21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

B1-215

CIGRE 2012

Integrated Development and Assessment of New Thermoplastic High Voltage Power Cable Systems

Mike FAIRHURST (1), Ankit GOWADIA (1), Gary STEVENS*(2), Ben PHILPOT (2), Janet THOMAS (2), James PILGRIM (3) and Paul LEWIN (3)

1 – National Grid PLC, Warwick Technology Park, Warwick CV34 6DA, UK

2 – GnoSys Global Ltd., The Surrey Research Park, Guildford GU2 7YD, UK

3 – ECS, University of Southampton, Southampton, SO17 1BJ, UK

SUMMARY

European policy drivers exist to improve the design and deployment of power cable systems in transmission networks, particularly the whole life cycle of future low carbon networks. As part of a new power cable development project called SUSCABLE, a new high temperature and recyclable thermoplastic blend HV power cable has been proposed and a new approach has been developed to carry out integrated assessment of multiple performance factors. From materials selection and cable manufacture to cable rating in common deployment situations, along with network constraint and life cycle assessment, the outputs were integrated to enable the whole life performance of the newly proposed cables to be critically assessed. This is the first time such an approach to integrated performance assessment has been carried out.

LEETS is a methodology and software tool which brings together these multiple assessments and enables comparison of different cable technologies, their manufacture and deployment with account of the local environmental and end of life management options. This method is ideally suited to carrying out assessments in response to the requirements of various stakeholders, be it the materials supplier, the cable manufacturer or the utility deploying and operating the cable.

High voltage cables typically use XLPE as the dielectric but it is energy intensive to produce and difficult to manufacture and recycle. New cable designs utilizing new thermoplastic blend insulation materials are capable of operating at higher conductor temperatures, are not cross-linked, and offer significant economic and environmental benefits across the complete life cycle.

This paper will illustrate, through the use of a new LEETS-Cable model, how alternative cable systems can be compared across the whole life cycle including manufacture, deployment, operation and end of life management. The paper will discuss how potential benefits are assessed using the model which integrates cable rating and system studies with account of the deployment environment for cable operation under both continuous and fault conditions.

KEYWORDS

Power cable systems, transmission networks, high temperature cables, cable ratings, integrated assessment, whole life assessment, economics and environmental, thermoplastic blend insulation

g.stevens@gnosysgroup.com

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, the move to low carbon networks and green procurement - these affect industry across the whole cable life cycle from manufacture to deployment and end of life management.

Economic factors are providing a force for change in materials supply and the need for process energy reduction during manufacture. So, coupled environmental and economic drivers are becoming more important for efficient cable production and in meeting procurement requirements including increasingly those satisfying 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 and LCC

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 environment and end of life management options. 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 by enabling 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].

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 followed by degassing and it is difficult to recycle. New cable designs based on new uncrosslinked thermoplastic materials have been developed. These can operate at higher conductor temperatures if required; potentially up to 150°C. These were the subject of a recent UK Technology Strategy Board project.

METHODOLOGY

An integrated methodology was applied bringing together materials selection, cable manufacture, cable ratings for common deployments, along with network constraint and life cycle assessment. The outputs were integrated to enable integration of whole life performance via the LEETS-Cable model which included other environmental impacts and parallel economic and risk factors.

LCA Goal

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

Functional Unit

The functional unit (or unit of service provided by the cable circuit) was chosen to provide a fair comparison of the performance of alternative cable designs in different, yet common deployments and load conditions in the context of anticipated network applications identified by system constraint studies. This included a number of operational extremes ranging from low load factor continuous operation to high load factor and high peak transmission conditions requiring the maximum cable operating temperature for relatively short periods of time under emergency conditions - typically from one hour to ten or more hours. Hence the study used 1 kilometre of a 3 phase 400kV HVAC cable circuit consisting of 1 cable per phase and a base load of 35% of continuous rating.

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.

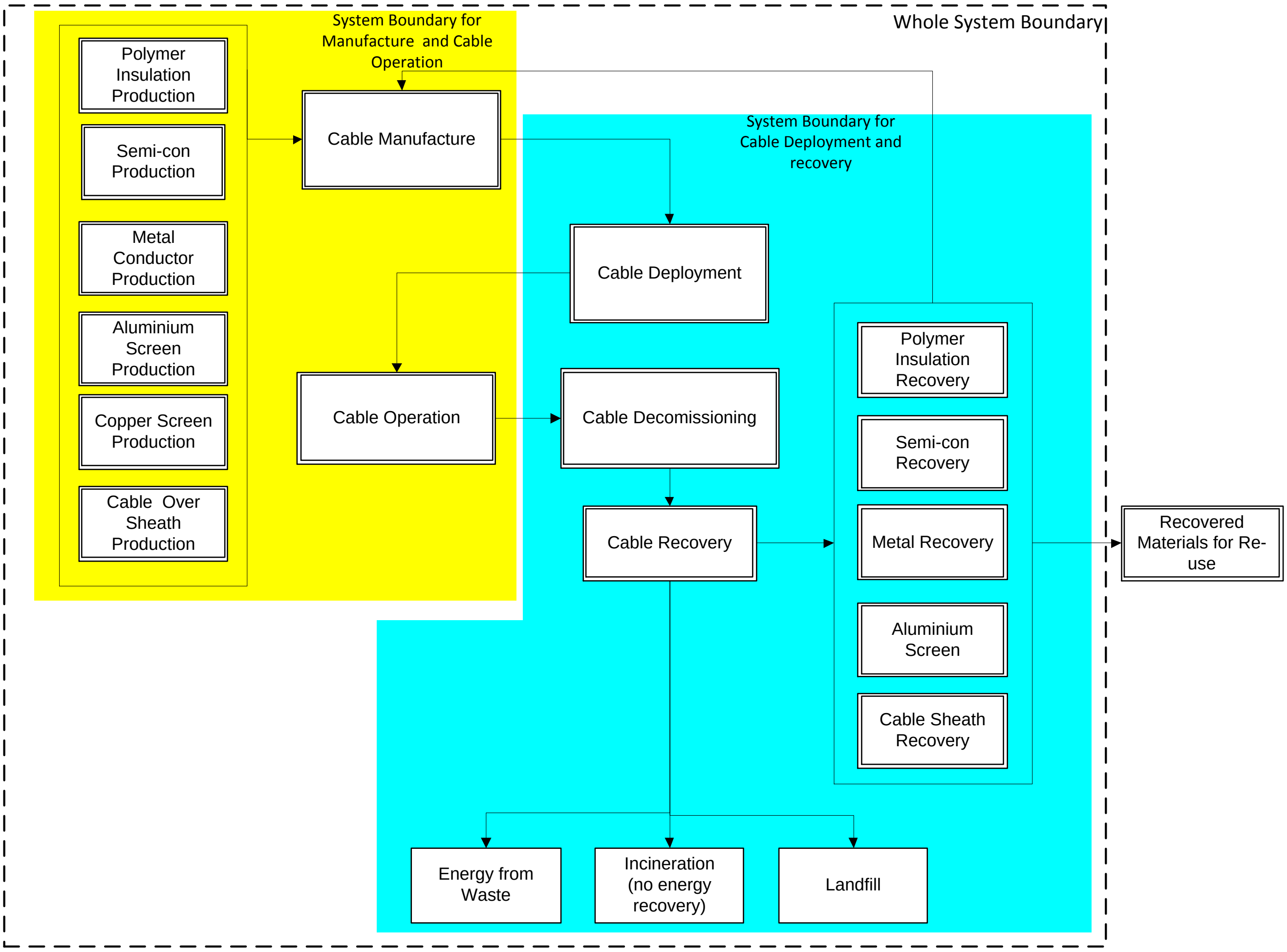

Figure 1: Whole Life Assessment System Boundary

At each of the stages in the life cycle a variety of inputs/outputs occur, such as raw materials, products, energy and environmental emissions. 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 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. 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. 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. The extrusion of the cable is assumed to be carried out on a vertical extrusion line or heated crosslinking catenary. In this paper the degassing stage is not included so the XLPE performance appears better than it will be in practice.

Cable Deployment

An assessment of cable deployment was made and there was no difference between cable types. Deployment options included cable tunnel deployment and direct buried in ducts or troughs with backfill. Transport to site was also considered with usual haulage and cable drum weight constraints. Some key differences 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 joint performance is not considered in this paper but has been the subject of other studies.

The deployment type will have an impact on the cable rating. Tunnel deployments limit cable current because of constraints on cooling arising from air flow limits particularly for long stretches of tunnel. The operation of directly buried cables is also limited by soil heating and drying effects which limit heat transfer. This is particularly evident in rural environments.

Operation

Network studies were carried out on a number of typical UK circuits to obtain representative inputs on circuit constraints and needs. The operational phase of the cable life cycle was modelled, particularly in regard to the cable rating and I^2R losses. Cable ratings studies, using finite element static and dynamic models, were applied to all deployment cases in order to compare the new cable with conventional XLPE insulated cables. LEETS-Cable used this data as part of the integrated assessment.

Additionally, National Grid carried out assessments of potential system failures in key locations. This established the system loadings that might occur and therefore the suitability of either conventional XLPE insulated cables or new high temperature cables in a number of specific situations.

End of Life

End of life scenarios were created for both the XLPE and new cables including materials recycling, incineration with energy recovery and landfill as possibilities.

RESULTS

Essential conclusions

Deployment of the cable has a significant economic cost and environmental 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. As the copper conductor is largely responsible for losses the new and XLPE cables will perform the same for the same ampacity and conductor size.

The differences in whole life performance are clear when the manufacturing and end of life management are considered as shown for global warming potential (GWP) in Figure 2. This may be compared with the GWP impact of different deployments (see Figure 2) and with the annual GWP contribution from lifetime operation of the cable circuit - see Figure 3, which shows the impact of the change in energy mix with time due to greater anticipated use of renewables generation in the future.

Reducing copper conductor size must be traded-off against increase I^2R losses – the smaller the conductor cross section, the larger the losses and reduced ability to handle higher emergency ratings. These trade-offs were explored and the conclusion reached was that larger conductor size is more favourable from a whole life perspective particularly when recycling is accounted for.

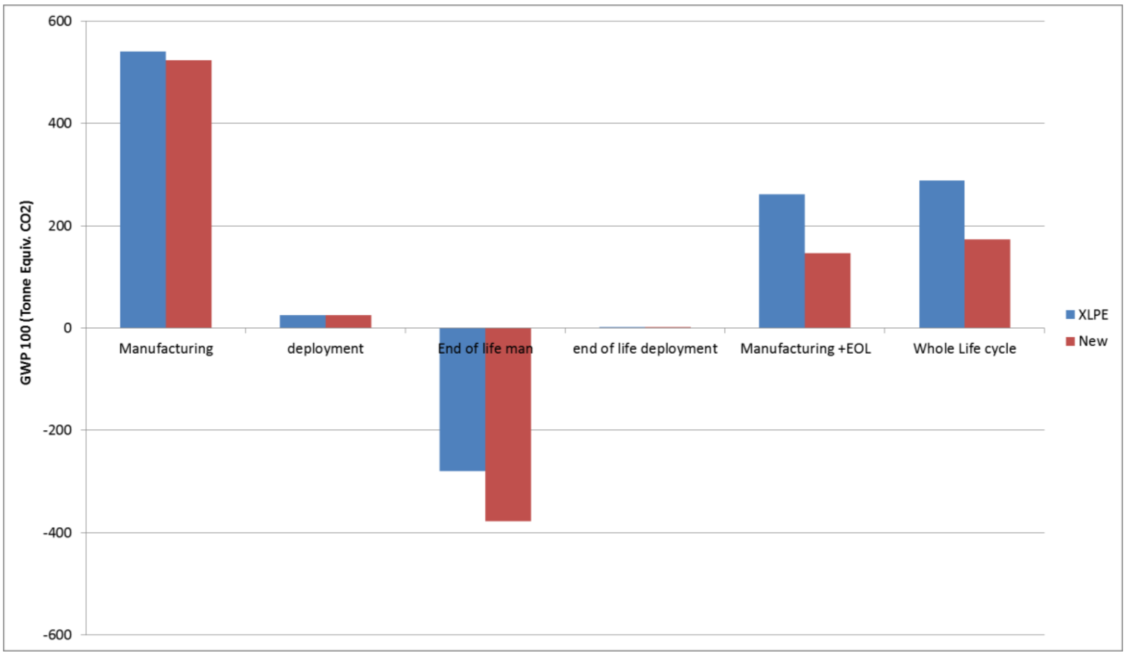

Figure 2: Whole life GWP by cable type for direct buried deployment excluding power losses

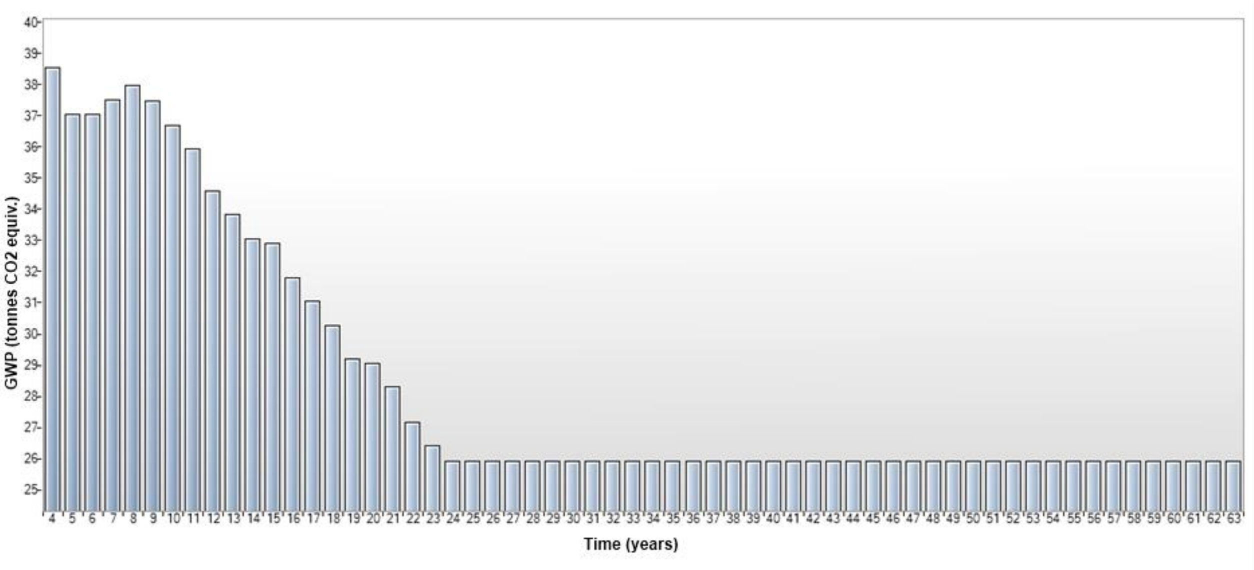

Figure 3: Lifetime annual GWP for operation of the cable circuit at 35% rated load with account of anticipated changes in UK energy mix.

The difference in GWP of tunnel deployment and the other deployment scenarios is a factor of 8 relative to surface troughs and 78 relative to direct buried, as shown in Figure 4. Re-using the tunnel at end of life significantly reduces the GWP in the second cable life cycle.

It is instructive to compare the net contributions to GWP of the different phases of the life cycle for the lowest impact deployment case - directly buried cables. For this case, Figure 5 shows that integrated whole life operational impact is significantly larger than that from other phases of the life cycle including cable manufacturing - a factor of 3.5 larger. In contrast, if cable tunnel deployment is used, the operational GWP is comparable to that of the deployment (compare Figures 4 and 5).

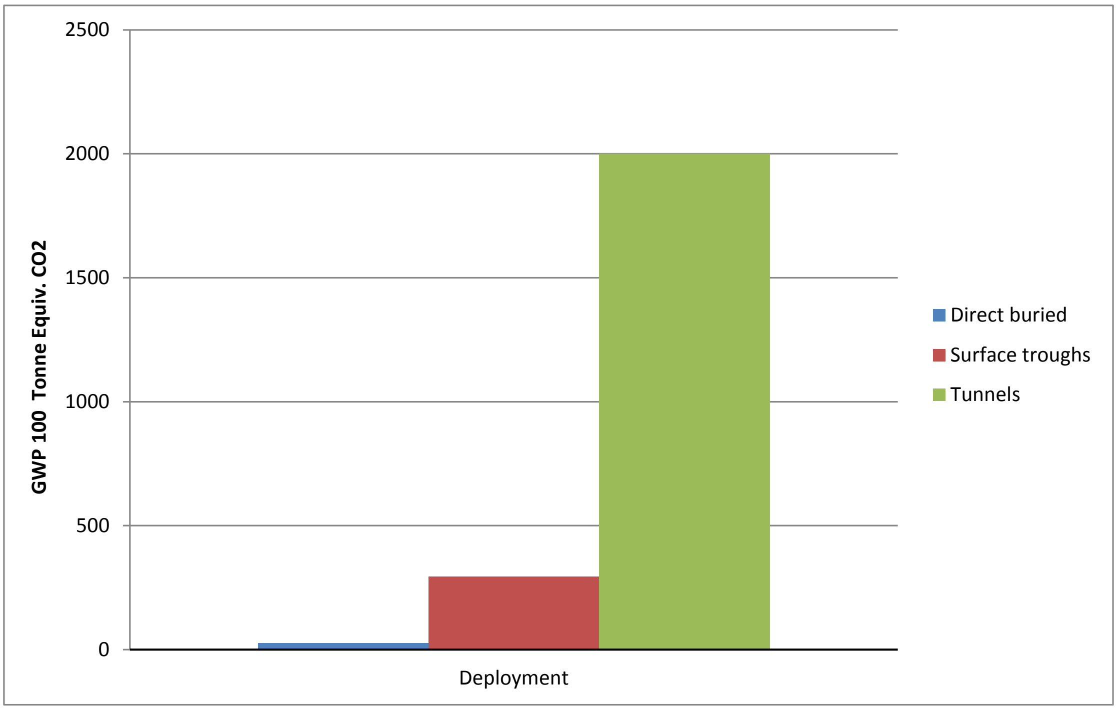

Figure 4: Cable deployment comparison based on GWP.

Life cycle carbon impacts are very sensitive to energy mix , as shown in Figure 3. The LEETS-Cable model provides many options for pre-defined forecasts of long term changes internationally as well as in the UK with account of increased renewable generation. Operational impacts were based on UK forecasts. The life cycle data for manufacture of the cables also incorporates a variety of generation mixes as components may be sourced from a number of different countries with their own generation mix profile.

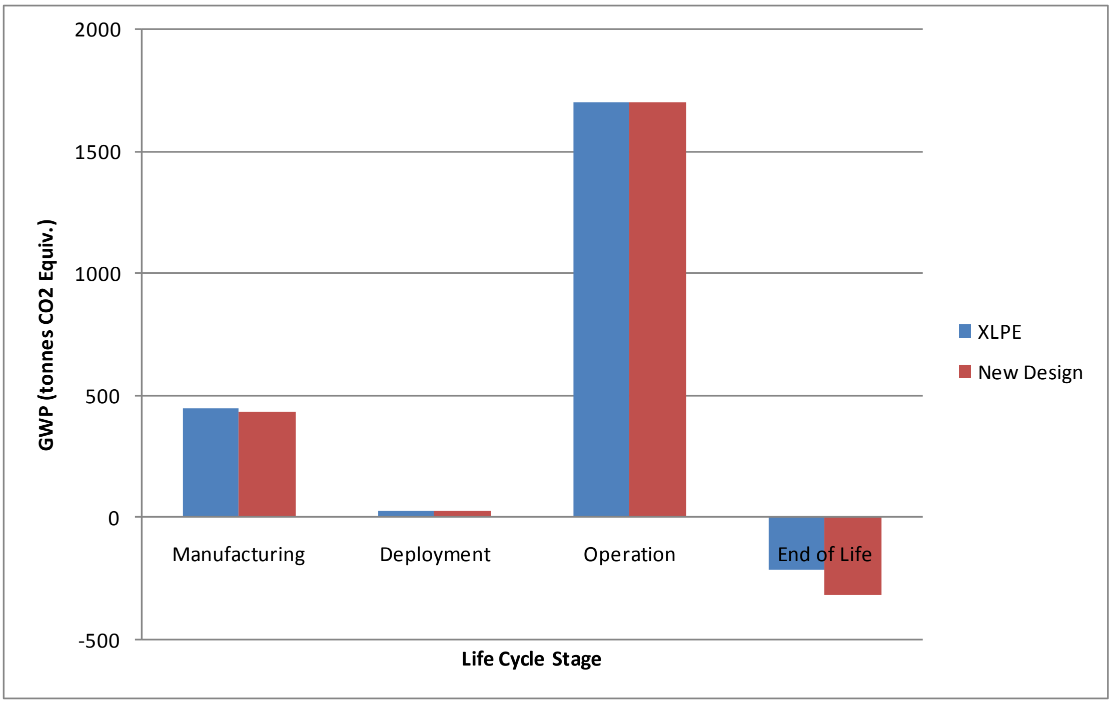

Figure 5 Whole Life GWP for direct buried XLPE and new design cables

Operating new cables at 150°C compared to 90°C for XLPE leads to a significant increase in transmission losses, especially at higher loads (Figure 6). However, this is usually only for very short periods in comparison with the whole life of the cable, so the overall its impact is relatively small.

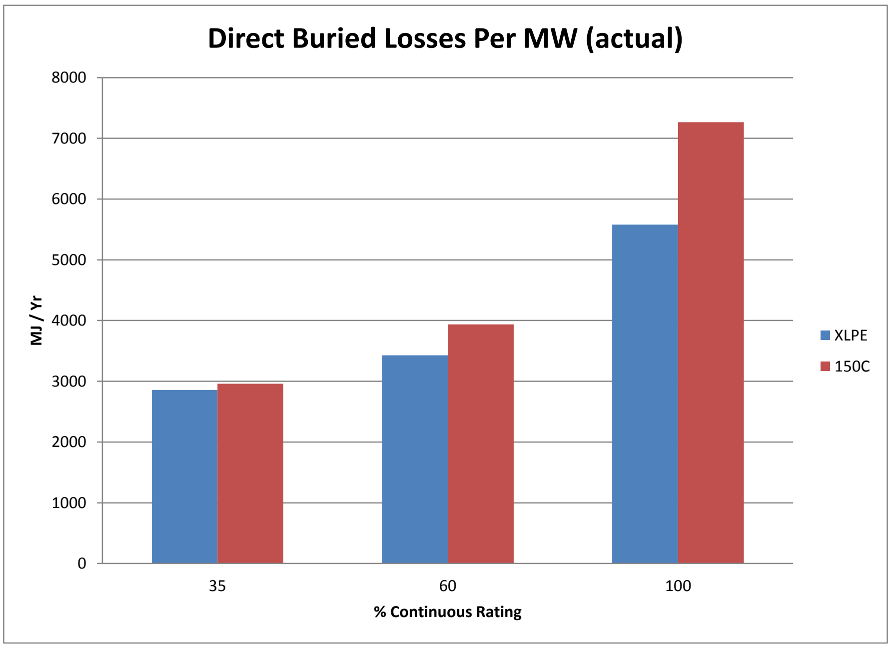

Figure 6: Annual transmission losses by load and cable type

Manufacturing process energy is substantially lower for the new cable design due to there being no need for cross-linking as shown Figure 7 and which contains no contribution for degassing. The overall carbon saving of the new cable was 125 tCO_2 across the life (60 years) compared to XLPE. The lower process energy for the copper of the new thermoplastic cable arises because of lower net energy required for conductor heating during processing and the absence of the crosslinking process step.

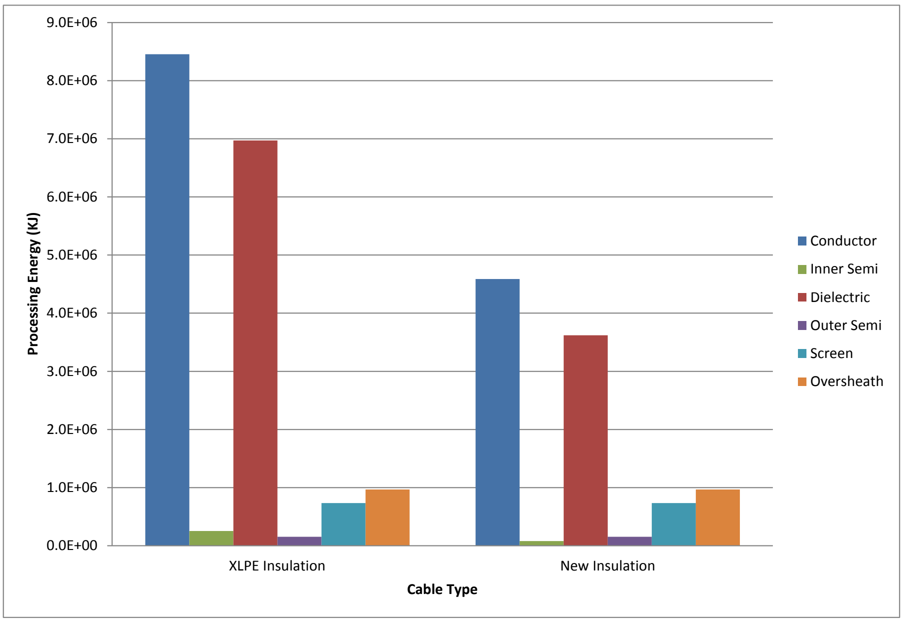

Figure 7: Processing energy during cable manufacture

Cable procurement and construction costs

The cable procurement cost and end of life costs have been taken from a report by the Highland Council in Scotland (for an XLPE system) [3]. This makes it clear that the costs may not be accurate and were difficult to obtain. The construction costs were taken from an LCC asset policy study carried out by GnoSys Global Ltd for National Grid [4].

Operation

Operation and maintenance costs are also estimated in the Highland Report[3]. For tunnels, a figure has been included for the operation of cooling fans based on data provided by National Grid. The costs of operational losses were evaluated as those appropriate to a large industrial user. 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 fault outage costs are also those that commonly apply in the UK. The longest time a circuit is likely to be in a fault state is 6 hours and the energy which should have been transmitted in this time at 35% load is calculated.

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.

Using international materials pricing, there is a materials cost reduction of approximately 14% for the new insulation material compared to XLPE and an overall cable cost reduction of about 17% is expected when all materials are considered. The additional process energy used can be quantified in terms of the energy supply cost. If we assume electrically sourced heating, then using the same price (5.5p/kWh) the processing costs could be significantly reduced as shown in Figure 8.

So overall, lower process costs and marginally lower materials supply costs offer distinct advantages to the primary cable cost of the thermoplastic cable – this does not include a consideration of XLPE cable degassing costs and accessory costs.

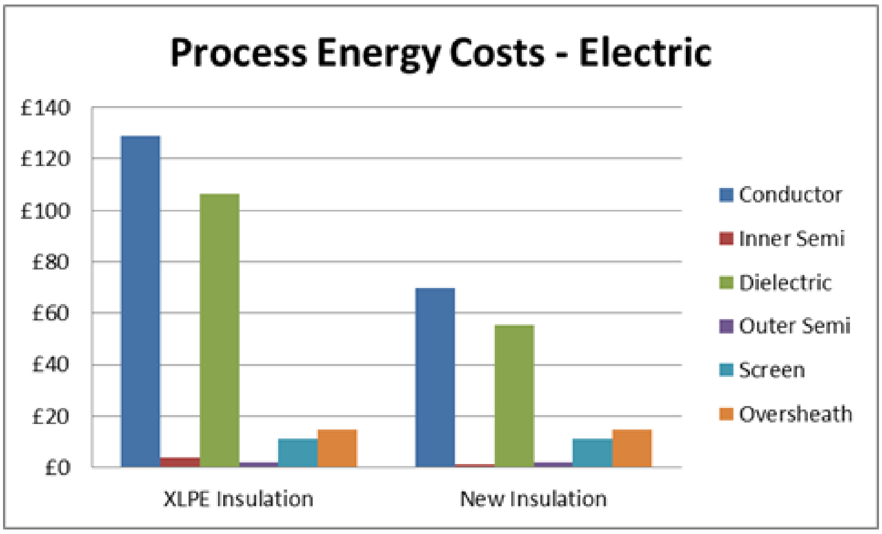

Figure 8: Process energy costs for cable manufacture using electricity – excluding embedded energy costs associated with materials as supplied.

TSO's

Emergency rating studies concluded that if a double cable circuit was replaced with a single new thermoplastic based cable circuit and operated up to 90°C prior to the fault, the 6hr emergency rating could be significantly enhanced by between 40 to 50% and this would reduce system constraint costs in the event of a fault. Key TSO benefits with the new cable 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. If the cost of cable supply is close to or possibly lower than that of XLPE cables the additional insurance value and future proofing of the new cables offers significant network whole life cost benefits.

CONCLUSIONS

The LEETS-Cable model has been developed to be applicable to any power cable system. It may be further complemented by whole life cost assessment accounting for planned outage and cable and accessory risk of failure. The cable model combines environmental impacts with economic and operational data to enable trade-offs in cable design and manufacture in relation to operation to be critically assessed. With whole life costing it also allows the incorporation of lifetime risk [2]. The environmental GWP impacts for cable manufacturing are small compared to the impact of lifetime operational impacts but comparable to cable tunnel deployment impacts. Although in this paper we have concentrated on GWP, other environmental impact factors were also analysed and these should also be considered to obtain a more complete picture of the whole life environmental performance.

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 cable is likely to give a significant cost benefit in terms of energy consumption during manufacture.

When manufacturing only was considered it was no surprise that the main contributors to GWP were the manufacture of the copper and dielectric components of the cable. The new cable design showed a reduction in GWP of the main wall dielectric component. 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 between the two dielectric components since the new design dielectric component is fully recyclable.

When considering environmental impacts in isolation, it would appear that the optimum cable design would use a small conductor size consistent with current rating requirements. However cable rating studies revealed that I^2R losses under continuous operation were too large for smaller conductor sizes to be practical. Therefore for most applications larger conductor size is more desirable.

System emergency and constraint studies carried out by National Grid concluded that if a double circuit was replaced with a single thermoplastic based cable circuit and operated to 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 centre on 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 to optimise cable design, cable deployment and in principle cable operation.

BIBLIOGRAPHY

[1] G C Stevens, B Philpot, P Haywood, S. Jayasinghe and C Smith. “Life Cycle Economic and Environmental Assessment of Transmission Systems (LEETS)” (C3-205, CIGRE 2008)

[2] G C Stevens, A Mitchel, P. Scobie, D Culley and J Fitch. “New Life Cycle Costing and Risk Approaches to” (CIRED 2011 to be published) see also CIGRE 2012.

[3] The Highland Council. “Cairngorms National Park Authority & Scottish Natural Heritage Undergrounding of Extra High Voltage Transmission Lines”. (Jacobs Babtie, 2005).

[4] GnoSys Global Ltd (National Grid), “Co-location of High Voltage Cable Systems Within Tunnels”, (2010).