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Life-cycle assessment of 11 kV electrical overhead lines and underground cables

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A B S T R A C T

The life-cycle impacts of five different 11 kV electrical power cables (three overhead lines and two underground cables) were analysed. These were compared by their embodied impacts in production and total lifetime operational impacts. The life-cycle results revealed there to be three key issues, the impacts of climate change, fossil fuel depletion, and particulate matter formation (PMF). The former two were of particular significance. The embodied impacts, which are those associated with the materials, were generally determined to be insignificant. The exception was for underground cables at low operating loads. Under these conditions PMF was more significant as a result of the high embodied impacts of the cables. Further analysis revealed that these impacts could be mitigated with an end of life material recovery program. At present the underground cables are not recovered, but if they were the recycling benefits would give rise to a notable improvement in PMF. For the other impact categories operational conductor losses were the dominant cause of impacts. In summary it was concluded that to minimise the life-cycle impacts of 11 kV cables the system with the lowest conductor resistance should be selected.

1. Introduction

Modern society is underpinned by a complex web of economic and social activities; commerce, transport and leisure interweave providing support to not only sustain, but also enhance our ways of life. With this we have created unprecedented environmental impacts and significant demand upon our resources. Much of this is associated with our current supply of energy, which is utilised to satisfy our intense consumption activities. These activities require vast quantities of resources, thus placing great burdens upon our natural environment.

Anthropogenic induced climate change is now largely accepted as a reality. It is therefore clear that concerted action must be taken; not only to limit, but also to reverse any long-term damage, and thus ensuring that we live on this planet in a sustainable manner. The electricity supply sector is somewhat unique given that technological and market changes, which may affect the generation of electricity, have broad sweeping, and knock-on, effects across the whole economy. Each economic sector consumes electricity and therefore any change in emissions affects the impacts of all other sectors. The electricity supply system suffers an approximate loss of 65% of the primary energy input (DTI, 2005) – predominantly as a result of waste heat during electricity production, but also through transmission and distribution losses (Allen et al., 2008a). The latter were calculated to be 7.4% in 2008 (see DECC, 2009; Anon, 2009a), therefore appropriate measures could provide a small benefit to society and an economic benefit to the electricity supply companies.

The present study concentrates on the appropriate selection of electrical power cables and considers both the embodied impacts of production and the effect of operational losses. Cables may be of the overhead or underground variety and with varying conductor size. Electricity suppliers, for reasons of cost and energy efficiency targets, need to ensure that the correct distribution method is chosen. Overhead lines are often selected by distributors for economic reasons, but they are considered to be more visually intrusive than underground cables (which are often used in urban areas). However, to date little work has been undertaken on the comparative environmental impact of the two systems. Therefore, this study was undertaken in order to assess the environmental impact of (11 kV) overhead lines and underground cables, including all aspects of their life cycle from production, installation, through to use and finally end of life treatment.

2. Goal and scope

The goal of this work was to determine the life-cycle impacts of a range of 11 kV electrical power cables, as used in the high voltage distribution network. This work will help identify (before installation) the most environmentally appropriate cable selection. A total

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Table 1
Cable conductor size and max normal loading.

Conductor size	Absolute max loading (A)	Max normal loading (A)
25 mm^2 overhead (copper)	205	102.5
38 mm^2 overhead (copper)	261	130.5
100 mm^2 overhead (copper)	482	241
95 mm^2 underground (aluminium)	283	141.5
185 mm^2 underground (aluminium)	407	203.5

of five options were identified, three overhead lines and two underground cables, which were compared based on their embodied impacts in production and total lifetime operational impacts. The five cables each had different conductor sizes, conducting materials and loading capacity.

Comparison of the cables by conductor area was not considered as an appropriate mechanism. This was especially true when comparing an overhead with an underground conductor due to the different conducting materials and cooling mechanisms. Copper and aluminium have different conductive properties and naturally experience different resistive forces in conduction. This is demonstrated by comparing the maximum loading capacity (A) of the conductor cables, as shown in Table 1. The conductors are required to have a capacity equal to twice the maximum normal loading (see Section 3.1).

Table 1 demonstrates that conductor area is not directly related to carrying capacity because of the different aluminium and copper conductors. In the context of this report the term ‘oversized cables’ will refer to a larger carrying capacity and not necessarily a larger conductor diameter.

2.1. System boundaries & functional unit

The system boundaries of the base data are consistent with the ecoinvent version 2.0 (Anon, 2009b) database, which was used as the background data for this study and modelled in the proprietary LCA software package *SimaPro* version 7.1. The exception was the base data for the wooden poles, which was taken from the IDEMAT database (Anon, 2005), due to the absence of the correct tree species within ecoinvent V2.0. The impacts of capital equipment (infrastructure) were included within the boundaries of study. Unless otherwise stated all energy is measured in higher heating values (HHV) and has been traced upstream into primary equivalents. The base ecoinvent data has been tailored towards to specific needs of this project. The system boundaries were further dictated by the selected methodology as defined in Section 3 (Methodology and Assumptions). For the full life-cycle comparative results the functional unit was ‘1 kWh of electricity transmitted through 1 km of an 11 kV cable installed in a rural environment’.

The flow chart of Fig. 1 shows the system boundaries of study.

3. Methodology & assumptions

This project was undertaken in conjunction with an electricity distribution company. Many of the assumptions within this section were based on their analysis.

3.1. Operational parameters

3.1.1. Maximum normal cable loading

This was assumed to be equal to 50% of its absolute max loading. In respect of the energy losses on the three overhead lines and two underground cables the 11 kV systems are designed so that they can withstand a prolonged single fault and that most demands can be restored within a few hours. This is implemented with “open rings” and a switch in the middle that may be closed. For example, consider two circuits, Fig. 2.

The substation at end A normally feeds loads B, C, D, E on the way to the open point just after E and near F. Conversely, the substation at end J normally feeds loads I, H, G, F to the open point just after F and near E.

If there is a fault between A and B, a switch is opened up at B (to prevent flowing electricity) and the “open point” is closed between E & F so that substation J is now feeding all the loads C, D, E, F, G, H, and I. That implies that the circuit rating between J and I (or vice versa between A and B) has to be sufficient to carry this abnormal load. This means that the maximum normal loading of these circuits can only be up to 50% of the maximum absolute loading.

3.1.2. Constant temperature conductors

As advised by the collaborating electricity distribution company a constant conductor operating temperature was assumed. This was 30 °C for overhead lines. At maximum loading these conductors are expected to operate at 50 °C, however max normal loading is 50% of the absolute maximum. For the underground conductors the maximum temperature was 90 °C.

3.1.3. Load demand

Demand load varies by season and throughout the day; changing 24 h a day and 365 days a year. The ratio of actual kilowatt hours transmitted throughout the year versus the kilowatts at peak demand × 8760 h (one year) is termed the “load factor”. Detailed analysis of the collaborating electricity distribution company load demands for every half hour of the financial year 2006/7 gave a load factor of 0.664. Thus the losses, which are a function of the square of the load current, are represented by a ‘loss load factor’ which is the square of the load factor, i.e. 0.664^2, which equals 0.44.

3.2. Further assumptions

3.2.1. Country specific modifications

The cable and conductor component list included Russian and Egyptian copper, Norwegian aluminium, Finish timber, plus UK and German steel. Where possible the base ecoinvent data for materials was modified for the country specific electricity mixtures. Ecoinvent contained data for the electricity markets in Finland, Norway, the UK (although the authors model of UK electricity was applied, see Section 6.1.3) and Germany. For the missing countries of Russia and Egypt the electricity generation mix was modelled in SimaPro using data from the International Energy Agency, IEA (2009).

The energy sector in Russia utilises a high percentage of combined heat and power (CHP), which generates electricity and heat simultaneously. These two different commodities are generated from a single fuel input which must be effectively allocated to the heat and electricity outputs. The heat production leaves the studied system boundary with is associated (allocated) impacts. An energy based allocation, an exergy based allocation (see for example, Van Gool, 1992; Hammond and Stapleton, 2001) and an economic based allocation were considered. An exergy based allocation was selected due to the consideration of both quantity and quality of energy produced. Further discussion and analysis between different methods was completed by Jungmeier et al. (1998) on a biomass CHP plant. However, an exergy based allocation is also the recommended method in the ecoinvent database (Dones et al., 2007). The exergetic quality of heat may be calculated with Equation (1).

$$\theta = 1 - \frac{T_0}{T_p} \tag{1}$$

where θ = Exergetic quality; T_0 = Ambient temperature, K; T_p = Process temperature, K.