising current is required to take the core through the alternating cycles of flux at the rate determined by system frequency. In doing so, energy is absorbed. This is known as the core-loss. The core-loss is present whenever the transformer is energised.

D. Load Loss

The flow of a current in any electrical system also generates loss dependent upon the magnitude of that current. Transformer windings are no exception and these give rise to the load loss of the transformer. Load loss is, of course, present only when the transformer is loaded and its magnitude is proportional to the load squared.

E. Control of Core-loss

The core loss of a transformer arises because the core must be taken through its alternating cycles of magnetisation. The magnitude of this loss must therefore be a function of the ease with which this can take place, which is, in turn, a property of the material from which the core is made. The first material to be recognised as capable of being 'easily' magnetised and demagnetised was soft iron. Accordingly early transformer cores were made from soft wrought-iron wire and that from Sweden was at one time particularly prized because of its high purity. Wire was used rather than solid metal because it was recognised that, in addition to the losses produced in overcoming the reluctance of the magnetic circuit to being taken repeatedly through its cycles of magnetisation,* the alternating fluxes cutting the core induced eddy-currents within it. Constructing the core from a bundle of wires effectively reduced the cross-section of the eddy-current paths and, by increasing the resistance of these paths, reduced the flow of the eddy-currents.

For the early transformer designers it was the reduction of core-loss which was seen as the key area for improvement in efficiency and where the greatest economic gains were to be made. Even a fairly brief review of progress in this area underlines the advances which can be made in

* The term reluctance is not used in its strictly electromagnetic sense here, but it is suitably descriptive. Strictly speaking, it is actually the coercive force required by the magnetic material that the magnetising current must provide, but most practising electrical engineers more than a few years past the end of their academic careers will probably no longer recall this.

a parameter which might have been considered as having little room for improvement. After all, by the 1920s transformer efficiencies of 98% were fairly commonplace.

The first step forward took place in about the year 1900 when it was recognised that the addition of small amounts of silicon or aluminium to the iron greatly reduced the magnetic losses. By this time the iron wire had already been replaced by laminations around 0.35 mm thick which brought the same benefits as regards reduction in eddy-current losses whilst making core fabrication simpler than it had been using wire.

The addition of silicon reduces hysteresis loss, increases permeability and also increases resistivity, thus reducing eddy-current losses. The presence of silicon had the disadvantage that the steel became brittle and hard so that, for reasons of workability and ease of core manufacture, the quantity had to be limited to about 4.5%. There followed a period of more gradual improvement arising from the recognition that the elimination of impurities, including carbon, also had a significant effect in the reduction of losses, so that although the first steels containing silicon had specific loss values of around 7 W/kg at 1.5 T, 50 Hz, similar alloys at the present time having high levels of purity have losses less than 2 W/kg at this condition.

The next major development took place in the USA in the 1940s. Until this time steel for the laminated cores had been produced by a hot rolling process which resulted in random orientation of the grains, or crystals, of magnetic material within the steel. The steel was thus isotropic, that is its properties were similar irrespective of the directions in which they were measured.

In the 1920s it had been recognised that the steel crystals were themselves anisotropic and in 1934 the American N P Goss patented an industrial process which sought to align the grains along the rolling direction, thus combining the most favourable magnetic properties of these grains in that direction. The Goss patent was brought to commercial realisation by the American ARMCO corporation in 1939. They produced the first commercial grain-oriented cold-rolled silicon steel. It had a thickness of 0.32 mm with a loss of 1.5 W/kg at 1.5 T, 50 Hz.

The incentive for the next step improvement in core steels resulted from the rapid increase in energy costs arising from the oil crisis of the 1970s. This was the production of high permeability steels, or ORIENTCORE HiB, to use the trade name adopted by the Japanese Nippon Steel Corporation, who were responsible for its introduction.

The Goss process for the cold reduction of the silicon steel resulted in the majority of the grains being aligned within 6° angular of the rolling direction. The Nippon Steel process involves the use of aluminium nitride in the melt as a grain growth inhibitor at the initial ingot stage together with a simplified but more closely controlled cold-rolling process to give a material having most grains aligned within 3° of the ideal. Its major advantage is its high permeability and higher saturation than the previous material, allowing it to be used at higher flux densities.

As in the case of the previous cold-rolled material, initial introduction was quickly followed by a period of further improvement; the addition of a so-called stress coating which reduces eddy-currents and the production of reduced thicknesses which further reduce eddy-currents in the built-up core.

The final phase in the development up to the present time of what is generally referred to as 'conventional' core steel was the introduction, in about 1985, of domain refined high permeability steel, commonly known as laser-etched steel, although the laser etching process is simply the means of domain refinement adopted by the Nippon Steel Corporation. Other methods of domain refinement are possible and have been used commercially by other manufacturers. Domain refined steels 0.23 mm thick can achieve losses as low as 0.85 W/kg at 1.7 T, 50 Hz.

F. Ultra Low Loss Materials

The term conventional steels is used to define those magnetic materials described thus far, to distinguish them from a type of magnetic material which made its appearance in the early 1970s

and has developed in parallel with conventional steels. This is amorphous metal. Although amorphous metal promises significant savings in loss, there are practical problems associated with its use coupled with high costs which have restricted its adoption to a limited range of transformers in the USA and made its use almost non-existent in the UK.

Amorphous metals have a non-crystalline atomic structure and the constituent atoms are randomly distributed within the bulk of the material. They rely for their structure on a very rapid cooling rate of the molten alloy and the presence of a glass forming element such as boron. Typically they might contain 80% iron and the remainder boron and silicon.

Various production methods exist but the most popular involve spraying a stream of molten metal alloy on to a high-speed rotating copper drum. The molten metal is cooled at a rate of about 10^6 °C per second and solidifies to form a continuous thin ribbon. The quenching technique sets up high internal stresses so these must be reduced by annealing between 200°C and 280°C to develop good magnetic properties. Earliest quantities of the material were only 2 mm wide and about 0.025-0.05 mm thick. By the mid 1990s a number of organisations had been successful in producing strip up to 200 mm wide.

The need for a glass forming element, which happens to be non-magnetic, gives rise to another of the limitations of amorphous steels, that of low saturation flux-density. POWERCORE¹® strip has a saturation level of around 1.56 T. Specific loss at 1.35 T, 50 Hz, is just 0.12 W/kg.

Whilst the sizes of strip available are still unsuitable for the manufacture of large power transformer cores, in the USA in particular many hundreds of thousands of distribution transformer cores with an average rating of around 50 kVA have been built using amorphous material. In Europe use of the material has been on a far more limited scale with the main impetus being in Holland, Sweden, Switzerland, Germany and Hungary. In the UK its use has been almost exclusively by GEC Alsthom who have built just a few hundred distribution transformers.

Another of the practical problems associated with amorphous steel is its poor stacking factor which results from a combination of the very large number of layers of ribbon needed to build up the total required iron section and also the relatively poor flatness associated with this very thin ribbon.

Despite all of the above problems the use of amorphous metal in distribution transformer cores has been proven to be a practical proposition and significant benefits by way of reduction in iron loss have been shown to accrue. In the UK the procurement policies of organisations who seek a return on capital outlay on short timescales may fail to recognise the value of low losses and the benefits to their systems of exploiting modern technology. It is the climate which has allowed this situation to develop in the UK which this document seeks, above all, to address. More will be said about this later.

G. Control of Load Loss

The progress in the reduction in load losses has not been nearly so spectacular as that which has been obtained in the case of no-load loss. There was never any question from the outset that the first electrical machines should have windings of copper. Copper has continued to be used almost exclusively ever since and cannot really be improved upon as a basic conductor material. In the case of transformers one exception is for windings intended to be encapsulated in epoxy resin as used in air-cooled dry-type transformers. This will be discussed further later.

The improvements in copper windings over the years have been mainly in the way in which copper is used, but before discussing these it is necessary to look a little closer at the nature of load losses.

There are three categories of load loss which occur in transformers :

¹POWERCORE is a Registered Trademark of Allied Signal Inc., Metglas Products.

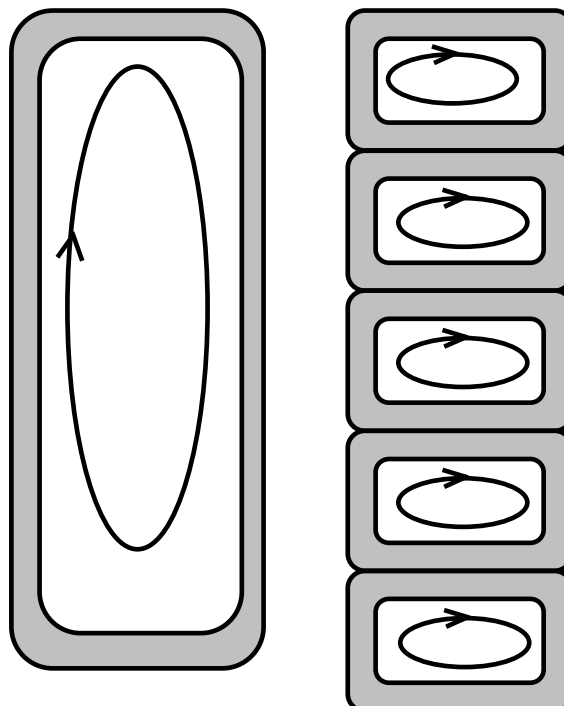
- Resistive losses, often referred to as FR losses.
- Eddy-current losses in the windings due to the alternating leakage-fluxes cutting the windings
- So-called stray losses in leads, core-framework and tank due to the action of load-dependent stray alternating fluxes.

Resistive losses, as the term implies, are due to the fact that the windings cannot be manufactured without electrical resistance (at least, until commercial superconductors are successfully developed) and are therefore a "fact of life" which cannot be eliminated for the transformer designer. There are, however, ways in which they can be reduced, all of which have a cost. The ways normally open to the designer are as follows :

- Use of the lowest resistivity material. This, of course, normally means high-conductivity copper.
- To use as large a cross-section of copper as possible. One of the costs of this route is self evident, that is a larger cross-section involves more copper . Increased copper-section means that the core needs to be larger in order to enclose this, hence, more iron is necessary, a larger tank, more oil and higher material costs on all counts. There is also a third additional cost and this is that eddy-current losses are increased if a larger copper section is used.
- One of the earliest improvements to be made in winding-wire technology was to make the conductors rectangular in section rather than circular. This assists in the accommodation of as large a cross-section as possible within the minimum core window. Circular conductor is now only used in the smallest distribution transformers.
- To use the lowest practicable number of winding turns. This means that a core providing the highest practicable total flux should be used. Largest total flux implies highest practicable flux-density and the largest practicable core cross-section. Again the cost of this option is the resulting increase in transformer size and raw materials.

The designer's method of controlling eddy-current losses is to subdivide the winding conductor into a number of individual strands, see Figure T G-1.

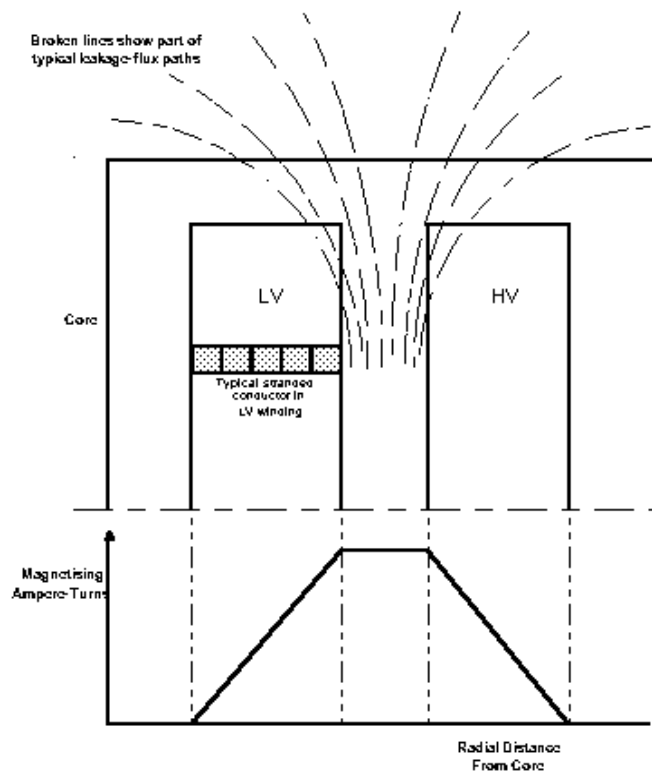
Figure T G-1 Using Stranded Conductors to Reduce the Cross-Section of the Eddy-Current Path



This reduces the copper cross-sectional area in the direction of flow of the eddy-currents and is equivalent to the building up of the core from laminations rather than from solid steel. Note that the space factor of stranded conductors is poorer than solid conductors (although the insulation shown in Figure T G-1 is not to scale). The disadvantage of the use of multistrand conductors is that the strands must be transposed at intervals throughout the winding, otherwise each strand will be cut by a different level of leakage flux, see Figure T G-2, and circulating currents will flow between strands via the point at which they are commoned at the winding ends. If a winding conductor is subdivided into ten strands, ten transpositions will be needed throughout the winding. Transpositions take up space within the winding and also create problems for the transformer manufacturer, since ten transpositions, for example, require that ten large and heavy drums of copper winding-wire must be rearranged on their stillage on ten separate occasions as the winding proceeds.

For many years this problem of winding eddy-current losses placed a limit on the extent to which transformer load-losses could be reduced. The method of reducing I^2R losses is by increasing the cross-section of the winding conductor as indicated above. However there comes a time when to do this becomes uneconomic. Subdividing a conductor into ten strands is fairly straightforward; even using twenty strands may, on occasions, be acceptable, but more than this not only becomes difficult and costly to carry out but is very wasteful of space within the winding and is thus defeating its objective. Hence a limit point is reached.

Figure T G-2 Variation of Leakage-Flux with Radial Position Within Windings



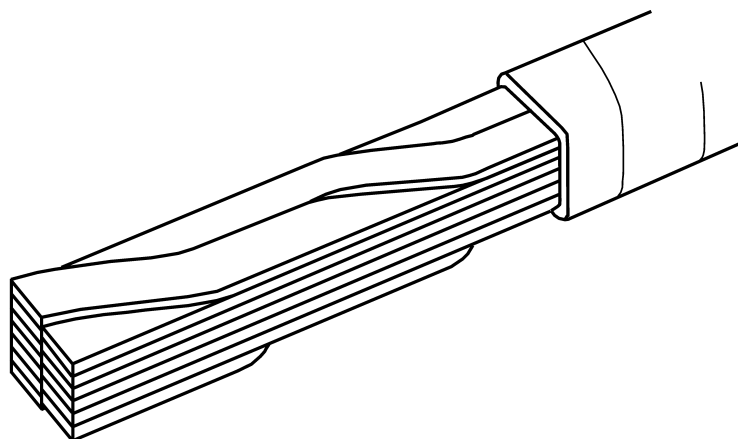
This was the situation until the mid 1960s when continuously transposed conductor (CTC), was introduced. Figure T G-3 shows a short length of CTC. Since the voltage between strands is normally only a few millivolts compared to a voltage between turns which can be a hundred volts or more in a large transformer, interstrand insulation does not need to be as substantial as that between turns. Thus CTC consists of a large number of enamel insulated strands arranged in two stacks side by side. At intervals of about 50 mm along the length of the conductor the top strand of one stack is moved sideways to the top of the adjacent stack and at the same time the lowest strand from the other stack is moved across in the opposite direction. Thus the strands are continuously rotated, or transposed. CTC makes possible a very great increase in the

number of strands. Cables containing up to eighty plus strands are available and if this is not enough then it is possible to manufacture a winding with two or more CTC cables in parallel. Of course, individual cables must then be transposed during the winding process.

Although CTC is not suitable for use on distribution transformers and the smaller system transformers, most larger transformers can benefit by way of reduced losses by its use for low-voltage windings and, for the largest transformers, it can be beneficial in both high-voltage and low-voltage windings.

The leakage-flux occurring in transformer windings is greatest at the winding ends. Particularly in larger transformers this can result in a greater eddy-current problem in this area. The impact of the problem can be reduced by the use of flux shunts adjacent the winding ends which help to ensure that the flux remains at a fairly constant level throughout the length of the winding. Such measures lead to increased costs, of course, and can only be justified on large transformers.

Figure T G-3 Continuously Transposed Conductor



The introduction of CTC represented the most significant advance in transformer design as far as reduction in load losses is concerned. Prior to its introduction eddy-currents in some high-current, high impedance designs could often approach 30% of the I^2R loss and beyond this no further reduction in losses was practicable. Since its use, coupled with the use of flux shunts to control the distribution of leakage flux, eddy-current losses can now usually be contained within 10-15% of the I^2R loss.

Stray losses also present more of a problem on large transformers, because the physical size of the leads and the currents they carry are greater. Stray losses can also be controlled by the use of flux shunts or by shields. Careful consideration of the routing of leads can be another means of reducing the magnitude of stray losses. Whereas twenty years ago stray losses were often determined empirically and, when an unproven configuration might become necessary, uncertainty was allowed for by means of increasing tolerances, designers now have calculation techniques, such as finite-element analysis, which lend themselves to computer calculation.

These computer programmes are not only able to more accurately estimate stray-losses but also to assist with design of lead arrangements and shield configurations which minimise these losses.

H. Aluminium Versus Copper

Copper has been the preferred choice of conductor material for transformer designers from the outset. However, aluminium is quite a good conductor of electricity and is cheaper than copper, so the question arises as to why it should not be a viable alternative.

There are certainly instances of relatively large power transformers having been built with aluminium windings. Ratings as large as 60 MVA are on record. A number were made by German manufacturers in wartime when copper was not available to them and in the UK in the 1960s, when copper prices took a sharp upward turn, a few units were built, mainly as an experience gathering exercise at the request of aluminium producers.

The main disadvantage of aluminium compared to copper is that its resistivity is greater and for the same length and resistance, its cross-section must be 1.65 times that of copper. This in itself would result in the need for a very much larger core window to accommodate the increased cross-section, however the increased cross-section means that coil diameters are increased, the length of mean turn increases, which in consequence increases the winding resistance so that the cross-section must be increased still further and so the process continues. An increase in the size of core and windings results in increased tank size and a larger oil quantity with the result that any savings in the cost of the winding conductors is soon more than offset by increased costs in every other item.

Another serious disadvantage of aluminium, particularly for larger transformers is its poorer mechanical strength. Short-circuits, or even severe overloads, on transformers impose large mechanical forces on the windings; axial compressive forces within the windings, axial displacement forces if there is any magnetic imbalance between the windings - which is usually unavoidable, and mutual repulsion between them, which means that the inner winding experiences an inward crushing force and the outer winding an outward bursting force. All of these forces must be resisted by the strength of the winding conductor itself, a duty for which none of the alloys of aluminium can compare with work-hardened silver-bearing copper.

The one type of transformer for which aluminium has become the standard material is the cast-resin encapsulated dry-type which is often used within buildings where fire resistance is an important requirement. This type has increased in popularity world-wide, particularly with the demise of PCB (polychlorinated biphenyl) filled transformers which were once preferred for fire resistance. The coefficient of thermal expansion of aluminium matches that of epoxy resin more closely than does that of copper. Hence, there is less of a tendency to set up internal stresses under load which could lead to minute cracks within the resin and, consequently, damaging high partial-discharges.

Dry-type transformers are worthy of special consideration from an energy efficiency point of view and this aspect will be discussed more fully below.

I. Optimisation of Losses

For all of the reasons identified above, any transformer made today should be capable of having losses significantly less than one produced even ten years ago. However, it will always be the case that those designed to have the lowest losses cost a little more and, conversely, in a competitive situation higher losses must always have the attraction to the manufacturer that they enable costs to be kept down. Few manufacturers, though, would aim to ignore losses entirely. Certainly none would today offer a transformer having a core built of hot-rolled steel. (It would probably not work out cheaper, anyway). In fact, most manufacturers do not even use the older types of cold-rolled steel.

Nevertheless, there does not appear to have been the demand in the UK for a level of losses that the present state-of-the-art would permit, nor does the UK appear to be as keen as some overseas countries to make energy savings. The example has already been mentioned that despite the relatively high cost of amorphous steel, its adoption in the USA has resulted in around 500,000 amorphous steel cored distribution transformers having entered service, compared to the few hundred in the UK. This despite the suggestion in some quarters that the American utilities have a poor record of investment.

It is clear that one of the reasons is the way in which prospective users perform their economic assessments. It has been standard practice in the electricity supply industry for many years, for utilities to compare the extra cost of a higher efficiency transformer with the value of the energy savings which will result, by "capitalising" losses and relating the initial capital cost to the lifetime cost of these losses. The process is explained further in an example which appears later.

Typically, a particular utility may apply loss capitalisation values of £3,000/kW for no-load loss and £625/kW for load losses. This means that a lifetime cost of one kilowatt of no-load loss is considered to be £3,000, or alternatively, it is worth reducing the no-load loss by one kilowatt if this can be achieved for £3,000 or less. Likewise if the load loss can be reduced by one kilowatt for less than £625, then this also would be worthwhile. This will become clearer from the example.

An important factor in arriving at loss capitalisation values is the value of "Test Discount Rate" used. This is a means of weighting the evaluation process so that a measurable benefit will accrue from the expenditure of extra capital at the outset. For many years a test discount rate of 5% was common. At times when money is "tight" and there is a greater need to justify any proposed extra capital investment, then higher levels of test discount rate can be applied. For example, in the UK in the 1980s, when the government sought to apply cash limits to the then publicly owned utilities, a test discount rate of 10% was introduced.

J. Industrial Users

Most transformers, even at the smaller sizes, are designed and made for a particular customer's requirements. Distribution transformer manufacturers will aim to maintain a number of fairly standardised designs which might be produced in a small number of variants to meet different customers' requirements and these manufacturers will aim to use as many standardised components or sub-assemblies as possible, but the concept of large production runs of totally standard units as is the case for motors or switchgear, for example, does not really apply to transformers. (An exception is in the case of cast-resin transformers where the restrictions arising from the limited number of available moulds does introduce some constraints in the number of variants which can be produced.)

The previous section has mentioned how a utility when procuring transformers can aim to ensure it buys transformers which are the most economic for its circumstances and, hopefully, as energy-efficient as possible. Many industrial organisations, however, do not recognise the options which are available to them nor do they consider the case for energy efficiency. If transformer losses are considered at all it is often in the context that transformers have a high-efficiency and such losses as they do have are likely to be negligible.

When an industrial user issues an enquiry for transformers this rarely gives the potential suppliers an indication of any loss capitalisation values. In this situation tenderers will usually aim for lowest first-cost in the interest of being competitive or, alternatively, they may offer an existing design which has been produced to suit another customer's requirements (usually an REC) which may put a completely different emphasis on the value of energy.

It should be clear from the explanations above that transformer losses can be made as low as the user wishes them to be and also that no-load loss can be traded for load loss by the transformer designer and vice-versa. A transformer manufacturer can therefore tailor the design offered to

suit the requirements of the purchaser, provided the purchaser makes these requirements known, either by advising capitalisation values which he will use in performing the tender assessment or by simply stating in the enquiry something like "this transformer is required to supply a plant which will have a high load-factor so that great emphasis should be placed on obtaining low losses." Of course it will still be necessary for the intending purchaser to have some indication of the value to him of energy saved, in order that he can make a comparison of alternative tenders.

The important factor for the industrial user to recognise however, is that he can make the decision to opt for energy-efficient transformers and it is not necessary to let the transformer manufacturer make this decision for him. The quantitative effects of capitalising losses for various financial constraints are clearly shown in the following example of the application of the processes to an industrial user.

K. Typical Cost of Losses to Industry

Consider a typical small factory which has two 11/0.415 kV transformers. The factory operates for 50 weeks of the year and during this time the plant is running 10 hours per day, weekdays only. The transformers are energised 24 hours per day to provide power for lighting but their only significant load is whilst the plant is running.

It is often the case that such a factory will be considering the purchase of an additional transformer at the time of extending the electrical system. Perhaps it is planned to supplement two existing transformers because the factory load has grown to considerably more than could be handled with one of these out of service. The purchase might have been initiated by the installation of new plant which will mean that on completion the new installation will have three transformers normally carrying the equivalent of full-load for two, i.e. each transformer will normally carry two-thirds full-load.

The factory operates on a Seasonal Time of Day Tariff, supplied from the local REC.

The cost per year (of 351 days) for one kilowatt of iron loss (no load loss) is typically thus :

Supply capacity charge, say		£	18
Maximum demand charge - winter PM, say			40
Night units- 23.30 to 06.30, 7 hrs daily at, say, 2.5p/h	$7 \times 351 = 2,457$		61
Weekend units - 06.30 - 23.30, 17 hrs/day for 49 weekends at, say, 4.5p/h	$17 \times 98 = 1,666$		75
Evenings Mon to Fri - 20.00 to 23.30, 3.5 hrs/day at, say, 4.5p/h	$3.5 \times 253 = 885$		40
Days Nov to Feb - 06.30 to 20.00, 13.5 hrs/day at, say, 6.5p/h	$13.5 \times 86 = 1,161$		75
Days rest of year - 06.30 to 20.00, 13.5 hrs/day at, say 5p/h	$13.5 \times 167 = 2,255$		113
Total, per year		£	<u>422</u>

Over a 25 year lifetime this would amount to an enormous £10,550 per kilowatt

The cost of one kilowatt of copper loss (load loss) can be calculated in a similar manner:

Supply capacity charge (transformer at 66 % load)	0.436 x £18	£ 7.85
Maximum demand charge	0.436 x £40	17.44
Days Nov to Feb, 10 hours per day during period 06.30 to 20.00	0.436 x 10 x 86 = 375 units at 6.5p	24.37
Days rest of year, 10 hours per day, same time of day	0.436 x 10 x 167 = 728 units at 5p	36.40
Total, per year		<u>£ 86.06</u>

or approximately £2,152 per kilowatt over a 25 year lifetime of the transformer.

Most accountants would not accept the above method of assessing lifetime cost, probably rightly so when a life of 25 years is expected, since costs incurred a long time ahead can be expected to have been eroded by inflation, or, alternatively to meet a commitment some years ahead cash can be set aside now which will accrue interest by the time the payment is due. The alternative viewpoint is that these losses will continue to have the same magnitude and the cost of electricity will have increased in line with inflation.

Generally the accountant's view prevails so that the cost of making provision for the lifetime cost of losses is expressed in terms of the sum which must be set aside now to pay for these. This can be calculated from the following expression:

$$C = \{ a (1 + b)^n + b - a \} / \{ (1 + b)^n - 1 \}$$

Where

C is the cost per £ annual cost of losses

a is the rate of interest payable for loans at the date of purchase (expressed on a per unit basis)

b is the rate of interest obtainable on sinking funds (expressed on a per unit basis)

n estimated lifetime of transformer in years

Typically 'a' might be taken as 9% for a large organisation seeking a long term loan and 'b' as 7%. For a value of 'n' equal to 25 years 'C' is then 0.1058

Hence the capitalised value of no-load loss is $422 / 0.1058 = £3,988/\text{kW}$.

and the capitalised value of load loss is $86.06 / 0.1058 = £813/\text{kW}$.

It is clear from the above that the industrial user would benefit from procuring a lower loss transformer than one designed for a REC which capitalised no-load and load losses at £3,000/kW and £650/kW respectively.

L. Test Discount Rate

In the above example the lifetime cost of losses has been converted to an equivalent capital sum per kilowatt which will meet the lifetime costs. The purchaser may therefore either spend up to that additional sum at the outset for each kilowatt reduction in losses or alternatively set it aside to pay for the losses during the transformer lifetime. Both alternatives have the same weighting and there is therefore no constraint on the spending of extra capital initially, provided it will produce at least an equivalent saving in losses. The concept of test discount rates (TDR) was applied to publicly owned utilities some years ago to control capital spending so as to ensure that extra expenditure was only incurred if it could produce real returns. The TDR applied by utilities has varied between 5 and 10% over the years since its inception. A 5% TDR requires that any additional capital spent over and above that necessary for the basic scheme should show a return of 5%.

Applied to a capitalising rate of C per £ as derived in the expression above, a TDR of r% has the effect of multiplying the cost of losses by a factor k, where

$$k = C / (C + r/100)$$

The effect of a 5% TDR on the capitalised cost of losses in the above example is thus

$$k = 0.1058 / (0.1058 + 0.05)$$

Hence $k = 0.679$

Cost of no-load loss thus becomes £2,707/kW and cost of load loss £553/kW and it is now the case that less initial expenditure will be allowed for improved energy efficiency. Use of a TDR greater than 5% reduces k and hence reduces the value placed on energy efficiency still further.

The above illustration demonstrates how an apparently straightforward cost comparison process can be influenced to reflect basic policy decisions. Thus, if a purchaser wishes to sway his assessment towards low first-cost, he can do so and conversely, if he wishes to invest in energy-efficient plant he can ensure that his procedures make this more likely. There are, of course, other factors used in the assessment process. These include load factor, future load growth profile, expected transformer life, and expected long-term trends in interest rates. Although the values assumed for all of these do not have such a marked effect on the derived loss capitalisation values as does test discount rate, they do nonetheless have an effect and it is therefore possible to influence the outcome of the capitalisation process. It can often be the case that the judgements necessary to arrive at these assumptions are more subjective than is that concerning the availability of investment capital and it is therefore important to know how they will effect on the outcome and to have a policy within the organisation which will ensure that the correct emphasis is obtained.

M. Dry-type Transformers

Dry-type transformers are intrinsically less energy-efficient than oil-filled types and they are more costly in the first instance. Because air is not as good or as reliable a dielectric as oil, even with resin encapsulated windings, it is necessary to allow greater electrical clearances. Air is not so good a cooling medium as oil either and all of these factors result in the transformer being larger than an oil-filled unit of the same rating. As explained above, the use of aluminium foil windings is also a factor contributing to this increase in size. Increased size inevitably means increased cost, which is the reason why a premium must be paid for a dry-type transformer.*

However, given that the user has very good reasons for paying the necessary premium for a dry-type transformer that does not prevent him from opting for an energy-efficient dry-type. Because the manufacture of cast resin windings requires costly capital equipment; not only moulds but foil-winding machinery, resin mixing and holding plant, resin curing ovens; there are only a few manufacturers of these windings and these people tend to produce them in large quantities. Many transformer manufacturers apparently offering cast-resin transformers in the UK do not, in fact, manufacture the cast-resin windings themselves. As a result there is a tendency for manufacturers to list standard ratings and losses. This can restrict the choice of losses available to a purchaser.

It is beyond the scope of this document to provide a treatise on the varieties of dry-type transformers which are available and of their various merits and demerits, but the prospective user must not automatically assume that the losses as listed in a price list are the only options available, nor should he assume that cast-resin is the only insulation system available. It is still

* There are, of course, alternative dry-types besides those having cast-resin insulation, some of which can have basically "conventional" copper windings. Whilst all of the different systems have their merits, cast-resin is probably the most popular at the present time and all suffer from the basic disadvantage of using air as a dielectric making them larger and more expensive than oil-filled transformers.

essential to calculate the cost of transformer losses throughout the transformer lifetime and it is also important to recognise that usually the reason for preferring dry-type is because the transformer will be in a building, in which case there is a need to dissipate the losses, probably at the expense of extra ventilation equipment all of which needs to be entered into the equation.

3. Economic Selection of Cables for Industry

A. Introduction

The function of a power cable is to distribute electric power as efficiently as possible from a source to a point of utilisation. Unfortunately, due to their electrical resistance, cables dissipate in the form of heat some of the power carried, so that 100% efficiency is not achieved. An idea of the extent of this heat loss can be obtained from the comparison that modern cables are capable of operating at temperatures as high as those of central heating systems.

The energy lost by using cables at such temperatures has to be paid for and becomes a surcharge on the cost of operating whatever equipment is being supplied. This surcharge continues for the life of the process involved and into the future for any subsequent use of that circuit²⁷.

The cost of energy is an important component of industrial and commercial running costs and every effort should be made to contain it as much as possible. The environmental and conservational aspects of wasted energy are important factors, even though they may be partly subjective, and it is evident that pressures from this direction will increase.

It may be observed that heat losses from a cable go hand in hand with a lower voltage at its delivery end. This may impair the efficient operation of the supplied process, thus further degrading the cost efficiency of production.

It therefore makes good sense to adopt distribution designs which go as far as is practicable to reduce energy losses²⁸.

In theory it would be possible to reduce the lost power to a negligible amount by increasing the size of the cable; however, as this also increases the cost of the cable it tends to cancel the savings from better distribution efficiency and a compromise has to be struck.

The best time to incorporate high-efficiency distribution is at the design stage when additional costs are marginal. It can prove to be difficult to reinforce a circuit at a later date.

The problem is to identify a conductor size which reduces the cost of the wasted power without incurring excessive cable costs. The basic approach to this problem was formulated by Lord Kelvin in 1881²⁹ and has been applied to numerous situations where cost (or weight) and efficiency need to be taken together to obtain an optimum solution.

B. Summary

The overall cost of supplying electric power to equipment or a process can be significantly reduced by giving consideration to the impact of conductor size on cost.

In meeting growing demands for preservation of the environment and for conservation, attention to the reduction of energy losses can prove to be a valuable investment over the entire economic life of the project.

Easily applied procedures are developed whereby selection of conductor sizes can be optimised for minimum overall project cost. These procedures are completely compatible with the requirements of the IEE Wiring Regulations (BS 7671). Each procedure and theoretical step is illustrated with step by step practical examples. Extensive appendices provide background explanations and data together with references to the relevant requirements and guidance in the IEE Regulations.

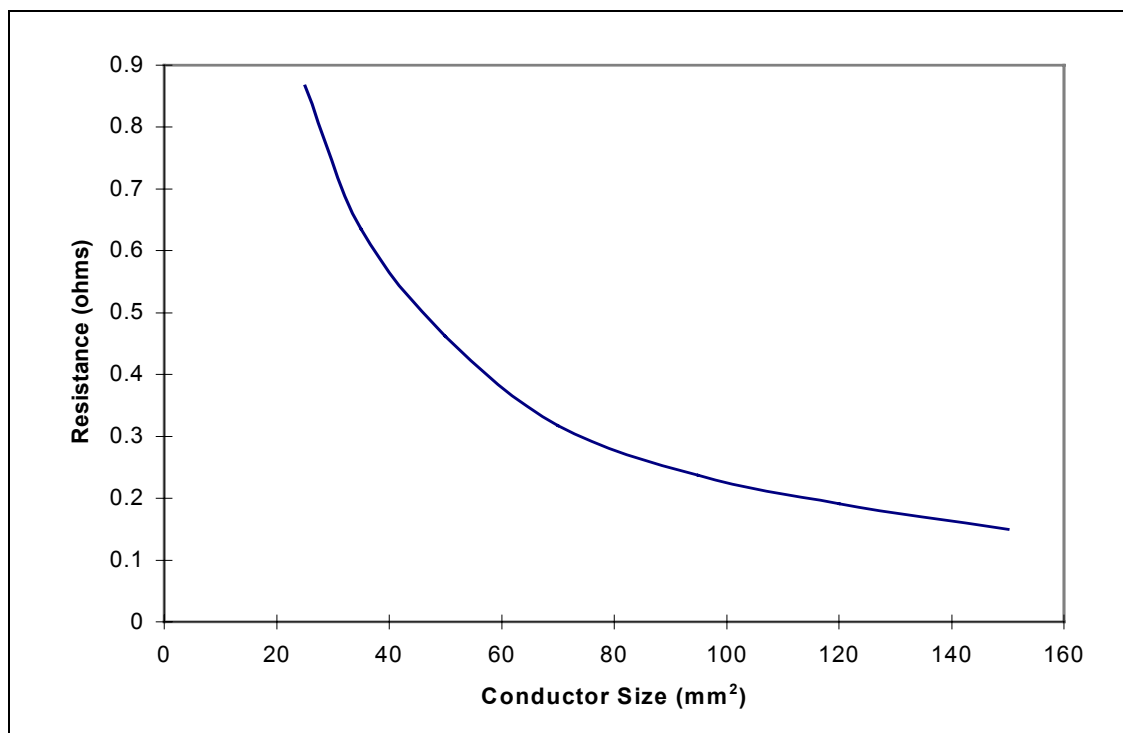
C. Selection of Conductor Size

i. Conductor Resistance and Energy Losses

All conductors exhibit a resistance to the flow of electric current and, although copper conductors have lower resistances than those of most other materials, there is a tendency to take advantage of this by using as small a conductor as possible; the limit being set by the maximum temperature acceptable to the supporting insulation. The value of electric current at this limit is called the thermal rating of a cable.

Figure CB C-1 shows the reduction in conductor resistance as the size of a cable is increased. Cables are manufactured in standard cross-sectional areas, as listed in Table 4-1 on page 35. The data for this graph can be found in Table CB K-2 on Page 93.

Figure CB C-1 Resistance per 1000m length against Conductor Cross-Section



The power lost, or rate of heat loss, per metre due to the resistance of the conductors is given by the equation

$$W = I^2 R \text{ Watt/metre} \quad (1)$$

where

I = electric current, amp.

R = conductor resistance, ohm.

If for an example we consider a pottery kiln which is rated at 70 kW and runs on a 400 V, 3 phase supply, the current would be 101 amp, see 'Relationship between Power of Equipment and Current to be carried by Cables' on Page 87. This load could be supplied by a 25 mm² 3 conductor cable for which the conductor resistance at working temperature is 0.866 milliohm/metre (i.e.

8.66×10^{-4} ohm/metre), see 'Cable Selection and the IEE Wiring Regulations' starting on Page 94.

The power loss is $101^2 \times 8.66 \times 10^{-4} = 8.83$ Watt/metre/conductor

If there are N_p conductors carrying current and the cable is L metre long, the total power loss (converted to kilowatts) along the cable is

$$\frac{I^2 R N_p L}{1000} \text{ kilowatt} \quad (2)$$

In our example the cable has 3 conductors and is 100 metres long from the supplier's meter to the kiln. The total power loss along the cable is

$$\frac{8.83 \times 3 \times 100}{1000} = 2.65 \text{ kilowatts}$$

Electrical energy is usually measured in kilowatt-hours or "units", so that if losses occur for T hours per month, the electrical units of energy lost amount to

$$\frac{I^2 R N_p L T}{1000} \text{ units or kilowatt-hours per month} \quad (3)$$

The loading, firing and unloading schedule of the kiln is such that it is switched on for a total of 400 hours per month. The energy lost in the cable amounts to

$$2.65 \times 400 = 1,060 \text{ units of electrical energy per month.}$$

The electricity supplier will charge for this energy at a rate of P pence per unit, so that the cost of the energy losses is

$$C_j = \frac{I^2 R N_p L T}{1000} \times \frac{P}{100} \text{ £ per month} \quad (4)$$

If the price per unit is 5 pence, the cost of wasted energy is

$$1060 \times \frac{5}{100} = \text{£}53 \text{ per month}$$

Most suppliers charge not only for the energy delivered, i.e. fuel consumed by their power stations, but also add what is called a demand charge because their plant has to be that much larger to supply the power. If the price per kilowatt is £ D per month, the demand charge for the power (see equation 2) taken by the cable is

$$C_d = \frac{I^2 R N_p L D}{1000} \text{ £ per month} \quad (5)$$

The demand price in this example is £3 per kW per month so that the additional charge for 2.65 kW is

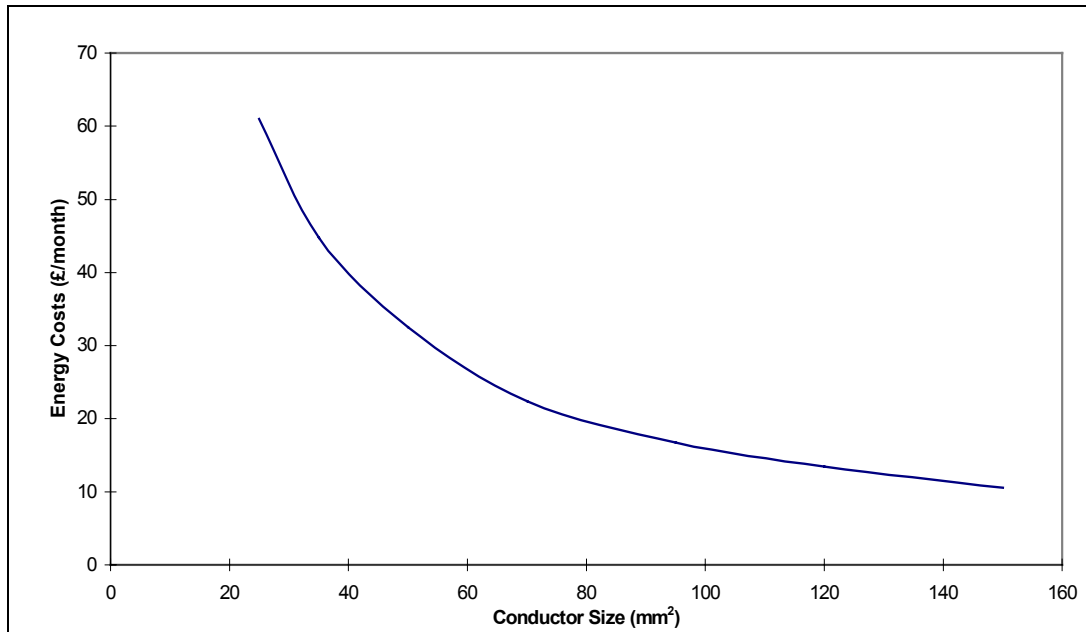
$$2.65 \times 3 = \text{£}7.95 \text{ per month}$$

The total cost of the losses incurred by distributing electric power from the supply intake to the kiln is

$$C_j + C_d = \text{£}53 + \text{£}7.95 = \text{£}60.95 \text{ per month}$$

An increase in conductor size with its accompanying reduction in conductor resistance will affect this cost. When these calculations are repeated for larger sizes of the same type of cable the reduction in energy costs with cable size can be displayed as in Figure CB C-2.

Figure CB C-2 Cost of Energy Loss per Month



The data for this graph can be found in Table CB K-3.

ii. Cost of a Cable Installation

Although the losses can be reduced considerably by using a larger cable, the cost of the installation rises and the reduced electricity charges have to be offset against a greater capital outlay to start with.

The cost of setting up an electric circuit comprises the cost of purchasing the cable and its terminations together with the cost of fixing it in place. There are also costs for the switch and control gear, but the cost of such equipment is determined by the maximum load (which is fixed) and not, primarily, by the cable size so that they can be ignored for present purposes.

If $£ P_c =$ the price per metre of the installed cable, and
 $£ P_t =$ the price for each finished termination,

the first cost (which includes labour and overhead costs)

$$C_i = L \times P_c + 2 \times P_t \quad \text{£} \quad (6)$$

For the 3-core 25 mm² cable used in the example,

$$P_c = \text{£}13.6 \text{ per metre and } P_t = \text{£} 18.5.$$

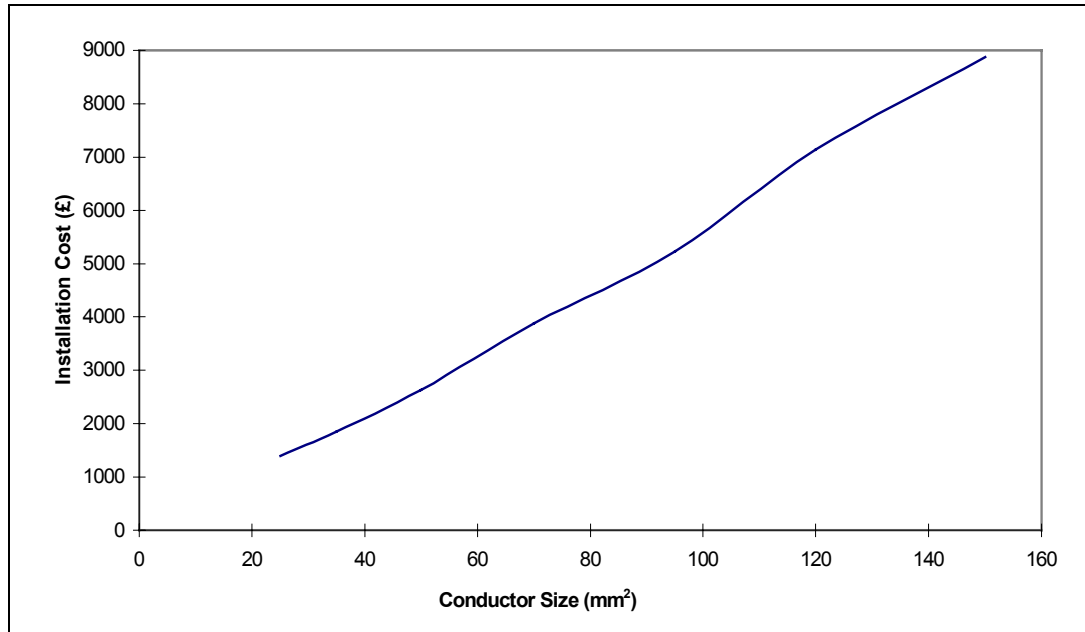
$$C_i = 13.6 \times 100 + 2 \times 18.5 = \text{£} 1,397$$

The installation cost for the range of sizes used in Figure CB C-2 is given in Figure CB C-3.

iii. The Combined Cost of a Cable Installation and of the Waste Energy

Figure CB C-2 and Figure CB C-3 together illustrate how changes in cable size affect the cost of supplying electrical energy to a production process. It is now necessary to add these two costs together in order to obtain a complete picture and then to see how this picture changes with different types of load and financial conditions.

Figure CB C-3 Installation Cost with Size



The data for this graph can be found in Table CB K-2 on page 93.

The problem here is that, while the cost of the cable installation occurs at one point in time (notionally at the start of the project), the costs for the wasted energy arise monthly throughout the life of the project and may well change during that time.

If the life of the project is expected to be N years, there will be a total of $12 \times N$ monthly payments of $\pounds(C_j + C_d)$. If this total is simply added to the installation cost C_i we obtain a figure which is equivalent to setting aside the amount $\pounds 12N(C_j + C_d)$ for future payments at the same time as C_i is paid. It is clear that this is not the most economical way of effecting payment for the energy losses because the money set aside could be invested for periods of up to N years and earn interest while it is waiting to be used.

Furthermore, smaller amounts could be invested at the start of the project sufficient to pay the costs of the losses later on. These smaller amounts are known as the "Present Value" (PV) of each future payment and the process of calculating each PV is known as "discounting" and is the inverse of compound interest³⁰. A formula whereby the total PV of any number of future payments can be calculated is developed in 'The Present Value of Future Sums of Money' starting on Page 88.

The formula takes into account changes in future payments caused by increases in load and cost of energy.

Let

N = the life of the project in years

i = discounting rate, % per year

a = average increase in load, % per year

b = average increase in price of energy over N years, % per year*

r_a = auxiliary quantity based on annual payments

r_m = auxiliary quantity based on monthly payments

PV = present value of $12N$ monthly payments

* increases due to inflation are not included because they affect all values approximately equally and are assumed to cancel out.

$$r_a = \frac{\left(1 + \frac{a}{100}\right)^2 \times \left(1 + \frac{b}{100}\right)}{1 + \frac{i}{100}} \quad (7)$$

$$r_m = (r_a)^{1/12} \quad (8)$$

Q is a factor which combines discounting with the effect of increases in load and energy cost

$$Q = r_m \times \frac{(1 - r_a^N)}{1 - r_m} \quad (9)$$

$$PV = Q \times (\text{first month's electricity payment}), \text{ £} \quad (10)$$

$$= Q \times (C_j + C_d) \quad \text{£} \quad (11)$$

PV is a value which can be added to the cost of installation, C_i , to obtain the total cost in terms of values as they were at the start of the project, i.e. all costs are now on the same financial basis.

For our example the project is planned to last for 30 years before the market changes or the plant is replaced, $N=30$.

The discount rate $i = 5\%$ per year

There is no increase in load for this cable, increase in productivity is to be met by the introduction of a second kiln at some future date, $a = 0$.

The cost of electricity is expected to increase by an average of 3% per year during the life of the project, $b = 3$.

From equations (7) and (8)

$$r_a = \frac{\left(1 + \frac{0}{100}\right)^2 \times \left(1 + \frac{3}{100}\right)}{\left(1 + \frac{5}{100}\right)} = 0.98095$$

$$r_m = 0.98095^{1/12} = 0.9984$$

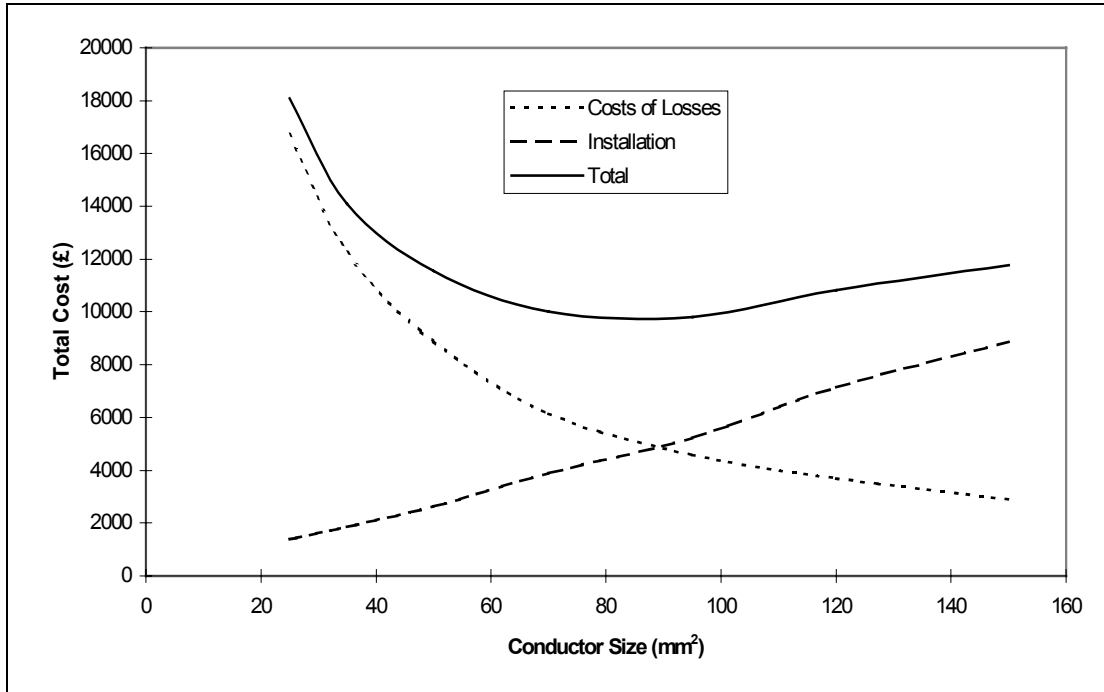
So that Q, the discounting factor is

$$\begin{aligned} &= 0.9984 \times \frac{(1 - 0.98095^{30})}{(1 - 0.9984)} \\ &= 0.9984 \times \frac{0.4384}{0.0016} = 274 \end{aligned}$$

The PV for the costs of electricity supplied during the life of the project because of the losses is given by

$$PV = 274 \times (53 + 7.95) = \text{£ } 16,700$$

Figure CB C-4 Total Cost and Conductor Sizes



Data for this graph can be found in Tables CB K-2, K-3 and K-4 on pages 93 and 94.

The total cost of supplying energy to the process at the far end of the circuit, but not including the cost of the energy consumed by the process, is given by

$$\text{Total cost} = PV + C_i \quad \text{£} \quad (12)$$

In the example, using the 25 mm² size of cable, the total cost in terms of values at the start of the project is

$$\text{£ } 16,700 + \text{£ } 1,397 = \text{£ } 18,097$$

We can now repeat the above calculation using the costs for other, larger, sizes of cable and add the results to the installation costs shown in Figure CB C-3.

When these totals are plotted in Figure CB C-4 the curve shows that as the cable size increases there is initially a rapid reduction in total cost, followed by a minimum.

The general shape of the curve is typical of the results to be obtained for all types of cable, although in some cases there may not be such a well defined minimum or the minimum may be outside of the range of cable sizes considered.

Comments on the conclusions to be drawn from Figure CB C-4 and how it is affected by changes in load and costs are made in the next Section.

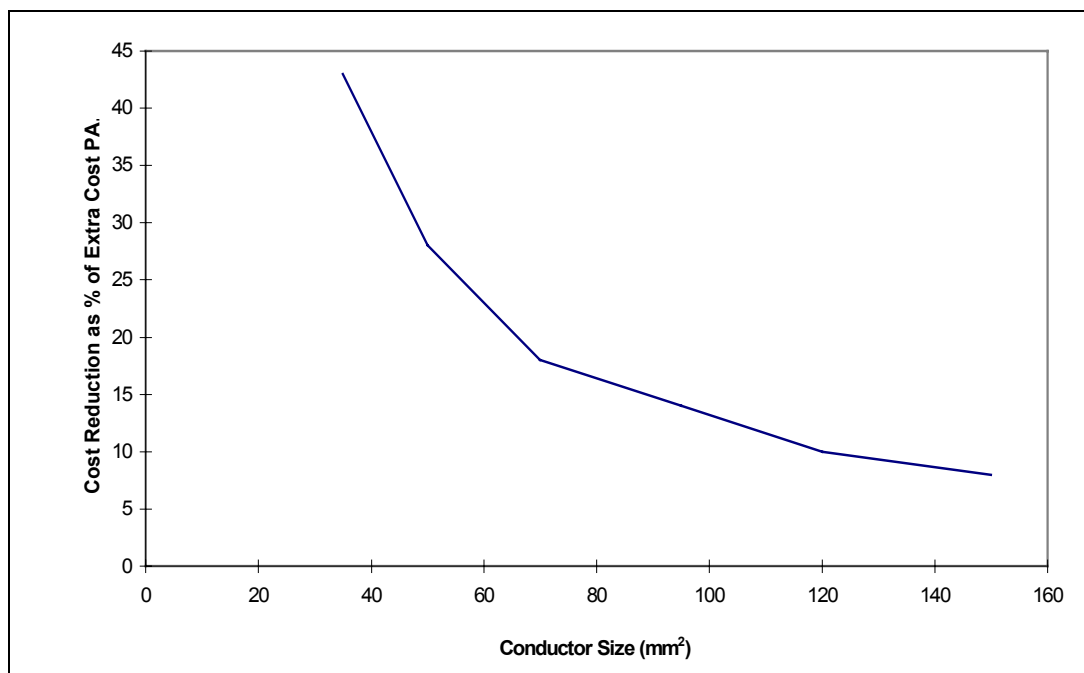
iv. Significance of Saving Waste Energy

The immediate impression from a cost/size characteristic such as Figure CB C-4 is the large reduction in overall costs to the project usually achieved by the first few increases in conductor size. However, it is possible to show that the relatively smaller savings which accompany further size increases can be a worthwhile investment.

Figure CB C-5 shows the reduction in wasted energy costs obtained each year expressed as a percentage of the additional installation costs as the conductor size is increased. In other words the reduction in the energy bill, obtained for every year during the project life, can be likened to

annual interest on the additional investment in installation cost. Figure CB C-5 can be obtained from the data in Table CB K-4 on Page 94.

Figure CB C-5 Annual Reduction in Energy Bill as a Percentage of Extra Cost



The percentage return on the first size increase is, as would be expected from the initial sharp reduction in wasted energy costs, high; but even the percentage return on the extra cost for six size increases is substantial and is tax free.

Looked at in this way there is a definite financial incentive to design many electrical circuits for higher energy efficiency and to reap the benefits in lower electricity bills.

D. Implications of Characteristic Curves

i. General Shape of Cost-Size Characteristic

The shape of the total cost-size curve in Figure CB C-4 is characteristic of curves portraying the combined costs of energy losses and installation. For 400/230 V distribution systems there is usually a sharp and substantial reduction in total cost as conductor size is increased above the minimum required to remain within the maximum working temperature. Further cost reduction, often quite significant, occurs as the size is increased still more. If size increase continues the curve usually flattens out and passes through a minimum.

The extent of the reduction in cost and the existence of a minimum depend on several factors including the cable and installation type and cost, the circuit utilisation (number of hours/month running at the design load), energy costs and project life-time. The effect of some of these factors will be demonstrated in a later section.

In theory the minimum cost size, if it occurs within the manufactured range of sizes, would be the most economical choice. However, there are a number of practical factors which usually impinge on the choice of conductor size.

There may be physical limitations on conductor size increase which have to be borne in mind. Increases of a few conductor sizes above the minimum thermal size are usually feasible*.

* This may not be the case for domestic type equipment, especially where the circuit calls for more than one conductor to be accommodated in a tunnel type terminal and space around the terminal is severely limited. However, economic sizing for this type of circuit is not likely to be worth-while.

Equipment terminals and clearances around them are usually designed to accommodate conductor sizes which are increased to meet requirements such as voltage drop, high ambient temperature and group reduction factors. The order of increase for these reasons can be, at most, in the region of 4 or more sizes, all though not all equipment is certain to provide for such a range.

Subject to confirmation in some cases, there should be no difficulty in accommodating the size increases envisaged for economic reasons.

E. Compatibility with the IEE Wiring Regulations

There are several requirements in the Regulations which control the minimum cross-section of a conductor, the most obvious of which is the need to respect a maximum working temperature; applications of these requirements are explained in '*Cable Selection and the IEE Wiring Regulations*' on Page 94.

A thermal minimum size of conductor is the smallest cross-section which can be used to carry the required current without the risk of overheating. A larger cross-section conductor runs cooler and the insulation has a longer expectation of serviceable life.

This requirement includes the effects of surrounding ambient temperature and mutual heating from other cables.

A minimum size forms a convenient starting point for calculations of economic conductor sizes, since conductors can be of larger cross-section but not smaller.

There are two other requirements in the IEE Regulations which directly affect the selection of conductor cross-section, usually to require a size larger than the thermal minimum; these are overload protection and limitation of voltage drop. The former is not always pertinent and is usually combined with the application of the coefficients for ambient temperature and grouped cables, see '*Cable Selection and the IEE Wiring Regulations*' on Page 94.

The latter is allied to the matter of avoiding excessive power loss since they both depend on the resistance of the conductor. A conductor size chosen to reduce the cost of energy loss of a circuit, will also reduce voltage drop and help to maintain an adequate receiving end voltage.

The size increase needed to avoid excessive voltage drop depends on the length of circuit but is often about one or two sizes larger than the minimum thermal size, an increase which usually results in a substantial cost saving.

The role of the mandatory size increases due to a high ambient temperature and mutual heating from other cables, along with increases to avoid uneconomic power loss and excessive voltage drop, can be demonstrated by extending the example used in Appendix 3 C.

Supposing that two other power cables are present, and that all three cables are now clipped together on a perforated steel tray which runs suspended from the ceiling. These additions will alter the current carrying capacity of the 25 mm² cable and a size change will be required.

Suppose that the ambient temperature around the cables is 40° C. Table CB K-10 (on page 98) indicates that the rating factor for 40° C is 0.87.

*The effect of this change by itself (see '*Cable Selection and the IEE Wiring Regulations*' on Page 94) would require a cable having a current carrying capacity of*

$$\frac{101}{0.87} = 116A$$

From column 5 of Table CB K-8 (page 97) it can be seen that this needs a 35 mm² conductor.

The group reduction factor for three cables run together is 0.81 (see Table CB K-11 on Page 98). Again, by itself this change would require a cable with a current carrying capacity of

$$\frac{101}{0.81} = 125A.$$

Referring to Table CB K-8 again this requires a 35 mm² conductor.

Since both the increased ambient temperature and the cable grouping are involved in the change, the requirement is for a cable with a current carrying capacity of

$$\frac{101}{(0.87 \times 0.81)} = \frac{101}{0.705} = 143A.$$

From Table CB K-8 this can be carried by a 50 mm² size of conductor.

The voltage drop to the kiln can be worked out from the voltage drop data provided in Table CB K-9 (page 98), by the following multiplication for the first few conductor sizes.

Voltage drop = $mV/A/m_r \times \text{length} \times \text{current}$.

(The reactive drop $mV/A/m_x$ for these sizes is too small to have any significant effect and has been ignored for simplicity.)

These size requirements are summarised in Table CB E-1, 'Summary of Effects of Size Increases' on Page 69.

Table CB E-1 Summary of Effects of Size Increases

Conductor size mm ²	Savings on total costs £*	Voltage drop % of 400V **	Group and ambient factors ##
25	-	3.75	Not Applicable
35	3,998	2.75	Not Applicable
50	6,557	2.0	OK
70	8,077	1.4	OK

* Table CB K-4, col 5. Single circuit cost reduction from 25 mm².

** Mandatory size increase because of presence of other cables and a higher ambient.

These examples have been simplified by retaining values of conductor resistance at 70° C, see Appendix 3 G - 'Load Variations during a Load Cycle and Cable Resistance' on Page 77.

The second column of Table CB E-1 is derived from the example in Appendix 3 C and shows the financial changes resulting from increased conductor sizes. Neglecting for the moment the effects of temperature and grouping, all of these sizes, including 25 mm², may be permissible as regards compliance with the Regulations, but the greater the increase in size the greater the saving in total cost.

The third column shows how the voltage drop along the cable decreases with increase in conductor size. Again, all sizes may be permissible, although the reduction in effectiveness of the kiln if process temperatures are critical might be

unacceptable with a 3.75% voltage drop and an increased conductor size could be desirable on this account alone.

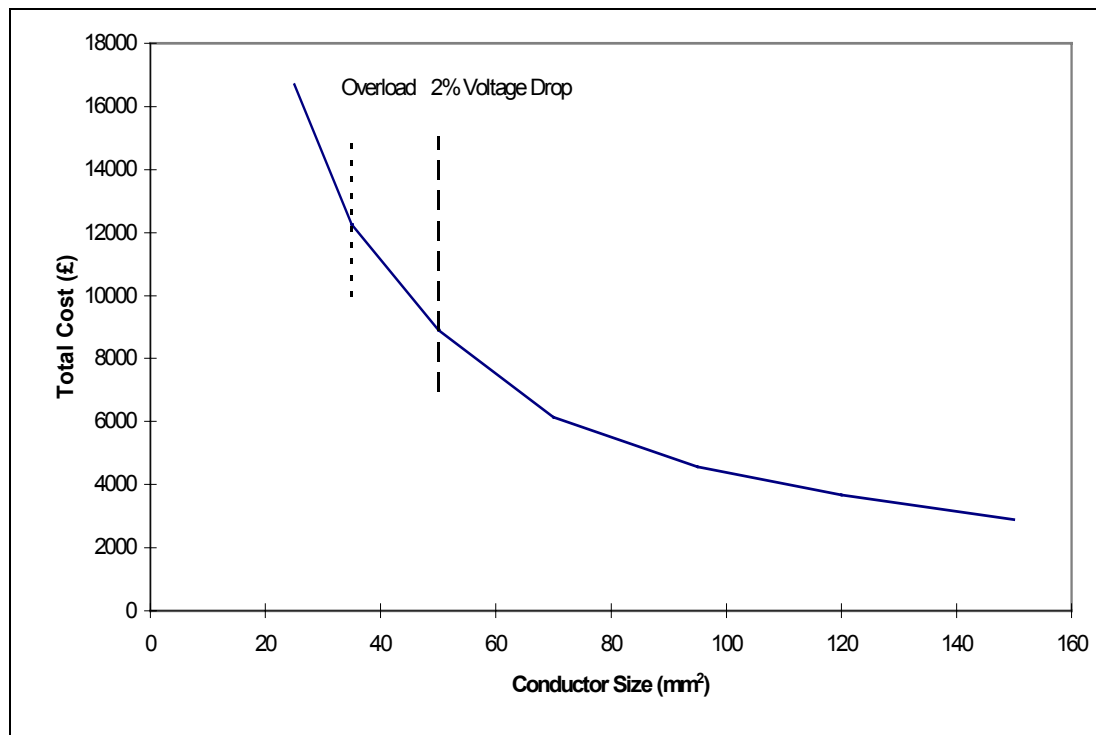
In some circumstances a voltage drop of 2.5% or less is considered desirable, suggesting that a 50 mm² conductor size is advantageous.

At this point it is important to observe that the one increase, to say 50 mm², would achieve both objectives; an increase in effectiveness of the kiln and a reduction in cost of wasted energy in the cable.

The final column indicates a mandatory increase to 50 mm² because of the mutual heating from additional cables grouped with the one feeding the kiln. This size increase reduces the resistance and hence the power loss in the kiln cable and compensates for the additional heating from the other two. Again it is clear that this size increase achieves more than one objective because all objectives can be met by a reduction in losses in the kiln cable.

It is evident that size increases above the minimum required to observe the conductor maximum working temperature, whether they are mandatory or taken in order to improve the economic performance of the project, are compatible with the IEE Regulations.

Figure CB E-1 Comparison with Voltage Drop



It is relevant to note here that there are further requirements in the Regulations which may call for an increase in conductor size which are concerned with the need to withstand short-circuits and earth-fault currents. It is not appropriate, by reason of space, to discuss the effects these requirements may occasionally have on conductor size. The principle for combining them with economic sizing is the same as for voltage drop.

Figure CB E-1 illustrates how Regulations concerning overload protection may also call for a size increase above the minimum permissible.

F. Savings with Different Types of Cable and Load Conditions

i. Choice of Cable According to Environmental Circumstances

The choice of type of cable and its terminations depends on the environmental conditions under which they have to operate. Typical conditions affecting cables are:

- temperature
- moisture
- mechanical abuse, including impact and vibration
- chemical abuse, including hydrocarbons
- overload and short-circuit
- flora and fauna
- theft and vandalism
- risk and results of fire and explosion
- solar and thermal radiation
- dust and stored materials

A more detailed description of a variety of environmental effects which may have a detrimental effect on the operation of a cable and its terminations is given in Appendix 5 of The IEE Wiring Regulations.

Some of these effects can be taken care of by appropriate methods of installation, (e.g. installation in building voids or attachment to structural steelwork) protecting the cable from the more extreme forms of a particular influence.

It is evident that the cost of installation can be significantly affected by environmental factors, and likewise the choice of an economic size.

For general installations the hazards which frequently need to be addressed are excess electrical load, mechanical abuse, high ambient temperature and moisture. Excess electrical load not only arises from inadequate load assessment in the first place but from failure to make provision for expansion and alteration in the future. Adequate provision for future loads not only avoids a much greater expense of reinforcement with additional cable and switchgear later on but, as can be seen from the analysis in the previous Section, is an economic investment which starts to provide a good return right from the start of the project.

Mechanical abuse, which can be a problem even during installation, points to the use of steel-wire armoured cables or cables in screwed steel conduit; the latter also provides some flexibility for alteration and addition, but is expensive in the largest sizes. Risk of severe mechanical damage is usually a problem for a limited part of the route only and can be dealt with economically by local protection or by the use of an alternative cable route.

High ambient temperature, if a feature of the whole route, is usually a case for increasing the size of the conductor; an option which also improves the economy of the project. Alternatively, the use of a cable having a higher temperature insulant such as XLPE or EPR provides a satisfactory solution; especially where a high temperature region does not involve the entire cable length or cable room is limited (this may be more important during installation). The price differential on these cables is decreasing.

Moisture is obviously a problem where cables are run underground (including under-floor installations which often suffer from unexpected moisture) or in the vicinity of some industrial processes or pipe-lines. Sheathed cables, or steel-wire armoured and sheathed cables, are generally suitable for moist or underground use and will withstand occasional immersion in water. Ordinary plastic cables are not best suited to continual immersion or wetting from

leakage and the manufacturer's advice should be sought if such conditions are expected. Local protection or re-routing can be a satisfactory solution.

It is pertinent to appreciate that the cost of a cable, its terminations and installation reflects the measures which have to be taken to meet the environmental conditions. Thus the choice of cable type is, to a great extent, limited by circumstances.

Given that an appropriate type of cable has been selected^{*}, it is helpful to review typical cost-size characteristics for the more popular types.

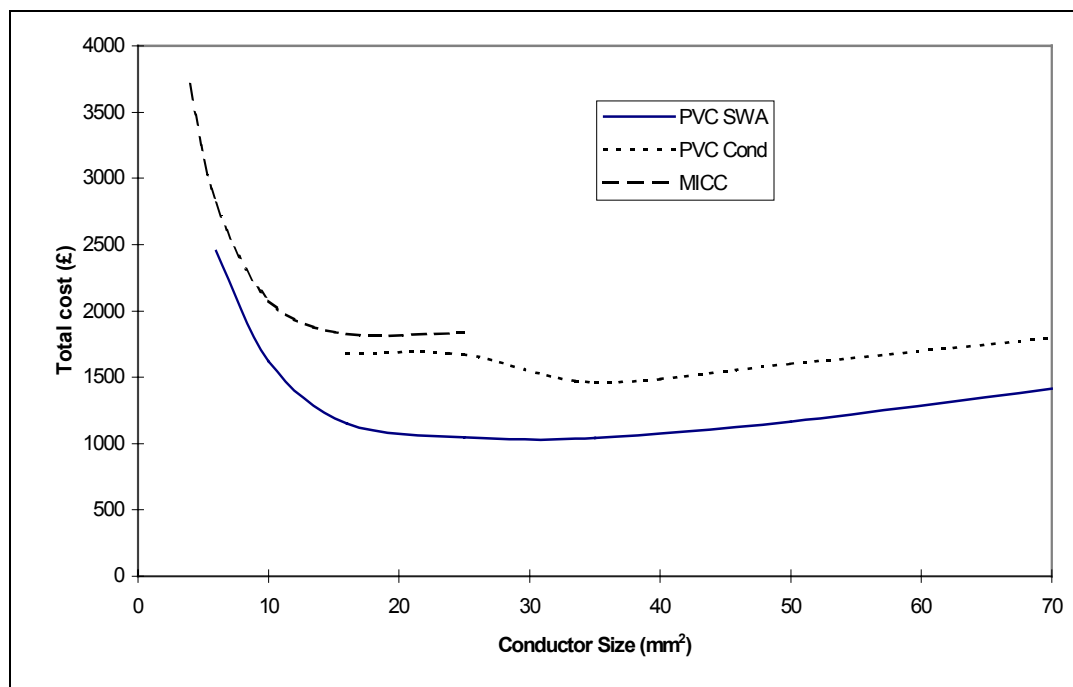
One point should be carefully noted about the figures to be described and the corresponding conclusions. The exact shapes of the characteristic curves, and hence the details of the conclusions, depend on the cable and energy prices used. Different values will produce different curves and the conclusions may need modification. One important feature of the cable and termination prices used in an economical assessment is that they must include all the costs of installation and jointing, including any work which has to be done to provide support. It follows that any economic selection is usually specific to one location.

The presentation of the figures which follow is intended to show what sort of information can be obtained from cost/size characteristics and, in general, the advantages of economic conductor sizing under a range of more likely circumstances.

ii. Characteristics for Different Cable Types

Installation costs for different types of cable affect the shape of the total cost/size curve, Figure CB F-1, where the characteristics of mineral-insulated cables, PVC cables in steel conduit and PVC-insulated steel-wire armoured cables are compared for a 10 kW single phase load. The higher current-carrying capacities of the smaller sizes of mineral-insulated cable carry a penalty of higher costs of losses. However, increasing the conductor size yields a dramatic reduction in overall costs.

Figure CB F-1 Different Types of Cable



^{*} A useful and more complete survey of the factors involved in the selection of a cable type, as well as a general review of installation cabling, is available in "Handbook of Electrical Installation Practice" Blackwell Scientific Publications.

An interesting feature, suggested by the particular cable prices used here, is that size for size the total costs of a circuit using mineral-insulated cable may not be very different from those incurred when using PVC-insulated cables in steel conduit.

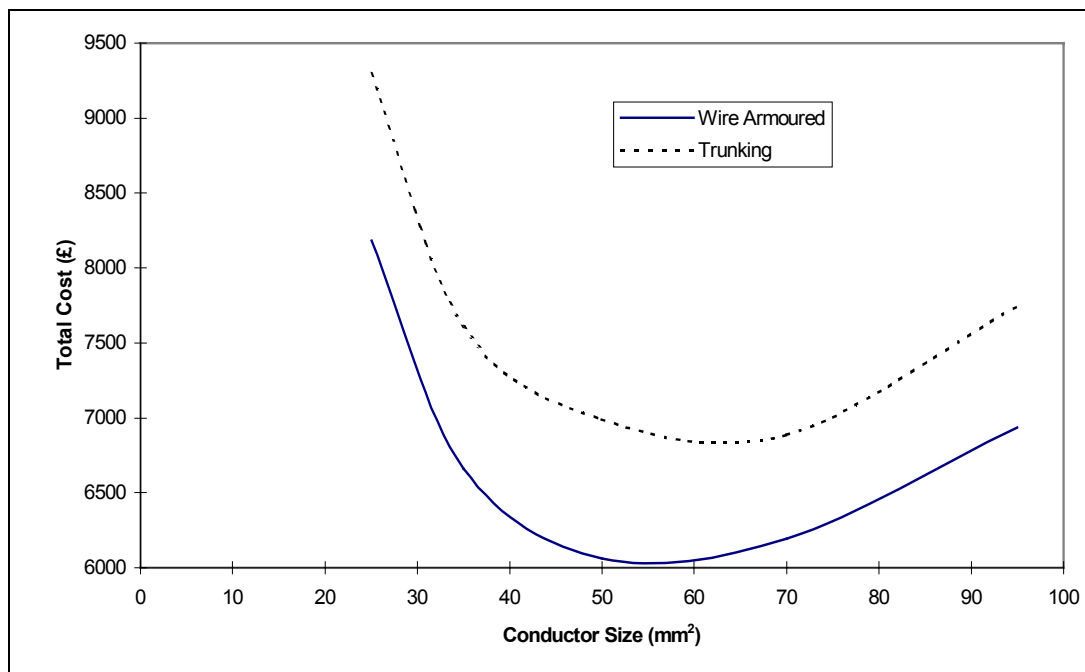
Mineral-insulated cable is chiefly of use where good fire resistance and low fire risk or a very neat and unobtrusive installation is a prime requirement.

PVC-insulated cable in conduit is mechanically very robust and permits limited alteration and additions to the wiring at a later date.

PVC-insulated steel-wire armoured cable is economical to purchase and install; a feature which is echoed by the lowest of the three characteristic curves in Figure CB F-1. It is quite robust and can withstand all but extreme mechanical abuse.

Figure CB F-2 shows characteristic curves for higher loads and greater distances, using 3 phase cables. Here the effect of the price difference between armoured cable and cable in steel trunking is clearly brought out. However, the difference shown here is rather artificial, in that trunking is chiefly of advantage when several circuits are to be installed on the same route. It has the great advantage that alterations and additions can be carried out very easily.

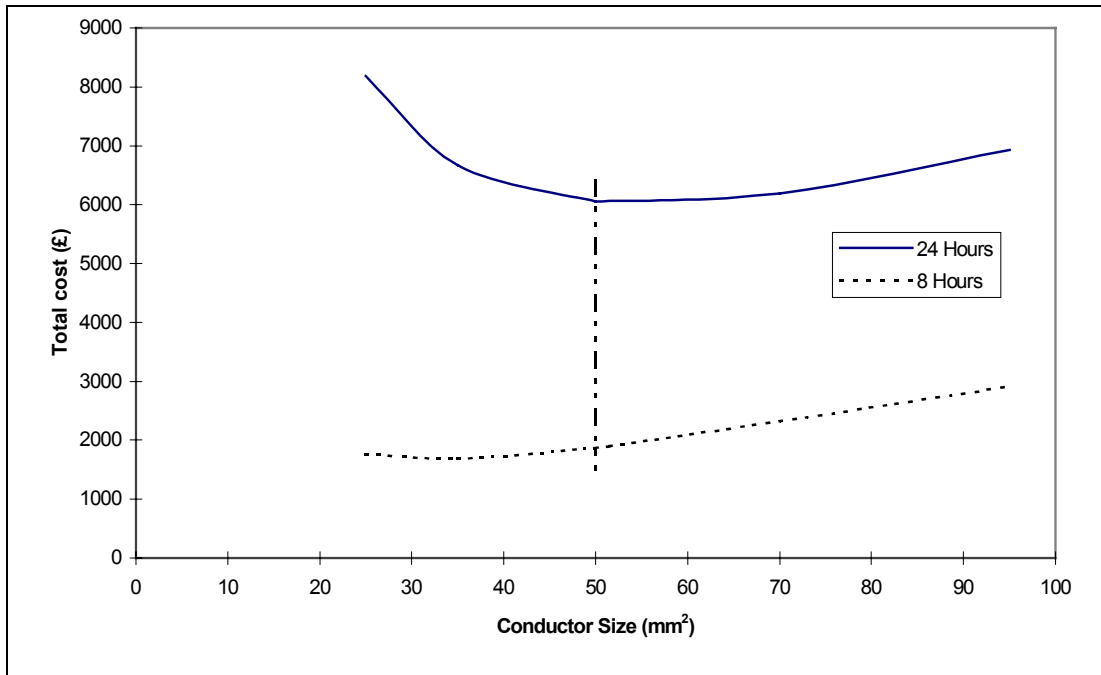
Figure CB F-2 PVC in Trunking compared with Wire Armoured Cable



iii. Circuit Utilisation

Circuit utilisation is one of the most important factors affecting the economy of a circuit. Clearly, to take an extreme case, where a circuit is hardly used the only cost to be considered is that of the cable and the obvious choice is to use the smallest cable permitted. Figure CB F-3 compares the characteristics of a continuously loaded circuit (i.e. 24 hours per day, 365 days per year) with that for a circuit loaded only for an 8 hour shift on 5 days per week with 2 weeks shut down per year, a utilisation of about 20%. In the latter case the typical minimum of a cost/size characteristic is only just discernible and only one increase in size above that determined by the thermal rating of the cable would be worth-while; but note that a small increase in the cost of electricity could make even two size increases worth while. The point of this example is that savings can be quite dramatic when utilisation is high, but for circuits which are poorly utilised (say less than 20%) the opportunity for savings is more delicately balanced on the prices of cable and electricity.

Figure CB F-3 Effect of Utilisation

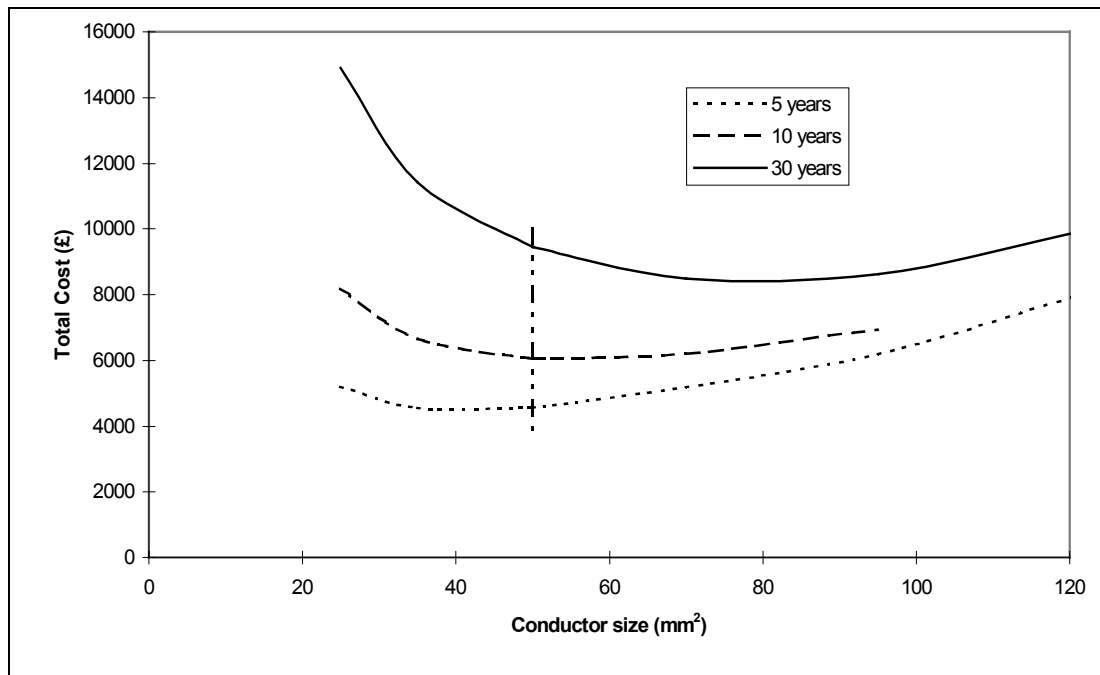


iv. Project Life-time

A similar situation applies when considering the economic advantages to be had when the project life-time is short, see Figure CB F-4 where life-times of 5, 10 and 30 years are compared. Savings even with project life times as short as 5 years are feasible.

Occasionally a project may not achieve the utilisation or lifetime anticipated. By assuming that a cable two sizes larger than the minimum is installed (see the vertical dotted lines in Figure CB F-3 and Figure CB F-4) it can be seen that the extra investment in cable, even in the event of poor project performance or early failure, can result in some saving or will mitigate the overall losses.

Figure CB F-4 Effect of Project Life



v. Lack of Anticipated Load Growth

Where a load increase is expected, the more economical and convenient solution is to install a cable size thermally adequate to carry the final load. The advantage of taking the alternative of installing a second cable later on depends on the rate and nature of the load growth.

Where average growth is modest, say of the order of 5% per year, use of a size determined by the final load provides also for savings in the costs of losses during the early years of the project. The formulae provided make it possible to include an average growth rate into the evaluation of the characteristic cost/size curve and this can be helpful in deciding what size to use. Figure CB F-5 shows curves for 0%, 5% and 7% growth rate.

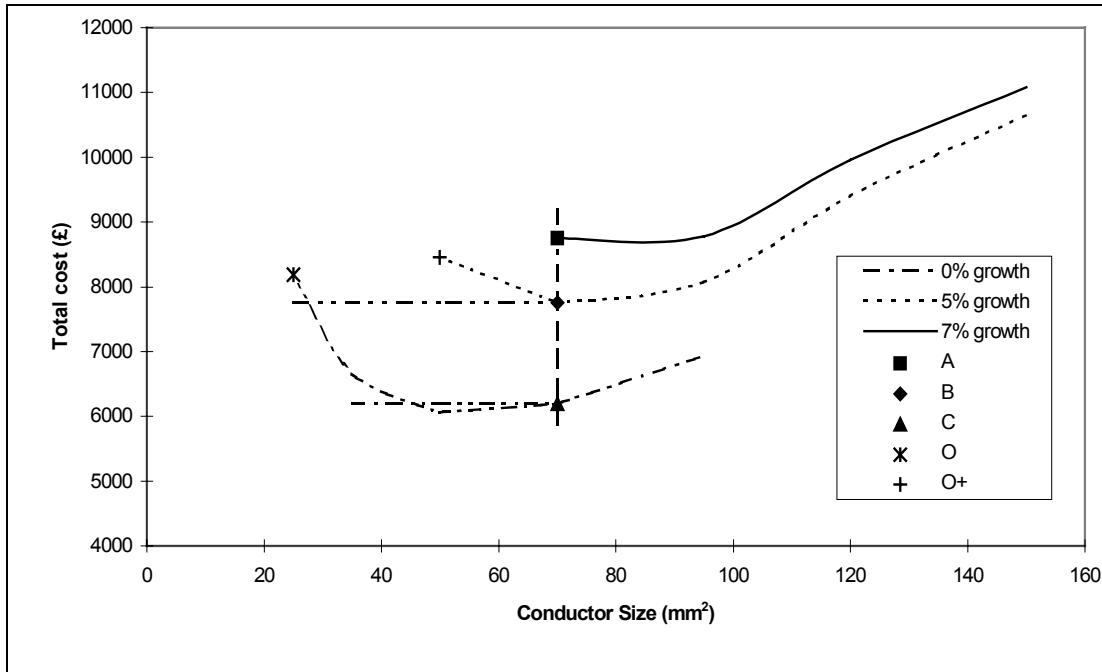
The first point on each curve is the size required for a conductor to carry the last year's load. (In the case of the curve for zero growth, the load for the last year is the same as that for the first.)

The characteristic curve for 5% growth rate shows that there is some scope for savings by use of a conductor a size larger than that required for the last year. For 7% growth there is nothing to be gained by using a larger conductor.

When plans for future growth involve present expenditure it is important to know what would happen if the expected rate of growth is not achieved. Would the additional expenditure on a larger cable become an unfortunate financial embarrassment? It is possible with a set of characteristic curves such as Figure CB F-5 to forecast what the result would be.

The vertical line is drawn from the cable size required if plans went ahead for, as it might turn out, a rather over optimistic 7% per year growth rate, point A. If the actual growth rate were only 5%, point B, or even if there were no growth at all, point C, that same cable size would prove to be a fortunate investment, because both points B and C correspond to total costs which are lower than the cost which would have been incurred had the minimum conductor sizes been installed, points O and O+.

Figure CB F-5 Different Load Growths

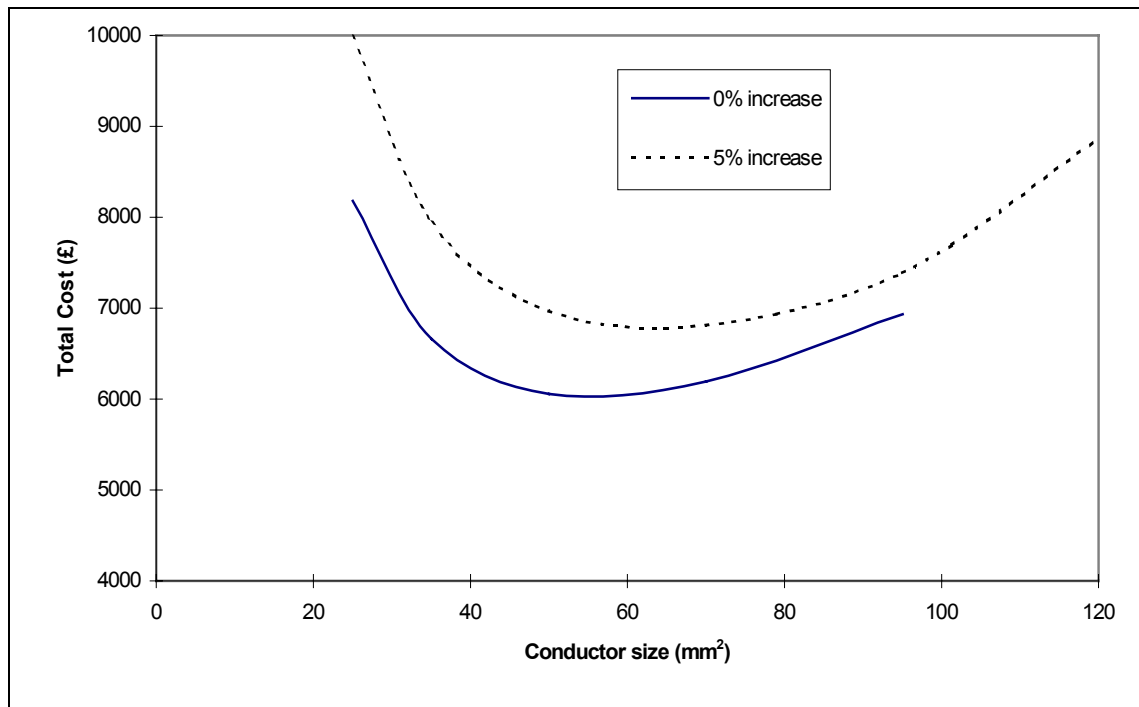


vi. Increase in Price of Energy During the Project Life

This is one of the more likely sources of error in a forecast of future operating costs and one where it is usually difficult or impossible to obtain reliable information. Fortunately, as can be seen from Figure CB F-6, future changes in costs of energy have only a marginal effect on the optimum conductor size and savings from the use of increased conductor sizes are valid whatever the energy costs.

Fortunately, as far as the selection of a conductor size is concerned, it is not necessary to spend a great deal of effort trying to obtain accurate data on energy costs. In the event that cost increases are higher than expected, although the total costs will rise, the selection of a particular size and the expectation of savings will remain valid.

Figure CB F-6 Increase in Cost of Energy



G. Load Variations during a Load Cycle and Cable Resistance

The example in Appendix 3 C was simplified by omitting some requirements and guidance in the IEE Regulations which do not affect the basic calculations for the characteristic cost/size curve.

The characteristic curves and example calculations in this report have generally taken the minimum thermally permissible conductor size as the starting point for cost/size characteristics because whatever other limitations may or may not apply no smaller conductor size can be used.

As explained in Appendix 3 E the additional requirements in the IEE Regulations often call for a conductor size larger than the thermally permissible minimum and are therefore compatible with economic sizes. Their requirements can be superimposed on the cost/size characteristic.

However, one feature of conductor size selection which cannot be so easily dealt with in parallel with economic size selection, but which was omitted from Appendix 3 C, is the effect that varying load currents have on the temperature and hence on the resistance of conductors. As load current is reduced, conductor temperature drops and with it conductor resistance and power loss.

In cases where a constant load is close to the current carrying capacity of a cable (as it was for the example in Appendix 3 C) it is convenient and reasonable to simplify calculations by using resistance values tabulated for 70°C without any adjustment. This was the course adopted for the examples in Appendix 3 C.

When the load varies during a process cycle the conductor size must be suitable for the maximum current and it follows that for other times in the cycle the current will be lower, and in particular lower than the current carrying capacity of the cable.

For cables installed in air (i.e. not laid directly in the ground) conductor temperature varies more or less in step with changes in load current and, because conductor resistance is influenced by temperature, conductor resistance changes as well. The values of resistance given in Table CB K-6 to Table CB K-9 (page 96 to 98) of this document, or in Appendix 4 of the IEE Regulations, apply to the maximum permissible working temperature for the cable, in the case

of PVC insulated cables this is 70° C. If a PVC cable is not carrying its full rated current, its temperature will be less than 70° C.

The reduction in conductor resistance when load currents are less than the full carrying capacity of a cable can be quite significant and will reduce the losses generated in the cable, see Equation (1).

The temperature rise of a PVC insulated cable when carrying its maximum permissible current is 40° K above an arbitrary ambient temperature of 30° C: if the conductor size is 50 mm² and the cable has 3 conductors, the permissible current or current carrying capacity is 151 A.

The temperature rise for a load current of 101A, as in the Appendix 3 C example is

$$\text{Temp.rise} = 40 \times \frac{101^2}{151^2} = 40 \times 0.447 = 17.9^\circ \text{ K}$$

The resistance of each conductor of this cable at 70° C (i.e. 30° C + 40° K) is 0.462 milliohm/metre (see Table CB K-2 and 'Resistance Adjustments for Partly Loaded Cables' on Page 100), so that at 17.9°K rise its resistance is

$$\begin{aligned} &= 0.462 \times \frac{234.5 + 30 + 17.9}{234.5 + 70} \\ &= 0.462 \times 0.927 = 0.428 \text{ milliohm/metre} \\ &= 0.000428 \text{ ohm/metre} \end{aligned}$$

The power loss is (from Equation 2)

$$\frac{101^2 \times 0.000428 \times 3 \times 100}{1000} = 1.31 \text{ kilowatt}$$

If the adjustment to the resistance for running the cable at a current lower than its permitted maximum had not been made the power loss would have been 1.414 kW. For larger conductor sizes, the reduction in power loss is even greater.

An adjustment to conductor resistance for loads less than the permitted maximum is particularly important because it reduces the costs of the losses and hence influences the shape of the cost/size characteristic and the selection of an economical size.

'Resistance Adjustments for Partly Loaded Cables' on Page 100 explains the derivation of a coefficient, C_t, which can be inserted in the power loss calculation (Equations 1 to 5 and their later equivalents) as a multiplier to the value of resistance so as to take account of varying values of current.

At the same time the coefficient C_a is included to allow for situations where the ambient temperature is persistently higher than 30° C and likewise the coefficient C_g is introduced to allow for mutual heating from other cables installed in the same group as the one under consideration, see Appendix 4 of the IEE Regulations.

The coefficient C_t is given by

$$C_t = 1 - \frac{\left[(C_g \times C_a)^2 - G \left(\frac{I}{I_t} \right)^2 \right] \times (t_p - 30)}{234.5 + t_p}$$

where $G = \frac{1 + \left(1 + \frac{a}{100} \right)^{2N}}{2}$

I_t = tabulated current carrying capacity of a cable for a 30° C ambient, see 'Cable Selection and the IEE Wiring Regulations'.

C_a = reduction factor for ambient temperatures higher than 30° C.

C_g = reduction factor for mutual heating from other cables in the same group.

I = conductor current at the time in a load cycle for which the loss is to be calculated, A.

t_p = conductor temperature for which it is derived, °C. (for PVC cables $t_p = 70^\circ \text{C}$.)

Note, the symbol I may carry various suffices to indicate different values in a loading cycle.

The reduction factor C_t is used to adjust conductor resistances not only for different values of load current during a process cycle, but also, when deriving a cost/size characteristic, for the larger sizes of conductor which have current carrying capacities higher than the maximum currents of a load cycle.

Applying the above equation to the previous example where a 50 mm² 3-core PVC cable is carrying a current of 101 A we have:

$C_a = 1$, the example did not refer to the ambient temperature being persistently higher than 30° C

$C_g = 1$ the example assumed that the cable is thermally isolated from any other cables.

$I_t = 151 \text{ A}$ and the conductor resistance at 70° C is 0.462 mΩ/m

$t_p = 70^\circ \text{C}$, for a PVC insulated cable.

$$C_t = 1 - \frac{\left[1 - \left(\frac{101}{151} \right)^2 \right] \times (70 - 30)}{234.5 + 70}$$

$$= 0.927$$

The conductor resistance = 0.927 x 0.462

$$= 0.428 \text{ m}\Omega/\text{m} \text{ or } 0.000428 \text{ }\Omega/\text{m}$$

which is the value derived above.

The effect on the total cost of using the cable in the example in Appendix 3 C can be seen by considering the calculation for the 50 mm² conductor size in Figure CB C-2 and Figure CB C-4 on page 63 and 66 .

The rating for a 50 mm² 3-core PVC/SWA cable is 151 A for a conductor temperature of 70° C.

$C_t = 0.927$ (as above) and when introduced into Equation (2) we obtain a power loss of

$$\frac{I^2 C_t R N_p L}{1000} \text{ kW}$$

$$\frac{101^2 \times 0.927 \times 0.000462 \times 3 \times 100}{1000} = 1.31 \text{ kW}$$

Equation (3) gives the losses expressed in units for 400 hours per month,

$$\text{Units} = 1.31 \times 400 = 524.24 \text{ units/month}$$

In the example the cost of electrical power = 5 pence/unit so that

$$C_j = \frac{524.24 \times 5}{100} = \text{£}26.2 \text{ per month}$$

As in Appendix 3 C, the demand charge is

$$C_d = 1.31 \times 3 = \text{£} 3.93 \text{ per month}$$

The value of these continuing monthly payments discounted to the starting date of the project is, using the same discounting factor $Q = 274$,

$$PV = 274 \times (26.2 + 3.93) = \text{£} 8,256 \text{ (8,916)}$$

The cost of installation, C_i , for a 50 mm² cable is £ 1,396.

The total cost of installation and running a 50 mm² cable is

$$\text{£}8,256 + \text{£}1,396 = \text{£}9,652 \text{ (10,312)}.$$

(The figures in brackets are values obtained when no allowance for reduction in conductor temperature is made.)

H. Changes in Energy Tariff

Appendix 3 C made the simple assumption that the price of electrical energy was constant throughout the running periods of the load. In the example in Appendix 3 C the kiln runs for 400 hours per month without any stipulation as to how that period is made up except for the implication that the price of energy is constant.

A more realistic approach is to recognise that the price of energy may change according to the time of day; e.g. there is a different tariff for day time and night time consumption. The timing of these tariff periods is related to the variation in demand for electrical power during the 24 hours and they are more generally referred to as peak and off-peak periods. This differentiation in price may be carried further by having lower prices for the weekend and variations with the time of year.

It is important to consider the pattern of energy price variation with that of the load. Not only is it more economical overall for a project to run as much as possible during the off-peak periods, but the selection of the most economical conductor size is also affected.

The energy cost equations described in Appendix 3 C have to be applied to the loads occurring during each tariff zone, depending on the way in which the load and energy prices change.

However, because of the large number of possible combinations, it is feasible to provide here only a general outline of the procedure for generating the costs for a cost/size characteristic. The procedure for a tariff with two price periods will be given, this being the most usual type; extension to tariffs which have a greater number of price zones will be obvious. A typical two zone tariff is given in Table CB H-1.

Table CB H-1 Typical Two Part Energy Tariff

Tariff zones hours	0000 to 0700	0700 to 2400
Unit Price pence per kWh	2.5	5.4
Demand price £/kW per month	2.1	2.7

First consider the application of such a tariff when the energy loss, for the period when the load is on, is constant.

In the example given in Appendix 3 C, a 70 kW kiln runs for 400 hours per month. The power losses are 2.65 kW when the kiln is running. (Equation 2). In the Appendix 3 C example the adjustment for conductor temperature, C_t , was not applied because the load current (101 A) was practically equal to the cable

rating (102 A) and the adjustment would have added needless complication to the example. This simplification will be continued here.

It is now necessary to be more specific with regard to the actual running times of the kiln and to match them against the tariff price zones.

Suppose that the kiln is charged on Mondays, that heating starts at 1700 hours on Monday and continues until Friday when it is switched off at 1700 hours. It cools down over Friday night, Saturday and Sunday to be ready for emptying and recharging on the Monday.

The total heating period is 96 hours for each weekly production cycle. The off or idle period is therefore 72 hours. The example from Appendix 3 C has been modified a little in that the monthly load period would now vary from the figure of 400 hours depending on the number of weeks in a month.

The patterns of loading and energy price zones can be set out as in Table CB H-2. (On the lines of Equations 3 and 4, but the calculation applies to a period of one production cycle or one week.)

Table CB H-2 Pattern of Loading and Energy Prices

Day	Time	Price per unit (p)	Losses (kW)	Cost = kW x duration x price (p)	Total cost of losses (pence)
Sun	0000 - 0700	2.5	0		0
	0700 - 2400	5.4	0		0
Mon	0000 - 0700	2.5	0		
	0700 - 1700	5.4	0		
	1700 - 2400	5.4	2.65	$2.65 \times 7 \times 5.4 = 100.17$	100.17
Tue	0000 - 0700	2.5	2.65	$2.65 \times 7 \times 2.5 = 46.375$	289.645
	0700 - 2400	5.4	2.65	$2.65 \times 17 \times 5.4 = 243.27$	
Wed				As Tuesday	289.645
Thur				As Tuesday	289.645
Fri	0000 - 0700	2.5	2.65	$2.65 \times 7 \times 2.5 = 46.375$	189.475
	0700 - 1700	5.4	2.65	$2.65 \times 10 \times 5.4 = 143.1$	
	1700 - 2400	5.4	0		
Sat				As Sunday	0

The total unit charge for losses during one production cycle is 1,158.6 pence or £11.59 and production is arranged to have one cycle per week.

Because of the unequal number of weeks in a calendar month (it is assumed here that energy bills are paid every calendar month) it is necessary to calculate an average energy cost by multiplying the weekly cost by the number of weeks worked in a year and dividing by 12. Assuming that 50 weeks are worked in a year, the average cost of losses for each calendar month is

$$C_j = 11.59 \times 50 / 12 = £48.29 \text{ per month.}$$

The demand charge is based on the highest kW demand made by the customer during each tariff time zone for each calendar month.

In this example the load, when it is on, and hence the losses, do not change during the day or from day to day and the following table expresses the monthly demand charge.

Table CB H-3 Calculation of Monthly Demand Charges

Charge zone hours	Demand price £/kW	Loss kW	Demand Cost of losses £/month
0000 to 0700	2.1	2.65	5.565
0700 to 2400	2.7	2.65	7.155

The total demand charge attributable to the losses for each calendar month is

$$C_d = 5.565 + 7.155 = \text{£}12.72 \text{ per month.}$$

(Applying Equation 5 for each tariff time zone)

For the average calendar month's electricity bill, the amount due to the loss will be the sum of these amounts,

$$C_j + C_d = 48.29 + 12.72 = \text{£}61.01 \text{ per month.}$$

If the financial arrangements and the cable costs are the same as in Appendix 3 C, the discounting factor Q will be 274 and the present value will be, (Equation 11)

$$PV = 274 \times 61.01 = \text{£}16,716$$

Calculation of the installation costs and the total project cost is the same as that in Appendix 3 C.

I. Combination of Energy Tariff and Varying Load

A more general situation is where the load changes during the process cycle.

It is convenient to define this periodic change, which is conveniently referred to as a load cycle, as the shortest pattern of changing load which repeats exactly. In many cases it repeats daily (may be with idle periods over a weekend), weekly or even annually; frequently its periodic time is set by a process which could last for part of a day or for many days. The term process includes not only industrial activities but also such items as lighting and heating which have a periodic time (usually a day, but could be a week) set by the occupants.

The point of defining the period of a load cycle is that it is usually convenient to evaluate the cost of losses for one load cycle whatever its duration, to gross this cost up to an annual total and then to divide by 12 to obtain the equivalent calendar monthly bill for the losses. If electricity bills are paid annually, the division into monthly parts is unnecessary.

The technique is illustrated by the following example. The periodic time is 24 hours, but it could just as well be any other period. The load cycle is set out in Figure CB I-1, consisting of a base load running for 24 hours, with additional processing loads coming on during the morning and dropping off in the evening. The peak load is 30 kW 3 phase. The cycle is constant for 5 days per week and 50 weeks per year. The tariff time zones are marked out against the load cycle.

The load cycle is divided into two sections to match the tariff zones and the power losses are evaluated for each zone. The amount of arithmetic can be reduced with the introduction of little error by calculating the r.m.s. (root mean

square) current and conductor temperature coefficient C_t for each tariff zone. This is done in the following tables.

The maximum current is 41.7 A, for which a 6 mm² 3-core PVC-SWA cable is appropriate. The maximum permissible current for this cable is 42 A and the conductor resistance at 70° C = 0.003695 ohm/m. The cable is 120 m long.

Figure CB I-1 Load Cycle and Tariff

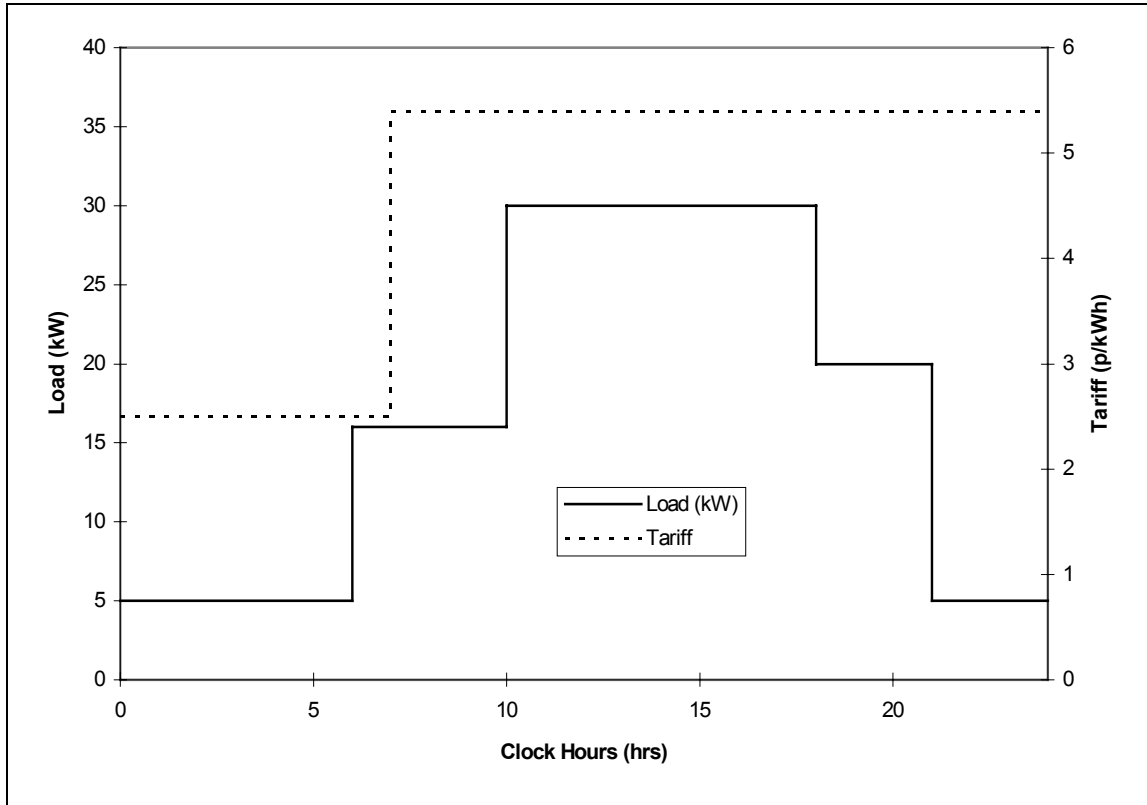


Table CB I-1 R.M.S. Current for Each Tariff Applied to Load

Clock time	Duration t (hours)	Load kW	Current I (A)	Current ² I^2 (A ²)	$I^2 \times t$ (A ² x hours)	Mean I^2 (A ²)	I r.m.s. A
0000 to 0600	6	5	6.944	48.22	289.3	783.1 ÷ 7	10.58
0600 to 0700	1	16	22.22	493.73	493.8	= 111.9	
0700 to 1000	3	16	22.22	493.73	1,481.2	17,830 ÷ 17	32.4
1000 to 1800	8	30	41.67	1,736.14	13,889		
1800 to 2100	3	20	27.78	771.61	2,314.8		
2100 to 2400	3	16	6.944	48.22	144.7		

Table CB I-2 Calculation of C_t and Power Loss for First Tariff Zone

Zone	Mean current (A)	I^2 (A ²)	$(I/I_1)^2$	C_t	Duration (hours)
0000 to 0700	10.58	111.9	0.06346	0.877	7

$$\begin{aligned} \text{Equation (2)} &= \frac{I^2 C_t R N_p L}{1000} \\ &= \frac{111.9 \times 0.877 \times 0.003695 \times 3 \times 120}{1000} = 0.1305 \text{ kW} \end{aligned}$$

$$\text{Equation (3)} = 0.1305 \times 7 = 0.9138 \text{ kWh per cycle}$$

The unit tariff between 0000 hours and 0700 hours is 2.5 pence and from

$$\text{Equation (4)} C_j = 0.9138 \times 2.5/100 = \text{£ } 0.0228 \text{ per cycle.}$$

The process is active for 5 days per week and 50 weeks in the year, so that the annual value of C_{j1}

$$= \text{£ } 0.0228 \times 5 \times 50 = \text{£ } 5.7 \text{ p.a. or £ } 0.475 \text{ per month.}$$

Table CB I-3 Calculation of C_t and Power Loss for Second Tariff Zone

Zone	Mean current (A)	I^2 (A^2)	$(I/I_t)^2$	C_t	Duration (hr)
0700 to 2400	32.4	1049	0.5805	0.9367	17

$$\text{Equation (2)} = \frac{1049 \times 0.9367 \times 0.003695 \times 3 \times 120}{1000} = 1.307 \text{ kW}$$

$$\text{Equation (3)} = 1.307 \times 17 = 22.22 \text{ kWh per cycle}$$

The unit price between 0700 hours and 2400 hours is 5.4 pence.

$$C_{j2} = 22.22 \times 5.4/100 = \text{£ } 1.2 \text{ per cycle}$$

$$= 1.2 \times 5 \times 50 = \text{£ } 300 \text{ per year}$$

$$= \text{£ } 25 \text{ per month.}$$

$$\text{Total } C_j (C_{j1} + C_{j2}) \text{ for one year} = \text{£ } 5.7 + \text{£ } 300 = \text{£ } 305.7 \text{ or}$$

$$\text{£ } 25.48 \text{ per month.}$$

$$\begin{aligned} (\text{Check total per cycle} &= \text{£ } 0.0228 + \text{£ } 1.2 = \text{£ } 1.2228 \text{ per cycle} \\ &= \text{£ } 305.7 \text{ per year}) \end{aligned}$$

Similarly the value of C_d is obtained from:

$$\text{for the 0000 to 0700 zone} = 0.1305 \times 2.1 = \text{£ } 0.274 \text{ per month}$$

$$\text{for the 0700 to 2400 zone} = 1.307 \times 2.7 = \text{£ } 3.53 \text{ per month}$$

$$\text{Total } C_d = \text{£ } 0.274 + \text{£ } 3.53 = \text{£ } 3.81 \text{ per month.}$$

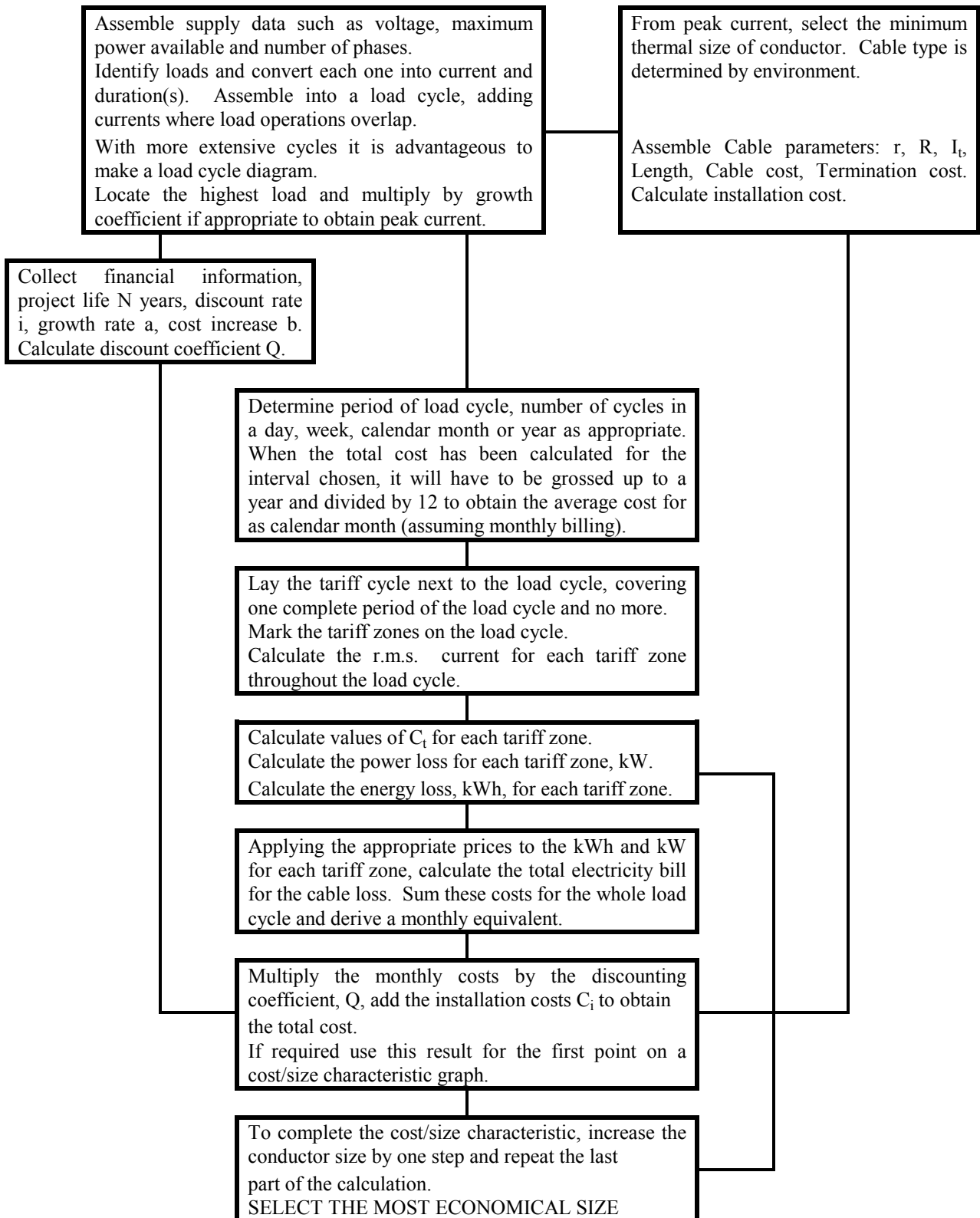
J. Conclusions

The effort required to forecast the most economical size of conductor is small in comparison with that which has to be made to select a conductor size to comply with the requirements of the IEE Wiring Regulations. On the other hand the reduction in electricity bills, because of the reduction in wasted energy, incurred over the whole life of the project can be quite significant.

The practice of using increased conductor sizes to provide a good standard of voltage regulation at equipment terminals, thereby contributing towards the efficient performance of equipment, is synonymous with economical conductor selection and reduced running costs. Conversely, to risk inferior performance from equipment by using the smallest permissible size of cable is wasteful and leads to unnecessarily high running costs.

Where the length of run is such that voltage drop is acceptable, it is nevertheless a good investment to increase conductor size as indicated by the appropriate cost/size characteristic. Table CB J-1 summarises the procedure for generating a cost/size characteristic.

Table CB J-1 Flow Chart and Summary



K. Additional Information

i. Relationship between Power of Equipment and Current to be carried by Cables

a. Power and Current.

When dealing with sizes of cable conductors it is convenient to think of the electrical current they carry from one point to another. There are direct relationships between the size of a conductor, measured in terms of its cross-sectional area, and the electrical current it can safely carry.

On the other hand, when considering electrical equipment one is more concerned with its capability to do useful work and a measure for this, usually given on the rating plate, is its electrical power consumption in kilowatts (motors used to be rated in horse power), kVA and sometimes amperes.

b. Symbols

The symbols used for the different quantities are:-

V = Voltage of supply, the unit is the volt and the abbreviation is V.

(The UK national declared voltage is now 230/400 V $\pm 10\%$, but a practical value, within that tolerance will, in most places, be 240/415 V.)

In a single phase supply V is often replaced with U_o , denoting a voltage to neutral or phase voltage. In a 3 phase supply, the voltage between the lines is U or line voltage and the system of voltages is known by U_o/U , e.g. 230/400 V.

I = Electrical current, the unit is the ampere and the abbreviations are A or amp.

W = Power, i.e. the capacity to do work, the unit is the Watt, the abbreviations and symbols are W, or kW. (The "k" stands for a multiplier of 1000, so that 1 kW = 1000 W.)

$\cos(\theta)$ = power factor, the cosine of the electrical angle between the maximum of the voltage and the maximum of the current in an alternating current circuit. Symbols $\cos(\theta)$ and pf.

VA = the product of the voltage and current in a circuit. Unit is volt-amperes, VA or kVA.

kW = pf x kVA.

c. Relationships.

The relationships between these quantities are as follows:-

For single phase circuits (i.e. 2 live wires + earth or protective conductor) $V = U_o = 230 \text{ V}$

In a circuit supplying only heaters or filament lights, or a circuit operating on direct current,

Watts = Voltage x Amperes ($W = V \times I$ or $I = W/V$)

kW = $(V \times I)/1000$ or $I = (kW \times 1000)/V$

In an alternating current circuit supplying motors, discharge lighting, control gear etc., there is usually a delay between the voltage and the current, referred to as a power factor. Power factor (pf) = $\cos(\theta)$ where θ is the angle of delay between the voltage and current.

Here Watts = Voltage x Amperes x power factor ($W = V \times I \times \text{pf}$)

$$\text{kW} = \frac{V \times I \times \text{pf}}{1000} \quad \text{or} \quad I = \frac{\text{kW} \times 1000}{V \times \text{pf}}$$

The simple product of $V \times I$ (more frequently $(V \times I)/1000$ or kVA) is sometimes used because it gives a direct measure of the electrical size of the equipment, ignoring power factor.

$$\text{kW} = \text{kVA} \times \text{pf}$$

For 3 phase circuits (3 or 4 live wires + earth or protective conductor)

Here there are virtually 3 single-phase circuits working in unison, but with a delay of 120 electrical degrees between the three line voltages. The declared voltage between the three lines is U and the corresponding voltage between each of the three lines and the fourth conductor (the neutral), if present, is U_0 . Unless it is planned to take, in addition, a single-phase supply only the three 400V lines need to be used.

$$\text{In general kW} = \frac{\sqrt{3} \times V \times I \times \text{pf}}{1000} \quad \text{or} \quad I = \frac{\text{kW} \times 1000}{\sqrt{3} \times V \times \text{pf}}$$

where $V = U$ or 400 V.

If the circuit supplies only heaters or filament lamps, the load

power factor is unity and $\text{pf} = \cos(\theta) = 1$.

In the example in Appendix 3 C i the pottery kiln is capable of heating at a rate of 70 kW. The current in the cable feeding the kiln will be

$$I = \frac{\text{kW} \times 1000}{\sqrt{3} \times V \times \text{pf}}$$

Since the load is a heating element the power factor will be unity.

$$\begin{aligned} I &= \frac{70 \times 1000}{\sqrt{3} \times 400 \times 1} \\ &= 101 \text{ A.} \end{aligned}$$

The name plate will probably be marked with a rating of 70 kW, but may be labelled 70 kVA. If it were a piece of equipment which included a motor it is possible that either the power factor (at full load) or the line current, would be marked also.

ii. The Present Value of Future Sums of Money

In Appendix 3 C iii the problem was to find the total cost of distributing electrical energy from a supply point to an industrial process during the lifetime of that process.

The cost of distribution includes not only the cost of installation of a cable and fittings but also the cost of energy losses occurring in that cable during the time the process is operated. (Note that the cost of energy used in the actual production process is NOT included in these considerations.)

The problem here is that the setting up costs occur at the beginning of the project while the costs of energy losses occur over a long period of time. Thus there is the problem of adding together costs which arise, and have to be paid for, at different times. This is where the time value of money must be included in the calculation³¹.

The simple addition of all future energy costs to the initial costs would be to imagine that sufficient money is to be put aside at the start of the project to pay all future bills, or put another way, that all future bills for energy costs would be paid when starting the project.

This would not be an economical way to make provision for such future payments and would unnecessarily inflate the total cost of the project. A more practical way would be to consider what the energy costs would be worth if the money were to be set aside to earn interest until the time came to pay each bill. It is evident that following this procedure smaller amounts would need to be set aside.

This analogy introduces the time value of money and shows how the cost of energy payments during the future life of a project can be expressed as equivalent values at the time of initiating the project. Although the payments are made during the life of the project, their equivalent values at the beginning of the project can be calculated. When converted into values needed at the start these future costs can be added to the installation costs.

The usual procedure for calculating the future value of an investment can be applied here.

If the rate of interest is 5% per year and the term of investment is 3 years, the value of £100 at the end of the period is

$$£100 \times \left(1 + \frac{5}{100}\right)^3 = £115.76$$

Conversely, if a bill of £100 is to be paid in 3 years time, an amount equal to

$$\frac{100}{\left(1 + \frac{5}{100}\right)^3} = £86.38 \text{ should be invested.}$$

The value required at the start is referred to as the Present Value (PV) and the process of calculating it is called "discounting". The rate of interest to be used when calculating a PV is the average rate which could be obtained if money were to be invested during the period of the project.

When a series of future payments is to be made the procedure becomes cumbersome if each payment is discounted separately, so a formula is used which provides the PV for a series of payments at regular intervals. On the assumption that the process will continue in a regular manner from the time of installation, it can be expected that the payments for energy will be regular and for the same, or an increasing, amount.

Define factor $r = \frac{1}{\left(1 + \frac{i}{100}\right)}$

where

i = rate of interest, (% per year)

C = amount to be paid each year, assuming that payment is made at the end of each period, (£).

The matter of increasing payments is dealt with later.

N = number of years a project is expected to run

The PV for a number of payments is given by

$$\begin{aligned} PV &= C(r + r^2 + r^3 + r^4 + \text{for } N \text{ terms}), (£) \\ &= C.r(1 + r + r^2 + r^3 + \text{for } N \text{ terms}), (£) \end{aligned}$$

(Note that the payment for the first year is made at the end of that year.)

The terms in parenthesis in the above equation form a well known mathematical series, and their sum for N terms is

$$\frac{(1-r^N)}{(1-r)}$$

The term $r \frac{(1-r^N)}{(1-r)} = Q$, the discounting factor and

$$PV = Q \times C$$

If in the above example a bill for £100 is to be paid at the end of every year for 3 years, the PV for the total would be calculated as follows:

$$r = \frac{1}{\left(1 + \frac{5}{100}\right)} = 0.95238$$

$$Q = 0.95238 \times \frac{(1 - 0.95238^3)}{(1 - 0.95238)}$$

$$= 0.95238 \times 2.85941$$

$$= 2.7232$$

$$PV = Q \times 100 = 2.7232 \times 100 = \text{£ } 272.32$$

Table CB K-1 illustrates how this example works.

Table CB K-1 Illustrating Present Value of Future Payments of £100 per Year

Interest = 5% p.a.

Present Value £	over	to pay a bill at the end of		
		1st year	2nd year	3rd year
95.24	1 year	£ 100		
90.70	2 years		£ 100	
86.38	3 years			£ 100
272.32				

Two other matters affecting payment can be included in this computation: a) increases in the cost of energy and b) increases in the level of production causing a greater usage of electricity and higher losses in the cable.

Such changes are likely to arise at any time and are difficult to forecast accurately so that it is probably not worth expending a lot of effort at the design stage trying to take them into account with precision. Unless firm information is available an approximate method is usually sufficient, whereby average rates of change during the project life are estimated.

If a = the percentage annual increase in load (amp) on the cable

b = the percentage annual increase in unit cost of electricity

The factor r can be redefined as

$$r = \frac{\left(1 + \frac{a}{100}\right)^2 \times \left(1 + \frac{b}{100}\right)}{\left(1 + \frac{i}{100}\right)}$$

In the example above, the cost of electricity is expected to rise by 2% each year and current carried by the cable is estimated to increase by an estimated 4% each year.

$a = 4\%$ and $b = 2\%$.

the rate of interest, i , remains at 5%.

$$r = \frac{\left(1 + \frac{4}{100}\right)^2 \times \left(1 + \frac{2}{100}\right)}{\left(1 + \frac{5}{100}\right)}$$

$$= 1.051$$

For a 3 year project, where the cost of losses will be £ 100 each year,

$$Q = 1.051 \times \frac{(1 - 1.051^3)}{1 - 1.051} = 3.3165$$

$$PV = Q \times 100 = 3.3165 \times 100$$

$$= \text{£ } 331.65$$

Note: if $r = 1$, the equation for Q cannot be evaluated, but from the original series it can be seen that in this case $Q = N$.

Monthly Payments.

Electricity accounts are usually settled each month even though agreements with regard to prices and financial matters may be made annually. In this case the following modifications to the derivation of the discounting factor Q may be appropriate. The difference in the value of PV from that based on annual payments is small.

let r_m be the monthly value of the factor r , then

$$r_m = \sqrt[12]{r}$$

If the life of the project is N years there will be $12N$ monthly payments, starting at the end of the first month, and the value of PV will be

$$PV = C_m(r_m + r_m^2 + r_m^3 + r_m^4 + \dots + 12N \text{ terms})$$

$$= C_m \cdot r_m (1 + r_m + r_m^2 + r_m^3 + \dots)$$

$$= C_m \cdot r_m \frac{(1 - r_m^{12N})}{(1 - r_m)}$$

But

$$r_m^{12N} = r^N, \text{ so that}$$

$$PV = C_m \cdot r_m \frac{(1 - r^N)}{(1 - r_m)}$$

$$Q_m = r_m \frac{(1 - r^N)}{(1 - r_m)}$$

$$PV = Q_m \cdot C_m$$

Suppose that the annual rate of interest during a project is 5%, and the project is expected to last for 10 years. The PV of 10 annual payments of £ 1,000 would be calculated as follows.

$$PV = Q \times \text{£ } 1000$$

$$r = \frac{1}{\left(1 + \frac{5}{100}\right)} = 0.95238$$

$$Q = 0.95238 \times \frac{(1 - 0.95238^{10})}{(1 - 0.95238)} = 7.7217$$

$$PV = 7.7217 \times 1000$$

$$= \text{£ } 7,721.70$$

The PV based on 120 monthly payments would be found as follows.

$$r = 0.95238 \text{ (the annual rate as before)}$$

$$r_m = \sqrt[12]{r} \quad \log_{10} 0.95238 = -0.0211897$$

$$\text{divide by 12} = -0.0017658$$

$$\text{anti-log} = 0.995942$$

$$= 0.99594$$

$$Q_m = 0.99594 \times \frac{(1 - 0.95238^{10})}{1 - 0.99594}$$

$$= 94.7$$

$$PV = 94.7 \times \frac{1000}{12}$$

$$= \text{£ } 7,891.67$$

The slightly higher PV when payments are made at the end of each month is because of the earlier payment of costs compared with payment at the end of each year.

iii. Data for Example in Appendix 3 C

Figure CB C-4 is based on calculations of losses etc. for a 70 kW load carried for 400 hours per month by cables having different conductor sizes, the smallest of which is used for the examples in the earlier part of the text. The cable assumed for the example is a 3-core PVC-insulated steel-wire armoured 600/1000V cable having a length of 100 metre.

The cable data is given in Table CB K-2.

Table CB K-2 Cable Data Used for Examples in Appendix 3 C

Conductor size mm ²	r mV/A/m at 70°C *	R (Ω/m x10 ⁻⁴) \$	Cable cost £/m #	Terminations cost £ each	Total installed cost £
25	1.50	8.66	13.6	18.5	1,397
35	1.10	6.35	18.1	20.5	1,851
50	0.80	4.62	25.9	22.5	2,635
70	0.55	3.18	38.3	26.0	3,882
95	0.41	2.37	51.7	29.5	5,229
120	0.33	1.91	70.7	33.0	7,136
150	0.26	1.50	88.0	37.0	8,874

Notes to Table CB K-2:

* This is the resistive voltage drop per amp per metre along the line conductor at its maximum working temperature of 70°C. From this the alternating current resistance for the conductor can be derived. The mV/A/m values are taken from column 5 of Table CB K-9.

\$ The resistance in ohm/m at 70°C is derived numerically from the voltage-drop value by dividing by $\sqrt{3}$. This comes about because 3-phase voltage drop values are conventionally expressed as values between the line conductors (line to line values). When multiplied by the line currents the mV/A/m values give the reduction, from one end of the cable to the other, in voltage between the line conductors. However, to calculate the power loss in each conductor it is necessary to know the resistance per metre along the conductor; this is obtained by dividing by $\sqrt{3}$.

The cable and termination costs are estimated values, accurate enough to illustrate the principles being explained.

The values in column 3 of Table CB K-2 provide the data for Figure CB C-1 in Appendix 3 C.

The cable installation costs for Figure CB C-3 of Appendix 3 C are obtained from the last three columns of Table CB K-2.

The cost of the energy losses along the cable when carrying the 101 A load is calculated using the equations given in Appendix 3 C, and the numerical working is given in tabular form for the seven sizes of cable as shown in Table CB K-3.

Table CB K-3 Calculation of Costs of Energy Losses

Current = 101A, length of cable = 100m, 3 conductors, duration of load = 400 hours/month.

Conductor size mm ²	Power loss I ² R W/m/cond	Power loss kW/cable	Energy lost kWh per month	Unit cost £ per month	Demand cost £ per month	Total cost £ per month
25	8.83	2.649	1,060	53	7.95	60.95
35	6.48	1.944	778	38.9	5.83	44.7
50	4.71	1.413	565	28.3	4.24	32.5
70	3.24	0.972	389	19.5	2.92	22.7
95	2.42	0.726	290	14.5	2.18	16.7
120	1.95	0.585	234	11.7	1.76	13.46
150	1.53	0.459	184	9.2	1.38	10.58

The values in the final column of Table CB K-3 provide the data for Figure CB C-2 in Appendix 3 C. of the Report.

Figure CB C-4 is constructed in Table CB K-4, the values being obtained with the use of the discounting factor Q determined in Appendix 3 C, the costs of energy losses from Table CB K-3, and the installation costs from Table CB K-2.

Total equivalent cost = PV + installation cost (Eqn 12)

Table CB K-4 Total Costs

Discounting factor Q = 274

Conductor size mm ²	Cost of energy loss £/month (Table CB K-3)	PV times energy cost (£)	Installation cost (£) (Table CB K-2)	Total equivalent cost (£)
25	60.95	16,700	1,397	18,097
35	44.7	12,248	1,851	14,099
50	32.5	8,905	2,635	11,540
70	22.4	6,138	3,882	10,020
95	16.7	4,576	5,229	9,805
120	13.5	3,688	7,136	10,824
150	10.6	2,899	8,874	11,773

Figure CB C-4 is constructed from columns 3, 4 and 5 - see Appendix 3 C.

iv. Cable Selection and the IEE Wiring Regulations

Status of cable ratings in the IEE Wiring Regulations

The IEE Wiring Regulations is the U.K. national implementation of the international regulations for electrical installations (International Electrotechnical Commission Publication 364 and its European derivative Harmonisation Document 384). The Wiring Regulations provide acceptable means for complying with U.K. safety legislation and, in the context of this report, provide authoritative data on permissible maximum current carrying capacities of practically all types of cable used in domestic, commercial and industrial electrical installations.

The current carrying capacity of a cable is defined as that steady magnitude of current, in amperes, which a cable can carry continuously without exceeding a specified maximum working temperature, and is briefly referred to as its thermal rating. This magnitude of current is influenced by the extent to which the cable environment (neighbouring objects, other cables and air temperature), affects heat dissipation from a cable.

Appendix 4 of The Regulations provides guidance on the selection of a suitable size of cable and installation method to carry a given current safely.

Smaller sizes of conductor cannot be used without a risk of overheating and a reduction in the safe life of the cable.

The maximum continuous temperature at which a cable can operate is primarily determined by the type of insulating material supporting the live conductors. The most common material for 230/400 volt general distribution and final circuits is PVC, which has a good life expectancy when working at temperatures up to 70°C.

Other materials, such as ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) can operate up to 90°C. For special environmental conditions there are butyl-rubber based insulants, but these are usually too expensive for general purpose work.

It is important to note here that the use of low energy loss sizes of conductor implies low conductor temperatures. Not only does this make appropriate the use of economical low temperature types of cable, but implies long operational life.

It is increasingly recognised that the most appropriate use of high temperature insulants in 230/400 V systems is not with a view to reducing conductor size through higher operating temperatures, but to avoid increasing conductor size because a cable route passes through local sites of very adverse thermal conditions such as the vicinity of boilers and hot equipment, cable bottle-necks, or passing unavoidably through thermal insulation.

Attention has been drawn to the fact that terminals on the majority of present day equipment complying with international standards are not intended to accommodate conductors which run continuously at temperatures above 70°C.

An advantage of EPR and XLPE insulants is that they can withstand high short-circuit temperatures and are chosen for this reason rather than to operate at high working temperatures.

a. Sample current-carrying capacities, voltage drops, ambient temperature and group reduction coefficients

The data and guidance provided here are intended to facilitate a practical examination of the technique of economic sizing of cables. Statements made here do not replace the Regulations.

The following guidance notes, sample values of current-carrying capacities, voltage drops and coefficients have been extracted for the reader's benefit from Appendix 4 of the IEE Regulations. The Regulations should be consulted before considering the design of an installation.

Table CB K-5 Mineral Insulated Cable - Current-Carrying Capacity

Maximum sheath temperature 70°C Ambient temperature 30°C

Conductor size mm ²	Number of conductors		
	2-cond A	3-cond A	4-cond * A
1.5	25	21	21
2.5	34	28	28
4	45	37	37
6	57	48	47
10	77	65	64
16	102	86	85
25	133	112	110

* 3-phase load.

Table CB K-6 Mineral Insulated Cables - Voltage Drop

Maximum conductor temperature 70°C.

Conductor size mm ²	Single-phase 2-conductor mV/A/m	Three-phase 3 or 4-conductor mV/A/m
1.5	28	24
2.5	17	14
4	10	9.1
6	7	6
10	4.2	3.6
16	2.6	2.3
25	1.65	1.45

Table CB K-7 PVC-Insulated Conductors in Conduit or Trunking - Current-Carrying Capacity and Voltage Drop

Maximum conductor temperature 70°C Ambient temperature 30°C

Conductor X-section mm ²	Current-carrying capacity A		Voltage drop mV/A/m					
	1 ph	3 ph	1 ph			3 ph		
1.5	17.5	15.5	29			25		
2.5	24	21	18			15		
4	32	28	11			9.5		
6	41	36	7.3			6.4		
10	57	50	4.4			3.8		
16	76	68	2.8			2.4		
			R	x	z	r	x	z
25	101	89	1.80	0.33	1.80	1.50	0.29	1.55
35	125	110	1.30	0.31	1.30	1.10	0.27	1.10
50	151	134	0.95	0.30	1.00	0.81	0.26	0.85
70	192	171	0.65	0.29	0.72	0.56	0.25	0.61
95	232	207	0.49	0.28	0.56	0.42	0.24	0.48

Note to Table CB K-7: r is the resistive voltage drop, x is the reactive voltage drop, and z is the vector sum of the two.

Table CB K-8 600/1000V Multi core PVC-Insulated Steel Wire Armoured Cables - Current Carrying Capacity

Maximum conductor temperature 70° C Ambient temperature 30° C

Conductor X-section mm ²	Multi-core cables mounted			
	clipped to a wall		on brackets or trays	
	1 ph A	3 ph A	1 ph A	3 ph A
1.5	21	18	22	19
2.5	28	25	31	26
4	38	33	41	35
6	49	42	53	45
10	67	58	97	83
16	89	77	97	83
25	118	102	128	110
35	145	125	157	135
50	175	151	190	163
70	222	192	241	207
95	269	231	291	251
120	310	267	336	290
150	356	306	386	332
185	405	348	439	378
240	476	409	516	445
300	547	469	592	510

Table CB K-9 600/1000V Multi-Core PVC-Insulated Steel-Wire Armoured Cable - Voltage Drop

Maximum conductor temperature 70° C

Conductor X-section mm ²	Voltage drop mV/A/m					
	2-core cable (1 ph loads)			3 or 4-core cable (3 ph loads)		
1.5	29			25		
2.5	18			15		
4	11			9.5		
6	7.3			6.4		
10	4.4			3.8		
16	2.8			2.4		
	r	x	z	r	x	z
25	1.75	0.170	1.75	1.50	0.145	1.50
35	1.25	0.165	1.25	1.10	0.145	1.10
50	0.93	0.165	0.94	0.80	0.140	0.81
70	0.63	0.160	0.65	0.55	0.140	0.57
95	0.47	0.155	0.50	0.41	0.135	0.43
120	0.38	0.155	0.41	0.33	0.135	0.35
150	0.30	0.155	0.34	0.26	0.130	0.29
185	0.25	0.150	0.29	0.21	0.130	0.25
240	0.190	0.150	0.24	0.165	0.130	0.21
300	0.155	0.145	0.21	0.135	0.130	0.185

Note to Table CB K-9: r is the resistive voltage drop, x is the reactive voltage drop, and z is the vector sum of the two.

Table CB K-10 Ambient Temperature Adjustment Coefficients

Cable type	Ambient temperature °C				
	30	35	40	45	50
70°C PVC	1.00	0.94	0.87	0.79	0.71
70°C Mineral	1.00	0.93	0.85	0.77	0.67

Table CB K-11 Group Reduction Factors, Cables Touching

Installation method	Number of cables				
	2	3	4	5	6
Clipped to surface	0.85	0.79	0.75	0.73	0.72
Clipped to perforated metal tray	0.86	0.81	0.77	0.75	0.74
Enclosed in conduit or trunking	0.80	0.70	0.65	0.60	0.57

b. Selection of conductor thermal size to suit load

Following the selection of a type of cable suited to the environmental conditions, it is necessary to select a minimum thermal size of conductor. This size is the smallest used for evaluation of a total cost/size characteristic. It must be large enough to carry the highest current demanded by the load.

1. Determine the maximum line current required by the equipment to be fed by the cable, see Appendix 3 K i, (this current may be marked on a name plate).

A ventilating fan motor is marked "20 kW, power factor 0.8, 400 volt."

Using the equations in Appendix 3 K i,

$$I = \frac{20 \times 1000}{\sqrt{3} \times 400 \times 0.8} = 36\text{A}$$

for 3 phase circuits.

If it is a single phase load marked "5 kW, power factor 0.75, 230 volt." the calculation would be

$$I = \frac{5 \times 1000}{230 \times 0.75} = 29\text{A}$$

2. If there is more than one piece of equipment, find the total current and the variation of the total with time, taking account of the possibility that all equipment may not be working at the same time.

This will provide a load cycle similar to those discussed in Appendix 3 G. The first task is to select a cable capable of carrying the highest load of the cycle.

The periodic time for a load cycle is defined by the duration over which the cycle repeats exactly. One such cycle is sufficient for conductor size selection, but the pattern with which the cycle repeats is important for an economic assessment.

3. Locate the highest value of current in the cycle.

4. The selection of a conductor size must take into account any growth in load during the life time of the project and the overload situation of the circuit.

If it is known that the loads will increase over the project life-time, multiply the value of the highest current by the coefficient

$$(1 + a/100)^N$$

Where a = average rate of growth per year, %.

N = duration of the project, year.

The result is the value of the highest current in the load cycle at the end of the final year, which the selected size of cable must be able to carry without overheating.

Selection of cable size to take care of overload depends on circumstances. The options are:

a) an overload will not be possible or

b) if the cable is to be installed by itself or, if it is in a group, whether or not all the grouped cables are subject to overload at the same time.

- If the cable will be in a group where simultaneous overload of all cables will not be possible (this is the most usual situation) the conductor size must be selected by inspection so that I_t is the larger of these two values

$$\frac{I_b}{C_a \times C_g} \quad \text{or} \quad \frac{1}{C_a} \sqrt{I_n^2} + \left(0.48 \times I_b^2 \times \frac{(1 - C_g^2)}{C_g^2} \right)$$

where I_b = peak current, including the allowance for growth, A. I_n = the rating of the circuit protective device, A.

C_a = ambient temperature coefficient.

C_g = group reduction coefficient.

- Where protection must be provided against overload and the cable will be either by itself or in a group where all cables will be simultaneously subject to overload, the conductor size must be selected by inspection so that

$$I_b \leq I_n \quad \text{and}$$

$$\frac{I_n}{C_a \times C_g} \leq I_t$$

- Where IEE Regulation 473-01-04 applies (overload will not be possible) the conductor size may be determined by the equation

$$\frac{I_b}{C_a \times C_g} \leq I_t$$

The points to build up the total cost/conductor size characteristic are then evaluated as shown in Appendices 3 C and G, starting with the thermal minimum size determined by the above procedures, followed by repeat calculations with successively larger sizes. For this operation the load cycle is used without any allowance for growth, because growth, if any, is taken into account in the calculations of the discounting coefficient Q and the resistance coefficient C_r .

v. Resistance Adjustments for Partly Loaded Cables

Source of current ratings and conductor resistance

Standard current carrying capacities or ratings are tabulated for a conductor temperature of 70° C when the cable is in an ambient of 30° C. Coefficients, C_a , are provided so that a rating can be adjusted to other ambient temperatures.

The resistance of a cable conductor at 70° C is obtainable from the values of mV/A/m_r provided in tables of voltage drop. The tables in this report have been extracted from more comprehensive tables in the IEE Regulations.

The mV/A/m values are provided for the calculation of voltage drop in a circuit but they can be used to obtain values of conductor resistance. For this purpose the resistive component mV/A/m_r is used. For conductors of 16 mm² cross-section and less there is no practical difference between the values of mV/A/m_r and mV/A/m.

The relation between a value of mV/A/m_r and a corresponding conductor resistance depends on the number of conductors in a cable. This comes about because of the convention used to express voltage drop. The voltage drop is conventionally expressed as a reduction in voltage between the live conductors at the receiving end of the circuit when the cable is carrying a given load. For a single phase circuit it applies to the line and neutral conductors while for a three phase circuit it applies between any two line conductors. The tabulation of the mV/A/m figures takes this difference into account.

To obtain the resistance of a conductor for a single phase cable

$$R = \frac{mV/A/m_r}{2} \text{ milliohm/metre}$$

and for a three phase cable (3 or 4 cores)

$$R = \frac{mV/A/m_r}{\sqrt{3}} \text{ milliohm/metre}$$

Effect of magnitude of current on conductor resistance

In Appendix 3 G the reduction in conductor temperature and resistance as the load current is reduced is explained and the effect on cable energy loss and cost is demonstrated. Adjustment to the conductor resistance is effected by multiplying the resistance for the maximum working temperature, derived from the mV/A/m tables, by a coefficient C_t . This amounts to introducing C_t into Equations (2) to (5) in Appendix 3 C.

Equation (2) becomes:

$$\text{power loss} = \frac{I^2 \times C_t \times R \times N_p \times L}{1000} \text{ kW}$$

where

$$C_t = 1 - \frac{\left(C_a^2 \times C_g^2 - \left(\frac{I}{I_t} \right)^2 \right) \times (t_p - 30)}{234.5 + t_p}$$

where C_a = ambient temperature coefficient

C_g = reduction coefficient for groups

I = load current for the first year, A

I_t = tabulated rated current for cable, A

T_p = maximum working temperature of cable for which I_t is tabulated, °C

Note that the constant 234.5 is only valid for copper

For a constant current the conductor temperature, although less than the maximum working value, is also constant, but where the current changes the temperature and resistance also change.

There are two situations envisaged in this report where it is desirable to adjust conductor resistance to take account of load changes:

- a) where a load current has different values during the course of a load cycle and
- b) where a load increases during the life-time of the project.

In the first case the coefficient C_t and the conductor resistance R should be calculated for each different value of current in the load cycle. Together with the accompanying calculation of wasted energy this can sometimes be a very tedious process.

The effort can be reduced considerably, with the introduction of only a small error, by calculating the root mean square (r.m.s.) current for each price zone of the energy tariff.

If the values of cable current during a tariff price zone are i_1, i_2, i_3 etc. and the duration of each value is t_1, t_2, t_3 etc. the r.m.s. value is

$$I_{\text{rms}} = \sqrt{\frac{i_1^2 t_1 + i_2^2 t_2 + i_3^2 t_3 + \dots}{t_1 + t_2 + t_3 + \dots}}$$

A single value of the coefficient C_t and the power loss for that tariff zone are calculated using I_{rms} in place of I .

The process is repeated for each tariff zone, see the example in Appendix 3 I.

In the second case all current values in a load cycle are assumed to increase more or less gradually during the project life. As far as the change in load current is concerned this increase is accommodated by introducing the growth coefficient "a" into the calculation of the discount coefficient Q , see Appendix 3 K ii, but this does not take into account the accompanying change in conductor resistance.

The arithmetic is reduced by introducing a Coefficient G into the calculation of each value of C_t . The above equation for C_t becomes

$$C_t = 1 - \frac{\left(C_a^2 \times C_g^2 - G \times \left(\frac{I}{I_t} \right)^2 \right) \times (t_p - 30)}{234.5 + t_p}$$

where

$$G = \frac{1 + \left(1 + \frac{a}{100} \right)^{2N}}{2}$$

a = average growth in load current, percent per year

In the most usual cases there is no load growth so that $a = 0$ and $G = 1$ and the equation reverts to the original form.

Numerical investigation showed that the effect of a variation in C_t during the life of a project can be represented with sufficient accuracy by using an average of the first and last years' values of C_t .

Let I_1 = the value of I in the first year

and I_2 = the value of I in the last year

$$I_2 = I_1 \times \left(1 + \frac{a}{100} \right)^N$$

Then

$$I_2^2 = I_1^2 \times \left(1 + \frac{a}{100} \right)^{2N}$$

The average value of $(I/I_t)^2$ in the equation above for C_t is

$$\begin{aligned} \frac{I_1^2 + I_2^2}{2 \times I_t^2} &= \frac{I_1^2 + I_1^2 \left(1 + \frac{a}{100} \right)^{2N}}{2 \times I_t^2} \\ &= \frac{I_1^2}{I_t^2} \times \frac{1 + \left(1 + \frac{a}{100} \right)^{2N}}{2} \end{aligned}$$

$$= G \times \left(\frac{I_1}{I_t} \right)^2$$

$$\text{where } G = \frac{1 + \left(1 + \frac{a}{100} \right)^{2N}}{2}$$

Suppose that we have a daily load cycle with 3-phase currents of 20 A from 0000 to 1200 hours and 30 A from 1200 to 2400 hours during the first year of a project. Cable length is 50m. $C_a = 1$ and $C_g = 1$.

The tariff has two zones, from 0000 to 0700 hours and 0700 to 2400 hours.

The project life is 20 years, growth during this time averages out to 1.5 % per year.

The highest current during the first year is 30A

The highest current during the last year is

$$30 \times \left(1 + \frac{1.5}{100} \right)^{20} = 40.4 \text{ A}$$

This current will require a 6 mm² 3-core cable.

For this cable mV/A/m = 6.4 and R = 3.695 milliohm per metre

$I_t = 43 \text{ A}$.

$$G = \frac{1 + \left(1 + \frac{1.5}{100} \right)^{2 \times 20}}{2} = 1.407$$

For the first tariff zone of 7 hours

$$C_t = 1 - \frac{\left(1 - 1.407 \times \left(\frac{20}{43} \right)^2 \right) \times (70 - 30)}{304.5} = 0.908$$

first year's power loss

$$= \frac{20^2 \times 0.908 \times 3.695 \times 3 \times 50}{1000 \times 1000} \text{ kW}$$

$$= 0.2013 \text{ kW}$$

For a 7 hour period the energy lost

$$= 0.2013 \times 7 = 1.41 \text{ units}$$

For the second tariff zone, 0700 to 2400 hours, it is convenient to find the rms value of the current.

$$I_{rms} = \frac{(20^2 \times 5) + (30^2 \times 12)}{17}$$

$$= 27.44 \text{ A}$$

$$C_t = 1 - \frac{\left(1 - 1.407 \times \left(\frac{27.44}{43}\right)^2\right) \times (70 - 30)}{304.5}$$

$$= 0.943$$

For a 17 hour period the power lost

$$= \frac{27.44^2 \times 0.943 \times 3.695 \times 3 \times 50}{1000 \times 1000}$$

$$= 0.3935 \text{ kW}$$

For a 17 hour period the energy lost

$$= 0.3935 \times 17 = 6.69 \text{ units}$$

The energy lost during one cycle is

$$1.41 + 6.69 = 8.1 \text{ units.}$$

Conductor resistances obtained from other sources

If it is desired to obtain conductor resistances from other sources, they will probably be tabulated for a temperature other than 70° C.

Conversion from resistance values at one temperature to values at another, say to 70°C, can be easily effected by use of the following equation.

$$R_{t_2} = R_{t_1} \times \frac{(234.5 + t_2)}{(234.5 + t_1)}$$

where

t_1 = temperature °C for which the resistance is tabulated.

t_2 = temperature °C at which the resistance is required.

R_{t_1} = value of resistance at temperature t_1 .

R_{t_2} = required value of resistance at temperature t_2 .

The figure of 234.5 applies only to copper conductors.

vi. Typical Costs of Cable and Terminations

The following costs for cable and terminations are provided so that readers can gain experience in the application of the techniques described in this report.

Although the figures given are thought to be realistic they should not be used for quotation purposes since they can become out of date.

They apply to cable and terminations installed with the usual supports and fixings. The usual trade discounts, overheads and charges are included.

The installed cost of a length L metres of cables with a termination at each end is calculated by

$$\text{Installed cost} = (\text{cable price} \times L) + (\text{termination price} \times 2)$$

Table CB K-12 Mineral-Insulated Copper-Sheathed Cable (m.i.c.c.) Installed Prices

Conductor size mm ²	Installed Price (£)					
	2 conductors		3 conductors		4 conductors.	
	cable/m	termination each	cable /m	termination each	cable/m	termination each
1.5	8.6	7.49	9.25	8.09	10.98	8.53
2.5	10.11	7.51	11.85	8.1	13.66	8.57
4	12.59	7.91	14.06	8.65	15.42	11.04
6	14.94	7.94	15.66	10.74	17.9	11.08
10	17.38	10.01	18.99	10.76	22.84	11.11
16	21.63	10.55	25.37	11.17	29.71	15.43
25	27.07	14.4	31.51	25.99	37.17	26.51

Table CB K-13 PVC Unsheathed Cable in Steel Conduit or Trunking - Installed Prices

(connecting tails and entry holes included)

Conductor size mm ²	Installed price per metre (£)			Conduit or trunking
	2 wire	3 wire	4 wire	
1.5	11.59	12.07	12.55	C
2.5	11.89	13.12	13.15	C
4	12.39	13.27	14.15	C
6	12.87	13.99	17.11	C
10	16.27	18.29	22.61	C
16	17.75	22.80	25.29	C
25	23.41C	22.99T	27.03T	
35	22.05	26.98	32.35	T
50	26.81	34.78	42.75	T
70	32.37	45.12	53.87	T
95	41.53	59.87	72.19	T
120	52.77	76.73	97.68	T
150	62.99	92.12	118.12	T

C = Conduit; T = Trunking

Table CB K-14 PVC-Insulated Steel-Wire Armoured Multi Core Cable - Installed Prices

Conductor size mm ²	Installed price (£)					
	2-core		3-core		4-core	
	cable/m	termination each	Cable/m	termination each	cable /m	termination each
1.5	2.54	9.71	2.93	10.25	3.35	10.91
2.5	2.96	9.71	3.39	10.25	3.95	10.91
4	3.96	9.71	4.58	11.43	5.74	12.10
6	4.62	11.71	5.7	11.57	6.68	12.23
10	6.52	14.51	8.25	15.45	8.72	16.78
16	6.72	16.11	9.96	16.91	10.3	18.24
25	10.58	17.70	13.60	18.50	19.40	21.00
35	13.24	19.30	18.10	20.50	25.80	23.00
50	17.44	20.50	25.90	22.50	38.30	26.00
70	24.00	22.00	38.30	26.00	51.60	29.00
95	-	-	51.70	29.50	61.60	33.00
120	-	-	70.70	33.00	100.50	35.00
150	-	-	88.00	37.00	125.00	37.50

L. List of Symbols

a = average growth of load over N years, percent per year.

b = average increase in price of energy (P and D) over N years, percent per year.

i = discount rate, percent per year.

VA = product of volts \times amperes in a circuit or passed by equipment.

kVA = $VA/1000$.

kW = electrical power, kilowatt = 1000 Watt.

kWh = kilowatt hour or "unit", unit of electrical energy.

pf = power factor in an A.C. circuit.

r_a = auxiliary quantity, used when payments are made yearly.

r_m = auxiliary quantity, used when payments are made each calendar month.

r = voltage drop due to the resistance of a conductor, $mV/A/m$.

t = duration of part of a load cycle, hour. May take a suffix.

t_1, t_2 = temperatures above $0^\circ C$ of conductors, $^\circ C$.

t_p = maximum working temperature of a cable for which I_t applies.

x = voltage drop due to the reactance of a conductor, $mV/A/m$.

z = voltage drop due to the impedance of a conductor, $mV/A/m$.

C_a = coefficient which multiplies the value of I_t to adjust it to a different ambient temperature.

C_d = cost in \pounds for maximum power supplied.

C_g = coefficient which multiplies I_t to take account of heating from other similar cables in a group.

C_i = cost of installing cable and terminations, \pounds .

C_j = cost in \pounds for units of energy used.

C_t = coefficient which multiplies a conductor resistance to adjust its value to a lower working temperature.

D = price for providing a supply, or demand charge, in \pounds/kW per month or for period covered by bill.

G = coefficient to adjust conductor resistance to an average value during the project life time.

I = Electric current, amperes, or conductor current for a given load, amperes. (I may carry a suffix to indicate special situations.)

I_n = standard rating of an overcurrent protection device, ampere.

I_t = tabulated current carrying capacity, ampere.

L = length of cable route, m.

N = duration of project for which cable is installed, year.

N_p = number of active conductors in a cable.

P = price per kWh or "unit" of electrical energy, pence.

P_c = price of installed cable, \pounds/m

P_t = price of installed and jointed termination, \pounds each.

PV = present value of costs to be paid in the future.

Q = discount factor, to provide PV of multiple future costs.

R = conductor resistance, ohm.

T = duration of current flow, hour.

U = nominal line to line voltage of an electrical system, volts.

U_0 = nominal line to earth (usually also to neutral) voltage of an electrical system, volts.

V = voltage at point of supply to a circuit or at terminals of equipment, volts.

W = electrical power, Watt.

4. Types of Copper

Copper has the highest conductivity of any of the commercial metals. It has good mechanical properties at low, ambient and elevated temperatures and has excellent resistance to corrosion. It is mined in every inhabited continent. Ore reserves, and the continuing development of mining techniques, are such that future supplies are assured.

There are three popular types of copper; high conductivity, phosphorous de-oxidised and oxygen free.

In addition there are a wide variety of less-common high conductivity copper alloys with improved properties for special applications. Further details of all these materials are available in another document³².

A. High-Conductivity Copper

High Conductivity (HC) Copper, with a nominal conductivity of 100% IACS (International Annealed Copper Standard), is the first choice material used for electrical applications such as earthing strip and wire, busbars, cables and windings for motors and transformers. It was designated C101 in British Standards, Cu-ETP in BS EN specifications and CW003A or CW004A in the BS EN computer designations. HC copper is very readily worked hot and cold. In annealed form, it has excellent ductility which means that it can easily be bent to shape. It is available in all fabricated forms.

It work hardens relatively slowly and can be annealed in neutral or oxidising atmospheres. Oxygen is intentionally present in HC copper to combine with residual impurities so that they have no effect on conductivity. The oxygen can be reduced to steam if the copper is annealed in atmospheres containing excess hydrogen, causing embrittlement. 'Bright' annealing atmospheres therefore have to be carefully controlled.

When copper is being cast to shape, normal shrinkage is largely offset by the evolution of steam formed from dissolved oxygen and hydrogen. When conditions are correct, this gives a level 'set' to the top of the casting and has led to the expression 'tough pitch' to describe high conductivity copper. This is not now so relevant since most copper is now cast continuously and the desirable oxygen content is reduced. When in cast form, copper does not have quite such a high conductivity as it has after being worked and annealed.

The addition of silver to copper improves elevated temperature properties, especially creep strength. Since silver is counted as copper in the specification, the material is still designated C101 (or Cu-ETP(Ag)) and the required silver content is agreed separately at the time an order is placed.

B. Deoxidised Copper

The use of deoxidants when casting copper ensures that excess oxygen is removed which produces a material that can readily be brazed or welded without fear of embrittlement. Phosphorous is the preferred deoxidant and conductivity is slightly reduced. This copper, C106 (Cu-DHP, CW024A), sometimes also called 'DONA copper', is standard for the production of tubing for fresh water services. It is available in rod and strip form but, besides being available as tube, is normally used in sheet form as the preferred material for fabricated items such as hot water cylinders. The phosphorous content reduces conductivity to about 92% of that of HC copper for the minimum of 0.013% or to 73% if at the maximum of 0.05% phosphorous. This is still a better conductor than many materials. For castings, boron is frequently used as a deoxidant and many other additions also have a deoxidising effect.

C. Oxygen Free High-Conductivity Copper

Designated C103, (Cu-OF or CW008A), this copper is made only by casting in a controlled atmosphere. It can subsequently be worked exactly as normal high conductivity copper. It is

used for applications where high conductivity of over 100% IACS is required in addition to freedom from the possibility of embrittlement in reducing atmospheres. It may be welded or brazed without special precautions needed for normal high conductivity copper. There is a grade of higher purity still, C110 (Cu-OFE, CW009A) that is normally only required for high-vacuum electronic applications such as transmitter valves. This is certified to have a very high purity and low residual volatile gases.

D. High-Conductivity Copper Alloys

For electrical applications such as resistance welding electrodes where service is at high temperatures under heavy stress, special alloys are available. The most popular of these is copper chromium, CC101 (CW105C), which contains up to 1% of chromium and is fully heat treatable to excellent room temperature properties which are maintained well as operating temperatures rise. Conductivity is around 80% IACS which makes the material suitable for applications such as rotor rings for use in heavy-duty rotating electrical machines.

5. Methods of Financial Appraisal

A. Evaluating the savings

Some savings, such as those due to tariff changes, are easy to calculate, but those arising from changes in consumption require the use of statistical methods using data from meter readings. The CUMulative SUM deviation method (contracted to CUSUM) is a valuable technique for this purpose.

CUSUM measures bias in equal interval sequential data. If data about a building is gathered at regular intervals and a change in consumption takes place, CUSUM can detect the time and quantify the amount of the change. CUSUM is easy to calculate and can detect changes of the order of 1 to 2 %.

An example can be found in 'Good Practice Guide 165' (Reference 1).

B. Methods of Financial Appraisal

Before any method of appraisal can be applied, it is first necessary, having identified the opportunity, to gather all the facts which will help to build the case for the project. All the costs and benefits accruing in each year must be identified and the cash flow established as shown below for a simple hypothetical project.

Year	Cost (£)	Benefit (£)
0	40,000	
1		18,000
2		18,000
3		18,000
4		18,000
5		18,000

i. Payback

The simplest parameter to calculate is payback. It is simply the capital cost divided by the annual savings: -

$$\text{Payback} = \frac{\text{Capital Cost}}{\text{Annual Savings}}$$

$$\text{Payback} = \frac{40,000}{18,000} = 2.22 \text{ years.}$$

Payback is simple to calculate, easy to understand, gives a result in tangible units (years), and does not require any assumptions about project lifetime or interest rates. However, it has the disadvantage of not taking account of savings beyond the payback period, the residual capital value of the plant and the time value of money.

Properly calculated, payback gives a measure of liquidity - the time taken before the net cash flow is positive and the project is no longer a drain on resources. It also provides a measure of risk - if the payback period is short then the project is much less likely to be affected by variations in, for example, interest rates, than if the payback were longer.

The main problem is that the simplicity of payback encourages misuse. Many organisations set simple payback barriers to filter out the less likely projects, but for the reasons set out above this may not reflect the true worth of a project. A project with a payback of two years and a lifetime of three years may be accepted while one with a payback of three years and a lifetime of fifteen years may be rejected. Clearly, the longer project will be the most beneficial to the

organisation, but may not be fully considered by management because it does not clear an artificial payback hurdle.

ii. Undiscounted Financial Analysis

There are four other parameters which are based on the simple undiscounted cash flow, which are:-

- Gross return on capital
- The total benefit from the project over its lifetime divided by the capital cost, expressed as a percentage.
- Net return on capital
- The total benefit from the project over its lifetime **less the capital cost** divided by the capital cost, expressed as a percentage.
- Gross average rate of return
- The gross return on capital (as above) divided by the lifetime
- Net average rate of return
- The net return on capital (as above) divided by the lifetime

All these parameters differ from payback in that they take into account savings made after the project has paid back its initial cost. Taking the figures from the example cash flow the gross revenue is £90,000 and the net revenue is £50,000.

$$\text{Gross return on capital} = \frac{90,000}{40,000} \times 100 = 225 \%$$

$$\text{Net return on capital} = \frac{50,000}{40,000} \times 100 = 125 \%$$

$$\text{Gross annual average rate of return} = \frac{90,000}{40,000} \times 100 \times \frac{1}{5} = 45 \%$$

$$\text{Net annual average rate of return} = \frac{50,000}{40,000} \times 100 \times \frac{1}{5} = 25\%$$

In situations where the project lifetime cannot be known the assumed lifetime, shorter than that anticipated, should be clearly stated.

iii. Discounting

The purpose of discounting is to take account of the time value of money, i.e. the value of a sum to be received next year is less than the value of the same sum received today. The time value is allowed for by applying a discount factor to costs and earnings in all future years. The discount factor is normally found from a table of values but can be calculated from

$$\text{Discount rate} = \frac{1}{(1+r)^n}$$

where r is the discount rate expressed as a decimal

n is the number of years into the project

Discount Rate %	5	10	15	20
No of years into project				
1	0.952	0.909	0.870	0.833
2	0.907	0.862	0.756	0.694
3	0.864	0.751	0.658	0.579
4	0.823	0.683	0.572	0.482
5	0.784	0.621	0.497	0.402
6	0.746	0.564	0.432	0.335
7	0.711	0.513	0.376	0.279
8	0.677	0.467	0.327	0.233
9	0.645	0.424	0.285	0.194
10	0.614	0.386	0.247	0.162

Discounting is not a method of appraisal in itself but a modification to be applied when calculating parameters. It should not be applied to simple payback calculations, but can be applied to the four return-on-capital calculations discussed above. More commonly it is applied to the net return on capital to give Net Present Value.

The example cash flow, discounted at a rate of 10% becomes:

Year	Cost (£)	Benefit (£)	Discount Rate (at 10 %)	Present Value (£)
0	40,000		1	
1		18,000	0.909	16,362
2		18,000	0.826	14,868
3		18,000	0.751	13,518
4		18,000	0.683	12,294
5		18,000	0.621	11,178

Gross Present Value 68,220

Less Capital Cost 40,000

Net Present Value (NPV) 28,220

The net Present Value is of particular interest to financial managers because it tells them what the project will earn over its costs in today's money over its expected lifetime.

iv. NPV/Capital Ratio

The NPV/Capital ratio is a useful value because it takes into account the size of the project and is a direct reflection of the relative return. It is particularly useful when trying to identify projects to carry out within a fixed capital budget.

C. Selecting the Discount Rate

The appropriate discount rate is the cost of capital, i.e. the interest which has to be paid on borrowed money to finance the project. It will be a composite figure, representing the weighted average of all the sources of finance used by the organisation. Often the figure is somewhat arbitrary.

Inflation is not itself an issue because it affects both capital costs and revenue and therefore cancels out.

D. Internal Rate of Return

If the organisation has no standard discount rate it is not possible to calculate the Net Present value. To do so by assuming a value is dangerous, since the investment may have to stand comparison with another project for which a more or less advantageous rate has been assumed. Management may then seek explanations of the basis on which the assumptions were made. The alternative is to calculate the Internal Rate of Return which is the discount rate at which the NPV reduces to zero. The method has the drawbacks that there is no way to relate it to the size of the project and it cannot be calculated directly, requiring a successive approximation method. Care must be taken in the calculation of IRR especially when spreadsheet programmes are used - it is possible for the first value to be incorrect and cause the successive approximation to be incorrect - so all results should be carefully scrutinised.

E. Annual Equivalent Cost

The annual equivalent cost is another way of using discounting, preferred by some organisations. The NPV of the project is divided by the NPV of £1 over the same lifetime. For the example given in 'Net Present Value', the NPV of £1 would be £3.79, so the AEC is £28,220, or £7446. This represents the average future annual benefit at present money value.

F. Project lifetime

Clearly the project lifetime has a great influence on the financial appraisal because the more years are included the greater the NPV or IRR. The project life is usually less than the physical lifetime of the equipment in question perhaps because its function has become obsolete or can be carried out more effectively in another way. Assessing the project life can be very difficult and it will always remain so.

G. Sensitivity analysis

In most cases it will not be possible to accurately know all the data, for example, the design of the plant may not be finalised and future electricity costs cannot be determined accurately, so it is necessary to test the result to check how dependent the appraisal is on each variable, and take steps to refine the data accordingly. If the uncertainty can be reduced to the point where the variation does not exceed that due to a change in life time of ± 1 year then the appraisal can be considered sufficiently accurate.

H. Summary

This section has given a brief overview of the considerations and techniques required in the preparation of financial appraisals of energy saving projects. Those who are responsible for preparing and reviewing appraisals are referred to BRECSU Guide 165 for further detail.

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