New Fire Hazard and Environmental Burden Evaluations of Electrical Cable Installations Utilizing ISO 14040 Environmental Methodologies

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Abstract

Changing environmental interests and new fire safety performance concerns in the wire and cable industry (WCI) have generated studies into the fire hazard and eco-performance of various data and communication cabling system alternatives for computers and local area networks (LAN). To accurately assess the various alternatives, the installed electronic functionality and fire safety performance requirements of the various end-use product options must be equivalent. For high fire performance communication cables (HFP-cables), many existing local and national regulations differentiate between end product performance options and building fire protection needs. High fire-performance, high societal-value based PVC sheathed and perfluoropolymer (PFP) insulated (PVC/PFP) cables can be routed directly in concealed plenum spaces in buildings, while products that do not meet specific high fire performance criteria, such as low-smoke zero-halogen (LSZH/PE) cables or riser-rated cables (CMR or PVC/PE), often must be protected inside other structures that do meet these building fire standards, typically using steel conduit or trunking. However, some low fire performance LAN cables, even fire-protected inside steel conduits, failed to meet the minimum flame spread and smoke criteria that HFP-cables must meet in real-scale cable fire tests at BRE/FRS and Underwriters Laboratories (when tested as a cable in steel conduit system) [10]. Life cycle analysis (LCA) via ISO 14040 methodology is used to evaluate the various cabling alternatives using an appropriate functional unit; a CAT 6 communication LAN cabling system in a typical office building, including cable, steel conduit, couplings and supports as required per building codes for the installation. Key environmental impact assessments for energy consumption, greenhouse gas emissions, and human toxicity are all shown to favor the PVC/PFP systems once the steel conduit is included in the analysis to fire-protect the LSZH/PE or PVC/PE cables. The additional fire safety and installation advantages provided by the PVC/PFP cables more than offsets for the environmental burdens associated with the initial manufacture of just the cable, thereby providing superior overall fire safety, environmental performance, and economic benefits versus LSZH/PE and PVC/PE cables in steel conduits.

Keywords: Communication Cables; LAN Cabling; Life Cycle Analysis; Steel Conduit; Environmental Burden; CMR; CMP; LSZH; PFP; PVC; HDPE; High Fire Performance Cabling (HFP-Cables).

1. Introduction

A recent Design for Environment (DfE) study on wire and cable materials has identified their environmental burdens without full consideration of actual cable functionality [15]. In fact, the study has omitted the burdens associated with the copper wire despite the need for the conductor in order to transmit the signals for which the cables are designed. As shown in previous research by Williams, et. al., and as will be supported by this study, the copper wire accounts for the bulk of the environmental burden associated with cable construction [17]. The objective of the DfE/TURI wire and cable study was to provide industry with environmental performance data on cabling alternatives to use along with economic and technical performance data when selecting cables for a given application. However, omission of large environmental impacts, such as those from copper, even if similar in magnitude among alternatives, skews the perspective of the impacts from other materials and may miss an opportunity to make more significant environmental improvements.

The objective of this study is to identify the entire environmental performance for a LAN cabling system and identify the actual key contributors by including both the copper wire and the conduit, wireway, and support steel required in a typical cabling installation. This study will also show how the focus changes as a more robust functional unit is defined, progressing from cables without copper (not a functional system), to uninstalled cables (not functionally equivalent due to fire performance), and finally, to installed cables (functionally equivalent).

2. LCA Methodology

The goal of this life cycle analysis is to compare the environmental burdens of a PVC/PFP LAN cable installation to both PVC/PE and LSZH/PE LAN cable installations using equivalent industry accepted codes and standards which include both electrical and fire safety performance.

The system boundary includes raw material extraction from the ground through installation of the cabling systems to end-of-life as depicted in Figure 1. The use-phase, the time between cable installation and removal, is deemed both equivalent and insignificant with regards to environmental burden for these low-voltage cable installations. Cable installations are typically replaced due to technological obsolescence as opposed to cable failure, so no difference in life expectancy is expected. Therefore, the use-phase is excluded from this study.

The analysis quantifies raw material use rates, energy requirements, and emissions throughout the supply chain, incorporating efficiency, distribution, and conversion losses associated with electricity generation. Allocations for co-products along the supply chain are often required and are addressed individually, via system expansion, avoidance, mass allocation, or energy allocation based upon their own merits. Current literature often provides multiple options for the modeling of any particular intermediate. When possible, actual plant data is used. Otherwise literature sources consistent with the scope of this study and LCA database modules from Ecoinvent™ or others available in SimaPro™ life cycle software are used. When multiple sources are available for significant materials in the life cycle, models are critically evaluated to generate the most comprehensive representation of current manufacturing processes.

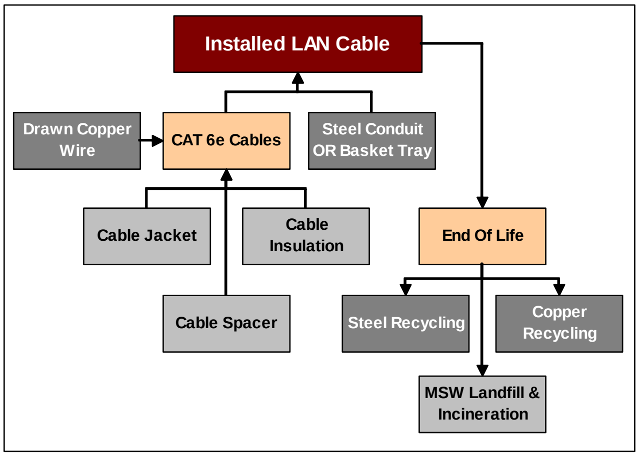

Figure 1. Cable Installation Life Cycle System Boundaries

Materials representing 1% or more of the mass associated with any of the main cable parts, PFP insulation, PVC jacketing, Copper, LSZH jacketing, HDPE insulation, steel support and conduit will be included. When literature or plant data is not available, stoichiometric or similar approximations may be used and detailed in this report. When data quality is poor or highly variable, sensitivity analysis shall be used to confirm overall accuracy. This study will follow the guide that inclusion at some conservative level of detail is preferable to omission.

End-of-Life (EOL) assessments account for the recycling of 95% of the copper and steel used in the installations [15] as well as the general disposal of the remaining plastics via municipal solid waste landfill or incineration. Ecoinvent™ based waste scenarios developed in SimaPro™ for U.S. municipal solid waste disposal are used [5].

Impact assessment methods available in the SimaPro® life cycle software are used for evaluation of the life cycle inventories. The Cumulative Energy Demand impact assessment from Ecoinvent™ 2000 is used to calculate the primary energy demand [7]. Both non-renewable fossil and nuclear fuels are included on a lower heating value basis. Other environmental impacts are calculated via the CML 2 baseline 2000 V2.1 impact assessment available in SimaPro™ [4,7]. Updates for the global warming potential values were made to agree with IPCC TAR 2001 [16].

3. LCA Basis

3.1 Functional Unit

Per ISO 14040, product systems are to be evaluated on a functionally equivalent basis to ensure fairness in the environmental comparison. Both data transmission and fire performance must be equivalent to make meaningful life cycle comparisons. For the comparison of PVC/PFP cables with LSZH/PE and PVC/PE cables, the additional burdens of the installation steel and conduit must be evaluated along with the burdens for the cable (with copper conductor) to facilitate code-accepted fire performance.

For this study, a complete LAN cable installation for a typical 27,000 ft^2 office building is used, including two CAT 6e cables for data communications and telecommunications per work station, wireways, conduit, supports, power poles, etc. utilizing TIA 568A and 569A design guidelines and industry best practices by Innovative Engineering Services (IES) and Masselli Cabling Design [12]. Table 1 identifies the bill of materials developed for both a LSZH/PE or PVC/PE installation and a PFP/PVC installation.

Table 1. Steel Requirements for CAT 6 LAN Cabling Installations in a Typical 27,000 ft2 Office Building

LSZH/PE & PVC/PE Installation Steel	Size	Qty	Mass (kg)
Wireway	8"	185'	713.3
Wireway	6"	180'	453.1
Wireway Fittings	8"	30	46.1
Wireway Fittings	6"	16	5.6
Conduit	2.5"	270'	264.5
Conduit	2"	600'	402.8
Conduit	1"	20'	6.1
Conduit Fittings & Couplers	All	750	312.6
Power Poles & Fittings		110	252.5
Threaded Rod	1/4"	640'	34.8
Brackets & mounting nuts	N/A	320	202.8
Mass of Steel			**2694.2**
Cabling Requirements	**Size**	**Qty**	**Mass (kg)**
CAT 6 CMR-Type Cable	22.5 AWG	21.95 km (72,000 ft)	910.9
PVC/PFP Installation Steel	**Size**	**Qty**	**Mass (kg)**
Basket Tray	18" x 2"	420'	333.8
Splice Kit		50	7.1
Trapeze Kit		90	73.5
Fittings & Drop-outs		180	26.3
Threaded Rod	1/4"	425'	23.1
Beam Clamps		250	28.3
"J" Hooks	CAT 21	160	11.2
Power Poles		110	244.5
Mass of Steel			**747.8**
Cabling Requirements	**Size**	**Qty**	**Mass (kg)**
CAT 6 CMP Cable	22.5 AWG	21.95 km (72,000 ft)	939.5

Adjustments to the original request for information (RFI) report were made for this study with the aid of IES to address only the plenum cable portion of the installation and to use only CAT 6e cable.

The general steel support layout assumes two main headers through the building using either square duct wireways (PVC/PE & LSZH/PE installs) or basket tray (PVC/PFP Installs) at 50% fill ratios. Branches from the header use either galvanized electrical metallic tubing (EMT) at 40% fill ratios (PVC/PE & LSZH/PE) or j-hooks (PVC/PFP) based on fire-performance requirements. The categories “LSZH/PE & PVC/PE Steel” and “PVC/PFP Steel” used in the results section of this paper refer to the steel itemized in Table 1 for each application. Both of these results categories have incorporated the credits associated with steel recycle and the burdens of transportation in their values. A life cycle process for each item at each size in Table 1 was developed individually in the life cycle model to account for the proper thickness and mass of zinc for galvanizing when required. Of note, an alternative support system for PVC/PFP cable would replace basket tray with j-hooks for support in the main headers. While this option is not evaluated in this study, it would result in a substantial reduction in steel use for the PVC/PFP system.

A CAT 6 cable consists of a copper conductor, insulation, jacket, and spacer. Results in this study will be broken down into these categories, each including the wire drawing, extrusion, compounding, foaming, and/or transportation required to process the material into an installed cable. The burden from copper is reduced by the credits given through the recycling of 95% of the copper wire at the end-of-life [15].

A PVC/PFP cable uses PFP insulation with approximately 10% recycled PFP. The jacket for a PVC/PFP cable is lead-free PVC polymer compounded with some combination of flame retardants, plasticizers, stabilizers, and fillers depending on manufacturer. For simplicity, a formula publicly available from Kemgard® and specifically for plenum grade cable is used as shown in Table 2 [22].

Table 2. PVC and LSZH Jacket Formulations

Material	Plenum-Grade PVC Jacket	LSZH Jacket
	wt%	wt%
Polyvinyl Chloride (PVC)	43.5%	
Ethylvinyl Acetate (EVA)		60%
Aluminum Trihydrate (ATH)	30.4%	30%
Phthalate Plasticizer	8.7%	7%
Ca/Zn Stabilizer	3.0%	3%
Kemgaurd HPSS	4.4%	
Brominated Flame Retardant	8.7%	
Antimony Oxide	1.3%	
LSZH formulation is from proprietary data and is estimated as a typical formulation. PVC non-lead formulation per http://www.kemgard.com/technical_articles/HPSSbrochureflexPVC.pdf		

The relative mass of the main components in the cable also vary considerably with manufacturer and type of CAT 6 cable. A review of cable specification sheets from major cable suppliers suggests most CAT 6e cables use 22 to 23 AWG wire. For this study, 22.5 AWG is assumed for all three cable types. Further breakdown, is detailed in Table 3.

LSZH/PE and PVC/PE cables are currently not commonly used for plenum applications due to fire-safety code requirements. This study will assume a typical breakdown by cable component similar to CMR-rated cable is used for both. While both HDPE and LDPE are used as insulation material, HDPE is used in this study. Only minor differences are seen between the two from a life cycle impact perspective.

For the PVC/PE installation, the same plenum-grade PVC used in for the PVC/PFP cable is assumed. Like PVC, the low-smoke zero-halogen jacket is a compounded polymer, including ethyl-vinyl-acetate polymer, flame retardants, plasticizers, and stabilizers. A typical composition as shown in Table 2 is expected.

Table 3. Cable Component Breakdown

Cable Component	PVC/PE	LSZH/PE	PVC/PFP
	%	%	%
Conductor	50%	50%	48%
Jacket	33%	33%	23%
Insulation	15%	15%	21%
Spacer	3%	3%	7%
Mass (kg/km)	42.0	42.0	43.1
Overall mass is typical of CAT 6 cables per and in agreement with Socolof, et. Al.[15] but with decreased copper use to match 22.5 AWG. LSZH/PE cable assumed equiv. in cable breakdown to CMR cable			

3.2 Life Cycle Models

3.2.1 Electricity. Grid electricity is modeled using region specific models from either Ecoinvent™ UCTE data for European supply, or data from Michigan State University for U.S. regional grids [7,13]. Some models, such as PVC and HDPE are only available as cradle-to-gate models where electricity supply is not transparent.

3.2.2 Co-generation. When known to be used, cogeneration electricity from natural gas is modeled assuming 50% efficiency for the natural gas (NG) used in the boiler. Additional losses associated with NG production and transportation are included via Ecoinvent™ processes [7]. Emissions per MJ NG supplied are evaluated using the Ecoinvent™ model, “Electricity, Natural gas cogeneration using best technology, at plant” [7].

Steam from NG co-generation is modeled as 100% efficient at the cogen facility with losses for NG production and supply included via Ecoinvent™ processes [7]. This combination of efficiencies for steam and electricity is consistent with an overall cogeneration efficiency of 75% at a 2:1 steam: electricity production ratio.

3.2.3 Perfluoropolymer (PFP). PFP is used as both the insulation material and as spacer material in PVC/PFP LAN cables. Its production includes multiple raw materials and intermediates along an extensive supply chain detailed in Figure 2. The unit processes were developed from DuPont plant data for hydrogen fluoride (HF), chlorodifluoromethane (HCFC-22), tetrafluoroethylene (TFE), and hexafluoropropylene (HFP). Trichloromethane models from Ecoinvent™ were modified to reflect chlorinated methane emissions reported in toxic release inventory data for two manufacturing sites which supply trichloromethane to DuPont [2]. The same data used in this study for the PFP supply chain was provided for use in the DfE/TURI Wire and Cable study [15]. Both HCFC-22 and TFE production lead to a substantial mass of co-product hydrogen chloride (HCl). Avoidance allocation as chlorine equivalents is used for the HCl co-product to avoid attributing fluorocarbon emissions to the less valuable HCl co-product.

PFP used in LAN cables may now be foamed (co-extruded with air), providing enhanced electrical and fire-load performance which allows lower PFP mass use rates. Mass rates shown in Table 3 are reduced by 30% to account for using foamed PFP in both CMP insulation and CMP spacers. Proprietary technical information suggests the enhanced performance may lead to 10% less copper usage for PVC/PFP cabling to obtain equal functionality. This study does not take credit for the potential reduced copper use.

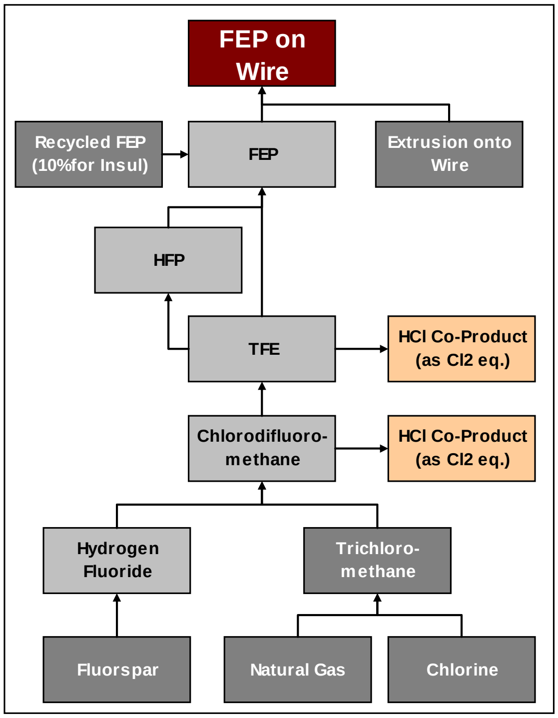

Figure 2. PFP Supply Chain for CMP Cable

3.2.4 Recycled PFP. The cable spacer is modeled entirely as recycled PFP [25]. Energy requirements are estimated at 5 MJ grid electricity and 3 kg steam per kg recycled PFP.

3.2.5 PVC production. As detailed in Table 2, PVC plenum cable jackets consist of just over 40% vinyl chloride suspension polymer. Secondary data for the production of this polymer is available in several LCA databases, including Ecoinvent™, Plastics Europe, ETH-Zurich, and more recently the U.S. LCI database [2,8,9,23] The recent U.S. data is not used due to its limited plant data set, limited focus on emissions data in the energy supply chain, and a host of favorable assumptions in the model development that yield energy and GHG emission results unexpectedly slightly better than the more comprehensive Plastics Europe data. The ETH-Zurich data is substantially higher in most impact categories but lacks the transparency to understand the reasons why. This leaves a decision to be made between the Plastics Europe data and Ecoinvent™ data. However, the Ecoinvent™ data is actually modeled directly from the Plastics Europe (2005) data with a few minor inclusions for waste treatment. Therefore, the Ecoinvent™ process is used in this study. The sensitivity to PVC model selection of an installed cable system is minimized by the use rate of PVC in the formulation and the limited mass use rate of PVC with respect to copper and steel.

The remaining components in PVC plenum cable jackets as shown in Table 2 are modeled as follows:

3.2.5.1 Phthalate Plasticizers. The same models by Ecobilan for phthalate plasticizers, particularly di-(2)-ethylhexyl phthalate (DEHP), used in the DfE/TURI Wire and Cable study are used here [6].

3.2.5.2 Brominated Flame Retardants. Literature data is not directly available for the manufacture of the various flame retardants used in the cabling industry. A model has been approximated for Di-(2)-ethylhexyl tetrabromophthalate using the phthalate plasticizer model for the stoichiometric proportion of organic compound. Bromine manufacture has been approximated as chlorine manufacture [2] with adjustments for the molecular weights of the two halogens to represent the halogen portion of the flame retardant. Brominated organic emissions could not be quantified and are not addressed in this model.

3.2.5.3 Aluminum Trihydrate (ATH). For the production of ATH, the stoichiometric reaction of Al_2O_3 with water, assuming 99% yield and 1 MJ electricity per kg ATH is used. Aluminum oxide manufacture is per Ecoinvent™ data. [2]

3.2.5.4 Stabilizers. The use rate of stabilizer is not substantial, thereby leading to minimal impacts. In the DfE/TURI Wire and Cable study, a typical composition for a Ca / Zn – based stabilizer was provided [15]. Zeolite data was available from ETH-Zurich [9]. Zinc data was taken from Ecoinvent™ [1]. Calcium contributions were assumed as Lime [2]. The remaining mass, including the 'stearate' portions were modeled using a paraffin model from Ecoinvent™ [2]. The intent of this model was to capture the raw materials associated with the stabilizer production. Energy and emissions from the production step for the stabilizer are not included.

3.2.6 Low-Smoke Zero-Halogen (LSZH) Cable Jackets. As shown in Table 2, the LSZH cable jackets include ethyl-vinyl acetate (EVA), plasticizer, stabilizer, and flame retardants. The plasticizer, stabilizer, and flame retardant (ATH) are modeled the same way as those for PVC jackets.

EVA is modeled using the ethyl-vinyl acetate co-polymer model available in Ecoinvent™ [2]. Electricity supply was adjusted to U.S. average grid supply.

3.2.7 High Density Polyethylene HDPE Cable Insulation. Several secondary datasets are available for the production of HDPE. Like PVC, the selected model is from Ecoinvent™ which is based on the 2005 Plastics Europe data [2,23]. Models from Plastics Europe (1998 APME), ETH-Zurich, and the American Plastics council (U.S. LCI data) were all evaluated, but not used for similar reasons as discussed for PVC model selection. For an application such as cable in plenum spaces, HDPE may be compounded with flame retardants, but such a composition is not available to be modeled.

3.2.8 Polymer processing. A model from IDEMAT for PVC extrusion is used to model the extrusion of compounded PVC into a cable jacket [11]. This model was selected since it specifically identifies PVC as the extruded plastic. Compounding energy was estimated at 0.44 kWh/kg (0.2 kWh/lb) which is about half the energy associated with extrusion. The impact of both is included in the results section along with the 'Jacket' data.

A model from IDEMAT for HDPE pipe extrusion is used for HDPE insulation extrusion onto the copper conductor [11] and included in the results with the "Insulation" portion of the LSZH/PE and PVC/PE cable installations. In comparison to the PVC extrusion model, the HDPE extrusion model has roughly 7% higher impacts for most impact categories, but 50% higher energy use.

Energy requirements are expected to be higher for PFP extrusion than those for PVC due to higher extrusion pressures and temperatures. Although data was not available, the burdens for PFP extrusion were estimated using the PVC pipe extrusion model with 2.5 times the energy requirements to approximate the energy consumption for the co-extrusion / foaming process used to produce a PFP coated conductor. The impacts from PFP extrusion/foaming are included in the results for "Insulation" for the PVC/PFP installations

Steel Components. Steel is manufactured using two main processes, the basic oxygen furnace (BOF) and the electric arc furnace (EAF). Both processes are required for the world steel market, but the EAF process is predominantly used in the production of engineering steel and wire rod, as opposed to the cold-formed sections required to produce wireways and conduit [18]. While basket trays (and wire rod) are more likely produced from EAF steel, this study assumes only BOF steel is used as a base case. An increase in cold-formed products from the EAF process is currently underway in the U.S., but the majority of the world market for cold-formed products remains via BOF steel. The environmental performance difference between processes is seen mainly in the amount of recycle steel used in the process, as EAF steel is supplied via 95-100% scrap steel while the BOF market is supplied with 12-30% scrap steel. A scenario analysis will be performed to indicate the impact of assuming a 100% BOF steel supply for all steel identified in Table 1.

Even after the steel process is identified, selecting the appropriate steel model is complex due to the various steel compositions and the breadth of available secondary data. Since steel is identified as the most significant contributor with respect to mass in a cable installation, great care must be taken to identify an appropriate BOF steel process. Within SimaPro™, models for chromium steel, high-alloy steel, low-alloyed and un-alloyed steels were available from databases such as Ecoinvent™, ETH-Zurich, BUWAL, and Franklin. Focusing on low and un-alloyed models, a significant discrepancy in impacts per kg steel was still evident. Consequently, an LCI from the steel industry provided by the International Iron & Steel Institute (IISI) was purchased and included in the analysis. Details on the extensive selection process and model development are available in a separate study by Barr, S. et.al [3].

The finalized model uses the "Blast Furnace Route for Hot Rolled Coil" model from the IISI LCI as the primary data [18]. However, this LCI specifically omitted polycyclic aromatic hydrocarbons (PAH), particulate matter < 10 micron, and other emissions from the coal supply chain as the coal industry did not provide data on these emissions. From the Ecoinvent™ model for un-alloyed BOF steel, the PAH emissions were by far the major impact in the CML 2 2000 human toxicity impact assessment [1]. As the Ecoinvent™ model is thorough with respect to the energy supply chain, the PAH and other emissions omitted in the IISI LCI that contributed more than 1% of the impact from the coal supply chain in each category of the Ecoinvent™ model were added to the IISI LCI data.

The steel life cycle model for producing (EMT) is depicted in Figure 3. After BOF steel manufacture, the steel is formed into slabs in a continuous caster. The slabs are hot-rolled into sheets and rolled into coils. To achieve the wall thickness of EMT (1.25-1.83 mm), the hot-rolled sheet must be cold-rolled. The process of cold-rolling involves pickling, rolling, annealing, and tempering. Modern hot-rolling mills are increasingly capable of producing the required thickness, but as a world average, cold-rolling is still required [18]. Ecoinvent™ models are used for the hot-rolling and cold-rolling steps [1]. At a tube mill, the cold-rolled strip is cold-rolled to form a tube, welded, and hot dip galvanized on the outside surface.

The main wireways for LSVH/PE and PVC/PE cable installations are modeled the same way as EMT without the seam welding. The basket tray for the PVC/PFP cable installation is modeled as galvanized drawn wire that is spot welded together. All couplings, fittings, J-hooks, and beam clamps are modeled as cast and galvanized products of BOF produced steel.

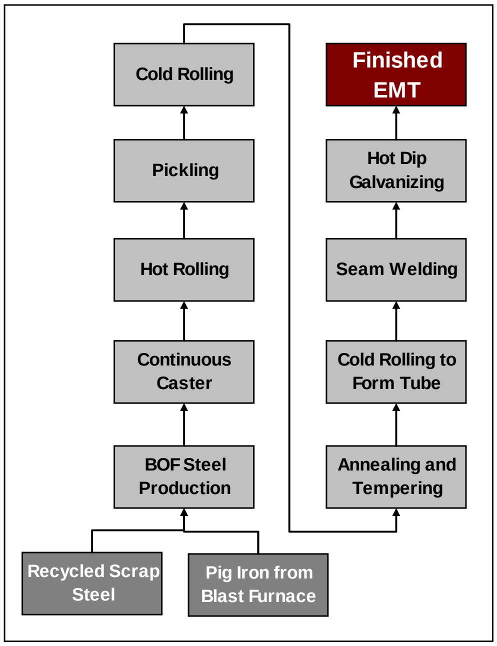

Figure 3. EMT (Conduit) Production Process

3.2.10 Zinc Galvanizing. The zinc galvanizing process is modeled using a modified version of the Ecoinvent™ zinc coating model [1]. The Ecoinvent™ model uses a thickness of 1.7 mil of zinc, but the thickness for EMT and other cable wireways, according to ANSI standard C80.3-2005, only needs to be greater than 0.8 mil. The model was adjusted to a 1.0 mil thickness to avoid overstating the impact of the zinc for galvanization.

3.2.11 Copper Wire. The copper wire process is modeled in three sections. Mined copper concentrate at beneficiation is converted to primary copper, which is drawn into wire and eventually recycled as feedstock to secondary copper. However, only primary copper has the purity requirements for wire and cable applications.

Secondary data for primary copper have substantial variation; particularly with regard to the CML 2 2000 human toxicity impact assessment. Within SimaPro™, three different Ecoinvent™ models for different regions (North America - RNA, Europe – RER, and the global market – GLO) were evaluated [1]. While the RNA model had somewhat higher energy and global warming impacts, the human toxicity impacts were a factor of 20 less than the RER model and four times less than the GLO model. In addition, a model from the ETH-Zurich database was available within SimaPro™ and included in the evaluation [9]. While similar to the RNA model in energy and GHG emissions, the impacts are higher in other categories except human toxicity. The ETH-Zurich model has the lowest human toxicity impact (roughly 1/8 of the RNA model).

Given the high degree of variability to the data, additional data, particularly emissions data was sought and found within the IPPC BAT for the non-ferrous metals industries [19]. Energy and raw material consumption data from the RNA and ETH-Zurich models are in agreement with the ranges shown in the IPPC BAT, while the RER and GLO data is lower than expected. Key air emissions for arsenic, lead, and copper, as well as sulfur dioxide from the IPPC BAT were compared with and found to be moderately lower than the RNA model, higher than the ETH-Zurich model, and substantially lower than the GLO and RER models. As a base case for this study, the Ecoinvent™ RNA copper data is used. The energy use and emissions for this model are within the extremes of the data available and relatively consistent with the IPPC BAT data. A sensitivity analysis across all models evaluated is included in section 4.5, Sensitivity Analysis.

For wire drawing, only one secondary data set was available via Ecoinvent™ [1]. The impacts from this step are roughly one-third of those for primary copper for GHG emissions and energy use, but less than 7% of the toxicity impacts.

A recycle model was developed for each region, with the scrap copper displacing the pure copper content in copper concentrate, at beneficiation (by region) [1]. Since the ETH-Zurich data is a cradle-to-gate evaluation for primary copper, an avoidance flow equivalent to half the burdens for the primary copper model was used. This is consistent with the avoidance of RNA copper concentrate in the RNA primary copper system.

4. LCA Results

On an equivalent functional unit basis, accounting for both electrical-performance and fire-performance per code standards, a PVC/PFP LAN cable installation has lower environmental burdens for primary non-renewable energy, greenhouse gas emissions, human toxicity, air acidification, photo-chemical oxidation, and eutrophication per the Ecoinvent™ Cumulative Energy Demand and CML 2 baseline 2000 impact assessments [4, 6].

4.1 Non-renewable Primary Energy

As shown in the breakdown of energy demand by installation component in Figure 4, non-renewable primary energy requirements are dominated by the copper wire and the steel used in conduit, wireways, power poles, and supports due to the substantial mass of steel required in the LSZH/PE or PVC/PE cable installations. The energy associated with steel is nearly twice the energy for the plastics (jacket + insulation + spacer) in an LSZH/PE and PVC/PE cables.

The energy use for copper is equivalent across all three installations as each uses the same amount of copper. But the impact of copper accounts for between 46% and 54% of the cable burden, excluding the steel. Reduction in one gauge size of copper would yield reduced energy use rates equivalent to 18-26% of the entire burden of plastic (i.e. jacket + insulation + spacer).

The PVC/PFP installation is more balanced across the different cable parts, using only one quarter the amount of steel and consuming 19-22% less energy compared to the LSZH/PE and PVC/PE installation, respectively. Although the energy use for the PFP insulation is higher than PE insulation, the fire performance of the PFP avoids the higher steel use and results in a net decrease of over 23,200 MJ per installation or 1060 MJ per installed km of cable.

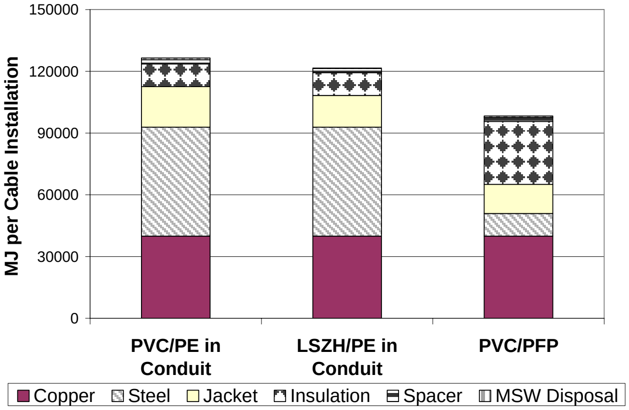

Figure 4. Non-Renewable Primary Energy by Installation Component

4.2 Greenhouse Gas emissions

Greenhouse gas emissions are closer for the three installations due to the higher energy use rate for PFP insulation compared to HDPE insulation and the hydro-fluorocarbon emissions in the PFP supply chain. However, they still favor the PVC/PFP installation due to the differences in steel requirements. Figure 5 breaks down the greenhouse gas contributions by cable component for each installation.

Steel accounts for more than 50% of the LSZH/PE and PVC/PE installations contributions to global warming. On a cable only basis (i.e. excluding steel), copper accounts for approximately 60% of the greenhouse burdens associated with the LSZH/PE or PVC/PE cables and 36% of the PVC/PFP cables. A reduction in conductor diameter by one wire gauge would decrease the overall burden by 580 kg CO2 eq. per installation – i.e. roughly one-third the burden of the plastics used in the LSZH/PE and PVC/PE installations.

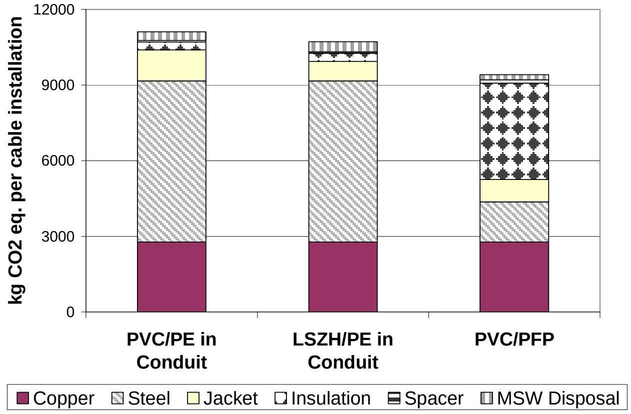

Figure 5. Greenhouse Gas Emissions by Installation Component

The fire performance of the PFP insulation allows for less steel use in the PVC/PFP installation, which results in a net decrease of 1300-1700-kg CO2 eq. per installation, or 60-77-kg CO2 eq. per installed km of cable.

Carbon dioxide from energy use represents over 97% of the GHG burden for the PVC/PE and LSZH/PE installations but only 73% for the PVC/PFP installation.

4.3 Human Toxicity from Industrial Emissions

In life cycle analysis, social, regional, and economic differences can influence the interpretations of life cycle results across multiple impact assessments. This is also true within the human toxicity impact category due to the varied toxicological impacts of various chemicals. Human toxicity from industrial emissions can vary due to emission quantity, can have acute and/or chronic effects, and may have impact globally, regionally, or only locally, as chemicals are released to the air, water, and/or soil. For this LCA study, the CML 2 2000 impact assessment method is used to quantify the toxicological effects from the industrial emissions from installed cabling systems [4]. This method normalizes the impacts of various industrial emissions as equivalent emissions of 1,4-dichlorobenzene.

For cabling systems, human toxicity is dominated by the copper wire life cycle as shown in Figure 6. Despite a 95% recycle rate, copper results in 75-85 % of the installation burdens and over 91% of the cable burden (i.e. excluding steel). The plastics in the cable installations account for less than 8% of the human toxicity burden. Human toxicity impacts from Municipal Solid Waste (MSW) landfill and incineration emissions account for less than 3% of the overall burden when copper and steel are included in the functional unit. Figure 6 shows the human toxicity impact from industrial emissions for each of the three cabling installations, broken down by installation component.

PVC/PFP cables are shown to have a lower human toxicity impact than either the LSZH/PE or PVC/PE cabling systems, but the main observation is the importance of copper on all three systems.

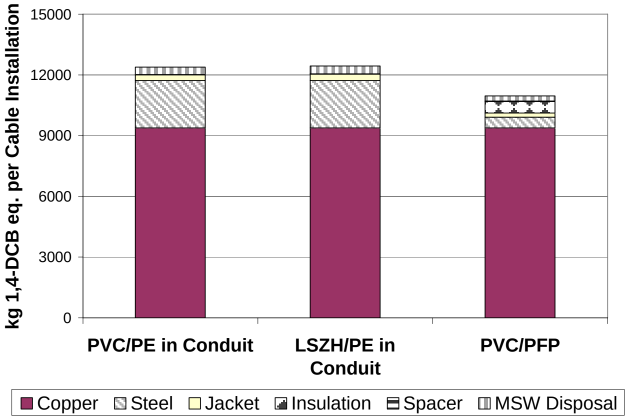

Figure 6. Human Toxicity from Industrial Emissions by Installation Component

Heavy metal air emissions of chromium VI, arsenic, and nickel from the copper supply chain account for 75% of the total burdens and overwhelm the impacts from the various chemicals of concern identified in the DfE/TURI Wire and Cable study [15].

4.4 Other Impact Categories

The trend continues for air acidification, photo-oxidation, and eutrophication potential as seen in Figure 7. (Note: Eutrophication is a process where bodies of water receive excess nutrients resulting in increased plant growth – such as algae bloom – which, in turn, may reduce the oxygen content in the water and may cause other species to die.) Data is presented for each category as a percentage of the value for the installation with the highest impact. For photochemical oxidation and air acidification potential, the PVC/PE in conduit has the highest impact at 9.6 kg C2H4 eq. and 264.4 kg SO2 eq, respectively. The LSZH/PE in conduit installation has the highest eutrophication impact at 15.3 kg PO4—eq. Emissions associated with copper and steel dominate across all of these categories at a combined 67% - 96% of the impact depending on installation and impact category. PVC/PFP cabling systems have an advantage in each impact category due to the lower steel use rate allowed by the superior fire performance of the PFP insulation.

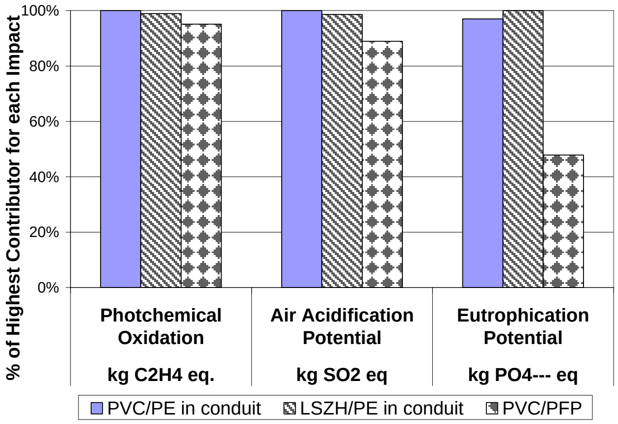

Figure 7. Additional Impact Assessments by Cable Installation Type

Ozone depletion is not included in this analysis due to the lack of emissions data for brominated flame retardants. Brominated hydrocarbons are identified as some of the most potent ozone depleting substances with impacts more than 7 times higher than the main ozone depleting substance found in the PFP supply chain [16].

4.5 Sensitivity & Scenario Analysis

Cables and cable installations are not all created equal. In addition to varying compositions for plenum jacket PVC, the mass of the different cable components is subject to substantial variation depending on CAT 6 cable type and manufacturer. Further, the building layout and building technical requirements could change the ratio of cable to steel. For instance, the conduit and cabling requirements for a trading floor would be dramatically higher than the requirements for an office building. Sensitivity across these scenarios can be done by mass ratio with the data already presented and is left to the reader as the permutations are numerous.

4.5.1 Scenario Analysis for Steel Manufacturing Process. Per the IISI LCI report, the world cold-formed steel is "predominantly" from the BOF process [18]. This is assumed to mean at most, 5% EAF steel is used. Allowing for a recent shift in the US market to as high as 30% EAF steel and accounting for current world steel production data [26], this would translate to 8% EAF steel, world-wide. This 8% has been applied across all steel items in Table 3 except wire rod and basket tray which are modeled as if manufactured from 100% EAF steel. The U.S. estimate is calculated from one conduit supplier's web page claiming 50% recycled steel in their supply chain based on 30% recycle for BOF steel and 100% recycle for EAF steel [24].

As shown in Table 4, the environmental impact reductions for the PVC/PFP steel installation are greater than those for the LSZH/PE installation due to the use of EAF steel for the basket tray, despite significantly lower steel mass use rates. For energy and greenhouse gas emissions, the 8% EAF steel in the LSZH/PE and PVC/PE installations translates to a 6% environmental impact reduction for steel and a 2-3% reduction to the full installation. The reductions for the PVC/PFP installation are close to 40% for GHG and energy for the steel and 5-6% of the full installation. Accounting for EAF steel would benefit the PVC/PFP installation, but the overall impact is minor.

Table 4. Steel Production Process Sensitivity by Cable Installation Type (Cradle-to-Grave)

Impact Category	Units	LSZH/PE & PVC/PE Steel		PVC/PFP Steel	
		All BOF	w/EAF	All BOF	w/EAF
Greenhouse Gases	kg CO2 eq	6463	6065	1612	1005
human toxicity	kg 1,4-DB eq	2381	2374	542	531
photochem. oxidation	kg C2H2 eq.	0.96	0.79	0.19	-0.09
air acidification	kg SO2 eq	40.71	40.61	6.72	6.56
eutrophication	kg PO4--- eq	9.21	8.96	1.75	1.36
Non renewable, all	MJ-Eq	52997	49946	10962	6288

8% EAF steel used in "w/EAF" cases, except for 100% EAF for basket tray and wire rod. Impacts are cradle-to-grave with 95% recycled steel

4.5.2. Sensitivity to Copper Life Cycle Model. The magnitude of the environmental impact from copper calls for a sensitivity analysis of potential copper life cycle models. As discussed earlier, regional data from Ecoinvent™ are available [1]. In addition, a model from ETH-Zurich [9], and a revised module from Ecoinvent™ for North America using emissions from the IPPC BAT for copper production are analyzed [19]. Table 5 shows the environmental impacts from copper across all categories on the same basis as used in the installation models, 21.95 km (i.e. 72,000 ft) of 22.5 AWG copper with 95% recycle.

Table 5. Copper Model Sensitivity – Cradle-to-Grave for 21.95 km of 22.5 AWG Copper

Impact Category	Units	RNA	RNA w/ IPPC	RER	GLO	ETH
Greenhouse Gases	kg CO2 eq	2770	2862	2325	1988	2830
human toxicity	kg 1,4-DB eq	9383	7413	205545	39927	1627
photochem. oxidation	kg C2H4	8.1	1.2	9.9	2.8	2.3
acidification	kg SO2 eq	209.9	36.4	253.7	72.8	57.0
eutrophication	kg PO4--- eq	3.3	3.3	2.5	1.3	1.2
Non renewable, all	MJ-Eq	39929	39682	34009	28388	44655

All regional data is from Ecoinvent™. RNA = North America, RER = Europe, GLO = Global. A case for IPPC data in place of emissions in the RNA model is labeled RNA-IPPC. ETH-Zurich data is European based and included as another data source, but is at a lower data quality due to lower confidence in the recycle model

The ranges for energy and global warming are reasonable across all models. A 30% drop in energy use from copper would result from using the model with the lowest energy. This would leads to a 7-12% reduction in the overall burden of the installation options. It would also bring the impact of the LSZH/PE and PVC/PE steel and PVC/PFP insulation above that of copper for non-renewable, primary energy use. The human toxicity burden has more than two orders of magnitude of range. However, even with the lowest data, the copper represents more than two times the burden of the plastics (jacket + insulation + spacer) combined.

4.6 Functional Unit Impacts

The following Figures 8 through 10 showcase the importance of identifying appropriate functional units in LCA studies. Omitting items that are similar across all alternatives AND relatively unimportant (i.e. transport of raw materials for cable manufacture) is common practice in life cycle studies. However, omitting similar items with substantial impacts can lead to misidentifying the key contributors.

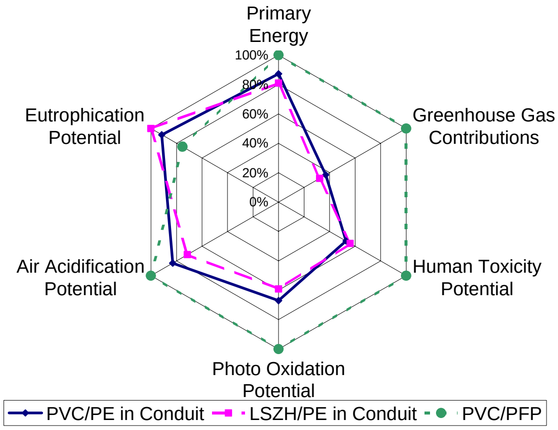

Figure 8. Cables without Copper – Relative Environmental Impacts by Cable Type

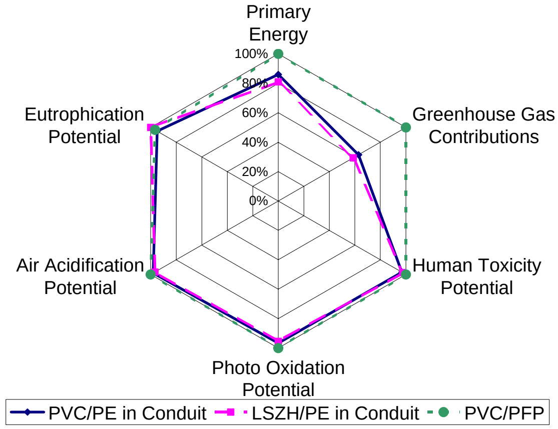

Figure 9. Cables with Copper (Uninstalled) – Relative Environmental Impacts by Cable Type

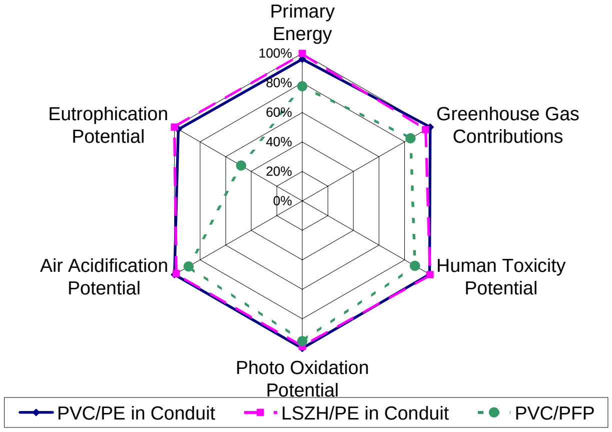

Figure 10. Installed Cables with Copper – Relative Environmental Impacts by Cable Type

For the jacket insulation, and spacers (i.e. a cable without the copper conductor), Figure 8 shows the relative impacts for each cable type as a percentage of the cable type with the maximum impact in each impact category studied. With the exception of eutrophication, the PVC/PFP cable has the highest burdens when the copper is ignored.

For complete cables (with the copper conductor), Figure 9 shows how the environmental impacts from copper dominate the overall impacts of the cable as human toxicity, photochemical oxidation, air acidification and eutrophication are all essentially the same for each cable type. The PVC/PFP cables remain higher in energy use and GHG impacts but the differential has become smaller.

Once the steel required for fire-safety performance and support is added to complete the cable installations, all of the environmental impact categories evaluated in this study favor the PVC/PFP installation as shown in Figure 10. PVC/PFP cable becomes the environmentally-favored cable when a holistic and truly functionally consistent basis is applied.

A more detailed demonstration of the problem caused by omitting of the copper conductor in a wire and cable life cycle analysis is presented in Table 6. In virtually every impact assessment category for both CMR (PVC/PE) and CMP (PVC/PFP) cables as evaluated in the DfE/TURI wire and cable study, the copper conductor has the highest environmental burden. In several categories, particularly human toxicity, it represents more than 90% of the entire burden for the cable. The full spectrum of impact assessment categories from CML 2 baseline 2000 have been used for this illustration as well as a breakdown of cumulative energy demand into non-renewable and renewable energy sources for completeness.

Table 6. Environmental Impacts of Cables with and Without the Copper Conductor

Impact category	Unit	CMR Cable w/ Copper	CMR Cable No Copper	% From Copper
abiotic depletion	kg Sb eq	1.552	0.680	56%
greenhouse gas emissions	kg CO2 eq	212.0	85.2	60%
ozone layer impact	kg CFC-11 eq	0.000009	0.000004	57%
human toxicity	kg 1,4-DB eq	455.8	27.8	94%
fresh water aquatic ecotox.	kg 1,4-DB eq	364.7	33.9	91%
marine aquatic ecotoxicity	kg 1,4-DB eq	269423	55516	79%
terrestrial ecotoxicity	kg 1,4-DB eq	2.05	0.36	82%
photochemical oxidation	kg C2H2	0.39	0.02	94%
acidification	kg SO2 eq	10.19	0.62	94%
eutrophication	kg PO4--- eq	0.26	0.11	58%
Non renewable, fossil	MJ-Eq	2874.2	1343.8	53%
Non-renewable, nuclear	MJ-Eq	477.4	187.8	61%
Renewable, biomass	MJ-Eq	40.6	2.7	93%
Renewable, wind, solar, geo	MJ-Eq	1.6	0.5	66%
Renewable, water	MJ-Eq	175.0	20.2	88%
Non renewable, all	MJ-Eq	3350.6	1530.7	54%
Impact category	**Unit**	**CMP Cable w/ Copper**	**CMP Cable No Copper**	**% From Copper**
abiotic depletion	kg Sb eq	1.866	0.993	47%
greenhouse gas emissions	kg CO2 eq	355.5	228.7	36%
ozone layer impact	kg CFC-11 eq	0.00124	0.00123	0%
human toxicity	kg 1,4-DB eq	474.9	46.9	90%
fresh water aquatic ecotox.	kg 1,4-DB eq	363.0	32.2	91%
marine aquatic ecotoxicity	kg 1,4-DB eq	341439	127532	63%
terrestrial ecotoxicity	kg 1,4-DB eq	1.99	0.30	85%
photochemical oxidation	kg C2H2	0.41	0.04	91%
acidification	kg SO2 eq	10.41	0.84	92%
eutrophication	kg PO4--- eq	0.25	0.10	59%
Non renewable, fossil	MJ-Eq	3530.3	1999.9	43%
Non-renewable, nuclear	MJ-Eq	449.1	159.6	64%
Renewable, biomass	MJ-Eq	45.3	7.4	84%
Renewable, wind, solar, geo	MJ-Eq	2.2	1.2	48%
Renewable, water	MJ-Eq	171.0	16.2	91%
Non renewable, all	MJ-Eq	3978.7	2158.7	46%

Analysis assumes 1-km of cable with and without copper on a cradle-to-crave basis. Impact assessments are from SimaPro™ LCA software incorporating both the CML 2 (2000) v 2.1 and the Cummulative Energy Demand V1.1 (adjusted for all LHV). Comparison of CMR and CMP data without steel requirements is not appropriate due to functional differences associated with fire performance, flame spread, and smoke generation. Ozone depletion data is incomplete due to lack of information available on brominated flame retardants.

Clearly, a significant portion of the copper burden is unavoidable as elimination of the copper eliminates the actual function of the cable. However, reduction in copper use by one gauge can have a significant impact on the overall environmental burden of a cable installation. Table 7 shows the environmental impact reductions as a percentage of the base case detailed in this study for each cable installation type if 23.5 AWG copper conductors could be used instead of 22.5 AWG.

Table 7. Potential Environmental Impact Reductions for Cable Installations with Reduced Copper Use

Impact Category	Units	PVC/PE Installation	LSZH/PR Installation	PVC/PFP Installation
Greenhouse Gases	kg CO2 eq	5.2%	5.4%	6.2%
human toxicity	kg 1,4-DB eq	15.9%	15.8%	18.0%
photochem. oxidation	kg C2H4	17.8%	18.0%	18.7%
acidification	kg SO2 eq	16.7%	16.9%	18.7%
eutrophication	kg PO4--- eq	4.6%	4.5%	9.3%
Non renewable, all	MJ-Eq	6.6%	6.9%	8.5%

Reductions in burden due to copper gauge reduction to 23.5 AWG as compared to 22.5 AWG in the base case

5. Recommendations & Limitations

Primary data sets from multiple copper wire and steel conduit/wireway and manufacturers would be preferred to the secondary data used here. Using the IISI LCA data for the steel is satisfactory for the steel manufacturing process, but the modeling of downstream processing from the hot-rolled steel, including the galvanizing process is desirable from actual suppliers. For copper production, clearly multiple facilities would need to be evaluated, to address the substantial variation in emissions resulting, presumably, from different feedstocks.

The variability in cable composition among cable manufacturers also leads to limitations in this study. However, differences in material use rates will only become substantial issues if fire-performance or functionality is changed due to the impacts from copper and steel.

The lack of life cycle data, particularly emissions data, for the brominated flame retardant supply chain makes the evaluation of ozone depletion potential invalid for these cabling applications.

Finally, extension of this analysis to various cable installation types, such as trading floors, and to evaluate 10-GIG cable installations is of interest.

6. Conclusions

A holistic study for the comparison of environmental impacts resulting from the life cycle of CAT 6 LAN cabling systems in plenum space applications has identified the copper conductor and the steel (used for support and for fire-safety code compliance for PVC/PE and LSZH/PE cabling systems) to be the key large contributors to energy use, greenhouse gas emissions, and human toxicity from industrial emissions.

Although environmental impact differences in the manufacture of the plastic materials exist, they can not be compared directly on a life cycle basis until they are put on a functionally equivalent basis. The superior fire-performance of PFP insulation allows the direct installation of cable without the use of steel conduit or trunking. The inclusion of all key contributors, including those that are the same across all options is required to properly analyze possible interactions to reduce the overall environmental burden.

The life cycle data presented in this study do suggest materials selection can make a difference in the environmental performance of the cable. However, the basis for the selection of environmentally-preferred cable materials is that they reduce either the copper use through superior electrical performance or reduce the steel use through superior fire-performance.

The installed PVC/PFP cabling system meets these criteria and out-performs both the PVC/PE and LSZH/PE installations in non-renewable energy use, greenhouse gas emissions, human toxicity, photochemical oxidation, air acidification and eutrophication potential. More than 1060 MJ and 60-77-kg CO2 eq. are saved per km of installed cable when PVC/PFP cabling is used.

Sensitivity analysis across key impacts to this study, including steel manufacturing process and the life cycle model selection for primary copper support the conclusions drawn by the base case analysis.

7. Acknowledgments

Special thanks are given to Innovative Engineering Services and Masselli Cabling Design for their support in identifying the building layout and bill of materials for a typical office building’s LAN cable system with and without conduit.

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