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Life Cycle Assessment of the Transmission Network in Great Britain

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Abstract—Analysis of lower carbon power systems has tended to focus on the operational carbon dioxide (CO₂) emissions from generating plant. However, to achieve the large cuts required it is necessary to understand the whole-life contribution of all sectors of the electricity industry. Here, a preliminary assessment of the life cycle carbon emissions of the transmission network in Great Britain is presented. Using a 40-year period and assuming a static generation mix it shows that the carbon emissions of the transmission network are around 10.6 gCO₂/kWh of electricity transmitted. Operational emissions account for 96% of this with transmission losses alone totalling 85%. Other significant contributors are sulphur hexafluoride (SF₆) emissions while the embodied CO₂ of the raw materials within the network infrastructure itself represents a modest 3.4%. While reductions in the carbon intensity of the generation mix is largely outside the control of transmission companies, investment decisions informed by whole-life cycle carbon assessments of network design could balance higher financial and carbon ‘capital’ costs of larger conductors with lower transmission losses and CO₂ emissions over the network lifetime.

Index Terms—Carbon dioxide, carbon footprint, life cycle, losses, transmission networks.

I. INTRODUCTION

CARBON DIOXIDE (CO₂) emissions, along with cost and energy security are the main concerns for electricity utilities. All major generators and network companies in the UK are part of the European Union Emissions Trading Scheme which aims to lower emissions under a cap-and-trade arrangement. This offers risks for companies who emit more than their allowance while offering opportunities for those able to reduce emissions. There is accordingly interest in the emissions associated with operation of power plants and network infrastructure. At the same time network companies are under continued regulatory pressure to keep costs as low as possible, often focussing on minimising capital expenditure. Decisions over network infrastructure often have significant implications for life time costs, energy use and carbon emissions. As such, there is a need to see operational emissions in the context of the whole network life cycle.

Transmission network infrastructure comprises substantial volumes of materials that consumed energy and emitted CO₂ during their manufacture and installation. Networks also consume energy and create additional CO₂ throughout their

operational lifetimes through transmission losses as well as routine maintenance and refurbishments. Finally, there are energy and carbon implications when decommissioning infrastructure at the end of its useful life. Such aspects can be captured as part of a life cycle assessment (LCA).

Previous LCA work in the electricity industry has predominantly focussed on electricity generation technologies, comparing the energy generated by and carbon emitted over the operational lifetime relative to the energy and carbon required to procure the fuel, build, operate, and decommission the power plants. Extensive studies show that renewable energy technologies including wind, wave and tidal stream, have significantly lower life cycle CO₂ emissions than fossil fuelled electricity generation (Tahara *et al.*, 1997; White and Kulcinski, 2000; Vestas, 2005; Parker *et al.*, 2007; Douglas *et al.*, 2008).

In contrast, there is a much more modest amount of work reported on electricity networks. Vattenfall (1999) summarise an analysis of the Swedish system across multiple voltage levels while others concentrate on specific assets or asset classes. Cigré (2005) report assessments of overhead transmission lines (OHL) while Jones and McManus (2008) provide a detailed comparison of embodied energy and carbon for a hypothetical one kilometre-long section of 11 kV rural distribution circuit with alternative OHL and cable constructions. Comparisons have also been published for oil-filled and cross-linked polyethylene (XLPE) cables (Drugge *et al.*, 1996). Several manufacturers publish Environmental Product Declarations (EPD) for specific assets, e.g. ABB (2003). Many LCAs focus on sulphur hexafluoride (SF₆) gas in circuit breakers (Bessede and Krondorfer, 2000; Preisegger *et al.*, 2001; Neumann *et al.*, 2004). Due to excellent electric arc-quenching and insulating properties, SF₆-based circuit breakers are generally replacing older technologies (Preisegger *et al.*, 2001). The interest arises as SF₆ has a very high global warming potential (23,900 tonnes of CO₂) and that significant amounts of gas leak each year, particularly from older types of circuit breaker. Neumann *et al.* (2004) examined the relative merits of air insulated (AIS) and SF₆ gas insulated switchgear (GIS) within representative 10 to 110 kV German distribution networks. It found that despite the release of SF₆, GIS-based systems performed better, primarily due to the ability to site compact, indoor, GIS substations close to urban load centres. This allowed very different network topologies with fewer substations and shorter higher voltage circuits that reduced

overall material use but, more importantly significantly reduced power losses. Other studies concur that losses tend to dominate both energy use and CO₂ emissions.

This paper presents a detailed account of the energy and CO₂ impacts of the entire high voltage electricity transmission network in Great Britain (GB). Although it deliberately applies some simplifying assumptions to achieve broad yet representative coverage, it provides a credible first approximation and identifies future research and regulatory challenges.

II. LIFE CYCLE ASSESSMENT AND TRANSMISSION NETWORKS

A. Life cycle assessment

Life cycle assessment (LCA) is an analysis of all the environmental impacts of a product, process or service from the extraction of raw materials, through production and use to eventual disposal. LCA studies should comply with the international standard ISO 14040 series (ISO, 2006), which specifies the general framework, principles and requirements for conducting and reporting such assessments. LCA can be used as a design improvement tool to identify the environmental factors attributed to specific materials or life cycle stages and allow informed improvements to be made. LCA addresses only the environmental issues that are specified in the goal and scope and is therefore not a complete assessment of all environmental issues of the system under study. Limitations to LCA include lack of data on processes or materials inventory which can lead to omissions and error (Baumann and Tillman, 2004).

The life cycle of an electricity network consists of a series of stages, as illustrated in Figure 1. Materials and manufacturing of the infrastructure components includes raw material extraction through to component processing. Transportation and installation includes energy consumption and emissions from the transportation of components to site and all materials and processes used during the installation procedure. Operations and maintenance (O&M) includes impacts related to processes or materials used during operation and maintenance practices throughout the lifetime which includes repairs and replacement materials. Decommissioning and disposal involves removal of materials as well as the effect of their recycling or disposal.

Calculations are made to quantify the amount of resource use and pollutant emissions in relation to the 'functional unit', in this case the transmission of a unit (kWh) of electricity. The carbon intensity is expressed as the CO₂ emitted per unit of electricity transmitted (gCO₂/kWh) while the equivalent for energy intensity is energy consumed per unit of electricity transmitted (kJ/kWh). Strictly speaking, this reduced set of impact measures is referred to as a life cycle inventory analysis (LCI). The inclusion of further environmental impact categories such as ozone depletion and acidification are required for a full LCA (ISO, 2006).

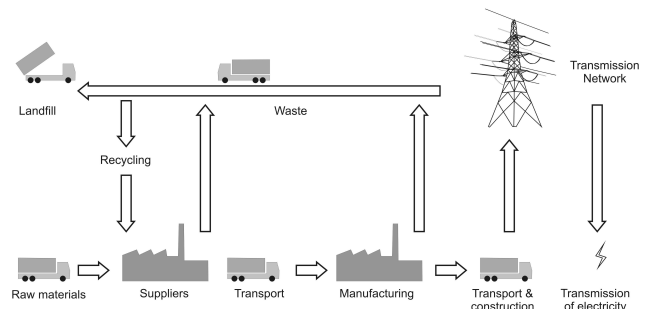


Figure 1. Transmission network life cycle, after Parker *et al.* (2007).

B. The GB Transmission Network

The GB transmission network operates at voltages of 400, 275 (and 132 kV in Scotland). The ownership of the network is a legacy of the former nationalised industry with the system in England and Wales owned by National Grid; by Scottish Power in southern Scotland and by Scottish and Southern Energy in northern Scotland. Since April 2005 the whole network has been operated by the transmission system operator, National Grid. The geographical spread of the system is shown in Figure 2 with key metrics for each voltage level given in Table 1. Around 350 TWh of electricity a year is transmitted across the network (National Grid, 2008), much of which was produced by fossil-fuelled generators.



Figure 2. Transmission network in Great Britain, after National Grid (2008).

	Network voltage (kV)			Total
	400	275	132	
Overhead line (circuit km)	11,557	5,859	5,254	22,670
Underground cable (circuit km)	179	498	210	887
Substations (number)	159	129	393	681
Transformers (number)	356	483	286	1145

Table 1. Transmission system summary as at end of 2007 (National Grid, 2008).

C. Study scope and boundary

The system boundary defines what is, and what is not, included in the analysis. The study has a ‘cradle to grave’ boundary by considering all energy input and carbon emissions from the extraction of the raw materials used in manufacture to the complete disposal of assets at their end-of-life (Figure 1). Physically, the system boundary starts at the transmission side of the generator substations and ends at the transmission side of the grid supply points connecting the distribution networks. Network assets include OHL, underground cable, substation switchgear and associated civil engineering work; relatively minor assets (e.g., surge arresters) have been ignored. Infrastructure in power plants, distribution networks, load sites and the undersea DC interconnections to France and Northern Ireland are excluded.

The assessment is intended as a first level estimate for the transmission system. Although the network infrastructure developed over many decades, the analysis assumes that the system was manufactured and assembled today using current technology and as a single unit. Further, its physical structure, operation and maintenance practices remain static over its design life. At the end of its life the system assets are assumed to be decommissioned. In this way the overall process of asset renewal is captured. A lifetime of 40 years is regarded as a reasonable assumption for the life time of major system assets and has been assumed for all components. All components are assumed manufactured in the UK and subject to UK energy measures and transport distances. The energy and emissions associated with the manufacture of capital plant and machinery used during the network life cycle have been excluded but the typically much more significant operational electricity and fuel consumption are included.

III. LIFE CYCLE INVENTORY ANALYSIS

A. Procedure

The raw materials used in the network infrastructure have been analysed directly in terms of their materials and mass. Where available, use was made of existing LCA studies of specific assets, by re-engineering them to suit UK embodied values based on the material content and energy use in manufacturing. Power losses during asset use are discounted as these are dealt with for the network as a whole.

The infrastructure is rather eclectic and represents the changes in transmission technology over the last half century. Discussions with staff at the transmission companies facilitated

development of a standardised infrastructure thought to be representative of the current network. Access to the detailed asset databases of the transmission owners was precluded and a fully detailed breakdown of all assets was not available. The information published in the Seven Year Statement (SYS; National Grid, 2008) was supplemented by basic data on ‘typical’ arrangements from National Grid and Scottish Power. Additionally, a range of contractors were consulted to gather information on construction methods.

B. Raw Materials and Manufacturing

Data for material embodied energy and carbon is largely taken from the Inventory of Carbon and Energy, a database of construction materials compiled by the University of Bath (Hammond and Jones, 2008). The UK-focussed dataset accounts for the energy and carbon cost associated with extraction of raw materials through to the processed materials. Other LCA studies have been used for other specific materials. Where material data was not available, data for a ‘similar’ material was selected, e.g., SF₆ gas production used values for halocarbon refrigerants from Campbell and McCulloch (1998). Table 2 summarises the main materials encountered.

Material	Embodied Energy (MJ/kg)	Embodied CO ₂ (kgCO ₂ /kg)
Aluminium (general)	155.0	8.24
Copper	55.0	3.88
Steel (general – wire)	24.4 – 36.0	1.77 – 2.82
Ceramics (fitting)	20.0	1.05
Paper (high quality)	26.2	1.50
High density polyethylene (HDPE)	76.7	1.60
PVC (general)	77.2	2.41
Carbon Black (Probas, 2009)	45.8	0.39
Mineral oil (McManus <i>et al.</i> , 2004)	49.9	3.09
Concrete (2% reinforced)	2.12	0.24
Concrete (general)	0.95	0.13
Aggregate	0.15	0.01
Clay pipe	7.00	0.49
SF ₆ (production; Campbell and McCulloch, 1998)	105.0	9.00

Table 2. Principal materials and their embodied energy and CO₂. Hammond and Jones (2008) unless specified.

While generation-related LCA studies suggest manufacturing processes (e.g., welding) add little to the overall impact (Vestas, 2005; Parker *et al.*, 2007), some materials particularly metals, can be sensitive to fabrication process (e.g. section); these are accounted for where known. For recyclable materials like steel the use of primary or secondary (recycled) sources has a major impact so ‘typical’ UK mixes given by Hammond and Jones (2008) have been used.

It is standard in LCA studies to use the weighted average emissions of the generating mix as the carbon intensity of electricity consumed; for the UK this was 0.52kgCO₂/kWh in 2007/08 (BERR, 2008). To reflect the higher primary energy

in the original fuels, a multiplier of 3.03 (McManus *et al.*, 2002) is applied to all electricity use. Where diesel fuel is consumed, direct carbon emissions of 2.63 kgCO₂/litre (DEFRA, 2005), are raised by 16% to factor in extraction, refining and transportation (Mortimer *et al.*, 2003).

1) Overhead Lines

Just over half of the overhead line in GB is at 400 kV (Table 1) and an eclectic range of tower designs, sizes and power transfer capacities exist. The OHL was modelled on typical tower configurations representative of each voltage level (Kelly, 2008; Osborne, 2007) and these can be seen in Table 3 and Figure 3. The 275 and 400 kV circuits were modelled as double circuit L2 steel lattice suspension towers carrying two sets of 3 phase conductor sets, an earth wire at the highest point and porcelain insulator sets from which the conductors hang. The phase conductors are twin bundle aluminium alloy (AAAC) with the earth wire of steel reinforced aluminium alloy conductor (AACSR). The 132 kV circuits use smaller L7 towers with single aluminium conductor steel reinforced (ACSR). The larger L6 tower used at 400 kV is shown for comparison and is considered in the Discussion. While most OHL is double circuit, around 7% of routes carry only one set of phase conductors. To account for the higher resource use, the existence and lengths of single circuit were estimated from the detailed circuit listings and diagrams in the SYS. Although special tower designs exist, single circuits were assumed to have the same tower infrastructure but half the number of phase conductors and insulators.

While the total length of conductors is based directly on the published figures, estimates of the number of towers required assumptions about the span between them. Typical spans between the towers (Table 3), based on straight line runs on flat land at standard tower heights provided a first estimate; were increased by 10% to account for shorter spans due to direction changes and topology. The resulting number of towers are given in Table 3 and compare well with National Grid's estimate of 22,000 towers in England and Wales alone (Osborne, 2007).

National Grid outlined the material use in a typical L2 tower which comprises steel angle section for the tower, 2% steel reinforced concrete for the foundations and porcelain insulators (Osborne, 2007). The material use in the smaller L7 tower was based on other data (CEGB, unknown) with values for the foundations and insulators scaled from the L2 figures. An additional 2% of the tower steel was added to cover minor components like spacers, arcing horns and paint, as well as the more substantial tension and terminal towers. The material use for conductors was based on published standards (BSI, 2001).

Overall, the OHL circuits require around 1.3 million tonnes (mt) of material: 29% steel, 49% reinforced concrete, 16% aluminium and 6% porcelain. The embodied energy is 43.8 PJ, embodied carbon is 2.6 mtCO₂, a disproportionate portion of which comes from the aluminium conductor (~64% of CO₂). Comparing the impacts of different voltage levels in pure material terms, the 132 kV circuits have a 70% lower carbon

impact per circuit kilometre than 275 kV.

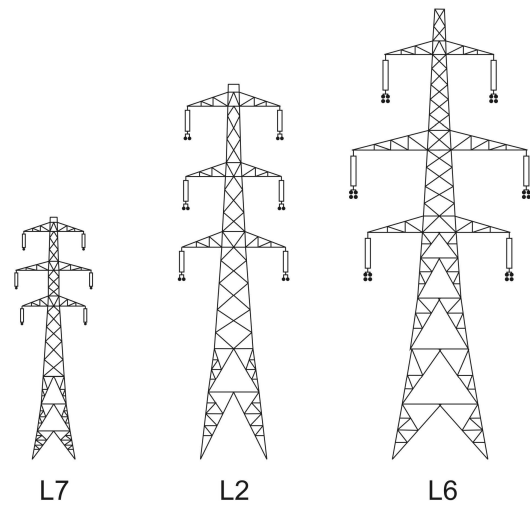


Figure 3. Schematic of steel lattice towers

	Voltage Level		
	132 kV	275/400 kV	400 kV
Tower type (Fig 3)	L7	L2	L6
Height (m)	26.9	41.6	50.6
Width (m)	9.4	12.2	20.9
Span (m)	305	366	366
Phase conductor cross-section (mm ²) and type	1 × 175 ACSR (Lynx)	2 × 660 AAAC (Sorbus)	4 × 400 ACSR (Zebra)
Earth conductor (mm ² , type)	1 × 70 ACSR (Horse)	1 × 160, AACSR (Keziah)	1 × 160, AACSR (Keziah)
Tower mass (t per tower)			
Steel tower	4.6	12.0	23.2
2% steel reinforced concrete foundations	11.5	19.2	30.5
Porcelain insulators	1.6	2.4	3.0
Conductor mass (kg/km)	842	2 × 1822.5	4 × 1620
Circuit kilometres	4,810	17,538	-
Total towers (estimate)	10,262	27,124	-

Table 3:Overhead line circuit and tower details

2) Underground Cables

The underground cables in service in GB also vary in age, rating and construction. The majority of cable is directly buried in trenches, with 275 kV regarded as more economical to bury than 400 kV (Osborne, 2007). A small but increasing amount of 400 kV cable is being installed in purpose-built tunnels.

The civil engineering materials and construction for directly buried cable were based on the Kirkby–Lister Drive cable replacement project in Liverpool (Electricity Alliance, 2007). Each circuit comprises a 1.5 m wide trench holding three single-core cables, 1.5 m below ground. A layer of sand-cement mixture assists heat dissipation with a 150 mm concrete layer provides impact protection. The construction of the cables was estimated from manufacturers' data sheets (Table 4). The 275/400 kV directly-buried cables were taken

to be single core 2500mm² copper conductor oil-filled cables while the 132 kV cable is single core 400mm² copper conductors with extruded XLPE insulation (5% has been added to HDPE materials data to capture the energy intensive process to convert it to XLPE). The 275/400 kV cable has an embodied carbon of 389 kilo-tonnes (kt) of CO₂ with the 132 kV cable a more modest 49 ktCO₂.

	Directly-buried		Tunnel
Voltage	132 kV	275/400 kV	400 kV
Diameter (mm)	66	150	150
Cross-sectional area (mm ²)	400	2500	2500
Insulator	XLPE	Oil / paper	XLPE
Conductor	Copper	Copper	Copper
Semi-conductor screens	Carbon Black / XLPE	Carbon Paper	Carbon Black / XLPE
Metal screen	Copper	Aluminium	Copper
Oversheath	HDPE	PVC	HDPE
Rating (MVA)	120	~1500	~1800
Reference	ABB, 2009	Taihan, 2008	ABB, 2009

Table 4. Assumed cable constructions

In the London area, National Grid has a programme of laying replacement circuits in new tunnels constructed using tunnel boring machines (TBM). It has been assumed that there are 50 km of tunnels housing single circuit 400 kV 2500mm² XLPE cables. The tunnel was based on the 20 km Elstree–St Johns Wood tunnel built by contractor Murphy Group in 2003. This had an internal diameter of around 3 m (Murphy Group, 2007) with 400 mm thick reinforced concrete rings forming the tunnel walls. The embodied energy and carbon for the mechanical and electrical systems were taken as 10% of the concrete walls. The total energy embodied in the 50 km cable tunnel system is 2.5 PJ with CO₂ of 261 ktCO₂.

Overall, the cable materials embody 8.5 PJ of energy and 700 ktCO₂. The 275/400 kV directly-buried cable represents around two-thirds of this. However, on a per kilometre basis, the tunnelled option is seven times more carbon intensive.

3) Substations and Transformers

Substations are very diverse in size and complexity but are laid out in ‘bays’ which connect the circuits. The bays comprise busbars, disconnectors, circuit breakers, connectors as well as measurement devices. It was not feasible to examine the layout of every single substation but a range of texts (Fletcher, 2001; ABB, 2001), satellite photography of sample substations and discussions (Bell, 2009) indicated that a double busbar with bus coupler arrangement was common. With one bay per circuit (including transformers and reactors) along with an additional bus coupler, analysis of the SYS suggested around 4700 breakers. In air insulated (AIS) substations there are approximately two disconnectors per breaker.

While only around twenty substations are full GIS installations it was important to capture the differences between this indoor, physically compact, but heavy switchgear and the large outdoor AIS substations. Several environmental

product declarations (EPDs) of SF₆-interrupted AIS and GIS breakers have been used for switchgear estimates (ABB, 2005; 2007a; 2007b) and similarly for AIS disconnectors (ABB, 2002). Estimates of other specific substation assets have not been included but transformers are dealt with below. Basic data on circuit breakers are given in Table 5.

The other materials used in each bay were based on typical 123 and 245 kV AIS bays (ABB, 2001) and include foundations and steel work for busbar supports, gantries and connectors; these were applied, respectively, to each 132 and 275/400 kV bay. Typical busbar constructions of hollow aluminium tube and damping wire were also separately estimated. The GIS bays were taken to have a third of the concrete of an AIS bay. This information is shown in Table 5. Other significant basic civil engineering was estimated from information supplied by Murphy Group (2007) for the 2005 extension of the 400 kV Monk-Fryston substation in Yorkshire; this included earthworks, fencing, drainage, roads and site finishes. The level of work is representative of medium-sized, multi-voltage level AIS substations (around 200×100m area). Based on the number of bays, all substations were grouped into small (<5), medium (5-9) and large (>10) installations with the basic civil engineering scaled from Monk-Fryston (small 50%, large 150%) with GIS substations assumed to be 30%. The equivalent of two additional bays at each substation were added to represent auxiliary equipment (batteries, etc). The embodied energy of the substations excluding the transformers is 13.6 PJ and 946 ktCO₂.

	AIS		GIS	
Voltage level (kV)	132	275/400	132	275/400
Circuit breaker (t):				
Aluminium	0.2	0.2	4.0	8.4
Copper	0.1	0.1	0.9	1.8
Steel	0.5	0.6	1.7	3.5
Porcelain	0.7	0.9	-	-
Other	minor	minor	0.6	1.8
Substation bay (t):				
Concrete foundations	125.5	166.1	38.3	
Steelwork	4.3	9.4	-	
Aluminium	0.2	1.1	-	
Basic civil engineering (t)				
Concrete	224.0		67.2	
Limestone chipping	6720.0		2016.0	
Fencing	36.0		10.8	
Transformer (t):				
Steel (per 100 MVA)		30.6		
Copper (per 100 MVA)		8.0		
Oil (per 100 MVA)		12.6		
Other (per 100 MVA)		6.9		
Concrete foundations	125.8	1296.0	125.8	1296.0

Table 5. Materials use in average AIS and GIS substations

Estimates for transformers and quad boosters were based on an EPD for a 500 MVA transformer (ABB, 2003) which provides an indicative per MVA breakdown of materials and energy used for its construction. These were found to be in agreement with other work. Details of individual transformer

winter ratings in the SYS allowed an estimate of the total MVA rating and materials use for all transformers across GB. The reinforced concrete in the transformer foundations and bunds were also estimated for typical 275/400 and 132 kV transformers (Table 5). The total energy embodied in the transformers is 12.9 PJ and CO₂ of 861 ktCO₂.

The total embodied energy across the GB substations was estimated to be 26.5PJ and embodied carbon of 1.8 mtCO₂. The analysis shows that a medium AIS substation embodies around 2,500 tCO₂ while despite the larger mass of high intensity aluminium in the switchgear, GIS substations have a smaller impact of 1,700 tCO₂.

4) Summary of Materials and Manufacturing

The total energy required for materials is 79 PJ and carbon emissions are 5.1 mtCO₂. In carbon terms OHL contributes 51%, substations 35% and cables 14%. Of the total 9.2 mt of materials within the network, concrete accounts for 53%, mostly within substations. Metals like aluminium, copper and steel represent, respectively, only 2.4%, 0.8% and 5.7% of the total mass. The materials actively involved in carrying current (most aluminium and copper and some steel) represent a very modest 3% overall. In terms of embodied energy and carbon, the picture is quite different with Figure 4 showing the contribution of each material to total mass and embodied CO₂. It shows that the metals dominate CO₂ (aluminium ~40%) while concrete and aggregate are more modest (27%) in carbon terms.

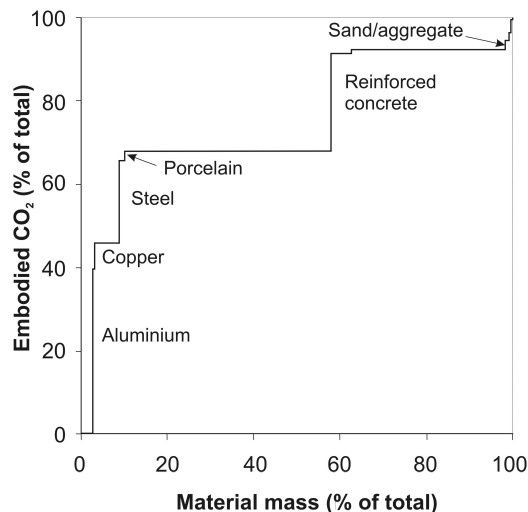


Figure 4. Cumulative contribution of key materials to overall network mass and embodied CO₂.

C. Construction

The construction of infrastructure has been analysed mainly in terms of the fuel consumption of contractor plant used. Typical construction methods and durations were identified through extensive discussions with contractors allowing estimates of fuel consumption to be made.

1) Overhead Lines

Typical OHL construction methods were outlined by

construction company AMEC (2007): laying track-ways, excavation of foundations, erection of tower steelwork and the 'stringing' of conductors. Stringing involves winching conductors up to the connection point on the insulators and ensuring correct tensioning (around 3.2 km can be strung per day). All impacts were due to fuel use, 90% of which was used in the delivery of the towers and for excavation plant. Around 3,300 litres of fuel per km is consumed requiring 1.9 PJ of energy and 130 ktCO₂ to erect all the OHL.

2) Underground Cables

Construction methods differ for directly buried or tunnelled cables. Tunnelling was based on the 20 km tunnel most of the emissions (87%) were due to the three electrically-driven 600 kW Lovat TBMs. At typical operating patterns (Lovat, 2007) for 100 hours a week over 15 months, the TBMs consumed 6.5 GWh. Other contributors included removal of earth, ventilation and deliveries of materials (Murphy Group, 2007): around 100,000 litres of fuel was consumed. This information was used for the whole 50 km length of tunnels, and suggested the energy requirement was 197 TJ and carbon emissions of 9.6 ktCO₂.

For directly buried cable, construction varies with site conditions and duration of operations. The Liverpool cable project is laying 10 km of 275 kV circuit in around two years in a mostly urban setting (Electricity Alliance, 2007); more efficient excavation allows a similar rural route to take 6 months. Assuming a compromise construction rate of 1.6 months/km, construction plant was estimated to use 14,300 litres of fuel per km; this equates to GB totals for buried cable of 560 TJ with CO₂ emissions of 38 ktCO₂.

The combined impact of tunnelled and buried cable construction is 756 TJ and 47 ktCO₂.

3) Substations and Transformers

Construction processes and plant for medium substations and transformers was again based on Monk-Fryston. The main impact was fuel use for the earthworks (96,000 litres). This figure was scaled for the other AIS and GIS substations as per the basic civil engineering used earlier. The total energy required to construct the substations is 2 PJ and carbon emissions are 135 ktCO₂.

4) Summary of Construction

The total energy required for construction is 4.6 PJ and embodied carbon of 312 ktCO₂. Substations and OHL are each around 43% each while underground cable is the remainder.

D. Operations and Maintenance

This stage assessed the processes and impacts arising from the 40 year operation of the network.

1) Electricity Losses

Half-hourly settlement data for April 2006 to March 2007 was procured from Elexon (2007), the GB balancing market administrator: annual losses were 6.1 TWh (~1.7%). In primary energy terms, losses represent 67 PJ per year while the carbon intensity of electricity suggests an annual carbon impact of 3.2 mtCO₂. Assuming constant loss rates and carbon intensity, the life time impacts are 2,663 PJ and 126.9 mtCO₂.

2) SF_6 Losses

The high global warming potential of SF_6 leads the transmission companies to publish data on usage and leaks from switchgear. Environmental statements from National Grid (2009) and Scottish Power (2008) suggest an annual GB loss of around 18 t of SF_6 , equivalent to 438 ktCO₂. Over the life cycle, SF_6 emissions equal 17.5 mtCO₂. The embodied energy and carbon of the replacement SF_6 gas is fairly low.

3) Inspection and Maintenance

Inspection procedures for the transmission network were determined through discussions with National Grid (Osborne, 2007) and were assumed to apply to the entire system. Helicopter inspections aim to cover the entire length of the OHL network every 3 years. National Grid used 813,000 litres of aviation fuel in the 2006-07 year (Osborne, 2007). It was assumed that 75% of this was used for inspection flights resulting in life time energy use of 1.1 PJ and CO₂ of 75 ktCO₂. The contribution from ground level visual inspections of OHL and quarterly substation inspections require modest amounts of fuel and take total embodied energy and carbon for inspections to 1.1 PJ and 78 ktCO₂, respectively.

As some of the infrastructure will be replaced for reasons other than network expansion, e.g., weather damage, a conservative 10% of all equipment is assumed replaced during the lifetime. The same proportion of the total energy and CO₂ impact from the materials stage has been allocated for this (7.9 PJ, 510 ktCO₂).

4) Summary of Operations and Maintenance

The total energy and carbon for the operations and maintenance stage is 2,672 PJ and 145 mtCO₂, respectively, made up almost entirely of electricity and SF_6 losses.

E. Decommissioning and Disposal

The final life cycle stage deals with the impacts associated with demolishing infrastructure and then either recycling the materials or disposing of them. Recycling of materials allows processing without the energy and carbon costs of raw material extraction, transportation and processing. The savings in energy and carbon can be 'credited' to the system, reducing the overall impacts (ISO, 2006). Some materials, particularly metals, are recycled effectively with, e.g. aluminium, able to avoid 95% of energy consumption compared to virgin material. Conservative estimates have been used for the energy recovery and carbon saving for recycling aluminium (90%), copper (70%) and steel (50%) components. For the OHL and substation all metals are recovered and recycled but no part of the underground cable infrastructure is extracted. The recycling potential for other materials was ignored.

The recycling of around 760 kt of material from a pool of 9.2 mt offers credits of 37 PJ of energy and 2.1 mtCO₂. The conservative estimates used here imply greater potential savings from recycling, particularly if the underground cable can be recovered. The energy and carbon required to recover and transport material for recycling or disposal was assumed to be equal to the energy and carbon involved in constructing the assets in the first place; this amount (4.6 TJ, 312 ktCO₂) is

small relative to the impact of recycling.

F. Life Cycle Summary

Figure 5 shows the energy and carbon impacts across each life cycle stage. Ignoring the recycling, the embodied energy of the network is 2,775 PJ while the embodied CO₂ is approximately 150.5 mtCO₂. The recycling credit brings these down to 2,722 PJ and 148.6 mtCO₂. The infrastructure itself represents approximately 3% of gross embodied energy and CO₂ (excluding recycle credit) while operations and maintenance dominate at 97% of energy and over 96% of carbon. Transmission losses alone account for 85% of total CO₂ while SF_6 losses are around 12%. Due to the dominance of the transmission losses, the overall benefit of recycling is a modest 1.4%.

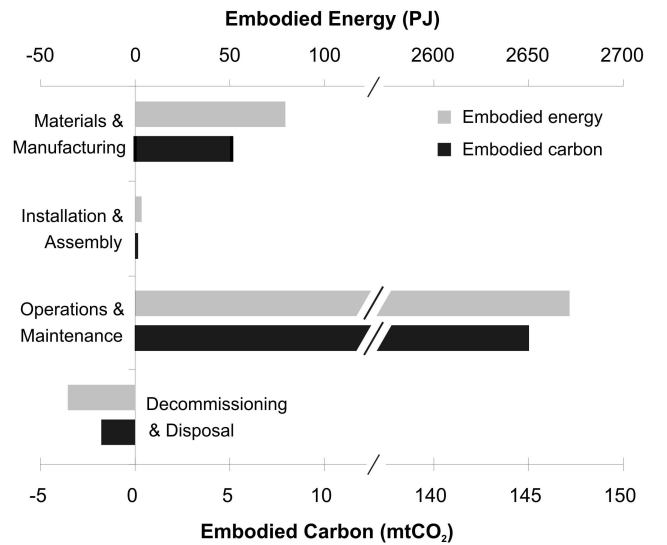


Figure 5. Embodied energy and CO₂ by life cycle stage

IV. DISCUSSION

A. Energy and Carbon Intensity

The energy and carbon intensity offer a convenient means of comparison between networks and other energy delivery mechanisms. These are calculated by dividing the overall embodied energy and CO₂ emissions by the electricity transmitted over the 40 year life cycle. The annual volume of electricity transmitted in 2006/07 was 350 TWh (1,260 PJ) (National Grid 2008). Assuming both this and losses remain constant, the energy intensity of the network is 194 kJ/kWh and the carbon intensity is 10.6 gCO₂/kWh. Given the importance and scale of the transmission network, the impacts appear relatively modest.

The results compare well with other work. Cigré (2005) report a carbon intensity of 0.25 gCO₂/kWh for the Swedish transmission system; this is largely materials and construction as, with an electricity mix of hydro and nuclear, losses are relatively CO₂-free. The intensity of materials and construction alone for the GB network is just under 0.4 gCO₂/kWh. When including the loss impact, Jones and McManus (2008) found

values of 2 to 4 gCO₂/kWh for different 11 kV conductor options. The comparison is reasonable given their analysis of a more limited asset set, lower loading conditions and no SF₆.

To test the reliability of the conclusions from the study a sensitivity study analysed how changes in assumptions affected the overall energy and carbon intensity of the network. They were largely insensitive to factors like asset lifetimes, material intensities and the make up and number of specific assets. The factors that matter are the volumes of electricity transmitted and the volume and CO₂ intensity of electricity losses; these deliver approximately proportional changes in intensity. More detailed consideration of asset types and specifically substation content will help improve confidence in the results. However, the largest single need is for further analysis of electrical losses, specifically how their impact can be reduced.

B. Reducing Electricity Loss Impacts

While the life time energy and CO₂ emissions are comparable with a single 1000 MW coal power station, and therefore relatively modest compared to the industry as a whole, the 127 mtCO₂ associated with losses remains a substantial carbon burden. Given the UK's binding target of reducing CO₂ emissions by 80% by 2050, cuts must come from all sectors of the industry.

The power flows that give rise to the losses are driven by market trading as well as operational requirements to manage constraints and security. Although, as transmission network operator, National Grid is incentivised to operate the network as efficiently as possible, losses are not separately specified as the operator can have limited impact on operational timescales. In the longer term, power flows are dictated by the location of generation and, while connection and loss charging would tend to penalise plant further from the load, decisions by individual generators on siting are typically driven by availability of resources. The drive towards the CO₂ targets requires large-scale expansion of renewable, new nuclear and carbon capture and storage (CCS) stations. These will tend to lower the carbon intensity of electricity, reducing that of the losses and the network life cycle CO₂. More renewables will also reduce the energy intensity of the losses as they will avoid substantial losses of primary energy as heat to the environment (CCS and nuclear will not reduce primary energy use). To a large extent therefore, the losses and their CO₂ impact are outside the direct control of the transmission companies. However, there is potential for decisions over grid infrastructure to deliver lower losses and carbon benefits.

Life cycle approaches can be applied to reduce network losses largely by trading off the greater capital costs of larger lower resistance conductors against lower losses (Curcic *et al.*, 2001). Calls for the replacement of OHL with underground cable in scenic areas have also been justified on the basis of reduced losses despite the typically much greater capital cost. Such assessments can be extended to life-cycle carbon to determine infrastructure options that optimise network CO₂ emissions. Jones and McManus (2008) offer an excellent comparison of options at 11 kV including the benefit of

upgrading circuits before end-of-life. Here, simple comparisons have been made between the L2 275 kV OHL construction and the directly buried cable (which have similar power transfer capability). In terms of materials impact, cable is undoubtedly more carbon intensive (632 tCO₂/km) than OHL (135 tCO₂/km). However, the larger cable cross-section lowers losses such that at an average loading the overall CO₂ impact of the cable is half that of OHL (the benefits increase at higher loadings). A similar comparison of the larger L6 tower construction (Figure 3) shows that, despite doubling the materials, the larger conductors lower the overall impact. In making comparisons, however, it is important to consider that each component is an integrated part of the network and that impacts must be seen within the context of the whole. For radial networks simple assessments like the above will suffice, but meshed transmission systems require detailed power flow assessment to gauge the system-level loss impact. Additionally, CO₂ cannot be viewed in isolation from the wider environmental, financial and reliability considerations.

C. Incentives and Carbon

Currently, the costs of transmission losses are borne by generators and consumers through the application of loss allocation factors. The transmission network owners are not exposed to the cost of losses, although they arguably are in a good position to lower them through appropriate infrastructure investment. While this might be regarded as 'overbuilding' the network and therefore counter to historic regulatory views on capital expenditure, direct incentives for loss reduction are already in place with UK distribution network operators to encourage investment in lower loss equipment (Ofgem, 2004).

An alternative approach would be to provide carbon incentives to the transmission network owners by allocating them the CO₂ associated with losses and incentivising reductions directly or through the Emissions Trading Scheme. Were this to happen it would require improved estimates of CO₂ that do not assume that all units of electricity have the same carbon intensity. In systems like GB where the generation mix varies significantly with demand, coal is often used at higher demand levels making the electricity produced relatively more carbon intensive (Realtimecarbon, 2009). With losses having a quadratic relationship with demand, transmission losses will have a disproportionately large CO₂ impact at higher demand levels that will offset any reductions at low demand. This suggests that the CO₂ impact of losses is currently underestimated and that the benefits of loss reductions may be more 'valuable' and more desirable than first thought. Further work is required on these issues.

V. CONCLUSIONS

This paper presented a detailed account of the energy and CO₂ impacts of the entire high voltage electricity transmission network in Great Britain (GB). It showed that the multi-millions of tonnes of materials used in the infrastructure had a substantial amount of embodied energy and CO₂, but that network losses had an impact that was two orders of

magnitude more significant. In terms of reducing the CO₂ emissions associated with the network, there appear to be opportunities for investment in infrastructure to lower losses. The regulatory and measurement issues this raises are briefly discussed.

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