WHOLE-LIFE COSTS AND ENVIRONMENTAL ASSESSMENT OF HIGH VOLTAGE POWER CABLE SYSTEMS

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ABSTRACT

This paper reports on a new whole-life cable model applied to a comparison of conventional XLPE and a novel high operating temperature thermoplastic cable system. It explores the whole life cycle including: manufacture, deployment, operation and end-of-life.

The new cable addresses a fundamental limitation inherent in existing electricity transmission and distribution networks by improving the capability of power cable system to tolerate increased peak demand whilst reducing whole-life environmental impact.

A new concept cable was successfully developed using new thermoplastic insulation materials that do not require cross-linking. This reduced the process energy required during manufacture and enabled recycling of the cable, further reducing the carbon footprint of the cable.

KEYWORDS

High voltage; cable systems; economic assessment; environmental assessment; whole-life; life cycle assessment; life cycle costs.

INTRODUCTION

There are many environmental drivers at a European level requiring the improvement of the design and deployment of power cable systems. These include the European Carbon Strategy, the EU Waste Framework Directive and the move to low carbon networks. Many of these do and will affect industry across the whole cable life cycle, not just manufacture but also deployment and end of life management.

Economics too is providing a force for change in the form of materials supply and the need for process energy reduction during manufacture. These environmental and economic drivers are becoming more and more important for efficient cable production and in meeting procurement requirements a number of which are increasingly reflecting green procurement policies.

Tools

In order to respond to these drivers, there are many methods for assessing the economic and environmental performance of products at production level, but few that deal with the whole life cycle. These methods include Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Total Cost Assessment (TCA) and a raft of technical approaches and studies. However, there hasn't been an approach to these assessments which aims to bring all aspects together in one methodology and tool.

LEETS

LEETS is a methodology and software tool [1] which brings together multiple assessments and enables them to be used to compare cable technologies, and their manufacture and deployment with account of the local environmental and end of life management options. As such it is ideally placed for carrying out assessments in response to the requirements of various stakeholders, be it the cable manufacturer or the utility using the cable.

LCC (derived from LEETS)

LCC is a new integrated life cycle cost and risk assessment methodology, which addresses whole life costs from original planning, to construction, operation and eventually the management of end-of-life of assets. The approach was developed to support asset investment and policy to enable optimum solutions to be identified, taking into account economic, environmental, health and safety and social costs, with explicit account of hazards and risks, including those arising from asset failure [2]. The use of LCC within the LEETS cable model is planned for subsequent projects.

HV Cables

High voltage cables typically use XLPE as the dielectric material. While this has excellent performance characteristics, it is energy intensive to produce, requires cross-linking and related degassing and is difficult to recycle.

New cable designs utilising new thermoplastic materials which are not crosslinked have been developed. These can operate at higher conductor temperatures if required; potentially up to 150°C. The materials used for so-called HTC cables are not cross-linked and offer both economic and environmental benefits. These were the subject of a recent UK Technology Strategy Board project [3].

METHODOLOGY

In order to meet the requirements of the project a number of methodologies, both laboratory and desk-based, were employed. Critically these included LCA studies, which was carried out and integrated into the LEETS-Cable model which included other environmental impacts and parallel economic and risk impacts.

Goal

The goal of the life cycle study was to evaluate the environmental impacts of the manufacturing, deployment, operation and end of life management phases of high voltage power cables. The benchmark scenario chosen was a typical XLPE cable technology for HVAC transmission which is currently employed by National Grid in the UK. The new thermoplastic cable used the same cable construction but with a thermoplastic replacement of the XLPE for the primary dielectric.

Close and Return

Functional Unit

The functional unit (or unit of service provided by the cable in a cable circuit) was chosen to provide a fair comparison of the performance of alternative cable designs in a number of different, yet common deployments, and load conditions in the context of what the cable is intended to deliver.

This study was unusual in requiring a number of operational extremes to be considered ranging from low load factor continuous operation to high load factor and high peak transmission conditions which may require the maximum operating temperature of the cable system to be used for relatively short periods of time under emergency conditions - typically from one hour to ten or more hours. Hence the study required a functional unit cable operational profile to be adopted for a unit length of 400kV HVAC cable. The primary functional unit was: carrying a load of 35% of continuous rating over 1 kilometre of a 3 phase 400kV HVAC cable system consisting of 1 cable per phase.

System Boundary

The system boundary includes product and material flows as well as energy use and emissions to air, water and land. It also highlights areas where there is potential for materials to be diverted from current disposal practices of incineration and landfill to recovery for further use i.e. re-use/recycling.

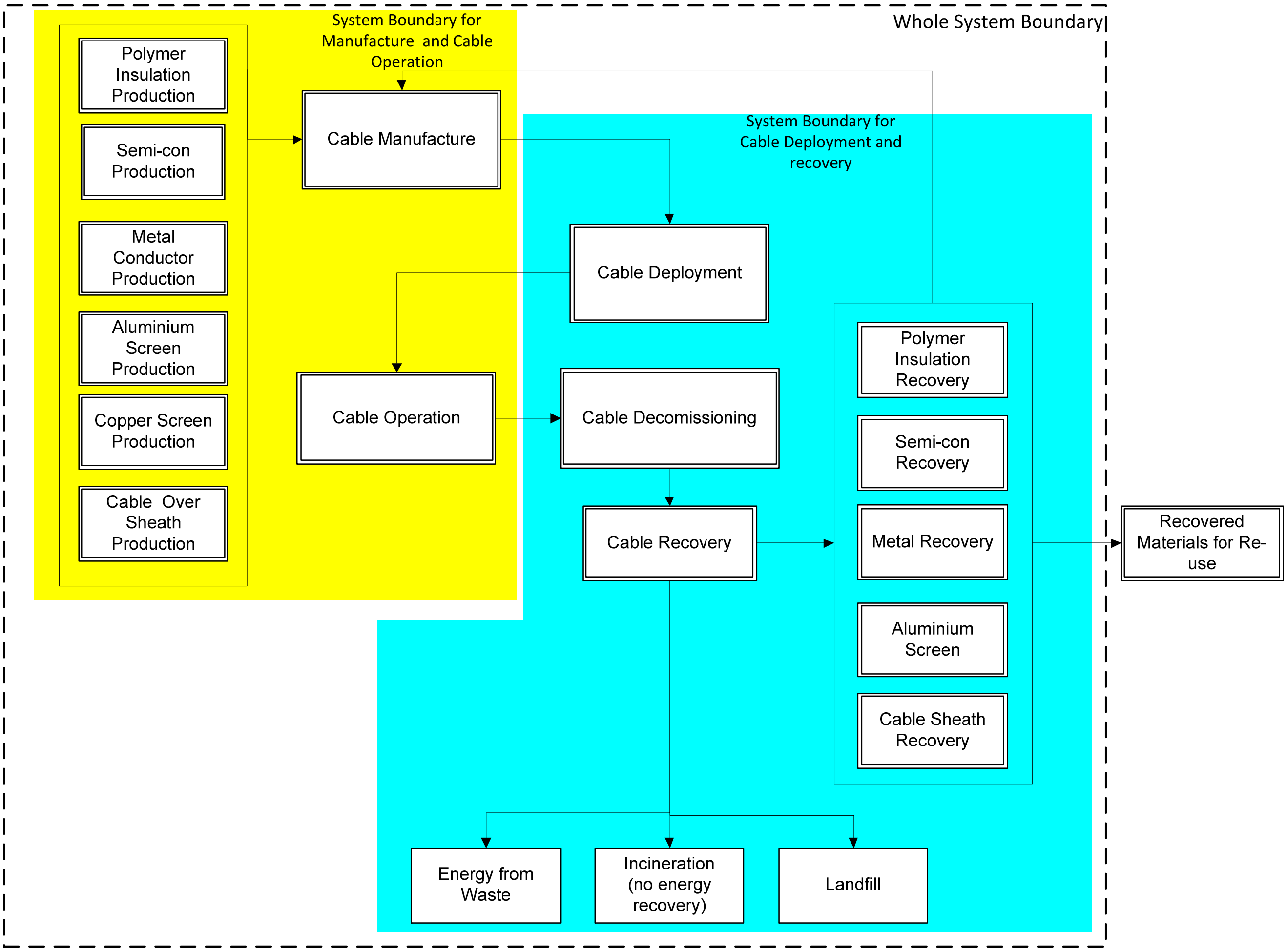


Figure 1: LCA System Boundary

At each of the stages in the life cycle a variety of inputs/outputs occur, such as raw materials, products, energy and environmental emissions. These are identified and quantified through this study. Figure 1 details the stages identified for the production of the primary cable, from raw material supply, to cable manufacture and deployment, then operation and finally material recovery and recycling. The system boundary includes the whole life cycle to achieve the functional unit and by definition it includes those factors specific to each deployment scenario which can create additional environmental and economic impacts and benefits.

The study and the Leets cable model assess each stage in the life cycle but the study is implemented as a streamlined model to capture the most important impacts and ensure the focus is maintained on cable performance rather than infrastructure which are common for different cable types. The cost and environmental impacts associated with putting in place the local infrastructure for deployment of the cable are also considered.

Cable Manufacture

The production of each of the raw materials used in the cable construction is assessed in addition to the actual cable production process. So the original production of the polymer sheathing compound, the insulation polymer, the semi-conductor compound and the metallic conductor material (electro-refined copper) are all considered for this LCA. The LCA for cable manufacture differentiates between extrusion followed by heated pipe catenary crosslinking in the case of the benchmark XLPE cable and extrusion combined with controlled cooling for thermoplastic blend cables. This also includes some assumptions on transport of the raw materials to the cable manufacturer. The extrusion of the cable is assumed to be carried out on a vertical extrusion line feeding a heated crosslinking catenary. In this paper the degassing stage is not included.

Cable Deployment

An assessment of cable deployment was made and there was no difference between cable type. Deployment options included cable tunnel deployment, lay direct or direct buried in ducts or troughs with backfill. Transport to site is assumed to be independent of cable type as it is more usual to transport the largest possible cable drums consistent with road haulage and maximum drum weight constraints, therefore transport to site is assumed to be the same for all cable types and deployment scenarios.

Some key differences would arise in relation to the effective number of cable joints used in deployment as the maximum length between joints increases for smaller conductor and cable sizes. Cable joints are not considered as they fall outside the system boundary.

The deployment type can also have an impact on the cable rating. Tunnel deployments limit the current in cables because of a limitation on cooling, which arises from air flow limits in the tunnel. This is particularly the case for long stretches of tunnel.

The operation of cables, buried directly in the ground, would also be limited by the heating and drying effects on the soil immediately surrounding the deployment. This could be particularly evident in rural environments due to the effect on nearby vegetation.

Operation

The operational phase of the cable life cycle was modelled, particularly in regard to the cable rating and the I^2R losses during transmission. The University of Southampton undertook a cable ratings study for a variety of cable deployments from direct buried to cable tunnel installations in order to compare the new cable system with conventional XLPE insulated cables. LEETS-Cable used this data.

End of Life

End of life scenarios have been created for the both the XLPE cable and HTC. Recycling, incineration with energy recovery, and landfill have all been considered as “End of Life” possibilities.

RESULTS

Essential conclusions include:

Deployment of the cable has a significant environmental and economic impact in addition to that of cable production and operation of the cable circuit.

The operation of the cable circuit and the conductor power losses (I^2R losses) are a dominant factor in overall environmental performance.

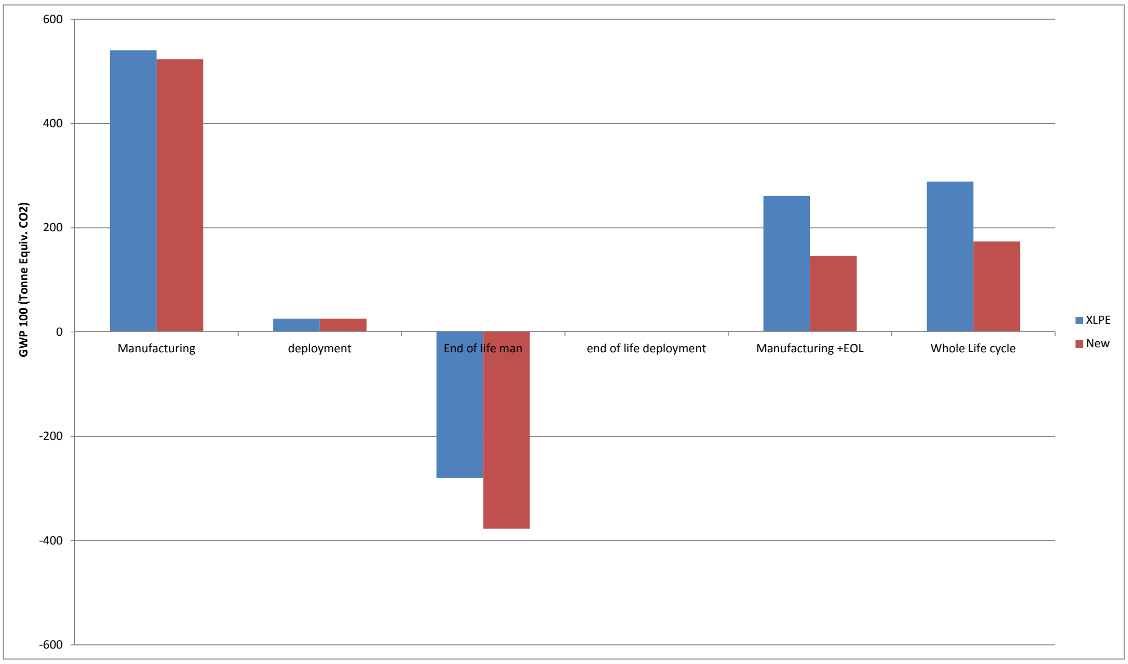


Figure 2: Whole life Global Warming Potential by cable type for direct buried deployment

The difference between Global Warming Potential impact (GWP) of tunnel deployment and the other deployment scenarios is a factor of 8 relative to surface troughs and 78 relative to direct buried (

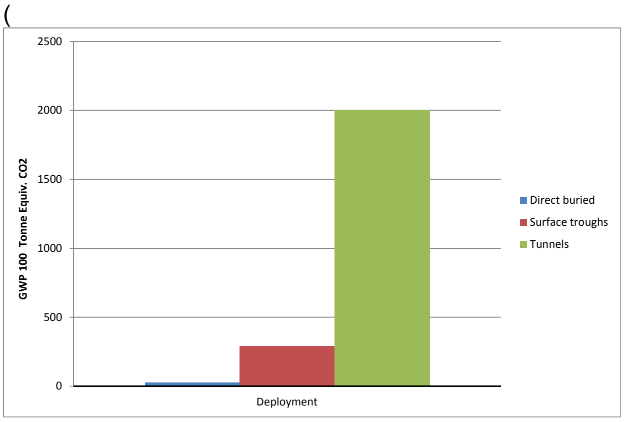


Figure 3).

Re-using the tunnel at end of life significantly reduces the GWP in the second cable life cycle.

Reducing copper conductor size must be traded against increase I^2R losses – the smaller the conductor cross section, the larger the portion of transmitted energy lost.

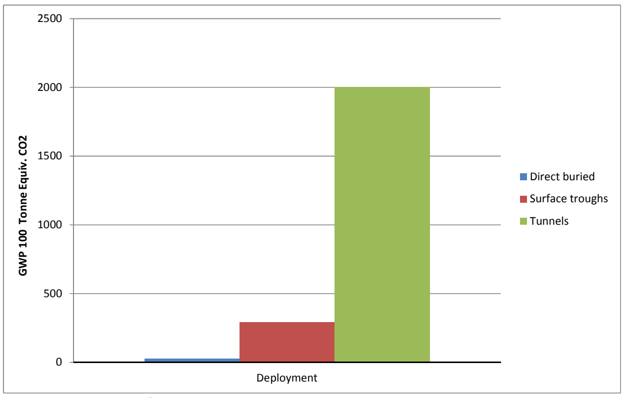


Figure 3: Global Warming Potential - Deployment Comparison

Life cycle carbon impacts are very sensitive to energy mix. This project used an example energy mix provided by National Grid which includes long term changes resulting from increased renewables generation in the UK. This was used for operational impacts where energy use plays a significant role.

The impact of the energy mix was clearly seen where the effect of decreasing coal-based generation and increasing renewables is evident. While this model looked only at mixes for UK, LEETS could operate similar models based on generation mixes from around the world.

The life cycle data for manufacture of the cables also incorporates a variety of generation mixes. Components of the cable will likely be sourced from a number of different countries, each with their own characteristic generation mix profile. The option to select the most appropriate mix is built into the LEETS-Cable model.

Operating cables at a higher conductor temperatures (150°C compared to 90°C for XLPE) leads to a significant increase in transmission losses, especially at higher loads (Figure 4). However, this is usually only for a very short period over the whole life of the cable so its impact is relatively small in comparison with the whole life impact.

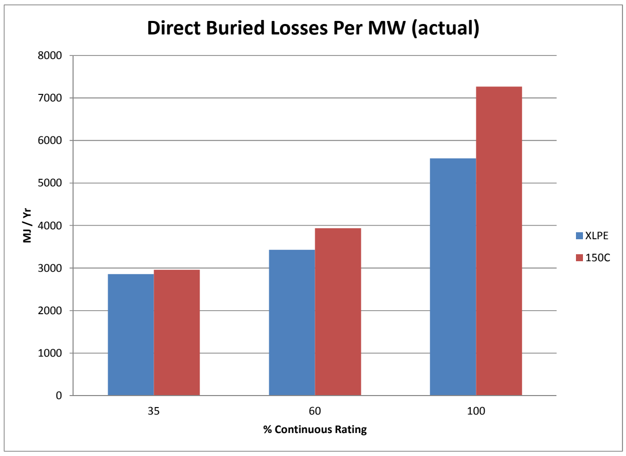
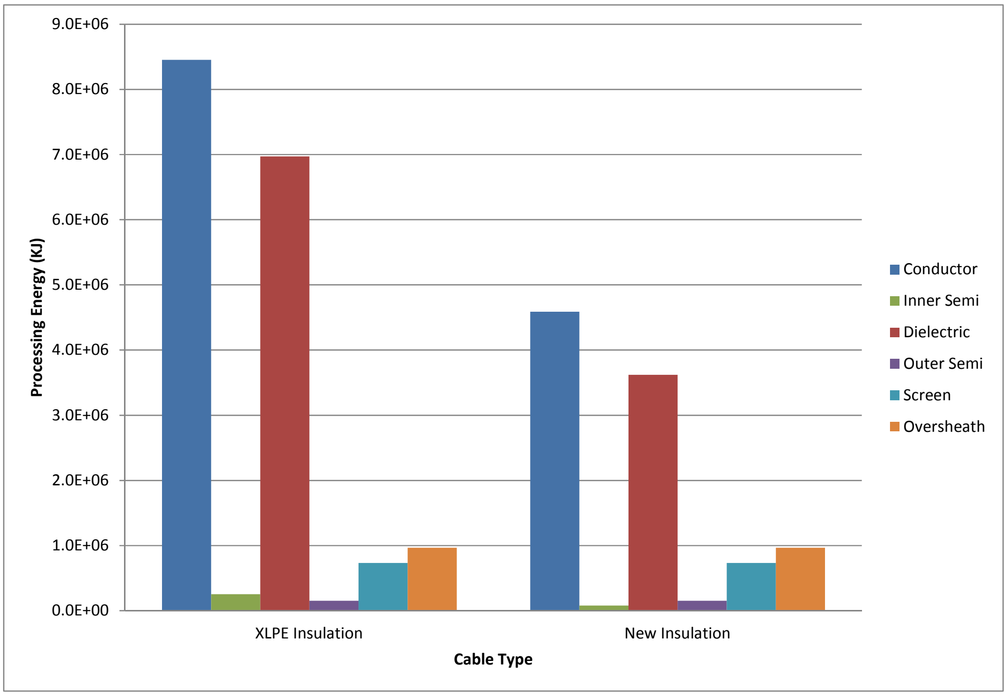


Figure 4: Annual transmission losses by load and cable type

Processing energy, from manufacture, are potentially substantially lower for the new cable design due to there being no need for cross-linking (Figure 5).

Figure 5: Processing energy during cable manufacture



The overall carbon saving of the new cable over XLPE was 125 tonnes CO_2 across the life time (60 years) for the functional unit employed.

Economic Analysis

Economic data has been difficult extremely hard to obtain partly because there is no current transmission system project on which this report can be based and partly because many of the detailed economics rest with external contractors and cable manufacturers rather than National Grid.

Manufacturing

The cable procurement cost (or direct purchase cost) and end of life costs have been taken from a report by the Highland Council in Scotland (for an XLPE system). This makes it clear that the costs may not be accurate and were difficult for them also to obtain.

Construction

The construction costs are taken from an LCC asset policy study carried out by GnoSys Global Ltd for National Grid [4].

Operation

Operation and maintenance costs are estimated in the Highland Report[1] as £5600 per km per year for a double circuit. Since these are relatively low level costs, they have been rounded up for use here. For tunnels, a figure has been included for the operation of cooling fans. This is based on data provided by National Grid [5].

The costs of operational losses are evaluated using a figure of 5.5 pence per kWh, somewhat below the consumer price of electricity since a wholesale price would be more appropriate. Currently, the losses are not paid for explicitly; rather the cost is incorporated into the price that distribution networks pay the generators. However, this may change in the future. The energy figure used to calculate the losses is for a 2500mm^2 cable operating at a continuous 35% max load. This equates to 259332 MJ or £3962 per year. We have assumed that the losses will be the same regardless of dielectric and deployment type.

The fault outages costs are also taken from the same report and are in alignment with the figures quoted by National Grid. Historical figures from National Grid indicate that the occurrence of one fault each year would be an overestimate of failures, however it simplifies the calculations. It should also be noted that this is per circuit not per km. The longest time a circuit is likely to be in a fault state for is 6 hours and the energy which should have been transmitted in this time at 35% load is 544.2 MWh. This results in an outage cost of £26121.60 for a single 6 hour outage.

Stakeholder Perspectives

Manufacturers

To better understand a manufacturer's perspective there are two key factors that must be considered: material supply cost and process energy costs.

Material prices were taken from Plastics Infomart [6]; "standard" low density polyethylene: $1600 per tonne, alternative "standard" insulation material: $1380 per tonne. This suggests a materials cost reduction of approximately 14% for the new insulation material.

A conversion to sterling and scaling for a km of cable results in:

- £6760 per km new thermoplastic material
- £8150 per km for XLPE

An overall cost reduction of about 17% due to lower commodity price and lower density of dielectric. Note that "standard" rather than "clean" grades of polymer were all that was available and the latter will be more costly.

Processing costs vary between XLPE and the new material because the new material does not require cross-linking. This additional step requires the heating of not only the dielectric but also the cable inside it (conductor and inner semiconductor). The additional energy use can again be quantified in terms of the energy supply cost. If we assume the heating is electric, then using the same price (5.5p/kWh) the processing costs could be significantly reduced as shown in Figure 6 and Figure 7.

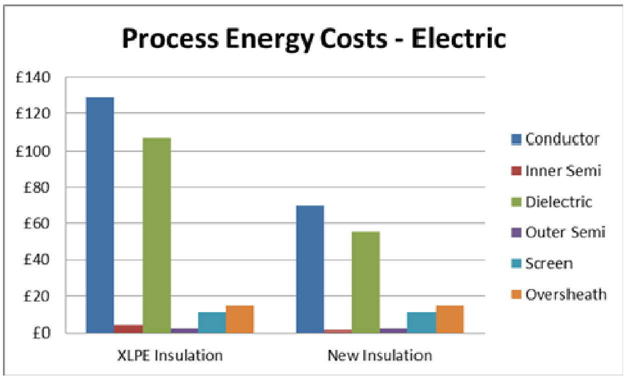


Figure 6: Process energy costs for cable manufacture (Electric)

Wholesale natural gas prices are slightly cheaper so using 1.3p/kWh, the processing costs would be:

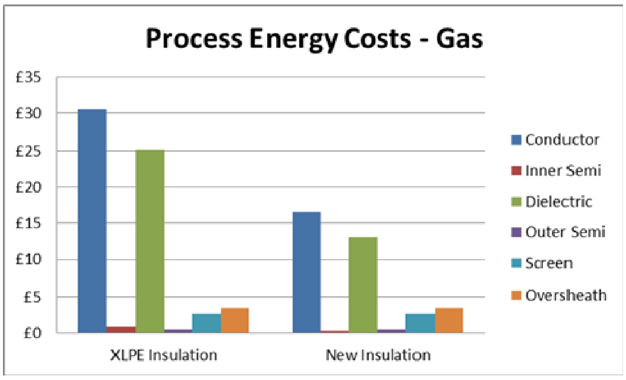


Figure 7: Process energy costs for cable manufacture (Gas)

TSO's

Emergency ratings studies carried out by National Grid concluded that if a double cable circuit was replaced with a single HTC circuit and operated within 90°C prior to the fault, the 6hr emergency rating could be significantly enhanced by between 40 to 50% and this would help to reduce the system constraint costs in an event of a fault.

Key TSO benefits with HTC are the ability to relax constraints during post-fault operation. In some cases this could be from 20 minutes using an XLPE cable to 6 or even 24 hours using the new design.

CONCLUSIONS

The LEETS-Cable model has been developed to be applied to any power cable system and its deployment in any circumstances. It may also complemented by whole life cost assessment including account of planned outage and cable and accessory risk of failure. The cable model now combines environmental impacts with economic and operational data to enable the consideration on trade-offs and to support decision making and the incorporation of life time risk is possible with the use of LCC.

The environmental impacts for the manufacturing process are small compared to the impact of lifetime operational energy losses. Since there was no manufacturing process data available from cable manufacturers certain assumptions were necessary in order to carry out the analysis effectively.

Although in this study we concentrated on Global Warming Potential (GWP), other CML environmental impacts were also analysed, these should also be considered to obtain a more complete picture of the whole environmental effects of our functional unit.

When manufacturing only was considered it was no surprise that the main contributors to global warming were the manufacture of the copper and dielectric components of the cable. The new cable design showed a reduction in the global warming impact of the main wall dielectric component in comparison with conventional XLPE insulation. When the end of life was also considered, carbon credits were gained for the recovery of copper and other recoverable cable components. This increased the difference in environmental impact between the two dielectric components since the new design dielectric component is recyclable.

Economic analysis showed that the process energy involved in the production of the two different cable systems has a significant effect on the cost of cable manufacture. The New Design HTC cable is likely to give a significant cost benefit in terms of energy consumption during manufacture.

When considering environmental impacts in isolation, it would appear that the optimum cable design with respect to global warming impact would use a small conductor size (consistent with current rating requirements) with the new design dielectric insulation. However cable ratings studies carried out at Southampton University revealed that the I^2R losses under continuous operation were too large in smaller conductors so smaller conductor sizes would not be practical. Larger conductor sizes lead to a lower resistance cable and lower I^2R losses, therefore larger conductor size could be more desirable, in some circumstances.

System emergency and constraint studies carried out by National Grid concluded that if a double circuit was replaced with a single HTC circuit and operated within 90°C prior to the fault; the 6hr emergency rating would help to reduce the system costs in an event of a fault.

TSO benefits with HTC are the ability to relax constraints during post-fault operation. In some cases this could be from 20 minutes using an XLPE cable to 6 or even 24 hours using the new design.

It is important to consider the LCA findings of the whole life cycle in conjunction with the results of the cable ratings studies, emergency ratings studies and the economic analysis in order to establish trade-offs for the in order to optimise the cable circuit design, cable deployment and in principle cable operation.

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