EPA 744-R-08-001
June 2008

Wire and Cable Insulation and Jacketing: Life-Cycle Assessments For Selected Applications

Chapter 3: Life-Cycle Impact Assessment

Office of Pollution Prevention and Toxics
Design for the Environment Program
U.S. Environmental Protection Agency

Chapter 3 LIFE-CYCLE IMPACT ASSESSMENT

Within LCA, the LCI is a well-established methodology; however, LCIA methods are less well-defined and continue to evolve (Barnthouse *et al.*, 1997; Fava *et al.*, 1993). For LCIA toxicity impacts in particular, some of the methods commonly being applied include toxicity potential, critical volume, and direct valuation (Guinee *et al.*, 1996; ILSI, 1996; Curran, 1996). There is currently no general consensus among the LCA community concerning which, if any, of these methods are preferable, however. Efforts are under way to determine the appropriate level of analytical sophistication in LCIA for various types of decision-making requirements and for adequately addressing toxicity impacts (Bare, 1999).

Section 3.1 of this chapter presents the general LCIA methodology used in this WCP study, which takes a more detailed approach to chemical toxicity impacts than some of the methods currently being used. This section also describes the data management and analysis software used to calculate LCIA results. Section 3.2 presents the detailed characterization methodologies for each impact category, as well as the LCIA results for each cable type. This section also discusses data sources, data quality, and the limitations and uncertainties in this LCIA methodology, as well as in the LCIA results.

Our LCIA methodology calculates life-cycle impact category indicators using established calculation methods for a number of traditional impact categories, such as global warming, stratospheric ozone depletion, photochemical smog, and energy consumption. In addition, this method calculates relative category indicators for potential impacts on human health and aquatic ecotoxicity, impacts not always considered in traditional LCIA methodology. The toxicity impact method is based on work for Saturn Corporation and the EPA Office of Research and Development by the University of Tennessee Center for Clean Products and Clean Technologies and used in the DfE Computer Display Project's LCA study (Socolof *et al*., 2001), and updated in the LCA conducted by the DfE Lead-Free Solder Project (Geibig and Socolof, 2005).

The LCIAs conducted in this study are done to compare the baseline cables (i.e., lead-stabilized) to alternatively constructed cables (i.e., lead-free or zero-halogen). The comparative impacts presented in this section are based on LCI data described in Chapter 2. The baseline and lead-free comparisons for both the CMR and CMP cables use the inventories from upstream through EOL. For the CMR zero-halogen alternative and the NM-B lead-free alternative, cable manufacturing (i.e., insulation and jacketing extrusion) data were not obtained; thus in order to compare these cables to the respective alternatives for the appropriate cable type, only comparable processes are included, as appropriate.

3.1 Methodology

In its simplest form, LCIA is the evaluation of potential impacts to any system as a result of some action. LCIAs generally classify the consumption and loading data from the inventory stage to various impact categories. Characterization methods are used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al*., 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and, therefore, cannot be directly compared.

Conceptually, there are three major phases of LCIA, as defined by the SETAC (Fava *et al.*, 1993):

- **Classification** – The process of assignment and initial aggregation of data from inventory studies to impact categories (i.e., greenhouse gases or ozone depletion compounds).
- **Characterization** – The analyses and estimation of the magnitude of potential impacts for each impact category, derived through the application of specific impact assessment tools. (In the WCP, impact scores are calculated for inventory items that have been classified into various impact categories and then aggregated into life-cycle impact category indicators.)
- **Valuation** – The assignment of relative values or weights to different impacts, and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impact scores across impact categories.

The international standard for life-cycle impact assessment, ISO 14042, considers classification and characterization to be mandatory elements of LCIA; valuation ("weighting") is an optional element to be included depending on the goals and scope of the study. Both the classification and characterization steps are completed in the WCP, while the valuation step is left to industry or other interested stakeholders. The methodologies for life-cycle impact classification and characterization are described in Sections 3.1.1 and 3.1.2, respectively.

3.1.1 Classification

In the first step of classification, impact categories of interest are identified in the scoping phase of the LCA. The categories included in the WCP LCIA are listed below:

- non-renewable materials use/depletion
- energy use
- landfill space use
- global warming (global climate change)
- stratospheric ozone depletion
- photochemical smog
- air acidification
- air quality (particulate matter loading)
- water eutrophication (nutrient enrichment)
- chronic cancer human health effects - occupational
- chronic cancer human health effects - public
- chronic non-cancer human health effects - occupational
- chronic non-cancer human health effects - public
- aquatic ecotoxicity

Radioactivity and radioactive landfill waste are not included as impact categories because they are simply proportional to the use of electricity across all alternatives. Terrestrial ecotoxicity is not included as a separate impact category because the method for calculating chronic non-cancer public health impacts would be the same as for terrestrial ecotoxicity.

The second step of classification is assigning inventory flows to applicable impact categories. Classification includes whether the inventory item is an input or output, the disposition of the output, and, in some cases, the material properties for a particular inventory item. Figure 3-1 shows a conceptual model of classification for the WCP. Table 3-1 presents the inventory types and material properties used to define which impact category is applicable to an inventory item. One inventory item may have

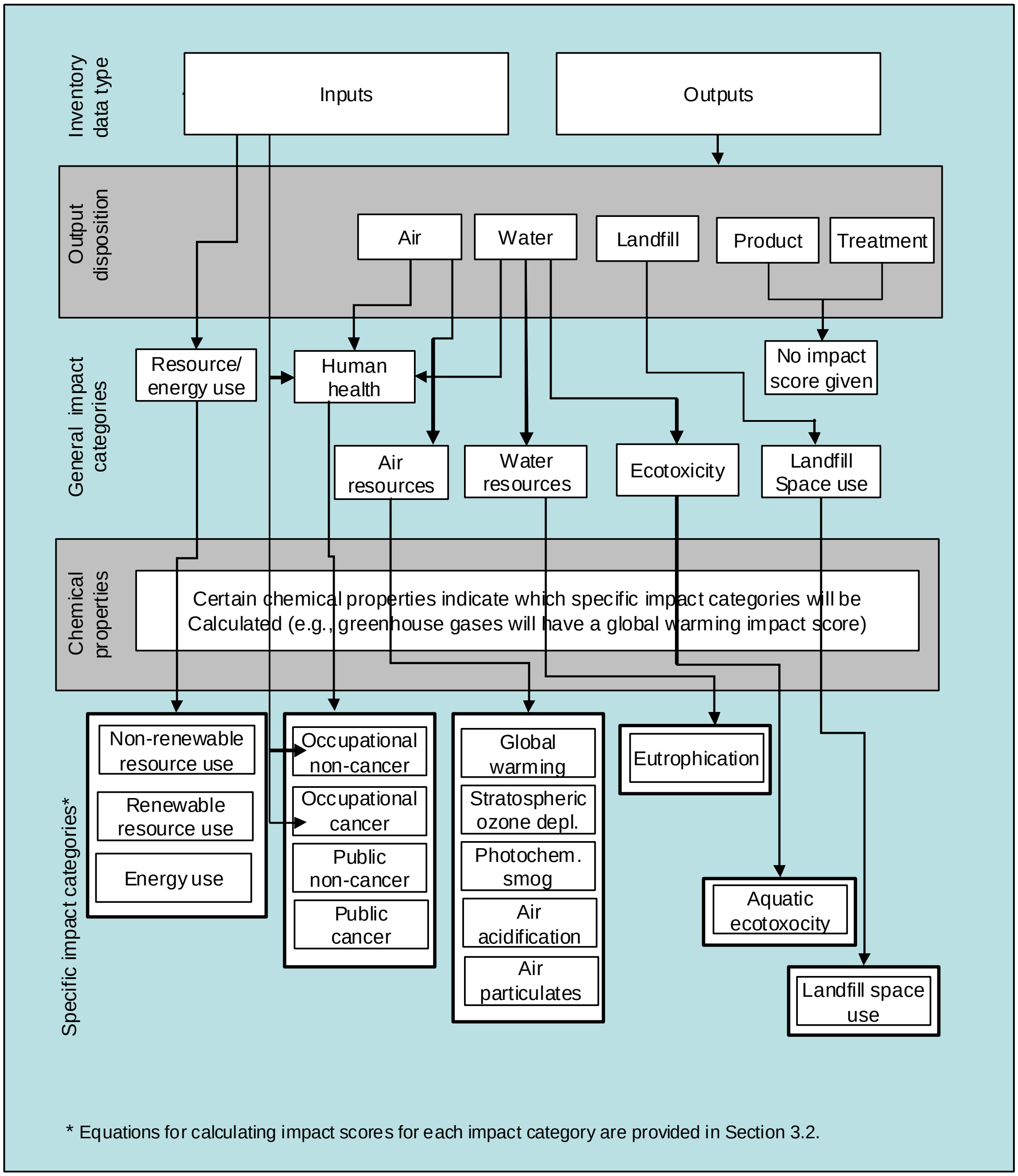

Figure 3-1. Impact Classification Conceptual Model

Table 3-1

Inventory Types and Properties for Classifying Inventory Items Into Impact Categories

Inventory Type			
Input	**Output**	**Chemical/Material Properties**	**Impact Category**
Natural Resource Impacts			
Material, fuel	N/A	Non-renewable	Non-renewable resource use/depletion
Electricity, fuel	N/A	Energy	Energy use
N/A	waste to landfill	Solid, hazardous, and radioactive waste	Landfill space use (volume)
Abiotic Ecosystem Impacts			
N/A	Air	Global warming gases	Global warming
N/A	Air	Ozone depleting substances	Stratospheric ozone depletion
N/A	Air	Substances that can be photochemically oxidized	Photochemical smog
N/A	Air	Substances that react to form hydrogen ions (H+)	Acidification
N/A	Air	Air particulates (PM10, TSP)[a]	Air particulates
N/A	Water	Substances that contain available nitrogen or phosphorus	Water eutrophication (nutrient enrichment)
Human Health and Ecotoxicity			
Material	N/A	Toxic material (carcinogenic)	Carcinogenic human health effects occupational
N/A	Air, soil, water	Toxic material (carcinogenic)	Carcinogenic human health effects public
Material	N/A	Toxic material (non-carcinogenic)	Chronic, non-carcinogenic human health effects occupational
N/A	Air, soil, water	Toxic material (non-carcinogenic)	Chronic, non-carcinogenic human health effects public (and terrestrial ecotoxicity)
N/A	Water	Toxic material	Aquatic ecotoxicity

[a] Acronyms: particulate matter with average aerodynamic diameter less than 10 micrometers (PM10); total suspended particulates (TSP); biological oxygen demand (BOD); total suspended solids (TSS).

N/A=not applicable.

multiple properties and, therefore, would have multiple impacts. For example, methane is a global warming gas and has the potential to create photochemical oxidants (to form smog).

Output inventory items from a process may have such varying dispositions as direct release (to air, water, or land), treatment, or recycle/reuse. Outputs with direct release dispositions were classified into impact categories for which impacts were calculated in the characterization phase of the LCIA. Outputs sent to treatment are considered inputs to a treatment process and impacts were not calculated until direct releases from that process occur. Similarly, outputs to recycle/reuse were considered inputs to previous processes and impacts were not directly calculated for outputs that go to recycle/reuse. Figure 3-1 graphically depicts the relationships between inventory type, dispositions, and impact categories. Note that a product is also an output of a process; however, product outputs were not used to calculate any impacts. Once impact categories for each inventory item were classified, life-cycle impact category indicators were quantitatively estimated through the characterization step.

3.1.2 Characterization

The characterization step of LCIA includes the conversion and aggregation of LCI results to common units within an impact category. Different assessment tools are used to quantify the magnitude of potential impacts, depending on the impact category. Three types of approaches are used in the characterization method for the WCP:

- **Loading** – An impact score is based on the inventory amount.
- **Equivalency** – An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical.
  - *Full equivalency* – all substances are addressed in a unified, technical model.
  - *Partial equivalency* – a subset of substances can be converted into equivalency factors.
- **Scoring of inherent properties** – An impact score is based on the inventory amount weighed by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighed using a toxicity scoring method).

Table 3-2 lists the characterization approach used with each impact category. The **loading** approach either uses the direct inventory amount to represent the impact or slightly modifies the inventory amount to change the units into a meaningful loading estimate, such as characterizing the impact of either non-renewable resource depletion or landfill use. Use of nonrenewable resources is directly estimated as the mass loading (input amount) of that material consumed; use of landfill space applies the mass loading (output amount) of hazardous, non-hazardous, or radioactive waste, and converts that loading into a volume to estimate the landfill space consumed.

The **equivalency** method uses equivalency factors in certain impact categories to convert inventory amounts to common units relative to a reference chemical. Equivalency factors are values that provide a measure (weighting) to relate the impact of an inventory amount of a given chemical to the effect of the same amount of the reference chemical. For example, for the impact category "global warming potential (GWP)," the equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical carbon dioxide (CO_2); therefore, GWPs are given in units of CO_2 equivalents.

Scoring of inherent properties is applied to impact categories that may have different effects for the same amount of various chemicals, but for which equivalency factors do not exist or are not widely accepted. The scores are meant to normalize the inventory data to provide measures of potential impacts. Scoring methods are employed for the human and ecological toxicity impact categories, based on the Chemical Hazard Evaluation Management Strategies (CHEMS-1) method described by Swanson *et al.* (1997) and presented below. The scoring method provides a relative score, or hazard value, for each potentially toxic material that is then multiplied by the inventory amount to calculate the toxicity impact score.

Using the various approaches, the WCP LCIA method calculates impact scores for each inventory item for each applicable impact category. These impact scores are based on either a direct measure of the inventory amount or some modification (e.g., equivalency or scoring) of that amount based on the potential effect the inventory item may have on a particular impact category. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

Inventory amounts are identified on a functional unit basis and used to calculate impact scores. For each inventory item, an individual score is calculated for each applicable impact category. The detailed characterization equations for each impact category are presented in Sections 3.2.1 through 3.2.12 and summarized in Section 3.3. The equations presented in those subsections calculate impacts for individual inventory items that could later be aggregated as defined by the user. Impact scores represent relative and incremental changes rather than absolute effects or threshold levels.

Table 3-2

LCIA Characterization Approaches for the WCP

Impact category	Characterization approach
Natural Resource Impacts	
Non-renewable materials use/depletion	Loading
Energy use	Loading
Landfill space use	Loading
Abiotic Ecosystem Impacts	
Global warming	Equivalency (full)
Stratospheric ozone depletion	Equivalency (full)
Photochemical smog	Equivalency (partial)
Acidification	Equivalency (full)
Air particulates	Loading
Water eutrophication (nutrient enrichment)	Equivalency (partial)
Human Health and Ecotoxicity	
Cancer human health effects occupational	Scoring of inherent properties
Cancer human health effects public	Scoring of inherent properties
Chronic non-cancer human health effects occupational	Scoring of inherent properties
Chronic non-cancer human health effects public	Scoring of inherent properties
Aquatic ecotoxicity	Scoring of inherent properties

3.2 CHARACTERIZATION AND RESULTS

This section presents the impact assessment characterization methods and the impact results by impact category. Within each impact category subsection (3.2.1 through 3.2.12), the characterization equations are presented, followed by the results for each cable type. The full life-cycle results for CMR and CMP, and the NM-B cradle-to-gate analyses are presented (the CMR 3-way analysis is presented in Chapter 4 since limited data prevented the presentation of detailed results). Finally, a discussion of the limitations and uncertainties associated with that impact category concludes each section. The LCIA results are based on the boundaries outlined in Chapter 1 and the inventory described in Chapter 2. Within the results subsections of Sections 3.2.1 through 3.2.12, the impacts are presented as total impacts, followed by top contributing processes and top contributing flows. Section 3.3 briefly summarizes the characterization methods and the overall life-cycle impact category indicators for the 14 impact categories for each cable type. A summary of the limitations and uncertainties also is provided in Section 3.3. Uncertainty and sensitivity analyses are presented in Section 3.4.

It should be reiterated that the LCIA results presented throughout this section are indicators of the relative potential impacts of the baseline (lead-based) and the alternative cables in various impact categories and are not a measure of actual or specific impacts. The LCIA is intended to provide a screening level evaluation of impacts and in no way provides absolute values or measures actual effects. Results herein are referred to as impact category indicators (representing the total impact score of a cable alternative in an impact category), impact results, impact scores, or simply impacts. Each of these terms refers to relative potential impacts and should not be confused with an assessment of actual impacts.

3.2.1 Non-renewable Resource Use

3.2.1.1 Characterization

Natural resources are materials that are found in nature in their basic form, rather than being manufactured. Non-renewable ("stock") natural resources are typically abiotic, such as mineral ore or fossil fuels. Renewable ("flow") natural resources are those that can be regenerated, typically biotic resources, such as forest products or other plants, animal products, and water. Consumption impacts from non-renewable resources (NRRs) are calculated using direct consumption values (e.g., material mass) from the inventory. Renewable resource use is not included in the impact assessment.

For the non-renewable materials use/depletion category, depletion of materials results from the extraction of non-renewable resources. Non-renewable resource impact scores are based on the amount of material inputs (which can be product or process materials), water, and fuel inputs of non-renewable materials. To calculate the loading-based impact scores, the following equation is used:

$$(IS_{NRR})_i = [Amt_{NRR} \ x \ (1 - RC)]_i$$

where:

IS_{NRR} equals the impact score for use of non-renewable resource *i* (kg) per functional unit;

Amt_{NRR} equals the inventory input amount of non-renewable resource *i* (kg) per functional unit; and

RC equals the fraction recycled content (post-industrial and post-consumer) of resource *i*.

Accounting for the data collection limitations in the inventory and the characterization method, we have assigned a "medium" data quality measure for the NRR impact category results. The following subsections describe the impacts for each cable type.

3.2.1.2 CMR results

The baseline (leaded) CMR cable uses 17 percent more non-renewable resources than the lead-free alternative, which is shown in Figure 3-2. The top contributing process is electricity production for cable extrusion for both alternatives (Figure 3-3) and inert rock is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-4). To protect confidentiality, Figure 3-3 combines the non-renewable resource inputs from all upstream electricity generation. Figure 3-3 includes the processes that contribute >5 percent of the total impacts, which represent 90 and 92 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-4 includes individual flows that contribute >1 percent to the total impacts and represents 99 percent of the total NRR impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are mostly a function of the differences in extrusion energy. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the non-renewable resource impact category (see Section 3.4). However, of potentially greater interest to manufactures is that when comparing insulation and jacketing of CMR cables, electricity production is the largest contributor to non-renewable resource depletion.

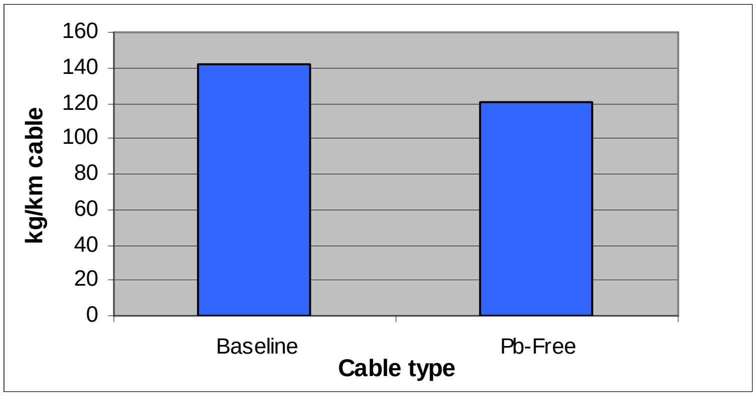

Figure 3-2. Total NRR Impacts – CMR Full life cycle

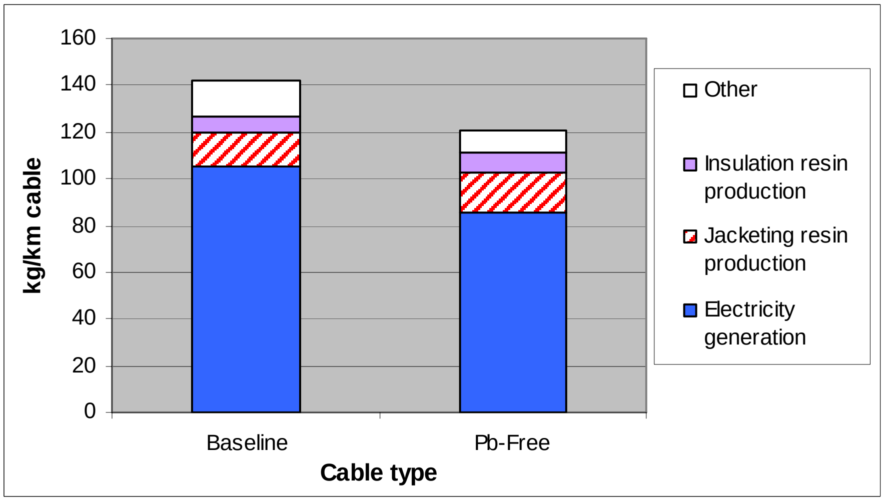

Figure 3-3. Top Contributing Processes to NRR Impacts – CMR Full life cycle

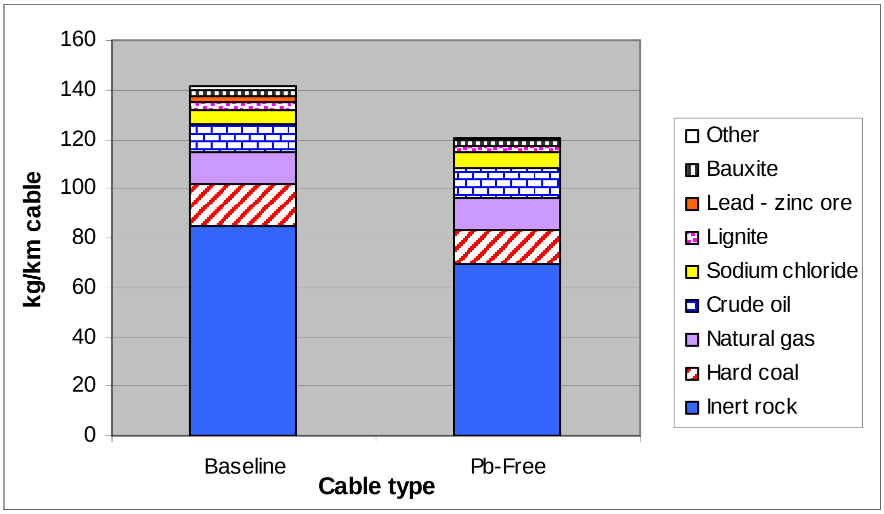

Figure 3-4. Top Contributing Flows to NRR Impacts – CMR Full life cycle

3.2.1.3 CMP results

The baseline cable uses 8 percent more non-renewable resources than the lead-free alternative, which is shown in Figure 3-5. The top contributing process is electricity generation for cable extrusion for both alternatives (Figure 3-6). To protect confidentiality, Figure 3-6 combines the non-renewable resource inputs from all upstream electricity generation and natural gas production. Inert rock is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-7). Figure 3-6 includes the processes that contribute >2 percent of the total impacts, which represent 90 and 89 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-7 includes individual flows that contribute >1 percent to the total impacts and represents 99 percent of the total NRR impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the non-renewable resource impact category (see Section 3.4). However, of potentially greater interest to manufactures is that when comparing insulation and jacketing of CMP cables, electricity production is the largest contributor to non-renewable resource depletion.

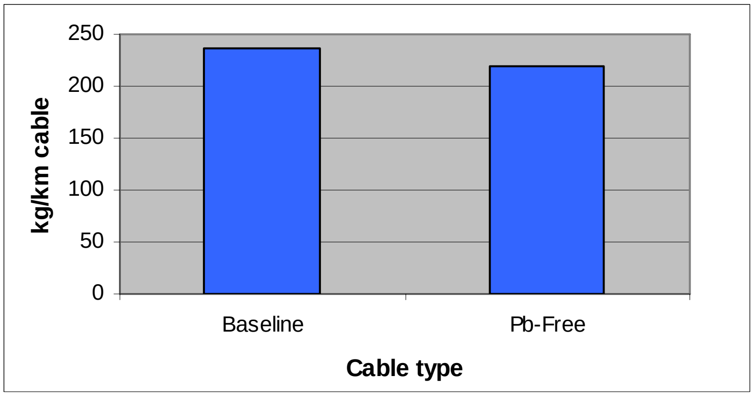

Figure 3-5. Total NRR Impacts – CMP Full life cycle

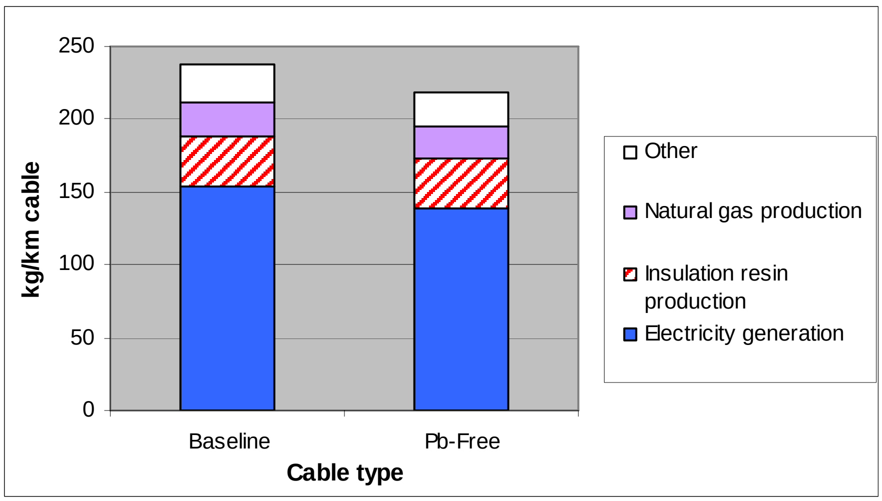

Figure 3-6. Top Contributing Processes to NRR Impacts – CMP Full life cycle

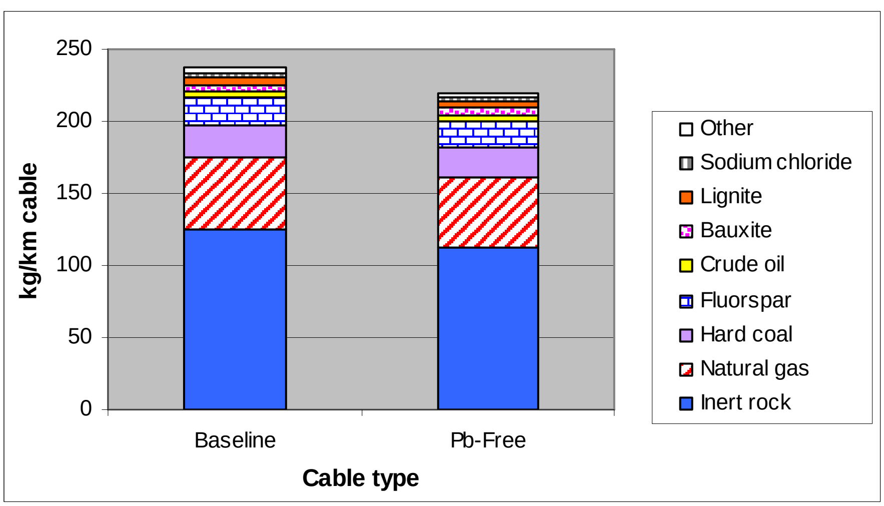

Figure 3-7. Top Contributing Flows to NRR Impacts – CMP Full life cycle

3.2.1.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable uses 18 percent more non-renewable resources than the lead-free alternative, which is shown in Figure 3-8. The top contributing process is production of the jacketing resin, PVC, for both alternatives (Figure 3-9). To protect confidentiality, Figure 3-9 combines the non-renewable resource inputs from all upstream electricity generation. The greatest individual flow is inert rock for the baseline cable and natural gas for the lead-free alternative (Figure 3-10). Figure 3-3 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-4 includes individual flows that contribute >1 percent to the total impacts and represent 99 and >99 percent of the total NRR impacts for the baseline and lead-free alternatives, respectively.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Understanding that jacketing resin production contributes greatest to NRR depletion for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of jacketing resin used. However, any substituted material would need to be examined for tradeoffs in the other impact categories.

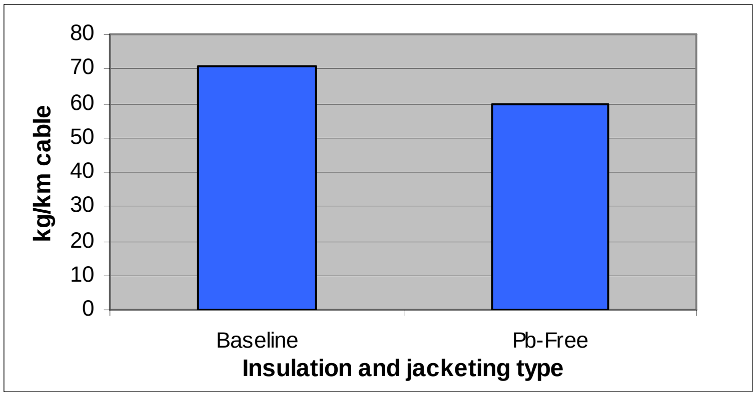

Figure 3-8. Total NRR Impacts – NM-B Partial life cycle

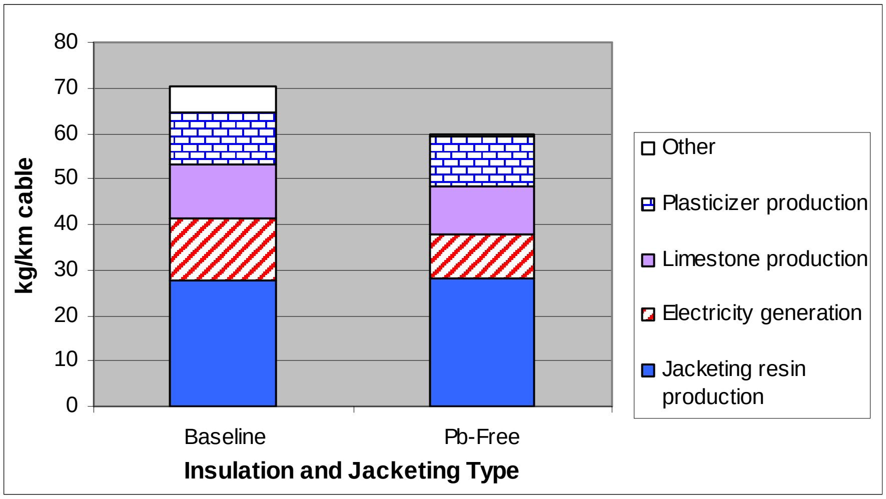

Figure 3-9. Top Contributing Processes to NRR Impacts – NM-B Partial life cycle

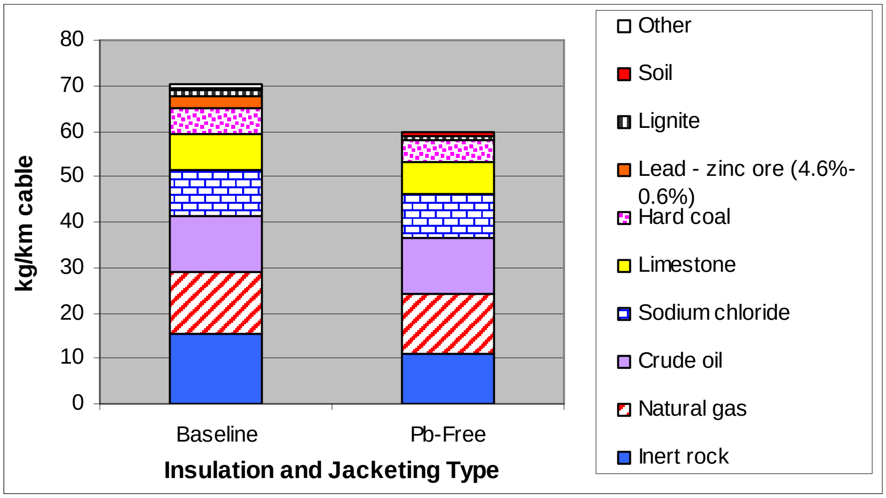

Figure 3-10. Top Contributing Flows to NRR Impacts – NM-B Partial life cycle

3.2.1.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. A limitation to the LCIA methodology for the NRR use category is that the results are based on the mass of a material consumed. Depletion of NRRs occurs from the extraction of these NRRs; however, the impact indicators do not relate consumption rates to the Earth's ability to sustain that consumption.

For all cable types, the inventory data was limited in the number of primary data sets collected for each process. Primary data were collected for each process from between 1 and 3 companies; where primary data were not available, secondary data were used, or in some cases, materials meeting decision rule criteria were not included.

The major uncertainty in the CMR and CMP inventory data that contribute to the NRR impacts is electricity for extrusion during cable manufacturing. This is explained in Section 2.2.4 and included in the uncertainty analysis in Section 3.4.1 and also discussed further in the sensitivity analysis (Section 3.4.2).

While the primary extrusion energy varied greatly among companies, another source of uncertainty is that the electricity generation process used in this study is from secondary data provided in the GaBi4 database. Data quality of the electricity generation inventory, as determined by GaBi4, is considered "good." In addition, an average U.S. electric grid mix was selected for use in the study to conform to the data collected from the manufacturing process, which were all in the United States, and which are within the geographic boundaries of this study. As a result, use of a secondary data set for electricity generation is not expected to be a large source of uncertainty.

The complete life-cycle of the NM-B cables was not available, and thus only limited cradle-to-gate analysis was conducted. As stated earlier, the NRR impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.2 Energy Use

3.2.2.1 Characterization

Energy consumption is used as an indicator of potential environmental impacts from the entire energy generation cycle. Energy use impact scores are based on both *fuel* and *electricity* flows. The impact category indicator is the sum of electrical energy inputs and fuel energy inputs. Fuel inputs are converted from mass to energy units using the fuel's heat value (H) and the density (D), presented in Table 3-3 below.

Table 3-3

Fuel Conversion Factors

Fuel	Heat Value (H) (MJ/L)	Reference	Density (D) (kg/L)	Reference
Heavy fuel oil #6 (residual)	38.579	(1)	0.944	(2)
Light fuel oil #2 (distillate)	36.739	(1)	0.843	(2)
Natural Gas	0.034	(3)	$7.58x\ 10^{-4}$	(4)

1. Davis, S.C. 1999. Transportation Energy Data Book, Edition 19. 1999. Center for Transportation Analysis, Oak Ridge National Laboratory, ORNL 6958, Appendix B, Table B1. Oak Ridge, Tennessee, September.
2. Energy Information Administration (EIA) 1999. International Energy Annual 1997. U.S. Department of Energy. DOE/EIA 0219 (97), Washington, DC. April.
3. Based on: Wang, M. 1999. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.5. Argonne National Laboratory, University of Chicago.
4. Calculated from: Perry, R.H. and D. Green (Eds.) 1984. Perry's Chemical Engineer's Handbook, 6th Edition, page 9-15, Table 9-13, and p. 9-16, Table 9-14. McGraw-Hill, Inc., New York, NY.

The impact score is calculated by:

$$(IS_E)_i = (Amt_E)_i \text{ or } [Amt_F \text{ x } (H / D)]_i$$

where:

IS_E equals the impact score for energy use (MJ) per functional unit;

Amt_E equals the inventory input amount of electrical energy used (MJ) per functional unit;

Amt_F equals the inventory input amount of fuel used (kg) per functional unit;

H equals the heat value of fuel *i* (MJ/L); and

D equals the density of fuel *i* (kg/L).

This category addresses energy use only. The emissions from energy production are outputs from the energy production process and are classified to applicable impact categories, depending on the disposition and chemical properties of the outputs (see Classification Section 3.1.1).

Accounting for the data collection limitations in the inventory and the characterization method, we have assigned a "medium" data quality measure for the energy use impact category results.

3.2.2.2 CMR results

The baseline (leaded) CMR cable uses 5 percent more energy than the lead-free alternative, which is shown in Figure 3-11. The top contributing process for both alternatives is electricity generation for the cable extrusion process. To protect confidentiality, Figure 3-12 combines the energy impacts from all upstream electricity generation. For both alternatives (Figure 3-13), the top contributing flows such as natural gas and crude oil are primarily from resin production processes; those such as hard coal and uranium are primarily resources used to fuel electricity. Figure 3-12 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 93 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-13 includes individual flows that contribute >1 percent to the total impacts, which represent 99 percent of the total energy impacts for both alternatives.

The overall differences between the cables are largely a function of the differences in energy associated with the extrusion process, which is slightly offset by a slightly greater amount of the jacketing resin, PVC, used in the lead-free alternative. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the energy use impact category (see Section 3.4). However, of potentially greater interest to manufacturers is that energy generation for cable extruding is the largest contributor to energy impacts for both alternatives. As a result, reductions in extrusion energy could lead to larger reductions in energy impacts relative to other processes.

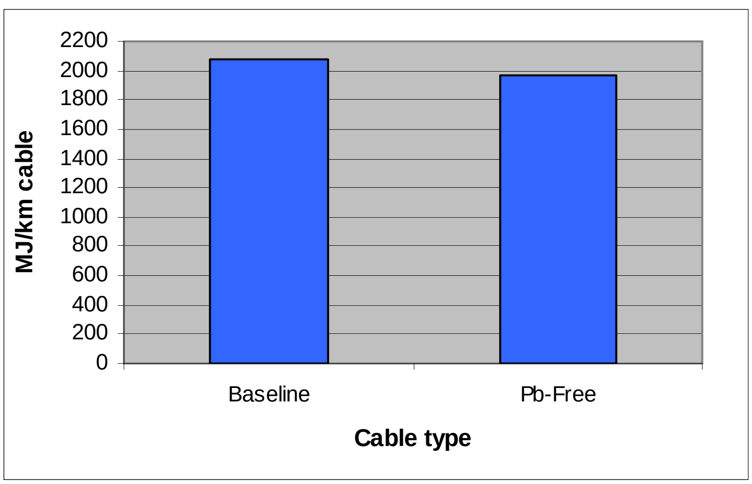

Figure 3-11. Total Energy Impacts – CMR Full life cycle

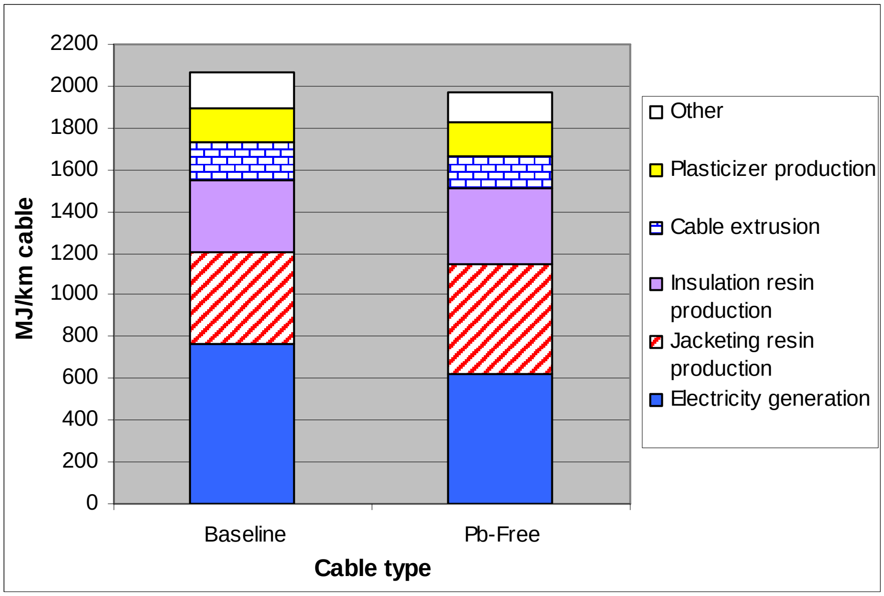

Figure 3-12. Top Contributing Processes to Energy Impacts – CMR Full life cycle

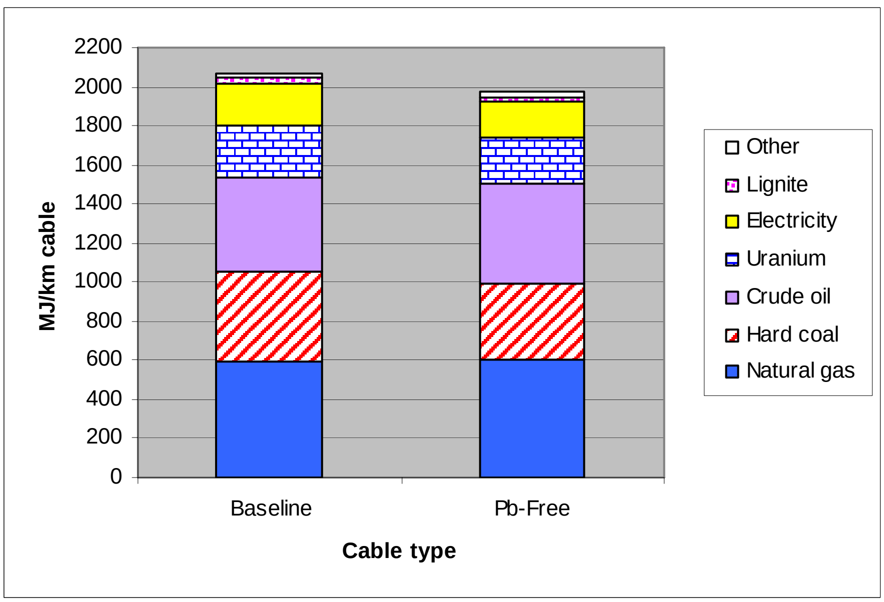

Figure 3-13. Top Contributing Flows to Energy Impacts – CMR Full life cycle

3.2.2.3 CMP results

The baseline (leaded) cable uses 6 percent more energy than the lead-free alternative, which is shown in Figure 3-14. The top contributing process for both alternatives is the generation of electricity for the cable extrusion process (Figure 3-15). To protect confidentiality, Figure 3-15 combines the energy impacts from all upstream electricity generation and natural gas production. For both alternatives (Figure 3-16), the top contributing flows such as natural gas and crude oil are primarily from resin production processes; those such as hard coal and uranium are primarily resources used to fuel electricity. Figure 3-

15 includes the processes that contribute >5 percent of the total impacts, which represents 89 percent of the total impacts for both the baseline and lead-free alternatives, respectively. Figure 3-16 includes individual flows that contribute >1 percent to the total impacts, which represent 99 percent of the total energy impacts for both alternatives.

The overall differences between the cables are mostly a function of the differences in energy associated with cable extrusion and the FEP insulation resin production processes. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the energy use impact category (see Section 3.4). However, of potentially greater interest to manufacturers is that generation of electricity for cable extrusion is the largest contributor to energy impacts for both alternatives, followed by natural gas production, and FEP resin production.

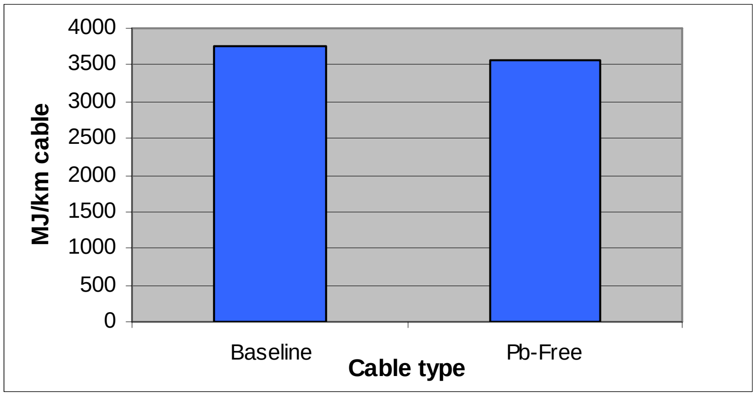

Figure 3-14. Total Energy Impacts – CMP Full life cycle

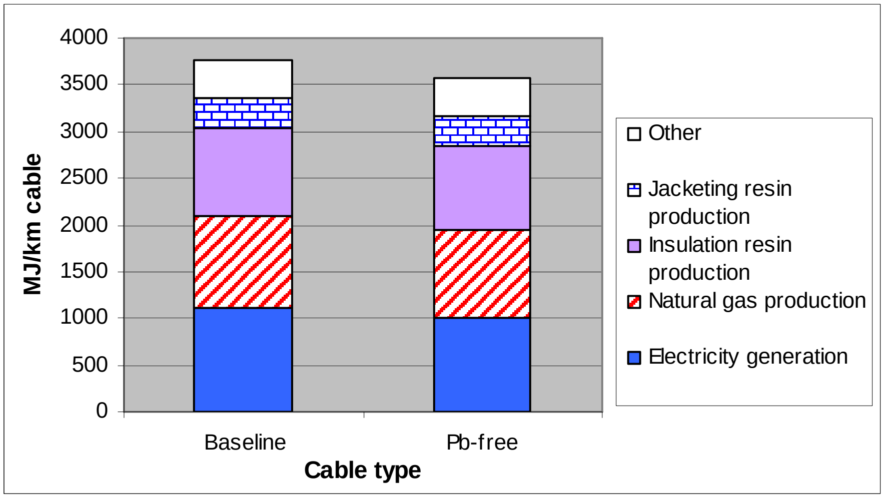

Figure 3-15. Top Contributing Processes to Energy Impacts – CMP Full life cycle

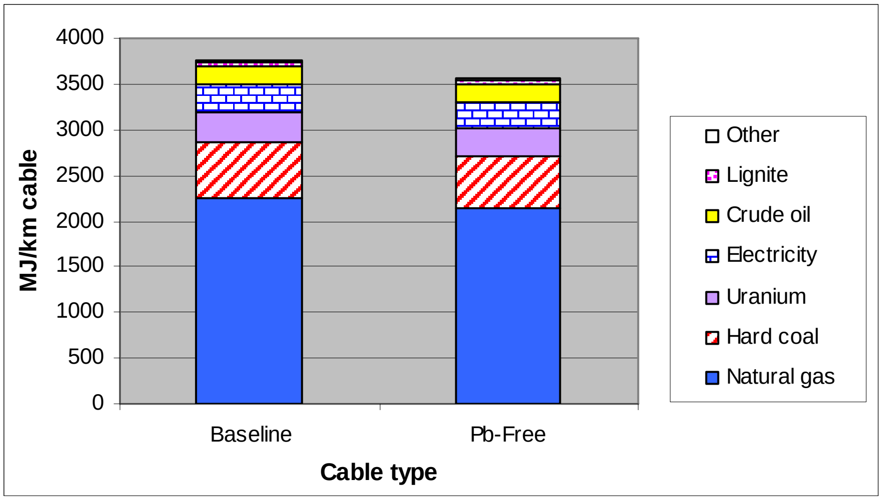

Figure 3-16. Top Contributing Flows to Energy Impacts – CMP Full life cycle

3.2.2.4 NM-B results

The baseline cable uses 6 percent more energy than the lead-free alternative, which is shown in Figure 3-17. The top contributing process for both alternatives is the production of the cable jacketing resin, PVC (Figure 3-18). To protect confidentiality, Figure 3-18 combines the energy impacts from all upstream electricity generation. For both alternatives (Figure 3-19), the top contributing flows such as natural gas and crude oil are primarily from resin production processes; those such as hard coal and uranium are primarily resources used to generate electricity. Figure 3-18 includes the processes that contribute >5 percent of the total impacts, which represent 90 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-19 includes individual flows that contribute >1 percent to the total impacts, which represent 98 and 99 percent of the total energy impacts for the baseline and lead-free alternatives, respectively.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Understanding that jacketing resin production contributes greatest to energy use impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of jacketing resin used. However, any substituted material would need to be examined for tradeoffs in the other impact categories.

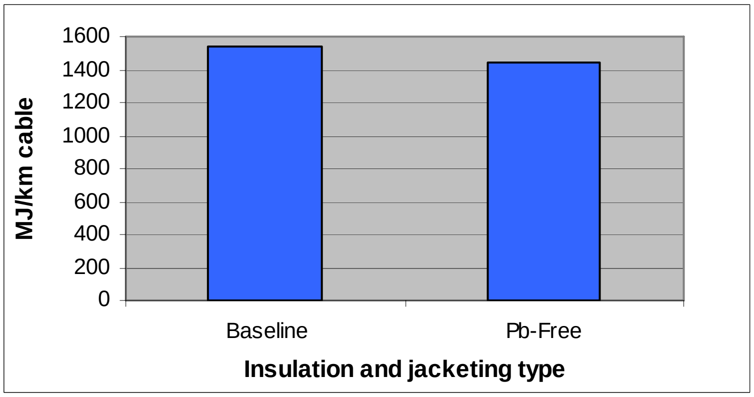

Figure 3-17. Total Energy Use Impacts – NM-B Partial life cycle

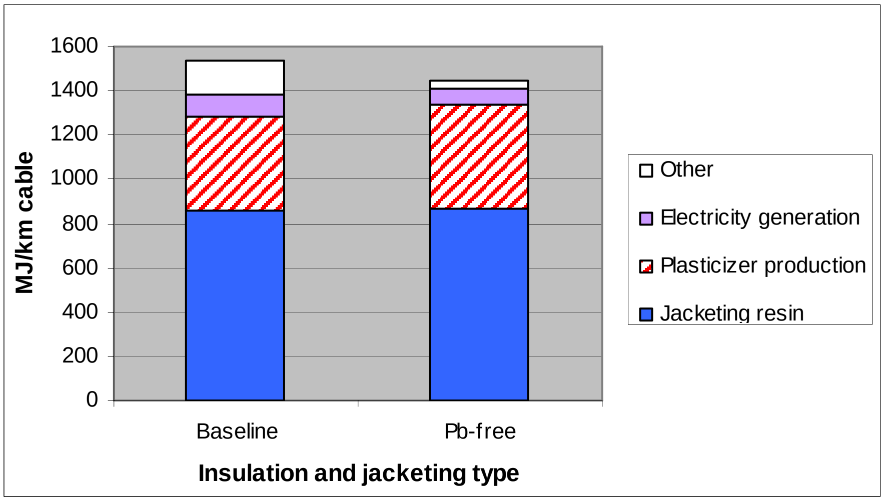

Figure 3-18. Top Contributing Processes to Energy Use Impacts – NM-B Partial life cycle

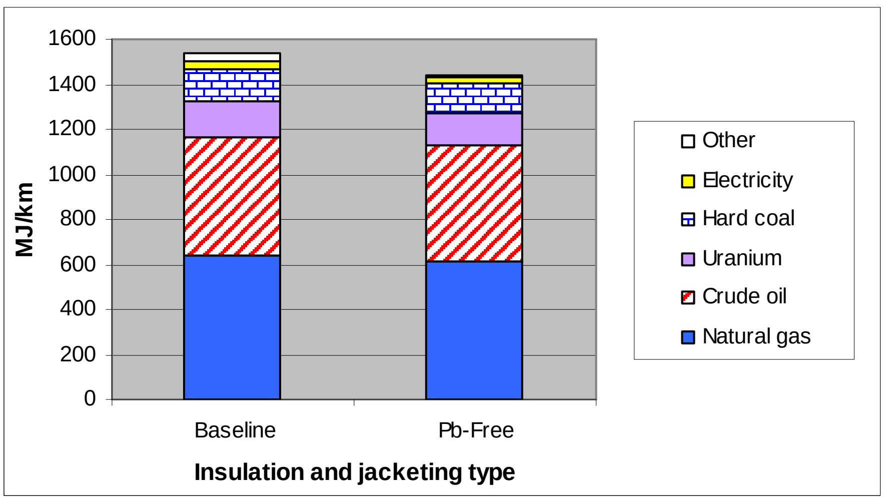

Figure 3-19. Top Contributing Flows to Energy Use Impacts – NM-B Partial life cycle

3.2.2.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology for the Energy Use category is a direct measure of the net calorific value of energy inputs,[15] and is not associated with great uncertainty.

[15] The calorific value of a fuel (or other substance, e.g., food) is the amount of heat released during the combustion of a specified amount of the substance. The *gross* calorific value is the heat evolved when all products of combustion are cooled to atmospheric temperature and pressure, and therefore includes the latent heat of vaporization and the sensible heat of water in the combustion products. This is the maximum energy that can be derived from a fuel. The *net* calorific value is the heat evolved when the products of combustion are cooled so that

The LCI contributes greater to the Energy Use category uncertainty. For the telecommunication cables, cable extruding, resin production, and electricity production contributed to most of the energy impacts. The extrusion and FEP production processes were each based on two primary data sets. As discussed in Section 2.2.4, extrusion data were highly variable, leading to sufficient uncertainty to be included in the uncertainty analysis is Section 3.4. The PVC and HDPE production processes, largely contributing as well, were from secondary data (described in Section 2.1.2.1).

The complete life cycle of the NM-B cables was not available, and thus only a limited cradle-to-gate analysis was conducted. Within the processes modeled, PVC production and phthalate plasticizer production were top contributing processes. PVC is discussed above, and phthalate production data were also from secondary data, and represent s a mix of various phthalate plasticizers in one process, as opposed to being specific to the plasticizers identified by the manufacturers. However, the most prevalent compounds are represented in the dataset used in this analysis. As stated earlier, based on the LCIA methodology and the LCI data, the Energy Use impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.3 Landfill Space Use Impacts

3.2.3.1 Characterization

Landfill impacts are calculated using solid, hazardous, and radioactive waste flows to land as the volume of landfill space is consumed. For solid waste landfill use, this category pertains to the use of suitable and designated landfill space as a natural resource where municipal waste or construction debris is accepted. For hazardous waste landfill use, this category pertains to the use of suitable and designated landfill space as a natural resource where hazardous waste, as designated and regulated under the Resource Conservation and Recovery Act (RCRA), is accepted. Similarly, radioactive wastes are included. For non-U.S. activities, equivalent hazardous or special waste landfills are considered for this impact category. Impact scores are characterized from solid, hazardous, and radioactive waste outputs with a disposition of landfill. The only radioactive waste outputs in the inventory of cables are from the portion of electricity produced using nuclear fuel. Impact characterization is based on the volume of waste, determined from the inventory mass amount of waste and material density of each specific hazardous waste type:

$$(IS_L)_i = (Amt_W / D)_i$$

where:

IS_L	equals the impact score for landfill (L) use for waste i cubic meters (m^3) per functional unit;
Amt_W	equals the inventory output amount of solid waste i (kg) per functional unit; and
D	equals density of waste i (kg/m^3) (see Appendix C).

the water remains as a gas. It is equal to the gross calorific value minus the sensible heat and latent heat of vaporization of water. This study uses net calorific energy value as the measure of energy impacts.

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the landfill space use impact category results.

3.2.3.2 CMR results

The lead-free alternative cable uses 9 percent more landfill space than the baseline cable (Figure 3-20). The top contributing process for the baseline cable and lead-free alternative is the landfilling of chopped cable (<0.014 m^3/km cable, Figure 3-21), and PVC waste and other industrial wastes are the greatest individual flow contributing to the impacts for both alternatives (Figure 3-22). Figure 3-21 includes the processes that contribute >3 percent of the total impacts, which represent 94 percent of the total impacts for both alternatives. Figure 3-22 includes individual flows that contribute >1 percent to the total impacts, which represent 99.5 and 99.2 percent of the total landfill space use impacts for the baseline and lead-free alternatives, respectively.

The overall difference between the cables is mostly due to the greater amount of cable sent to EOL, which is a function of the functional unit difference (i.e., there was greater resin mass in the lead-free cable as compared to the leaded cables to meet the same function. The uncertainty analysis described in Section 3.4 revealed that the landfill space use impacts are sensitive to the energy and EOL uncertainty parameters that were varied; thus, the difference between the baseline and lead-free alternative is not expected to be greatly distinguishable.

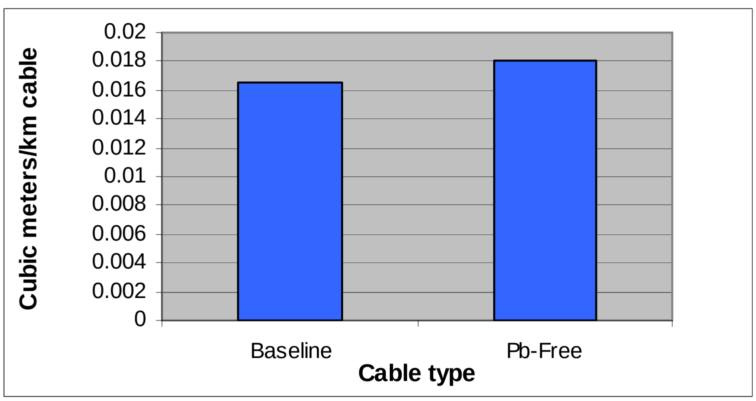

Figure 3-20. Total Landfill Space Impacts – CMR Full life cycle

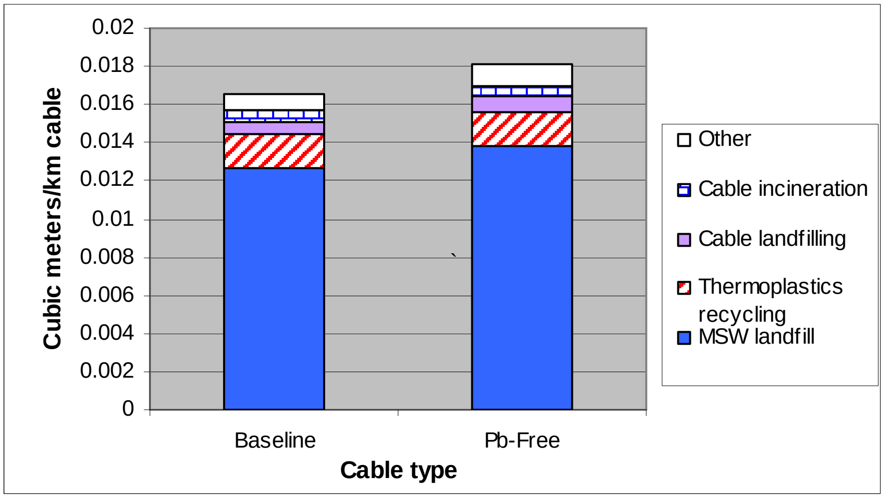

Figure 3-21. Top Contributing Processes to Landfill Space Impacts – CMR Full life cycle

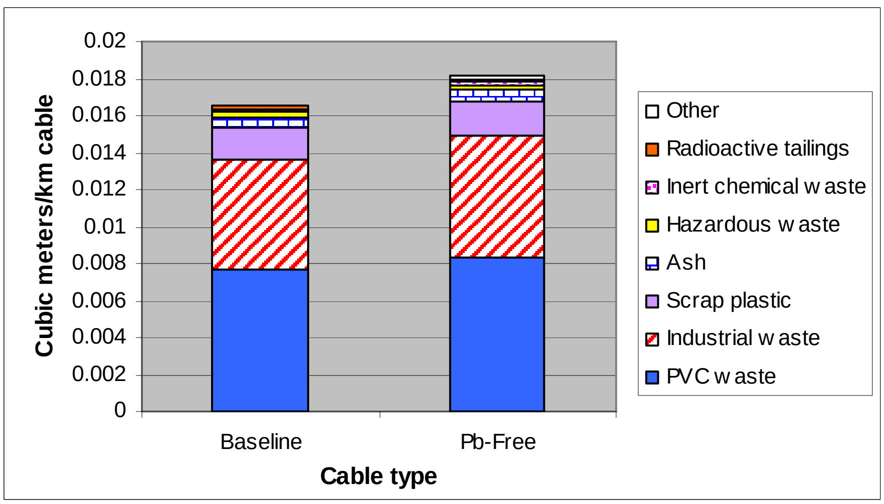

Figure 3-22. Top Contributing Flows to Landfill Space Impacts – CMR Full life cycle

3.2.3.3 CMP results

The lead-free alternative cable uses 9 percent more landfill space than the baseline cable, which is shown in Figure 3-23. The top contributing process for the baseline cable and lead-free alternative is the landfilling of chopped cable (Figure 3-24). The top contributing flow for both the baseline and lead-free alternatives is PVC waste (Figure 3-25). Figure 3-24 includes the processes that contribute >5 percent of the total impacts, which represent 81 and 82 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-25 includes individual flows that contribute >1 percent to the total impacts and represents 98 percent of the total landfill space use for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in cable composition and cable recycling. Due to the uncertainty associated with the cable recycling at end-of-life (see Section 2.4.5.1), an uncertainty analysis was conducted, which showed that by varying the proportion of the resins recycled after cable chopping from 0 to 20 percent of the cable, the differences between the cables was not greatly distinguishable for the landfill space use category (see Section 3.4).

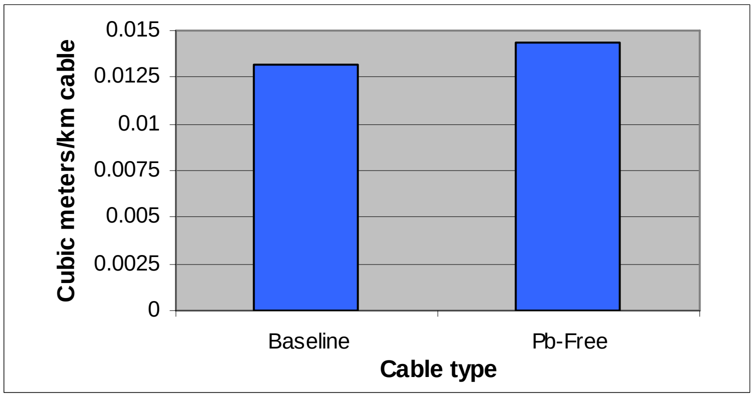

Figure 3-23. Total Landfill Space Use Impacts – CMP Full life cycle

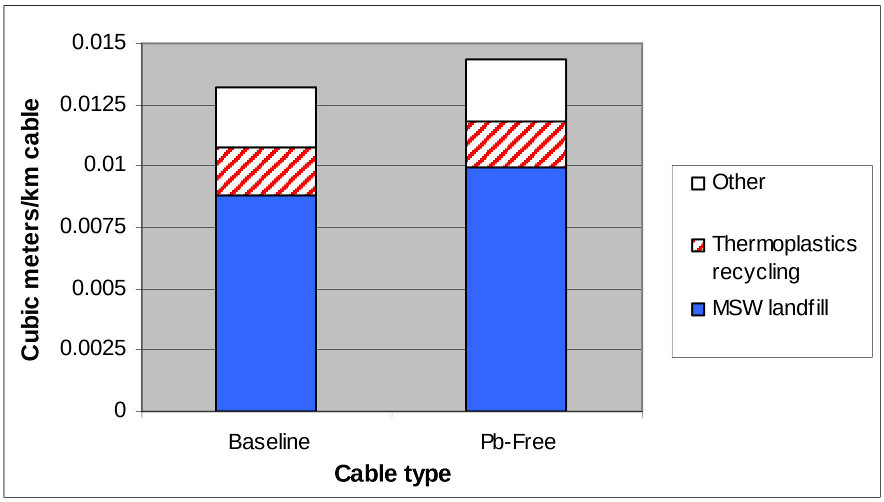

Figure 3-24. Top Contributing Processes to Landfill Space Impacts – CMP Full Life Cycle

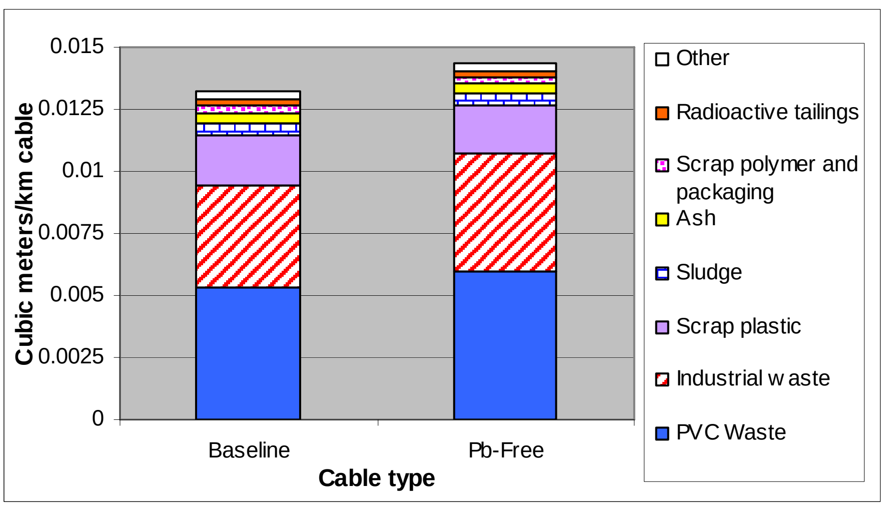

Figure 3-25. Top Contributing Flows to Landfill Space Impacts – CMP Full Life Cycle

3.2.3.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 13 percent greater landfill space use impacts than the lead-free alternative, which is shown in Figure 3-26. The top contributing process is the production of the limestone filler for both alternatives (Figure 3-27), and mineral treatment residue is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-28). Figure 3-27 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-28 includes individual flows that contribute >1 percent to the total impacts, and represent 99 percent of the total landfill space use impacts for both the baseline and lead-free alternatives.

Of note is that the impacts for both the leaded and lead-free constructions are driven by the limestone production process, the top contributing flow was copper ions, and the volume of waste is much smaller than the CMR and CMP results, which included EOL. When EOL was included, the leaded telecommunication cables had much greater burdens due to impact of lead during the EOL stage. Therefore, it is likely that if the full life cycle were considered for NM-B, these results would be driven by other processes and materials. Because we expect EOL to be a large driver of impacts for this category, the landfill space category for NM-B is given a "medium-to-low" quality rating (ratings are summarized in Chapter 4, Table 4-6).

Therefore, care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that limestone production contributes greatest to landfill space use for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of limestone. However, any substituted material would need to be examined for tradeoffs in the other impact categories.

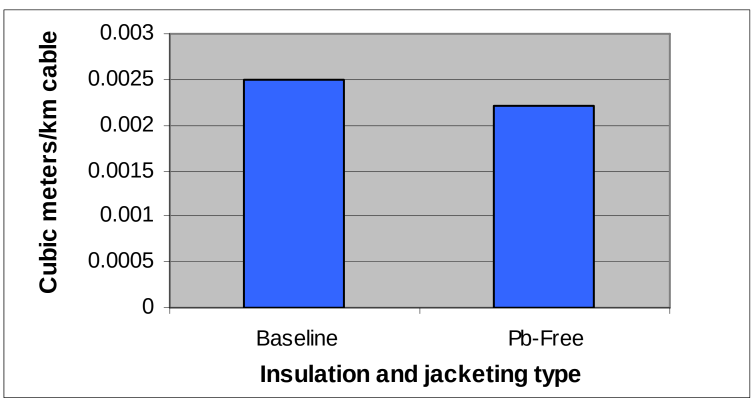

Figure 3-26. Total Landfill Space Use Impacts – NM-B Partial life cycle

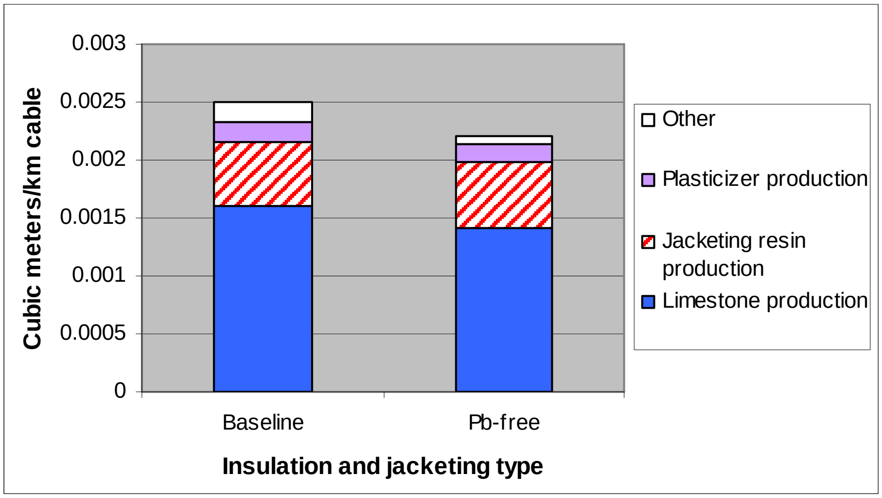

Figure 3-27. Top Contributing Processes to Landfill Space Use Impacts – NM-B Partial life cycle

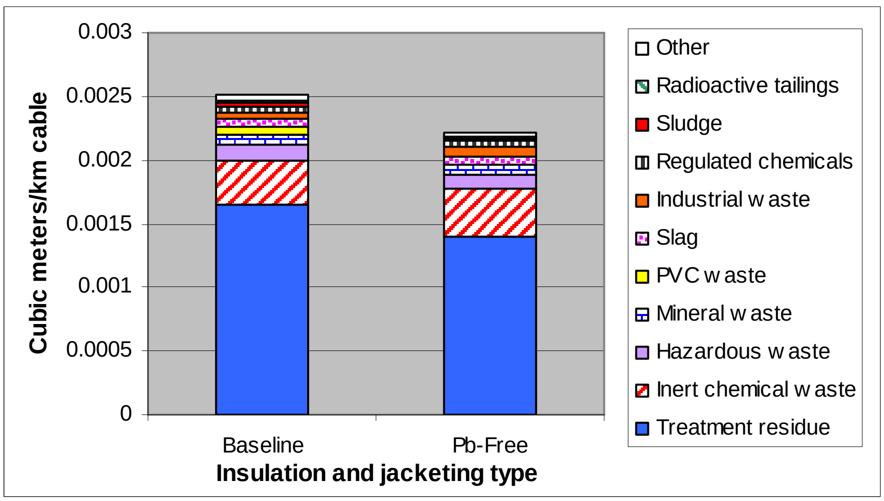

Figure 3-28. Top Contributing Flows to Landfill Space Use Impacts – NM-B Partial life cycle

3.2.3.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology for the Landfill Space Use category is a direct measure of the volume of waste put in landfills. The uncertainty in the LCIA methodology is whether accurate bulk densities are used to convert the mass data into a volume. For primary data, companies were asked for the bulk densities of wastes sent to landfills. For densities of output flows from secondary data, or when densities were not provided by the primary data suppliers, general bulk densities were collected from secondary sources (Appendix C).

The LCIA methodology for landfill space use is only used to represent the volume of landfill space used, and not the type of materials in the landfill waste. Toxic materials that are landfilled, and that potentially leach from a landfill, are addressed in other impact categories (e.g., public toxicity and aquatic ecotoxicity).

For LCI-based uncertainties, the CMR/CMP results showed landfill volume impacts deriving mostly from the landfilling of the PVC waste after chopping. The chopping data were from one primary data source.

The complete life cycle of the NM-B cables was not available, and thus only a limited cradle-to-gate analysis was conducted. Within the processes modeled, limestone and PVC production were top contributing processes. Secondary PVC and phthalate production data are discussed above under Energy Impacts (Section 3.2.2.5). As stated earlier, based on the LCIA methodology and the LCI data, the Landfill Space Use impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.4 Global Warming Impacts

3.2.4.1 Characterization

The build up of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere may generate a "greenhouse effect" of rising temperature and climate change. Global warming potential (GWP) refers to the warming, relative to CO_2, that chemicals contribute to this effect by trapping the Earth's heat. The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical CO_2; therefore, GWPs are in units of CO_2 equivalents. GWPs have been published for known global warming chemicals within differing time horizons. The LCIA methodology employed in the WCP uses GWPs having effects in the 100 year time horizon. Although LCA does not necessarily include a temporal component of the inventory, impacts from releases during the life cycle of cables are expected to be within the 100 year time frame. Appendix D presents the GWPs of global warming gases in the cable inventories. The equation to calculate the impact score for an individual chemical is as follows:

$$(IS_{GW})_i = (EF_{GWP} \text{ x } Amt_{GG})_i$$

where:

IS_{GW} equals the global warming impact score for greenhouse gas chemical *i* (kg CO_2 equivalents) per functional unit;

EF_{GWP} equals the GWP equivalency factor for greenhouse gas chemical i (CO_2 equivalents, 100-year time horizon); and

Amt_{GG} equals the inventory amount of greenhouse gas chemical *i* released to air (kg) per functional unit.

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the global warming impact category results.

3.2.4.2 CMR results

The baseline cable has an 8 percent greater global warming potential than the lead-free alternative, which is shown in Figure 3-29. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-30). To protect confidentiality, Figure 3-30 combines the global warming potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is carbon dioxide (Figure 3-31). Figure 3-30 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 95 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-31 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total global warming potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the global warming potential impact category (see Section 3.4). The generation of electricity for cable extrusion is the greatest contributor to global warming impacts. As a result, reductions in extrusion energy could lead to larger reductions in global warming impact relative to other processes.

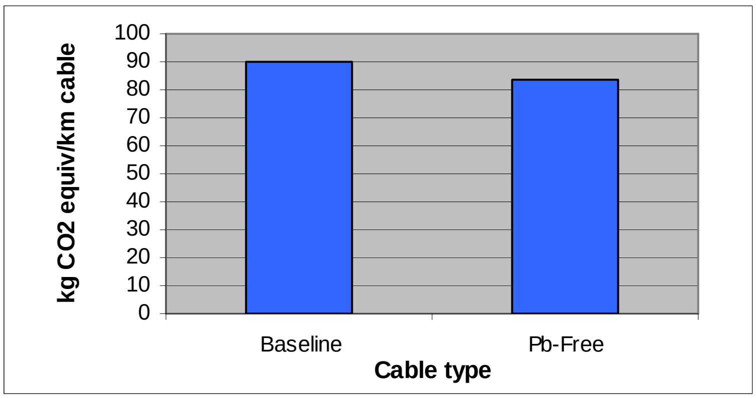

Figure 3-29. Total Global Warming Impacts – CMR Full life cycle

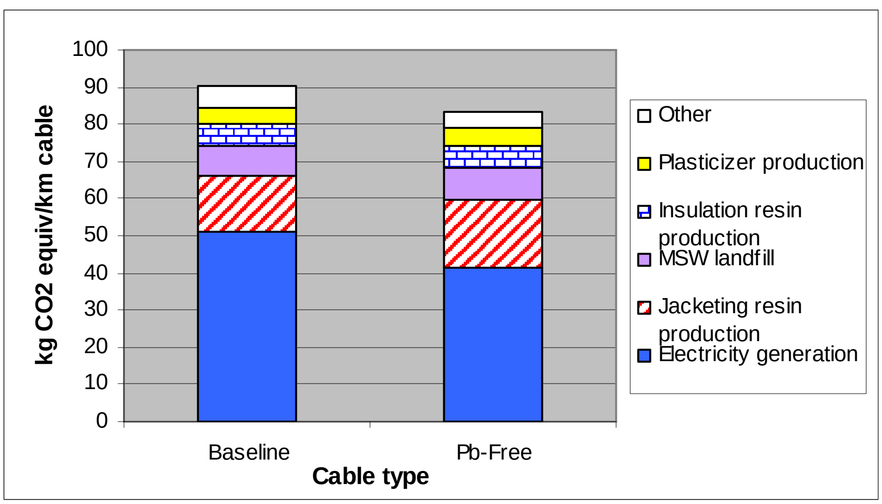

Figure 3-30. Top Contributing Processes to Global Warming Impacts – CMR Full life cycle

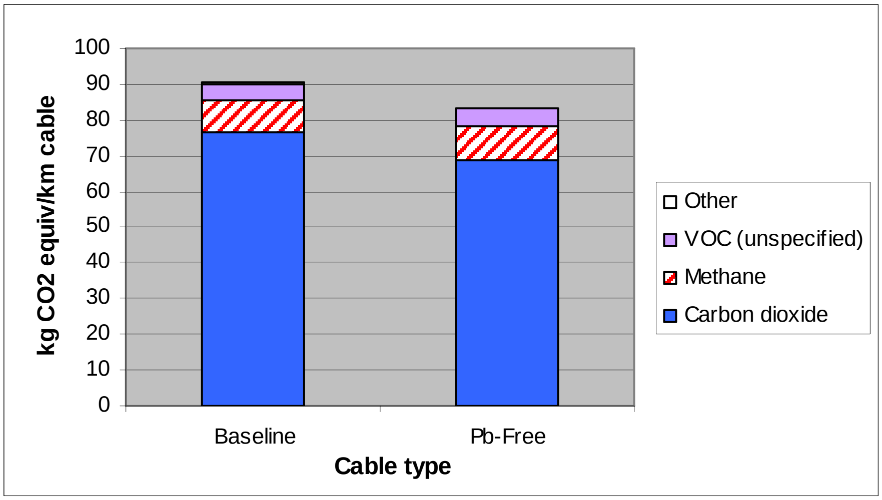

Figure 3-31. Top Contributing Flows to Global Warming Impacts – CMR Full life cycle

3.2.4.3 CMP results

The baseline cable has a 6 percent greater global warming potential than the lead-free alternative, which is shown in Figure 3-32. The top contributing process for the baseline cable and lead-free alternative is the production of the insulation resin, FEP (Figure 3-33). To protect confidentiality, Figure 3-33 combines the global warming potential impacts from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is carbon dioxide (Figure 3-34). Figure 3-33 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 91 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-34 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total global warming potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the global warming potential impact category (see Section 3.4). However, of potentially greater interest to manufacturers is that the production of insulation resin is the largest individual contributor to global warming for both alternatives.

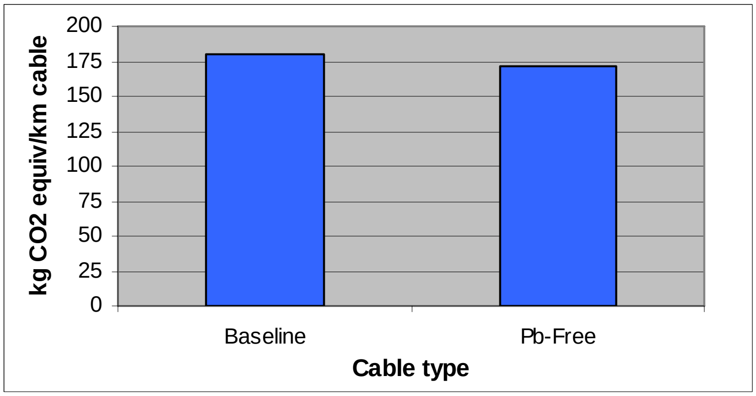

Figure 3-32. Total Global Warming Impacts – CMP Full life cycle

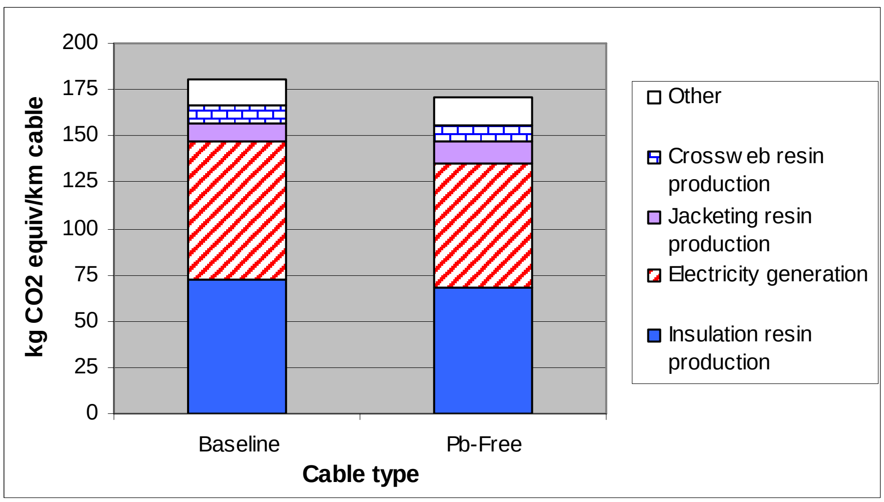

Figure 3-33. Top Contributing Processes to Global Warming Impacts – CMP Full Life Cycle

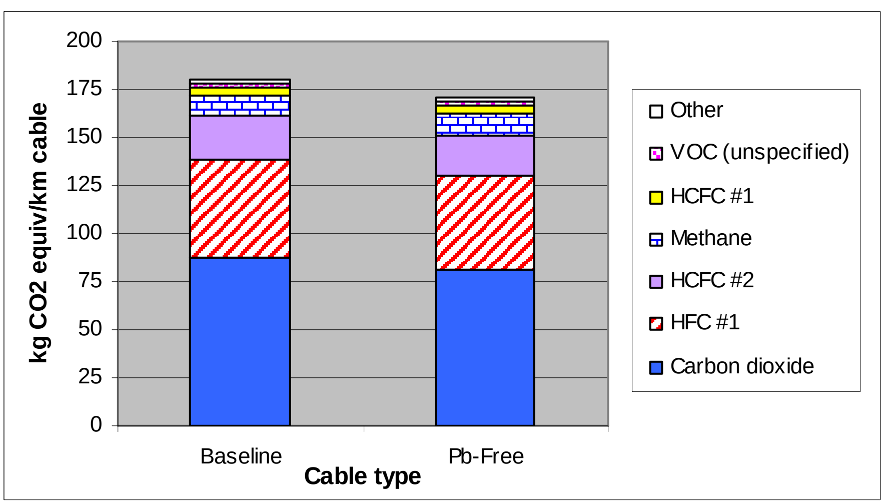

Figure 3-34. Top Contributing Flows to Global Warming Impacts – CMP Full Life Cycle

3.2.4.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 8 percent higher global warming potential impacts than the lead-free alternative, which is shown in Figure 3-35. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-36). To protect confidentiality, Figure 3-36 combines the energy impacts from all upstream electricity generation. Carbon dioxide is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-37). Figure 3-36 includes the processes that contribute >5 percent of the total impacts, which represent 95 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-37 includes individual flows that contribute >1 percent to the total impacts, which represents >99 percent of the total global warming potential impacts for both the baseline and lead-free alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to global warming impacts for both alternatives could provide the opportunity to reduce these impacts. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce carbon dioxide emissions).

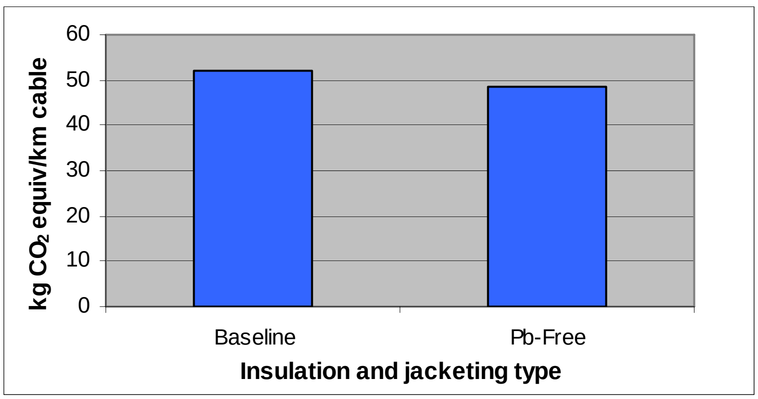

Figure 3-35. Total Global Warming Impacts – NM-B Partial life cycle

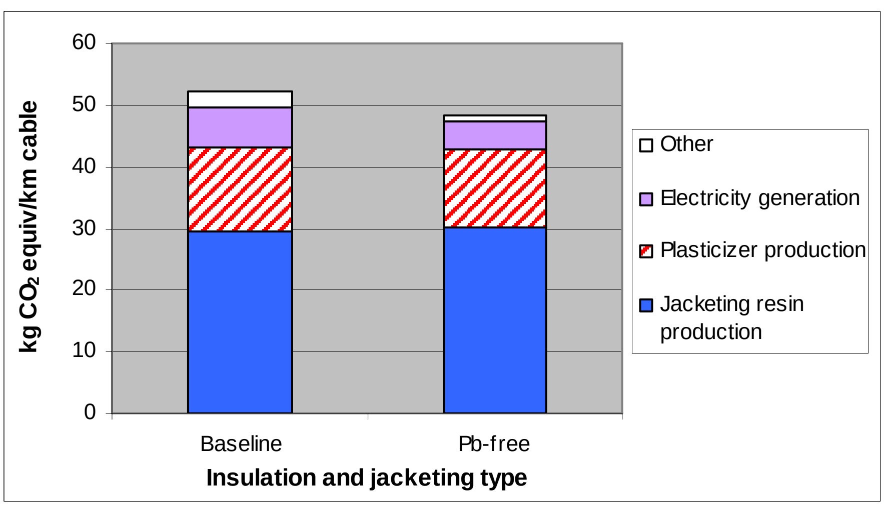

Figure 3-36. Top Contributing Processes to Global Warming Impacts – NM-B Partial life cycle

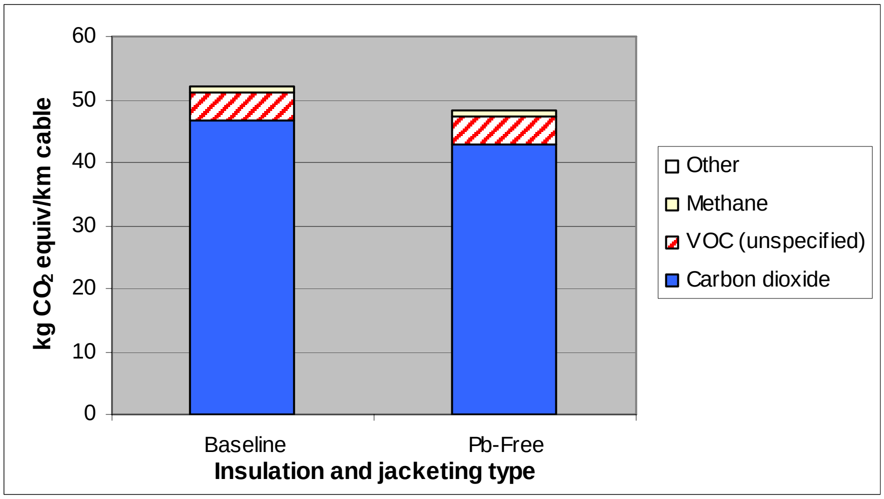

Figure 3-37. Top Contributing Flows to Global Warming Impacts – NM-B Partial life cycle

3.2.4.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology for the global warming category is based on equivalency factors for chemicals with global warming potentials, which are commonly used in LCA and are considered reliable data, to the extent that science is able to predict the radiative forcing of chemicals.

The LCI-based uncertainty is similar to that discussed under the Energy impact category (Section 3.2.2.5), as similar processes drive the global warming impacts. As stated earlier, based on the LCIA methodology and the LCI data, the Energy Use impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.5 Stratospheric Ozone Depletion Impacts

3.2.5.1 Characterization

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone-depleting chemicals released to air. Currently identified ozone-depleting chemicals are those with an ozone depletion potential (ODP), which is a measure of the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC), CFC 11 (trichlorofluoromethane) (Heijungs *et al.*, 1992; CAAA, 1990). The ODPs of chemicals in the cable inventories are provided in Appendix D. The individual chemical impact score for stratospheric ozone depletion is based on the ODP and inventory amount of the chemical:

$$(IS_{OD})_i = (EF_{ODP} \times Amt_{ODC})_i$$

where:

IS_{OD}	equals the ozone depletion (OD) impact score for chemical *i* (kg CFC-11 equivalents) per functional unit;
EF_{ODP}	equals the ODP equivalency factor for chemical *i* (CFC-11 equivalents); and
Amt_{ODC}	equals the amount of ozone depleting chemical *i* released to air (kg) per functional unit.

Accounting for the inventory and the characterization method, we have assigned a "low" data quality measure for the stratospheric ozone depletion impact category results. The low rating is due to the absence of upstream data on brominated phthalates and the generally high ozone depletion potentials of brominated compounds (see Section 3.2.5.5).

3.2.5.2 CMR results

The baseline cable has a 19 percent greater potential to deplete the stratospheric ozone layer than the lead-free alternative, which is shown in Figure 3-38. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-39). To protect confidentiality, Figure 3-39 combines the ozone depletion potential from all upstream electricity production. The top contributing flow for both the baseline and lead-free alternatives is CFC-11 (Figure 3-40). Figure 3-39 includes the processes that contribute >5 percent of the total impacts, which represent 99 and >99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-40 includes individual flows that contribute >1 percent to the total impacts and represents >99 percent of the total stratospheric ozone depletion impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the ozone depletion impact category (see Section 3.4). Given that complete upstream data were not included in the model for this analysis, electricity for extrusion was the greatest contributor. Increasing the energy efficiency of life cycle processes (particularly extrusion energy) would thus reduce the ozone depletion impacts.

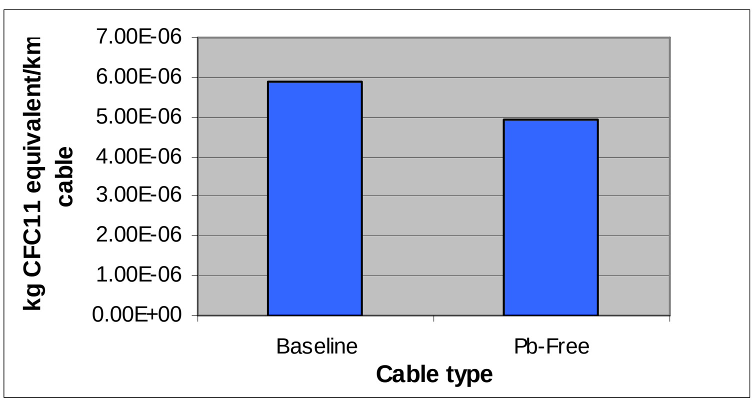

Figure 3-38. Total Stratospheric Ozone Depletion Impacts – CMR Full life cycle

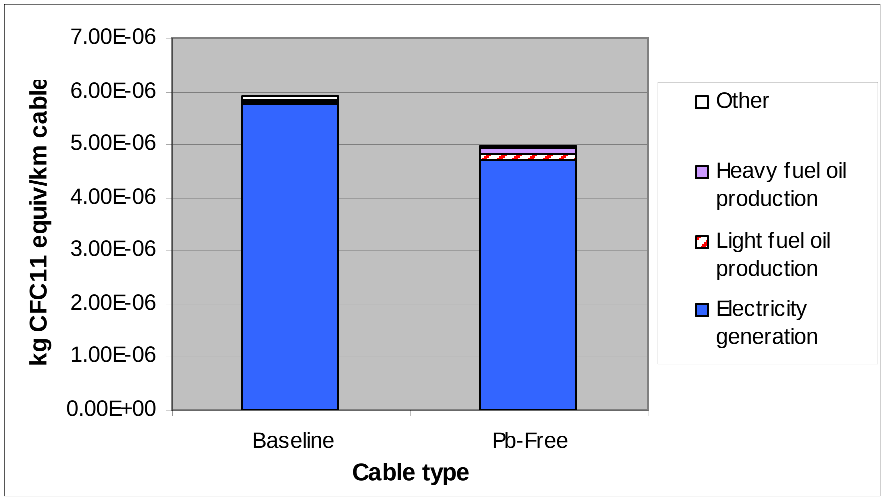

Figure 3-39. Top Contributing Processes to Ozone Depletion Impacts – CMR Full life cycle

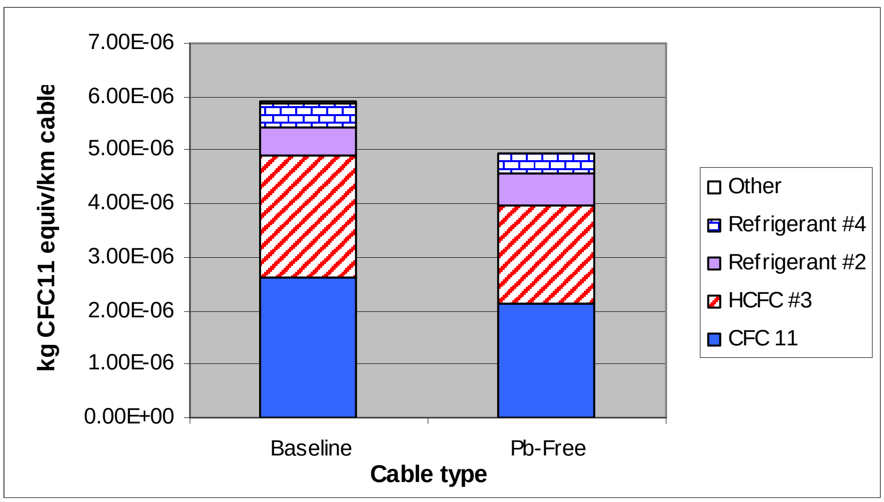

Figure 3-40. Top Contributing Flows to Ozone Depletion Impacts – CMR Full life cycle

3.2.5.3 CMP results

The baseline cable has a 5 percent greater impact on the stratospheric ozone depletion potential than the lead-free alternative, which is shown in Figure 3-41. The top contributing process for the baseline cable and lead-free alternative is the production of the insulation resin, FEP (Figure 3-42). The top contributing flow for both the baseline and lead-free alternatives is Refrigerant #5 (Figure 3-43). Figure 3-42 includes the processes that contribute >5 percent of the total impacts, which represent 99 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-43 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total stratospheric ozone depletion potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in the amount of FEP used in the cable. As the uncertainty analysis did not take into consideration differences in product formulation, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the differences between the cables remained for the ozone depletion potential impact category (see Section 3.4). In light of incomplete upstream data in the model for this analysis, production of insulation resin was the greatest contributor to impacts.

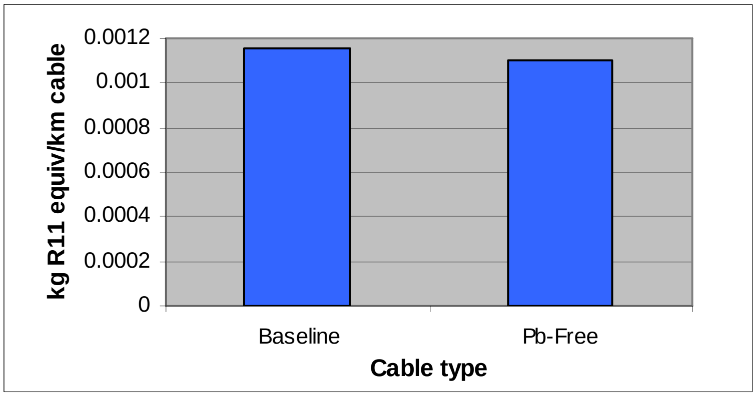

Figure 3-41. Total Stratospheric Ozone Depletion Impacts – CMP Full life cycle

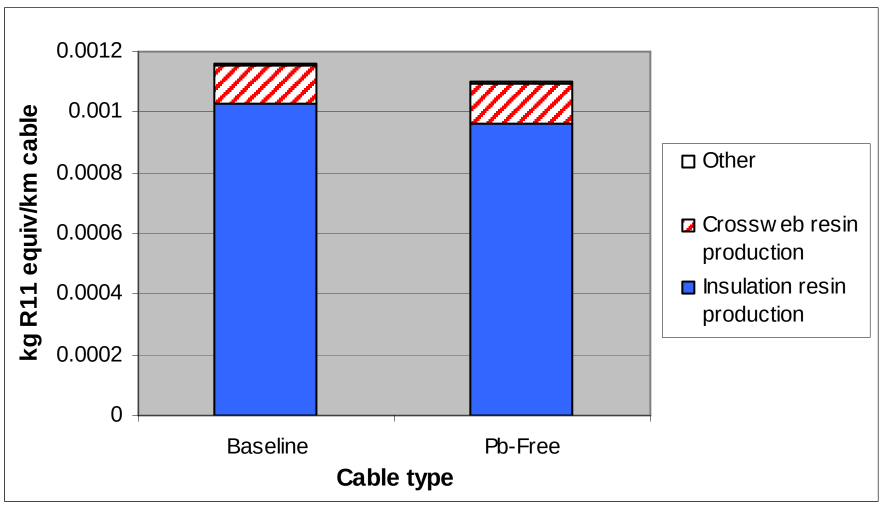

Figure 3-42. Top Contributing Processes to Stratospheric Ozone Depletion Impacts – CMP Full Life Cycle

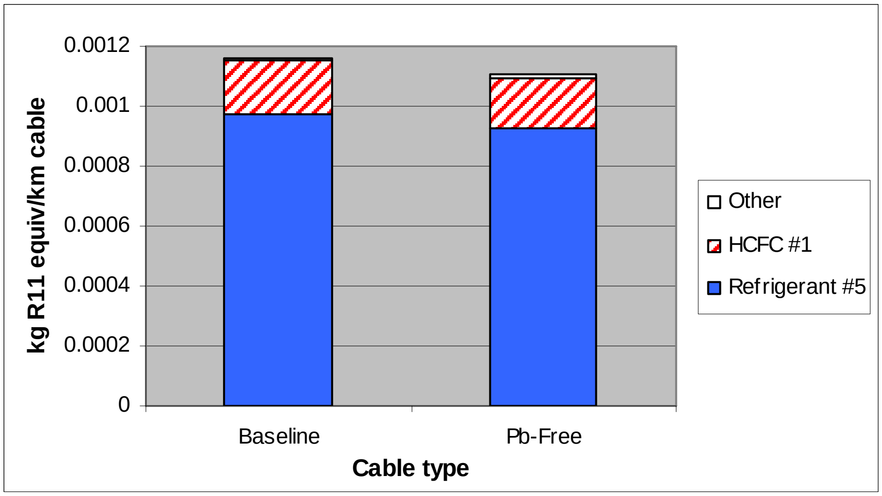

Figure 3-43. Top Contributing Flows to Stratospheric Ozone Depletion Impacts – CMP Full life cycle

3.2.5.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 48 percent higher ozone depletion potential impacts than the lead-free alternative, which is shown in Figure 3-44. The top contributing process is the generation of electricity for cable jacket compounding for both alternatives (Figure 3-45). CFC-11 is the greatest individual flow contributing to the impacts for both alternatives, followed closely by an HCFC (Figure 3-46). Figure 3-45 includes the processes that contribute >5 percent of the total impacts, which represents 99 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-46 includes individual flows that contribute >1 percent to the total impacts, and represent >99 percent of the total ozone depletion potential impacts for both the baseline and lead-free alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that electricity production contributes greatest to stratospheric ozone depletion impacts for both alternatives could provide the opportunity to reduce these impacts. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., CFC-11).

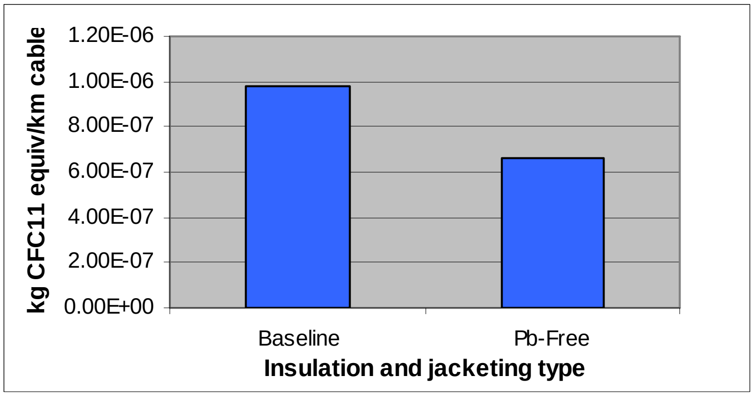

Figure 3-44. Total Stratospheric Ozone Depletion Impacts – NM-B Partial life cycle

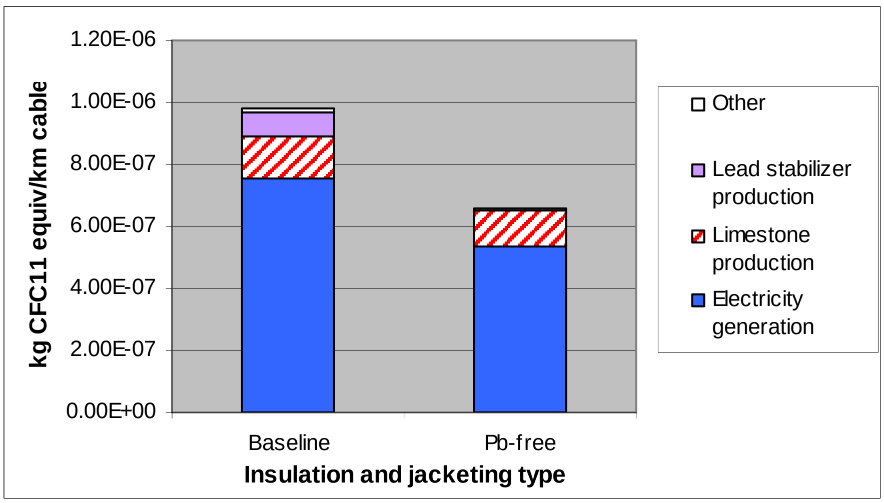

Figure 3-45. Top Contributing Processes to Stratospheric Ozone Depletion Impacts – NM-B Partial life cycle

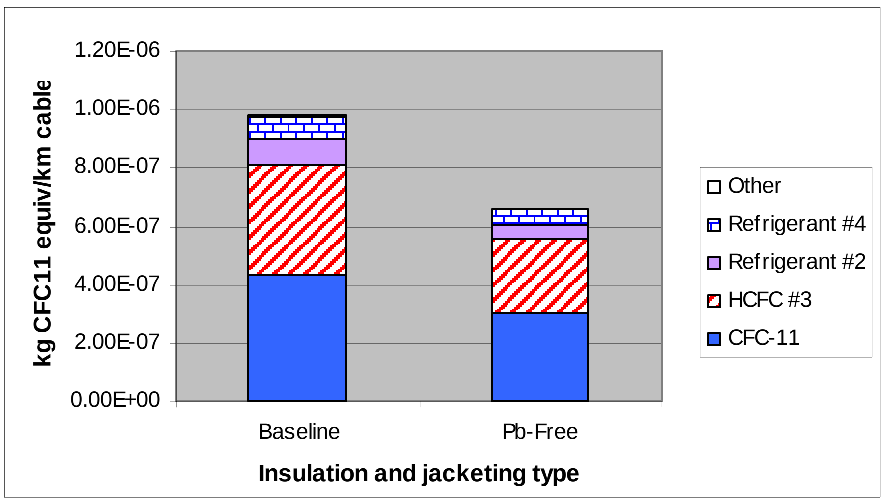

Figure 3-46. Top Contributing Flows to Stratospheric Ozone Depletion Impacts – NM-B Partial life cycle

3.2.5.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology is based on ozone depletion potential equivalency factors, which are commonly used in LCA and are considered reliable data.

For the CMR results, the LCI-based uncertainty is similar to that discussed under the Energy impacts (Section 3.2.2.5) and Global Warming impacts (Section 3.2.4.5), as electricity generation drives impacts for each of these categories. The partial life-cycle results for NM-B were also driven by electricity generation, but since there were no extrusion data in the NM-B model, the uncertainty is related to limitations of the process of electricity generation (discussed in Section 3.2.1.5, NRR impacts), recognizing also that the scope of the NM-B analysis is limited to cradle-to-gate processes. For the CMP results, FEP production was a greater contributor to stratospheric ozone impacts, and the production data were derived from 2 companies.

Further limitations to all cable types are related to missing upstream data. For example, the production process of brominated phthalates was not available, and small brominated hydrocarbons, expected to be among the byproducts of brominated phthalate production, typically have large ozone depleting potentials. Thus, these impacts may be underestimated, and cables with greater quantities of brominated phthalates would be even more underestimated. Based on the bill of materials from primary data collected, the leaded CMR used brominated compounds, while the lead-free ones did not. For CMP, both alternatives used brominated compounds; however, the lead-free cables used about 13 percent more than the leaded cables. Therefore, the CMR results might show a greater difference between the baseline and lead-free cable constructions, potentially resulting in a significant difference between alternatives. For the CMR results, the point estimate results showed the baseline cable construction to yield only 5 percent greater ozone depletion impacts than the lead-free. Given that 13 percent more of the brominated compound is used in the lead-free, this could reverse the results, which would likely remain indistinguishable, given energy uncertainty, as mentioned above in Section 3.2.4.5 and included in the uncertainty analysis (Section 3.4). Neither NM-B alternative used brominated compounds in the construction, and thus the limitations from brominated compounds are not expected to affect the NM-B results.

Based on the LCIA methodology and the LCI data, the Stratospheric Ozone Depletion impact category is given an overall relative data quality rating of “low” for all cable types.

3.2.6 Photochemical Smog Impacts

3.2.6.1 Characterization

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Photochemical oxidant creation potential (POCP) refers to the release of chemicals that contribute to this effect. The POCP is based on simulated trajectories of tropospheric ozone production both with and without volatile organic carbons (VOCs) present. The POCP is a measure of a specific chemical compared to the reference chemical ethene (Heijungs *et al.*, 1992). The list of chemicals with POCPs used in this methodology is presented in Appendix D. As shown in Table 3-2, photochemical smog impacts are based on partial equivalency, because some chemicals cannot be converted into POCP equivalency factors. For example, nitrogen oxides do not have a POCP; however, VOCs are assumed to be the limiting factor, and if VOCs are present, there is a potential impact. Impact scores are based on the identity and amount of chemicals with POCP equivalency factors released to the air and the chemical specific equivalency factor:

$$(IS_{POCP})_i = (EF_{POCP} \text{ x } Amt_{POC})_i$$

where:

IS_{POCP} equals the photochemical smog (POCP) impact score for chemical *i* (kg ethane equivalents) per functional unit;

EF_{POCP} equals the POCP equivalency factor for chemical (ethene equivalents); and

Amt_{POC} equals the amount of photochemical smog-creating oxidant *i* released to the air (kg) per functional unit.

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the photochemical smog impact category results.

3.2.6.2 CMR results

The lead-free alternative has a 7 percent greater potential to form photochemical smog than the baseline cable, which is shown in Figure 3-47. The top contributing process for the baseline cable and lead-free alternative is the production of the jacketing resin, PVC (Figure 3-48). To protect confidentiality, Figure 3-48 combines the photochemical smog formation potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is unspecified volatile organic compounds (Figure 3-49). Figure 3-48 includes the processes that contribute >5 percent of the total impacts, which represent 89 and 90 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-49 includes individual flows that contribute >1 percent to the total impacts, and represents 99 and >99 percent of the total photochemical smog formation potential impacts for the baseline and lead-free alternatives, respectively.

The overall differences between the cables are a function of a number of different parameters, one of which is highly uncertain: energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the photochemical smog formation potential impact category (see Section 3.4). However, the results do indicate that production of jacketing resin is the major contributor to smog formation potential.

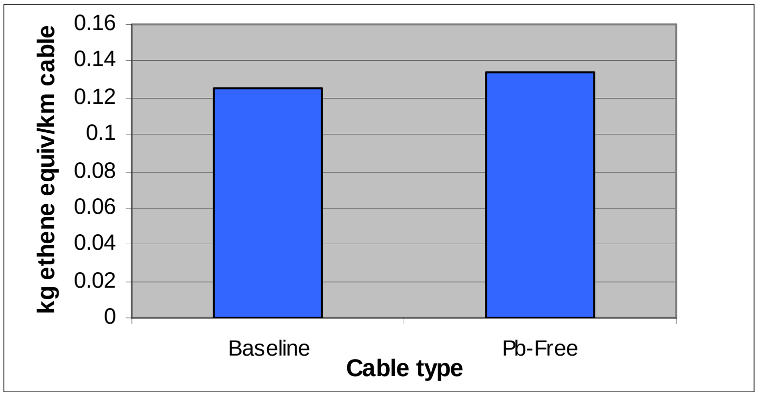

Figure 3-47. Total Photochemical Smog Impacts – CMR Full life cycle

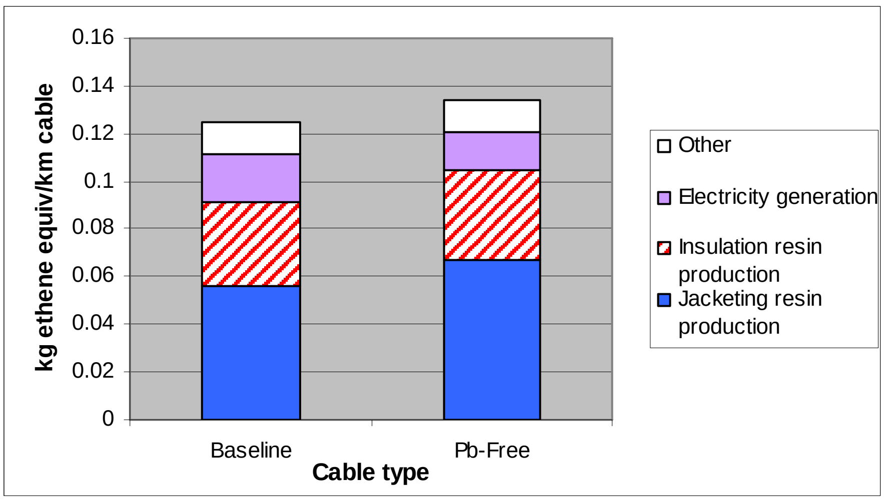

Figure 3-48. Top Contributing Processes to Photochemical Smog Impacts – CMR Full life cycle

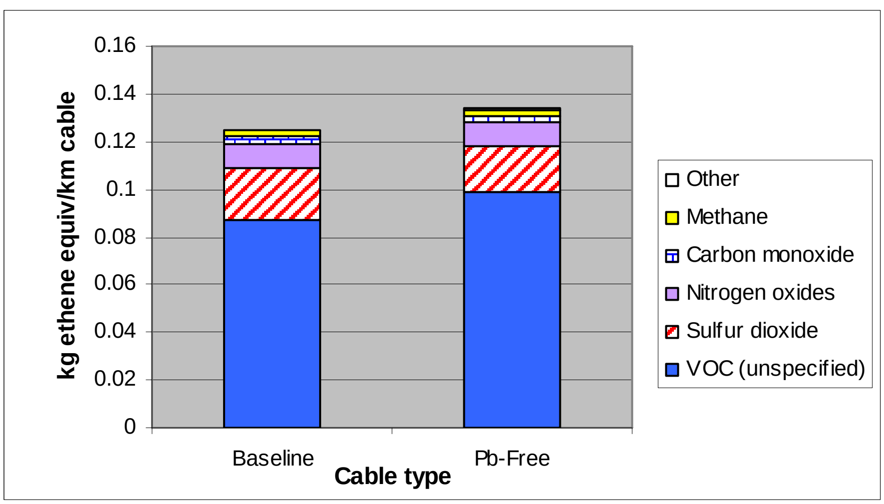

Figure 3-49. Top Contributing Flows to Photochemical Smog Impacts – CMR Full life cycle

3.2.6.3 CMP results

The baseline cable has a 2 percent greater potential to form photochemical smog than the lead-free alternative, which is shown in Figure 3-50. The top contributing process for the baseline cable and lead-free alternative is the production of the jacketing resin, PVC (Figure 3-51). To protect confidentiality, Figure 3-51 combines the photochemical smog formation potential impacts from all upstream electricity generation and natural gas production. The top contributing flow for both the baseline and lead-free alternatives is unspecified volatile organic compounds (Figure 3-52). Figure 3-51 includes the processes that contribute >5 percent of the total impacts, which represent 94 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-52 includes individual flows that contribute >1 percent to the total impacts, and represents 98 percent of the total photochemical smog formation potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use offset slightly by the lead-free alternative's use of more PVC resin. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the photochemical smog formation potential impact category (see Section 3.4). However, the results do indicate that production of jacketing resin is the major contributors to photochemical smog formation potential.

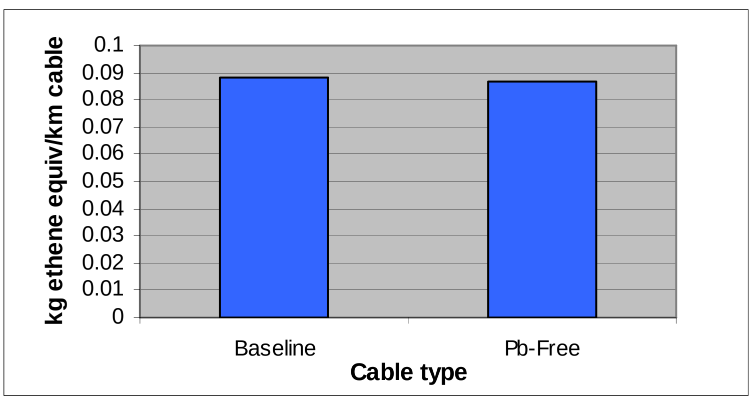

Figure 3-50. Total Photochemical Smog Impacts – CMP Full life cycle

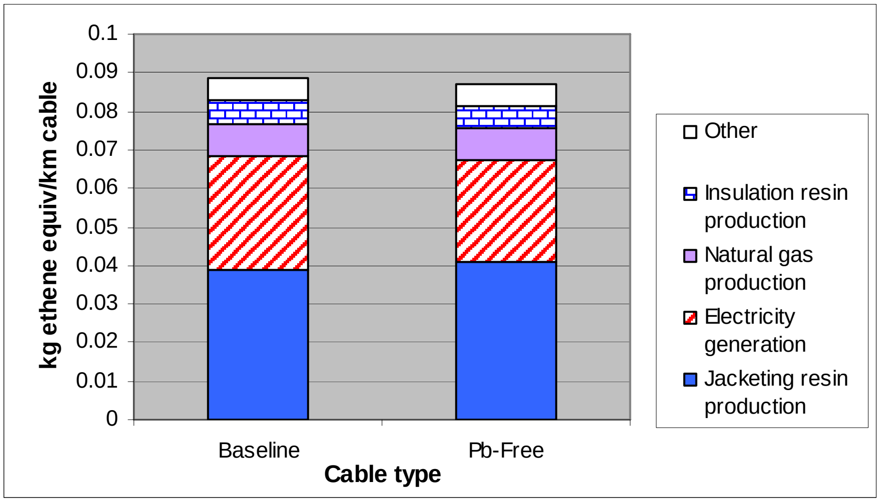

Figure 3-51. Top Contributing Processes to Photochemical Smog Impacts – CMP Full Life Cycle

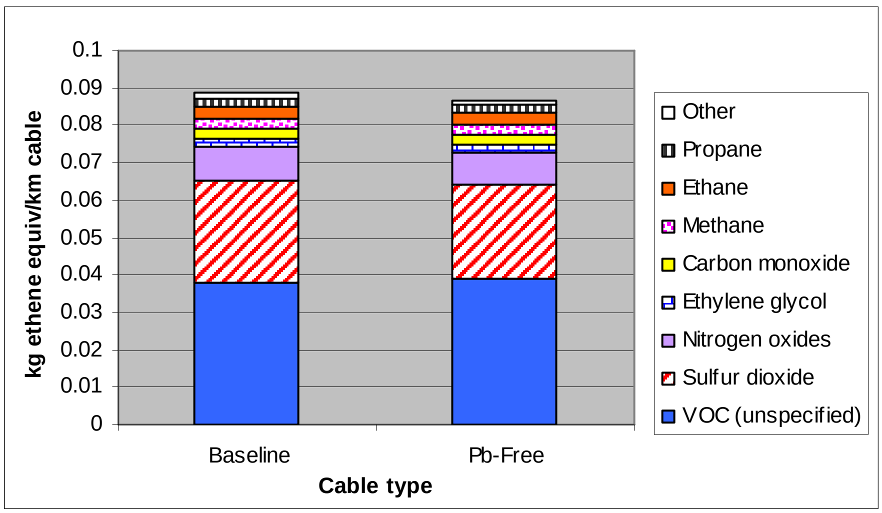

Figure 3-52. Top Contributing Flows to Photochemical Smog Impacts – CMP Full Life Cycle

3.2.6.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 0.2 percent higher photochemical oxidant potential impacts than the lead-free alternative, which is shown in Figure 3-53. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-54). Unspecified volatile organic compounds (VOCs) are the greatest individual flow contributing to the impacts for both alternatives (Figure 3-55). Figure 3-54 includes the processes that contribute >5 percent of the total impacts, which represent 97 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-55 includes individual flows that contribute >1 percent to the total impacts, which represents >99 percent of the total photochemical oxidant potential impacts for both the baseline and lead-free alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC production contributes greatest to photochemical smog impacts for both alternatives could provide the opportunity to reduce these impacts if PVC jacketing resin is reduced. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce VOC emissions).

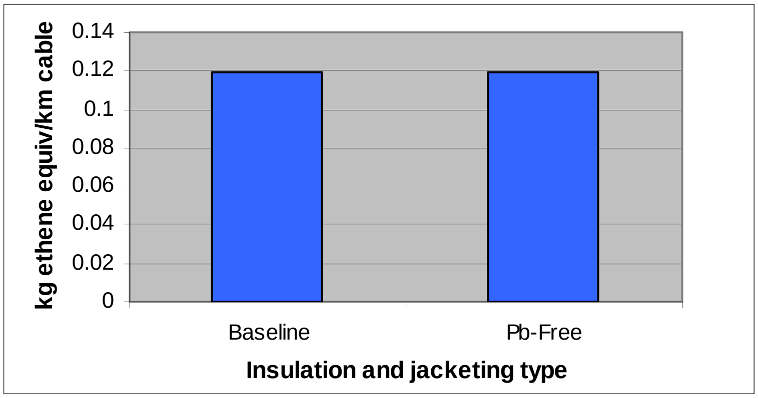

Figure 3-53. Total Photochemical Smog Impacts – NM-B Partial life cycle

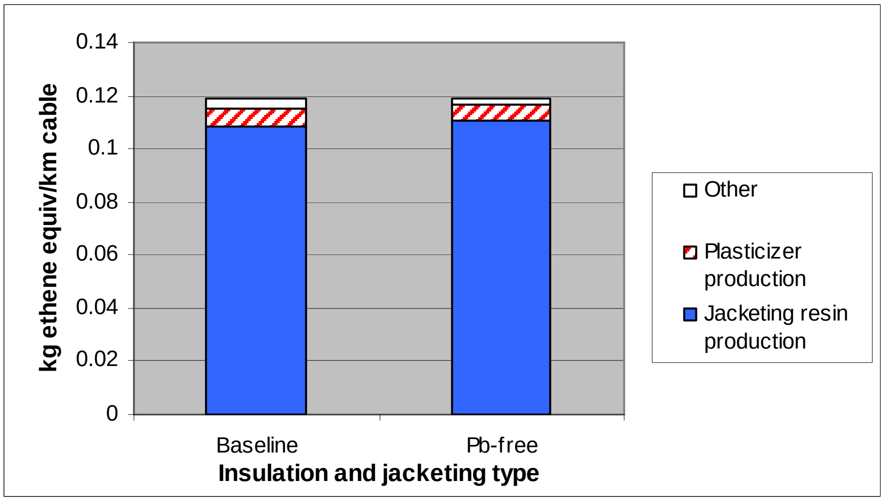

Figure 3-54. Top Contributing Processes to Photochemical Smog Impacts – NM-B Partial life cycle

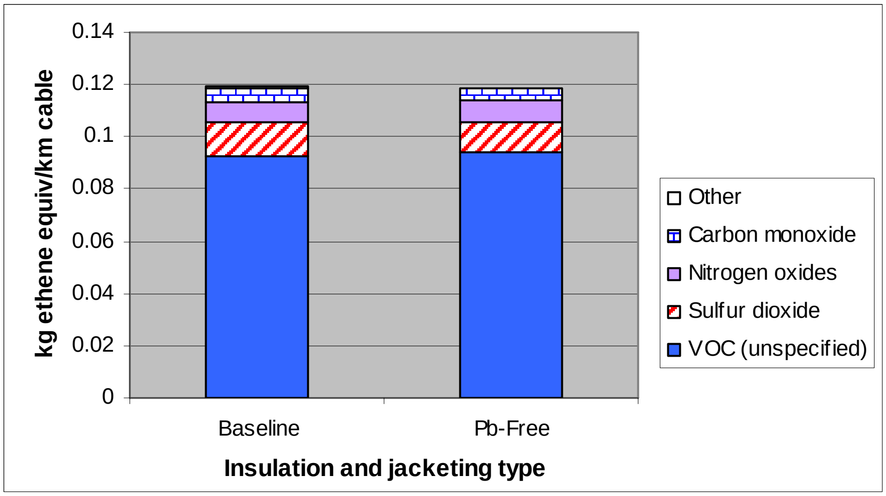

Figure 3-55. Top Contributing Flows to Photochemical Smog Impacts – NM-B Partial life cycle

3.2.6.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology uses the mass of a chemical released to air per functional unit and the chemical-specific partial equivalency factor. The equivalency factor is a measure of a chemical's POCP compared to the reference chemical ethene. As noted in Section 3.1.2, photochemical smog impacts are based on partial equivalency, because some chemicals cannot be converted into POCP equivalency factors (e.g., nitrogen oxide). The inability to develop equivalency factors for some chemicals is a limitation of the photochemical smog impact assessment methodology. However, the POCP equivalency factors are commonly used in LCA and are considered reliable data.

For all three cable types, results were driven by resin manufacturing (e.g., PVC, HDPE) and electricity generation (as used to fuel the manufacturing and/or upstream processes). As mentioned in the NRR and Energy impact sections (3.2.1.5 and 3.2.2.5, respectively), limitations to the PVC, HDPE, and electricity production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Photochemical Smog impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.7 Acidification Impacts

3.2.7.1 Characterization

Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. Impact characterization is based on the inventory amount of a chemical released to air that would cause acidification, multiplied by the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released, compared to sulfur dioxide (SO_2) (Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997). Appendix D lists the AP values that were used as the basis of calculating acidification impacts. The impact score is calculated by:

$$IS_{APi} = (EF_{AP} \; x \; Amt_{AC})_i$$

where:

IS_{AP}	equals the impact score for acidification for chemical *i* (kg SO_2 equivalents) per functional unit;
EF_{AP}	equals the AP equivalency factor for chemical *i* (SO_2 equivalents); and
Amt_{AC}	equals the amount of acidification chemical *i* released to the air (kg) per functional unit.

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the acidification impact category results.

3.2.7.2 CMR results

The baseline cable has an 8 percent greater acidification potential impact than the lead-free alternative, which is shown in Figure 3-56. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-57). To protect confidentiality, Figure 3-57 combines the acidification potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is sulfur dioxide (Figure 3-58). Figure 3-57 includes the processes that contribute >5 percent of the total impacts, which represent 88 and 90 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-58 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total acidification potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use, offset somewhat by greater impacts from PVC jacketing resin production for the lead-free cables. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the acidification potential impact category (see Section 3.4). However, results do indicate that generation of electricity for the cable extrusion process is the major contributor to air acidification.

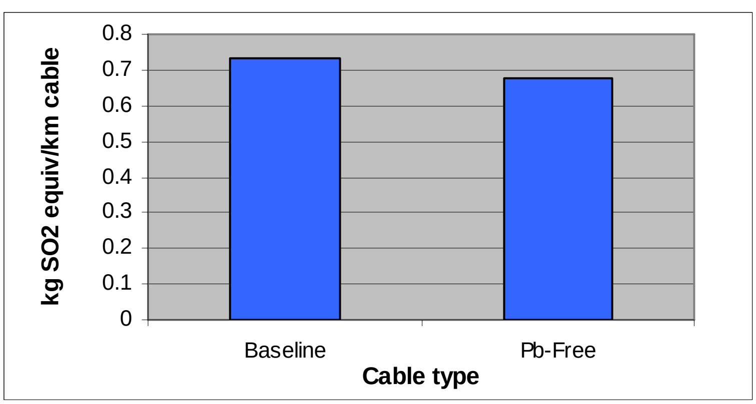

Figure 3-56. Total Air Acidification Impacts – CMR Full life cycle

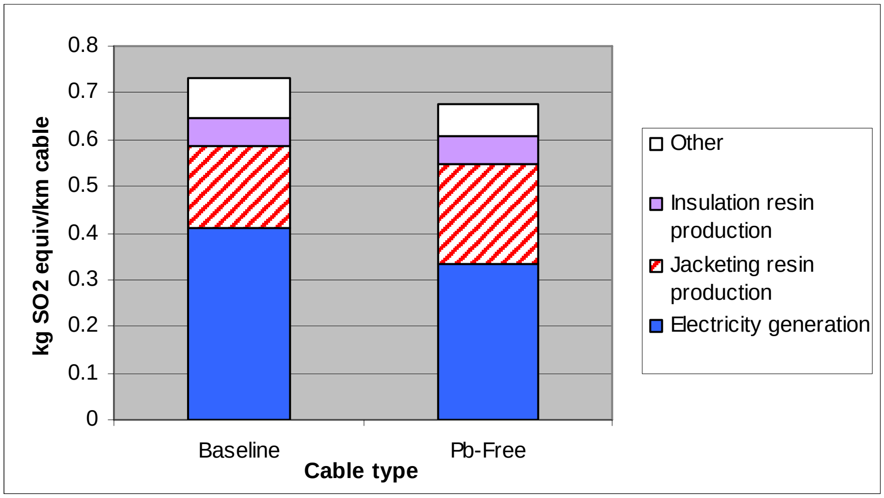

Figure 3-57. Top Contributing Processes to Acidification Impacts – CMR Full life cycle

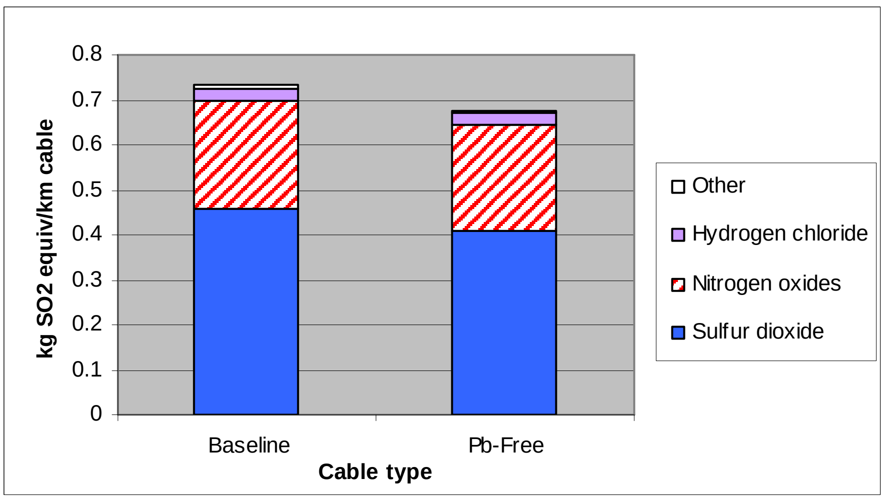

Figure 3-58. Top Contributing Flows to Acidification Impacts – CMR Full life cycle

3.2.7.3 CMP results

The baseline cable has a 7 percent greater potential to cause air acidification than the lead-free alternative, which is shown in Figure 3-59. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-60). To protect confidentiality, Figure 3-60 combines the acidification potential impacts from all upstream electricity generation and natural gas production. The top contributing flow for both the baseline and lead-free alternatives is sulfur dioxide (Figure 3-61). Figure 3-60 includes the processes that contribute >5 percent of the total impacts, which represents 91 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-61 includes individual flows that contribute >1 percent to the total impacts, and represents 98 percent of the total acidification potential impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the acidification potential impact category (see Section 3.4). However, energy efficiency in the extrusion process could reduce impacts for both alternatives, and slightly more so for the baseline alternative.

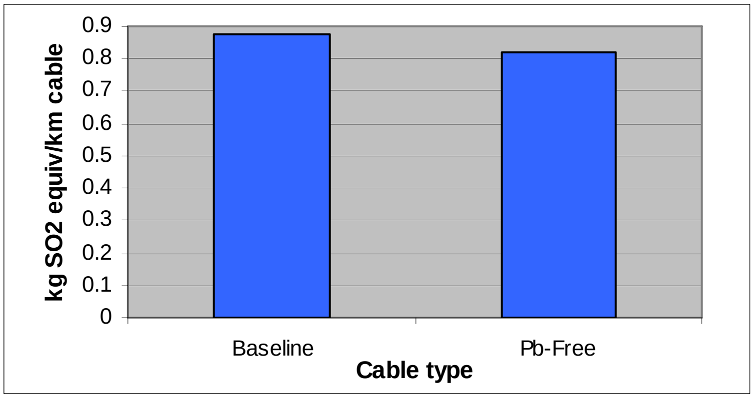

Figure 3-59. Total Air Acidification Impacts – CMP Full life cycle

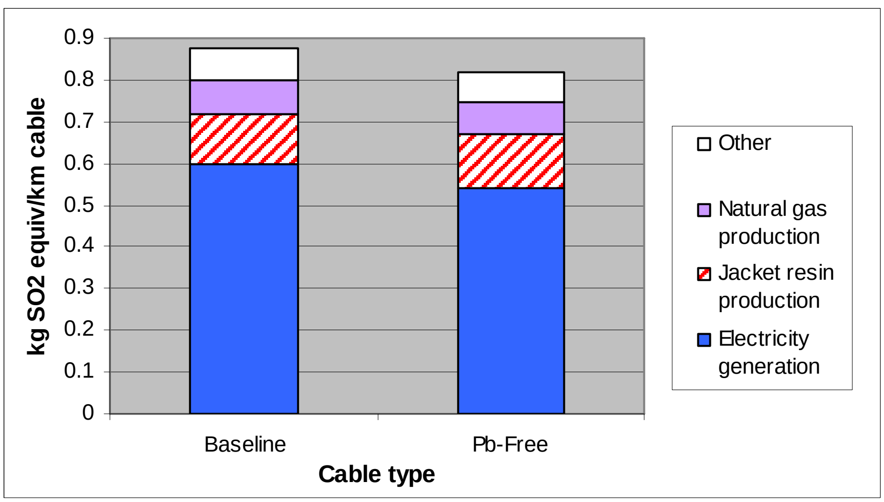

Figure 3-60. Top Contributing Processes to Air Acidification Impacts – CMP Full Life Cycle

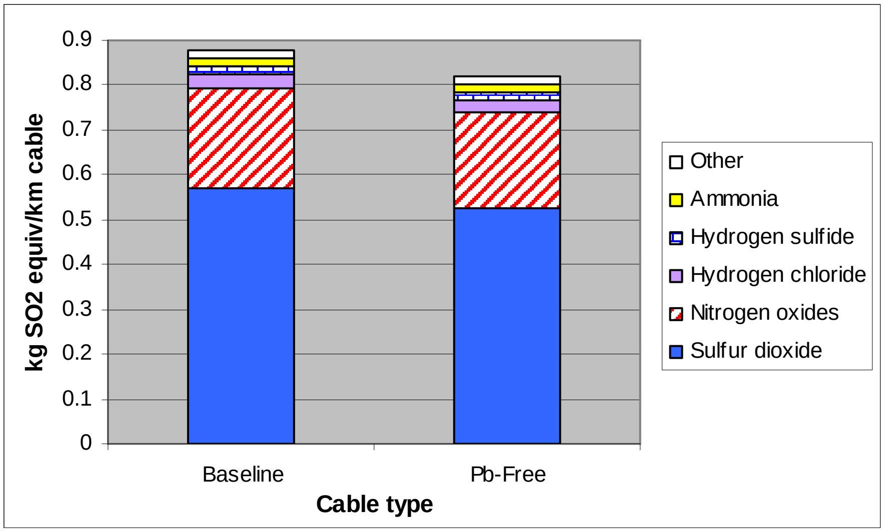

Figure 3-61. Top Contributing Flows to Air Acidification Impacts – CMP Full Life Cycle

3.2.7.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 7 percent higher acidification potential impacts than the lead-free alternative, which is shown in Figure 3-3-62. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-63). Sulfur dioxide is the greatest individual flow contributing to the impacts for both alternatives, followed closely by nitrogen oxides (NO_x) (Figure 3-64). Figure 3-63 includes the processes that contribute >5 percent of the total impacts, which represent 96 and >99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-64 includes individual flows that contribute >1 percent to the total impacts, which represent 99 percent of the total acidification potential impacts for both alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to photochemical smog impacts for both alternatives could provide the opportunity to reduce these impacts if jacketing resin is reduced. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., reduce sulfur dioxide and nitrogen oxide emissions).

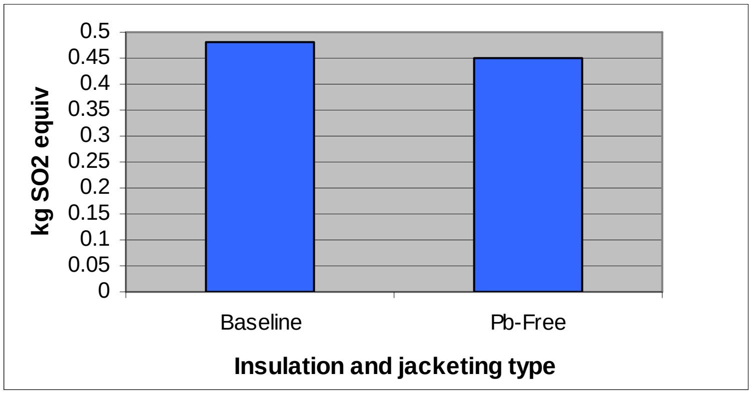

Figure 3-62. Total Air Acidification Impacts – NM-B Partial life cycle

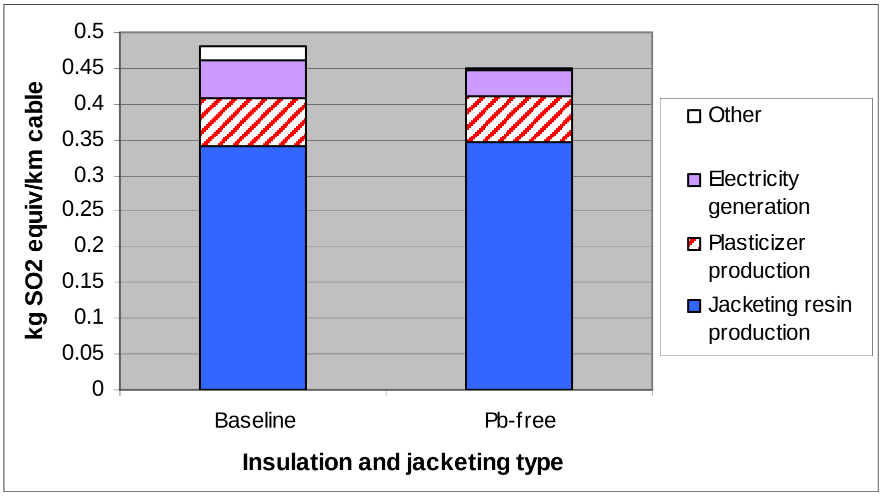

Figure 3-63. Top Contributing Processes to Air Acidification Impacts – NM-B Partial life cycle

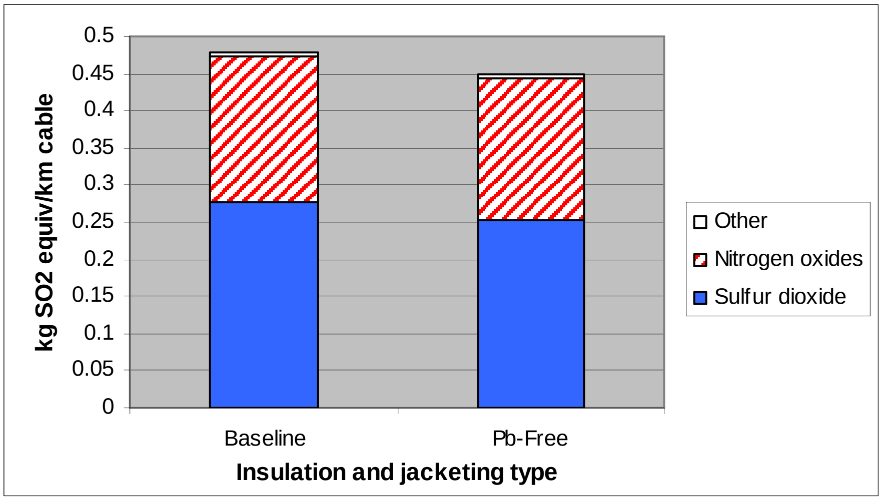

Figure 3-64. Top Contributing Flows to Air Acidification Impacts – NM-B Partial life cycle

3.2.7.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology characterizes acidification impact as a function of the mass of an acid-forming chemical emitted to air and the acidification potential (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per unit mass of the pollutant being released, compared to sulfur dioxide. This is a full equivalency approach to impact characterization, where all substances are addressed in a unified, technical model that lends more certainty to the characterization results than partial equivalency factors discussed with regard to photochemical smog (Section 3.2.6). The AP equivalency factors are commonly used in LCA and are considered reliable data.

For the CMR and CMP cable types, results were driven by electricity generation (as used to fuel the manufacturing and/or upstream processes), with PVC production as the second greatest contributor, contributing to a greater extent to the CMR alternatives. The NM-B results are highly impacted by the PVC production process. As mentioned in the NRR, Energy, and Smog impact sections (3.2.1.5, 3.2.2.5, and 3.2.6.5, respectively), limitations to the PVC and electricity production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Acidification impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.8 Air Particulate Impacts

3.2.8.1 Characterization

Air particulate impacts refer to the release and build up of particulate matter primarily from combustion processes. Impact scores are based on releases to the air of particulate matter with average aerodynamic diameter less than 10 micrometers (PM_{10}), the size of particulate matter that is most damaging to the respiratory system. Impact characterization is simply based on the inventory amount of particulates released to air. This loading impact score is calculated by:

$$IS_{PM} = Amt_{PM}$$

where:

IS_{PM} equals the impact score for particulate (kg PM_{10}) per functional unit; and

Amt_{PM} equals the inventory amount of particulate release (PM_{10}) to the air (kg) per functional unit.

In this equation, PM_{10} is used to estimate impacts; however, if only TSP data are available, these data are used. Using TSP data is an overestimation of PM_{10}, which only refers to the fraction of particulates in the size range below 10 micrometers. A common conversion factor (TSP to PM_{10}) is not available because the fraction of PM_{10} varies depending on the type of particulates. The particulate matter impact category not only serves to represent potential health effects associated with particulates (e.g., respiratory impacts), but also winter smog, which consists partially of suspended particulate matter or fine dust and soot particles. Winter smog is distinguished from summer smog (e.g., photochemical smog, which is the build up of tropospheric ozone concentrations due to VOCs and nitrogen oxides in the presence of sunlight). Winter smog is a problem that occurs mainly in Eastern Europe and has been the cause of health related deaths in the past (Goedkoop, 1995).

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the acidification impact category results.

3.2.8.2 CMR results

The lead-free alternative has a 4 percent greater impact on particulate matter production than the baseline cable, which is shown in Figure 3-65. The top contributing process for the baseline cable and lead-free alternative is the production of the jacketing resin, PVC (Figure 3-66). To protect confidentiality, Figure 3-66 combines the particulate matter production from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is dust (Figure 3-67). Figure 3-66 includes the processes that contribute >5 percent of the total impacts, which represent 94 and 95 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-67 includes individual flows that contribute >1 percent to the total impacts, and represents all of the total particulate matter production impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are a function of a number of different parameters, one of which is highly uncertain: energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the particulate matter production impact category (see Section 3.4). However, energy efficiency in the production of jacketing resin could reduce impacts for both alternatives, but more so for the lead-free alternative. In addition, any reduction in PVC use, which would be replaced with another material to reduce these impacts, would need to be evaluated for tradeoff effects in other impact categories.

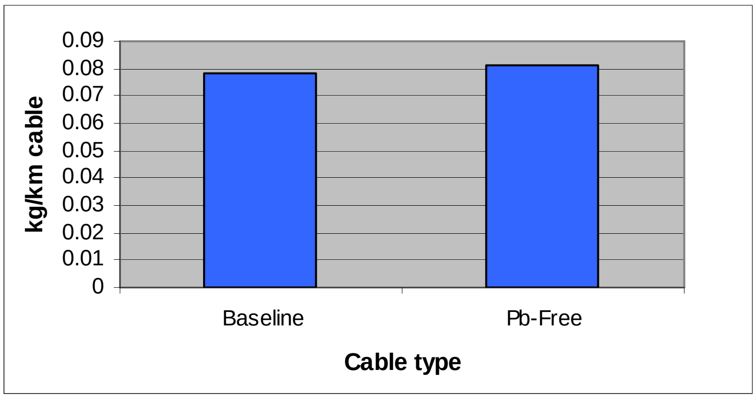

Figure 3-65. Total Air Particulate Impacts – CMR Full life cycle

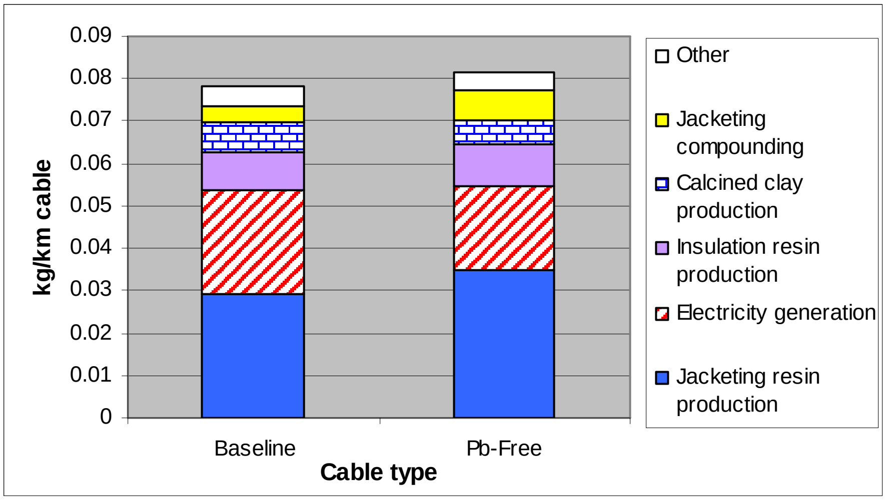

Figure 3-66. Top Contributing Processes to Air Particulate Impacts – CMR Full life cycle

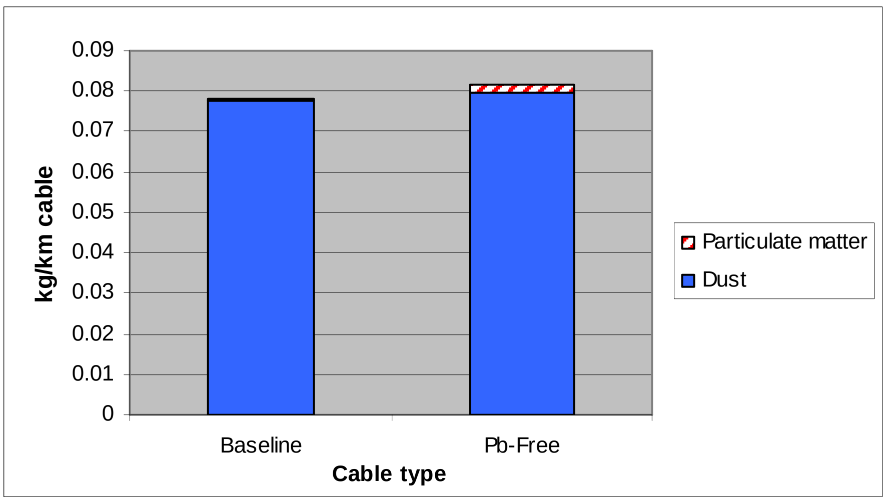

Figure 3-67. Top Contributing Flows to Air Particulate Impacts – CMR Full life cycle

3.2.8.3 CMP results

The baseline cable has a 3 percent greater impact on particulate matter production than the lead-free alternative, which is shown in Figure 3-68. The top contributing process for the baseline cable and lead-free alternative is the production of the PVC jacketing resin (Figure 3-69). To protect confidentiality, Figure 3-69 combines the particulate matter production impacts from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is dust (Figure 3-70). Figure 3-69 includes the processes that contribute >5 percent of the total impacts, which represents 96 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-70 includes individual flows that contribute >1 percent to the total impacts, and represents all of the total particulate matter production impacts for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the particulate matter production impact category (see Section 3.4). However, energy efficiency in the production of jacketing resin could reduce impacts for both alternatives.

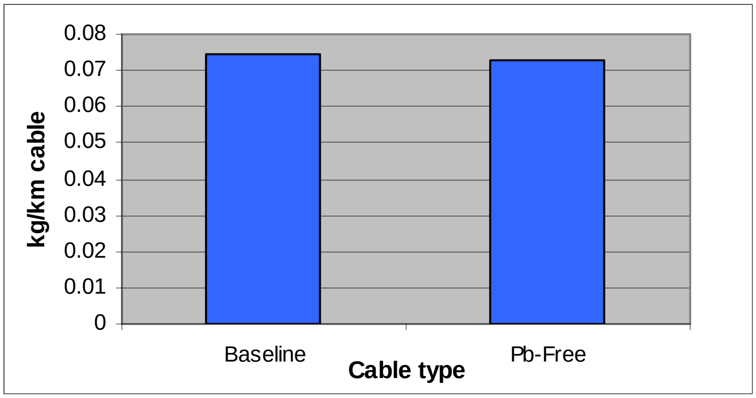

Figure 3-68. Total Air Particulate Impacts – CMP Full life cycle

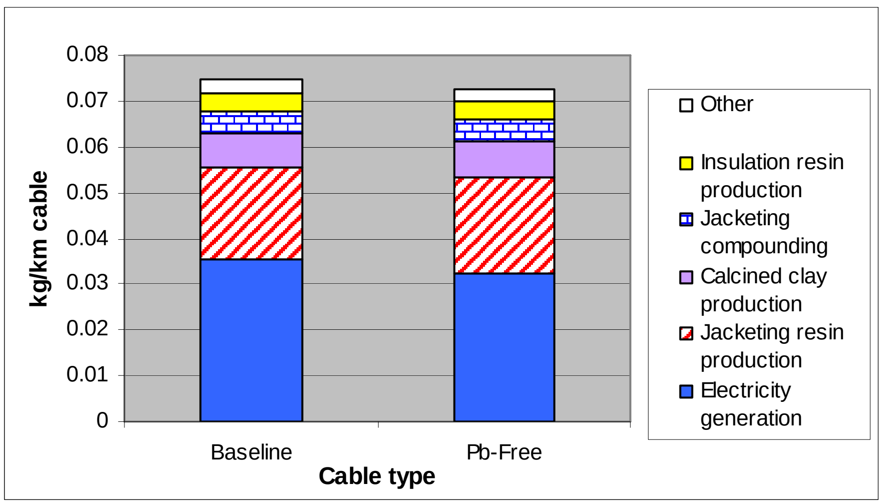

Figure 3-69. Top Contributing Processes to Air Particulate Impacts – CMP Full life cycle

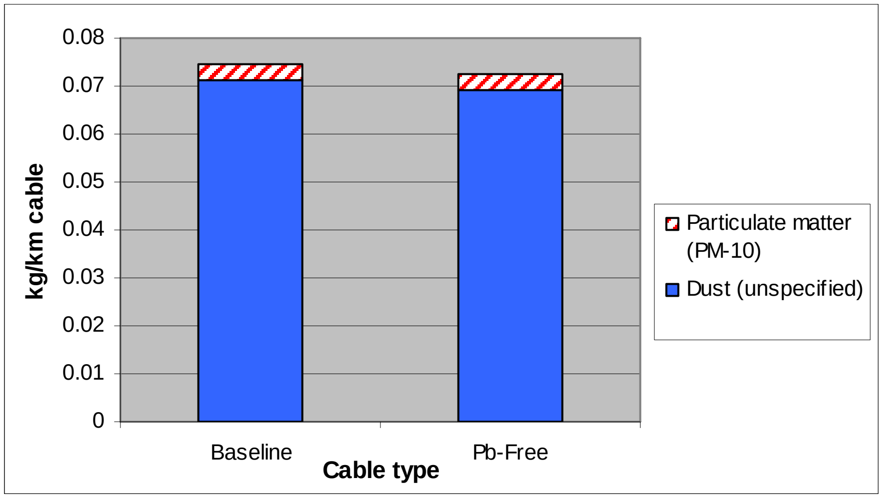

Figure 3-70. Top Contributing Flows to Air Particulate Impacts – CMP Full life cycle

3.2.8.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 14 percent more particulate matter than the lead-free alternative, which is shown in Figure 3-71. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-72). Dust is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-73). Figure 3-72 includes the processes that contribute >5 percent of the total impacts, which represent 94 and 96 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-73 includes individual flows that contribute >1 percent to the total impacts, which represents all particulate matter generation impacts for both alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to the particulate matter impacts for both alternatives could provide the opportunity to reduce these impacts if jacketing resin is reduced. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts would be to focus on reducing dust and particulate matter emissions.

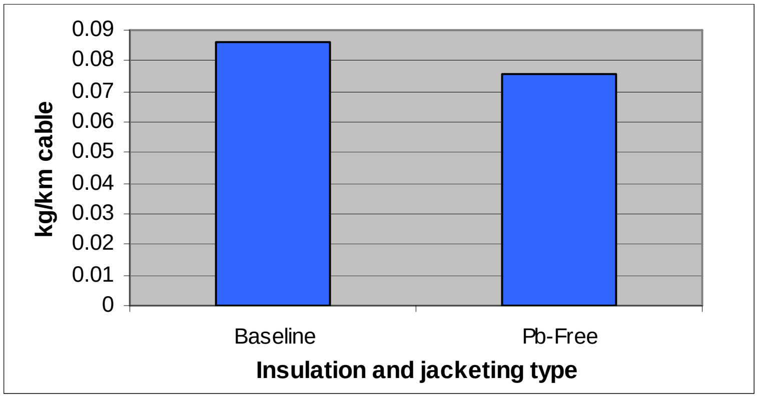

Figure 3-71. Total Air Particulate Impacts – NM-B Partial life cycle

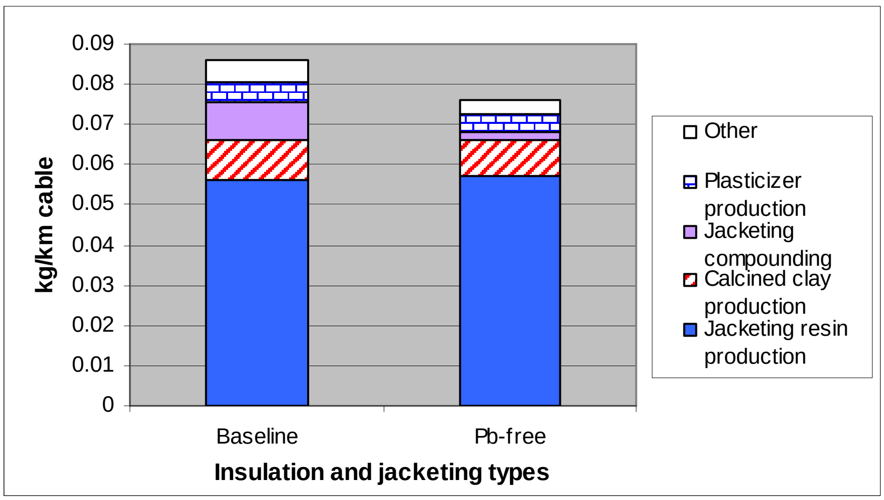

Figure 3-72. Top Contributing Processes to Air Particulate Impacts – NM-B Partial life cycle

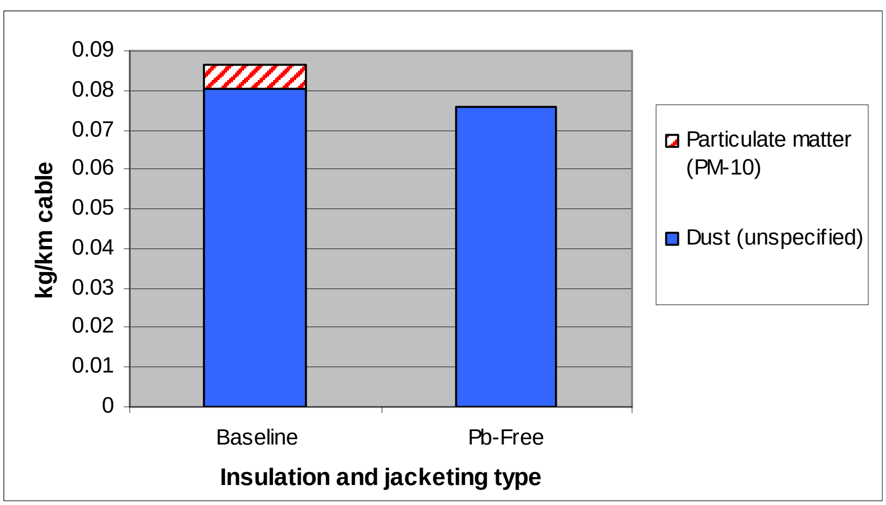

Figure 3-73. Top Contributing Flows to Air Particulate Impacts – NM-B Partial life cycle

3.2.8.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology is based on the mass loading of particulate matter, which is a direct measure of the inventory; thus, few limitations to the LCIA methodology are anticipated. However, the impact characterization is intended to be based on PM_{10} that is in the respirable range and considered more damaging to the respiratory system than larger particles, when considering the effects of particulate matter on human health. Because most of the inventory for this category is catalogued as unspecified "dust," it is not known if these are PM_{10} particles. If the dust includes a broader class of particulate emissions, it is likely that the results are somewhat overstated if they are to represent PM_{10} only. However, similar amounts of dust impacts were found for both the baseline and lead-free alternatives, resulting in an equivalent overestimate across alternatives; thus, no great effect on the comparative results is expected.

For all three cable types, results were driven primarily by PVC manufacturing and/or electricity generation (as used to fuel the manufacturing and upstream processes). As mentioned above in several impact category limitation discussions (e.g., Photochemical Smog), limitations to the PVC and electricity production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Air Particulate impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.9 Water Quality (Eutrophication) Impacts

3.2.9.1 Characterization

Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Equivalency factors for eutrophication have been developed assuming nitrogen (N) and phosphorus (P) are the two major limiting nutrients. Therefore, the partial equivalencies are based on the ratio of N to P in the average composition of algae (($C_{106}H_{263}O_{110}N_{16}P$) compared to the reference compound phosphate (PO_4^{3-}) (Heijungs *et al.*, 1992; Lindfors *et al.*, 1995). If the wastewater stream is first sent to a publicly-owned treatment works (POTW), treatment is considered as a separate process, and the impact score would be based on releases from the POTW to surface waters. Impact characterization is based on eutrophication potentials (EP) (Appendix D) and the inventory amount:

$$(IS_{EUTR})_i = (EF_{EP} \times Amt_{EC})_i$$

where:

IS_{EUTR} equals the impact score for regional water quality impacts from chemical *i* (kg phosphate equivalents) per functional unit;

EF_{EP} equals the EP equivalency factor for chemical *i* (phosphate equivalents); and

Amt_{EC} equals the inventory mass (kg) of chemical *i* per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable.

Accounting for the inventory and the characterization method, we have assigned a "medium" data quality measure for the water eutrophication impact category results.

3.2.9.2 CMR results

The baseline cable has a 19 percent greater impact in terms of eutrophication potential than the lead-free alternative, which is shown in Figure 3-74. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-75). To protect confidentiality, Figure 3-75 combines the eutrophication potential from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is chemical oxygen demand (Figure 3-76). Figure 3-75 includes the processes that contribute >5 percent of the total impacts, which represents 99 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-75 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total eutrophication potential impact for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the eutrophication potential impact category (see Section 3.4). However, energy efficiency in the extrusion process could reduce impacts for both alternatives, and more so for the baseline.

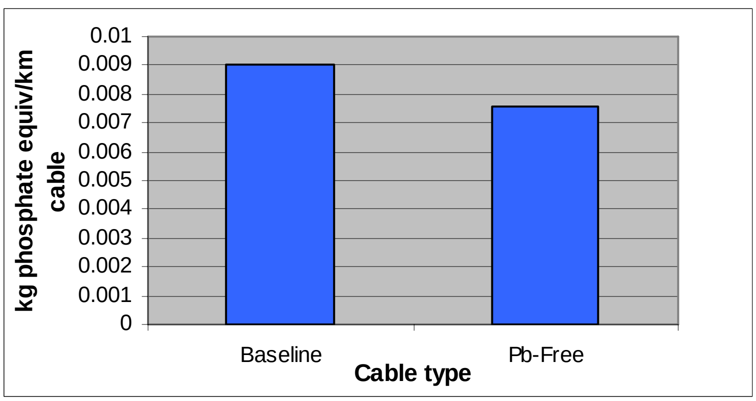

Figure 3-74. Total Water Eutrophication Impacts – CMR Full life cycle

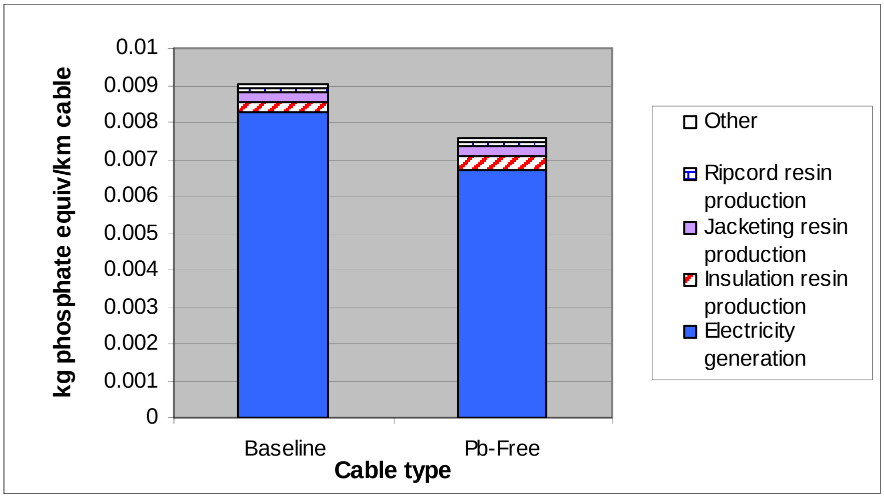

Figure 3-75. Top Contributing Processes to Eutrophication Impacts – CMR Full life cycle

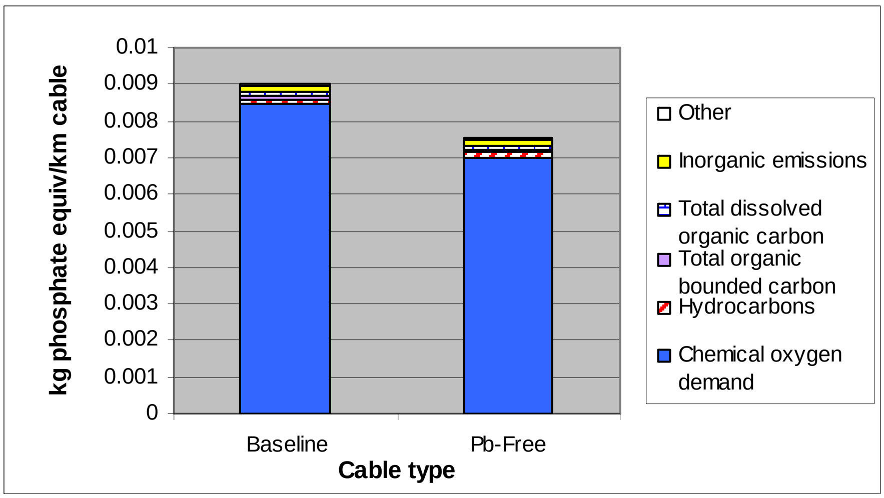

Figure 3-76. Top Contributing Flows to Eutrophication Impacts – CMR Full life cycle

3.2.9.3 CMP results

The baseline cable has 10 percent greater eutrophication potential impacts than the lead-free alternative, which is shown in Figure 3-77. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for the cable extrusion process (Figure 3-78). To protect confidentiality, Figure 3-78 combines the eutrophication potential impacts from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is chemical oxygen demand (Figure 3-79). Figure 3-78 includes the processes that contribute >5 percent of the total impacts, which represents 98 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-79 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total eutrophication potential impact for both the baseline and lead-free alternatives.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted, which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the eutrophication potential impact category (see Section 3.4). However, energy efficiency during the cable extrusion process could offer the greatest potential to reduce impacts for both alternatives.

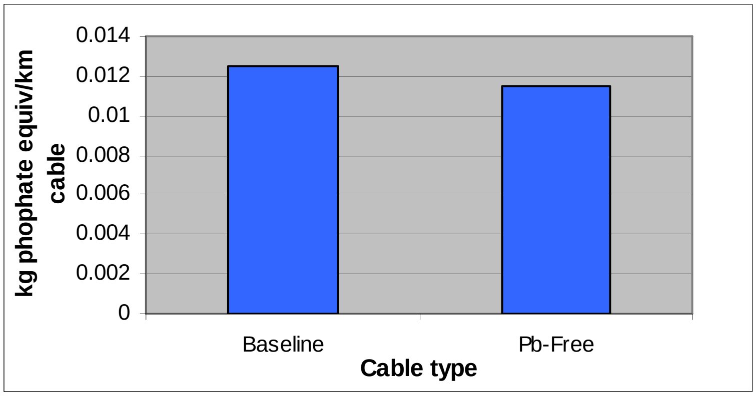

Figure 3-77. Total Water Eutrophication Impacts – CMP Full life cycle

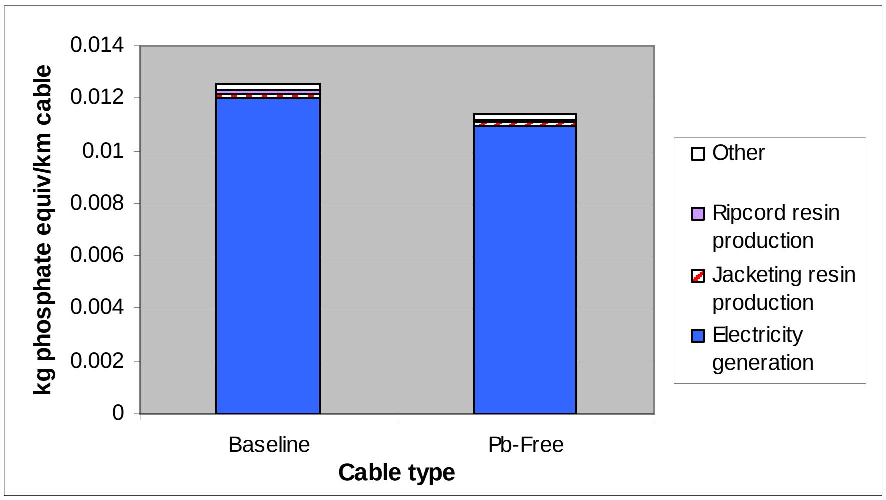

Figure 3-78. Top Contributing Processes to Water Eutrophication Impacts – CMP Full life cycle

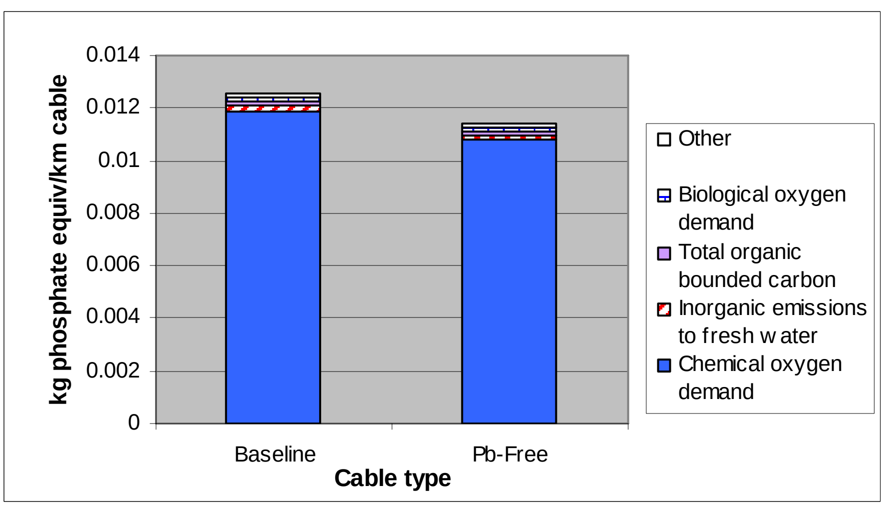

Figure 3-79. Top Contributing Flows to Water Eutrophication Impacts – CMP Full life cycle

3.2.9.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 25 percent higher eutrophication potential impacts than the lead-free alternative, which is shown in Figure 3-80. The top contributing process is the generation of electricity for cable compounding for both alternatives (Figure 3-81). Chemical oxygen demand is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-82). Figure 3-81 includes the processes that contribute >5 percent of the total impacts, which represent 95 and 96 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-82 includes individual flows that contribute >1 percent to the total impacts, which represent 96 percent of the total eutrophication potential impacts for both alternatives.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that electricity production from compounding contributes greatest to eutrophication impacts for both alternatives could provide the opportunity to reduce these impacts if electricity use is reduced. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., reduce chemical oxygen demand emissions).

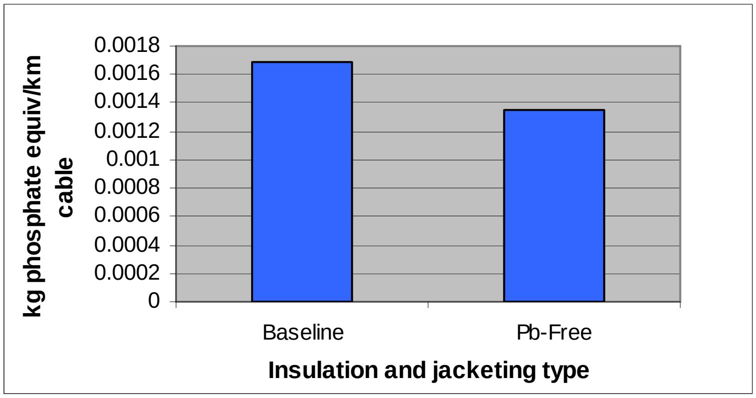

Figure 3-80. Total Water Eutrophication Impacts – NM-B Partial life cycle

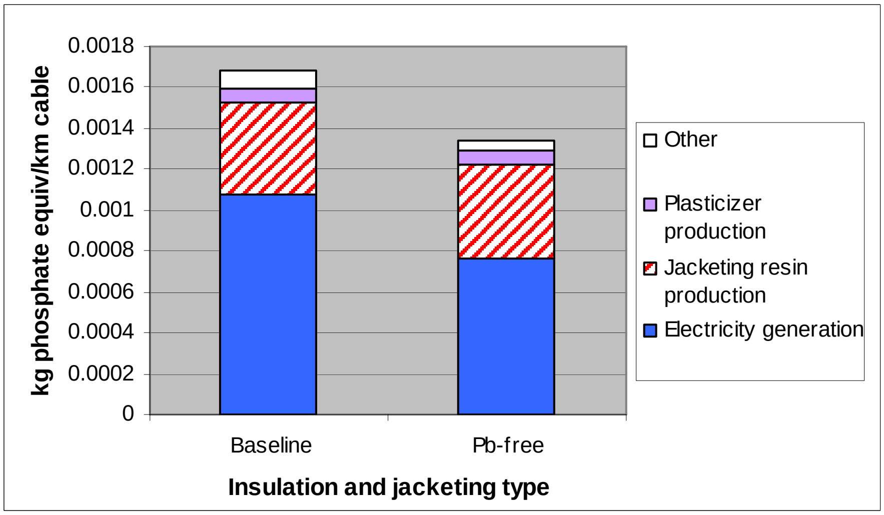

Figure 3-81. Top Contributing Processes to Water Eutrophication Impacts – NM-B Partial life cycle

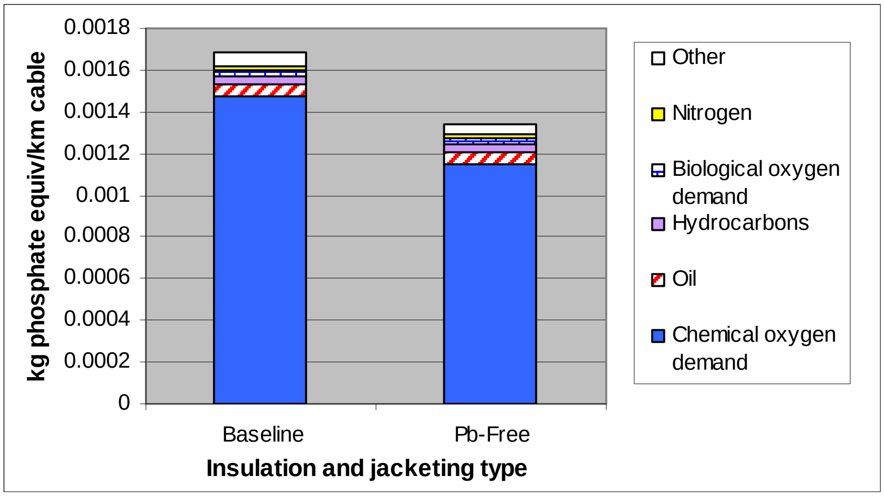

Figure 3-82. Top Contributing Flows to Water Eutrophication Impacts – NM-B Partial life cycle

3.2.9.5 Limitations and uncertainties

Overall limitations and uncertainties for any impact category are related to both the LCIA methodology and the underlying LCI data. The LCIA methodology calculates impacts from the mass of a chemical released directly to surface water, and the chemical's eutrophication potential (EP) equivalency factor. The EP is a partial equivalency factor derived from the ratio of nitrogen and phosphorus in the average composition of algae compared to the reference compound phosphate. As a partial equivalency approach, only a subset of substances can be converted into equivalency factors, which is a limitation of this LCIA methodology. The methodology, however, does take into account nitrogen and phosphorus, which are two major limiting nutrients of importance to eutrophication, and the EPs are commonly used in LCA and are considered reliable data.

For all three cable types, results were driven primarily by electricity generation (as used to fuel the manufacturing processes). For the NM-B cables, the cradle-to-gate analysis also showed PVC to be a large contributor. As mentioned above in several impact category limitation discussions (e.g., Photochemical Smog), limitations to the electricity and PVC production processes are that they were from secondary data (described in Sections 2.1.2.1 and 2.1.2.6). Based on the LCIA methodology and the LCI data, the Water Eutrophication impact category is given an overall relative data quality rating of "medium" for all cable types.

3.2.10 Occupational Toxicity Impacts

This section presents the LCIA characterization methodology and the LCIA results for the occupational human health impact category; however, some of the discussions relate to all of the toxicity impact categories in general (e.g., occupational human health, public human health, and ecotoxicity). The occupational human health impact results presented in this section include two impact categories: occupational non-cancer impacts and occupational cancer impacts. The results for these categories are provided within each of the subsections below.

3.2.10.1 Characterization

Potential Human Health Impacts

Human health impacts are defined in the context of life-cycle assessment as relative measures of potential adverse health effects to humans. Human health impact categories included in the scope of this WCP LCA are chronic (repeated dose) effects, including non-carcinogenic and carcinogenic effects. Chronic human health effects to both workers and the public are considered. This section presents the potential occupational health impacts, and Section 3.2.11 presents the potential public health impacts.

The chemical characteristic that classifies inventory items to the human health effects (and ecotoxicity) categories is toxicity. Toxic chemicals were identified by searching lists of toxic chemicals (e.g., Toxic Release Inventory [TRI]) and, if needed, toxicity databases (e.g., Hazardous Substances Data Bank [HSDB]), and Registry of Toxic Effects of Chemical Substances (RTECS), and other literature (see Appendix E). The review was done by the DfE Workgroup for the DfE Computer Display Project (Socolof *et al.*, 2001), and remains applicable to the WCP. Materials in the WCP inventory were excluded from the toxic list if they were generally accepted as non-toxic (e.g., nitrogen, calcium). The EPA DfE Workgroup also reviewed the list of chemicals that were included in this project as potentially toxic. The final list of potentially toxic chemicals in the WCP is provided in Appendix E.

Human (and ecological) toxicity impact scores are calculated based on a chemical scoring method modified from the CHEMS-1 that is found in Swanson *et al.* (1997). To calculate impact scores, chemical-specific inventory data are required. Any chemical that is assumed to be potentially toxic is given a toxicity impact score. This involves collecting toxicity data (described in Appendix E). If toxicity data are unavailable for a chemical, a mean default toxicity score is given. This is described in detail below. Ecological toxicity is presented in Section 3.2.12.

Chronic human health effects are potential human health effects occurring from repeated exposure to toxic agents over a relatively long period of time (i.e., years). These effects could include carcinogenicity, reproductive toxicity, developmental effects, neurotoxicity, immunotoxicity, behavioral effects, sensitization, radiation effects, and chronic effects to other specific organs or body systems (e.g., blood, cardiovascular, respiratory, kidney and liver effects). Impact categories for chronic health effects are divided into cancer and non-cancer effects for both worker and public impacts. Occupational impact scores are based on inventory inputs; public impact scores are based on inventory outputs.

This section addresses chronic occupational health effects, which refer to potential health effects to workers, including cancer, from long-term repeated exposure to toxic or carcinogenic agents in an occupational setting. For possible occupational impacts, the identity and amounts of materials/constituents as input to a process are used. The inputs represent potential exposures. It could be assumed that a worker would continue to work at a facility and incur exposures over time. However, the inventory is based on manufacturing one unit length of cable and does not truly represent chronic exposure; therefore, the chronic health effects impact score is more of a ranking of the potential of a chemical to cause chronic effects than a prediction of actual effects. Also, the fact that the inputs of the model are dependent on the boundaries of the various datasets, and that chemical intermediates that might be synthesized at a plant and consumed in subsequent reactions were unavailable from secondary data sets, limit the robustness of this impact category.

Chronic occupational health effects scores are based on the identity of toxic chemicals (or chemical ingredients) found in inputs from all of the life-cycle stages. The distinction between pure chemicals and mixtures is made, if possible, by specifying component ingredients of mixtures in the inventory.

The chronic human health impact scores are calculated using hazard values (HVs) for carcinogenic and non-carcinogenic effects. Calculation of the occupational non-cancer and cancer HVs are described below, and the public non-cancer and cancer HV calculations are described in Section 3.2.11.1. Appendix E provides example calculations of toxicity impacts for two sample chemicals.

Potential Occupational Toxicity Impact Characterization: Non-Cancer

The non-carcinogen HV is based on either no-observed-adverse-effect levels (NOAELs) or lowest-observed-adverse-effect levels (LOAELs). The non-carcinogen HV is the greater of the oral and inhalation HV:

$$inhalation: \qquad (HV_{NC_{inhalation}})_i = \frac{1/(inhal\ NOAEL_i)}{1/(inhal\ NOAEL_{mean})}$$

$$oral: \qquad (HV_{NC_{oral}})_i = \frac{1/(oral\ NOAEL_i)}{1/(oral\ NOAEL_{mean})}$$

where:

$HV_{NC\ oral}$	equals the non-carcinogen oral hazard value for chemical *i* (unitless);
$oral\ NOAEL_i$	equals the oral NOAEL for chemical *i* (mg/kg-day);
$oral\ NOAEL_{mean}$	equals the geometric mean oral NOAEL of all available oral NOAELs (mg/kg-day) (Appendix E);
$HV_{NC\ inhalation}$	equals the non-carcinogen inhalation hazard value for chemical *i* (unitless);
$inhal\ NOAEL_i$	equals the inhalation NOAEL for chemical *i* (mg/m^3); and
$inhal\ NOAEL_{mean}$	equals the geometric mean inhalation NOAEL of all available inhalation NOAELs (mg/m^3) (Appendix E).

The oral and inhalation NOAEL mean values are the geometric means of a set of chemical data presented in Appendix E. If LOAEL data are available, instead of NOAEL data, the LOAEL, divided by 10, is used to substitute for the NOAEL. The most sensitive endpoint is used if there are multiple data for one chemical.

The non-carcinogen HVs for a particular chemical are multiplied by the applicable inventory input to calculate the impact score for non-cancer effects:

$$(IS_{CHO\text{-}NC})_i = (HV_{NC} \times Amt_{TCinput})_i$$

where:

$IS_{CHO\text{-}NC}$	equals the impact score for chronic occupational non-cancer health effects for chemical *i* (kg noncancer-toxequivalent) per functional unit;
HV_{NC}	equals the hazard value for chronic non-cancer effects for chemical *i*; and
$Amt_{TC\ input}$	equals the amount of toxic inventory input (kg) per functional unit for chemical *i*.

Potential Occupational Toxicity Impact Characterization: Cancer

The cancer HV uses cancer slope factors or cancer weight of evidence (WOE) classifications assigned by EPA or the International Agency for Research on Cancer (IARC). If both an oral and inhalation slope factor exist, the slope factor representing the larger hazard is chosen; thus, given that there is a cancer slope factor (SF) for a chemical, the cancer HV for chronic occupational health effects is the greater of the following:

$$oral: \quad (HV_{CA_{oral}})_i = \frac{oral\ SF_i}{oral\ SF_{mean}}$$

$$inhalation: \quad (HV_{CA_{inhalation}})_i = \frac{inhalation\ SF_i}{inhalation\ SF_{mean}}$$

where:

$HV_{CA\ oral}$	equals the cancer oral hazard value for chemical *i* (unitless);
$oral\ SF_i$	equals the cancer oral slope factor for chemical *i* $(mg/kg\text{-}day)^{-1}$;
$oral\ SF_{mean}$	equals the geometric mean cancer slope factor of all available slope factors $(mg/kg\text{-}day)^{-1}$(Appendix E);
$HV_{CA\ inhalation}$	equals the cancer inhalation hazard value for chemical *i* (unitless);
$inhalation\ SF_i$	equals the cancer inhalation slope factor for chemical *i* $(mg/kg\text{-}day)^{-1}$; and
$inhalation\ SF_{mean}$	equals the geometric mean cancer inhalation slope factor of all available inhalation slope factors $(mg/kg\text{-}day)^{-1}$ (Appendix E).

The oral and inhalation slope factor mean values are the geometric means of a set of chemical data presented in Appendix E.

Where no slope factor is available for a chemical, but there is a WOE classification, the WOE is used to designate default hazard values as follows: EPA WOE Groups D (not classifiable) and E (non-carcinogen) and IARC Groups 3 (not classifiable) and 4 (probably not carcinogenic) are given a hazard value of zero. All other WOE classifications (known, probable, and possible human carcinogen) are given a default HV of 1 (representative of a mean slope factor) (Table 3-72). Similarly, materials for which no cancer data exist, but are designated as potentially toxic, are also given a default value of 1.

Table 3-72

Hazard values for carcinogenicity WOE if no slope factor is available

EPA classification	IARC classification	Description	Hazard value
Group A	Group 1	Known human carcinogen	1
Group B1	Group 2A	Probable human carcinogen (limited human data)	1
Group B2	N/A	Probable human carcinogen (from animal data)	1
Group C	Group 2B	Possible human carcinogen	1
Group D	Group 3	Not classifiable	0
Group E	Group 4	Non-carcinogenic or probably not carcinogenic	0

N/A=not applicable

The cancer HV for a particular chemical, whether it is from a slope factor or WOE, is then multiplied by the applicable inventory amount to calculate the impact score for cancer effects:

$$(IS_{CHO\text{-}CA})_i = (HV_{CA} \times Amt_{TCinput})_i$$

where:

$IS_{CHO\text{-}CA}$	equals the impact score for chronic occupational cancer health effects for chemical *i* (kg cancertox-equivalents) per functional unit;
HV_{CA}	equals the hazard value for carcinogenicity for chemical *i*; and
$Amt_{TC\ input}$	equals the amount of toxic inventory input (kg) per functional unit for chemical *i*.

Accounting for the inventory and characterization methodology and data, the occupational chronic non-cancer toxicity impact category is given a “medium” data quality measure. Occupational cancer toxicity is given a “medium to low” rating, given that most inventory flows contributing to potential cancer toxicity did not have cancer toxicity data, and were thus based on default hazard values.

3.2.10.2 CMR results

Potential Occupational Non-cancer Toxicity Impacts (CMR)

The lead-free alternative has an 8 percent greater impact on potential occupational non-cancer toxicity than the baseline cable, which is shown in Figure 3-83. The top contributing process for the baseline cable and lead-free alternative is the cable jacketing compounding process (Figure 3-84). To protect confidentiality, Figure 3-84 combines the occupational non-cancer toxicity impact from all upstream electricity generation. The top contributing flow for both the baseline and lead-free alternatives is a non-halogen flame retardant (Figure 3-85). Figure 3-84 includes the processes that contribute >3 percent of the total impacts, which represent 96 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-85 includes individual flows that contribute >1 percent to the total impacts, and represents 99 percent of the total potential occupational non-cancer toxicity impacts for both the baseline and lead-free alternatives. As noted in figure 3-85, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in the amount of the non-halogen flame retardant used in the cable jacketing. As the uncertainty analysis did not take into consideration differences in product formulation, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the differences between the cables remained for the potential occupational non-cancer toxicity impact category (see Section 3.4).

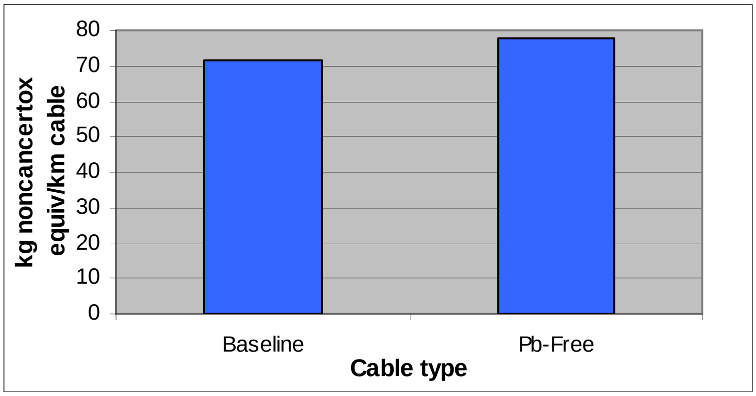

Figure 3-83. Total Potential Occupational Non-cancer Toxicity Impacts – CMR Full life cycle

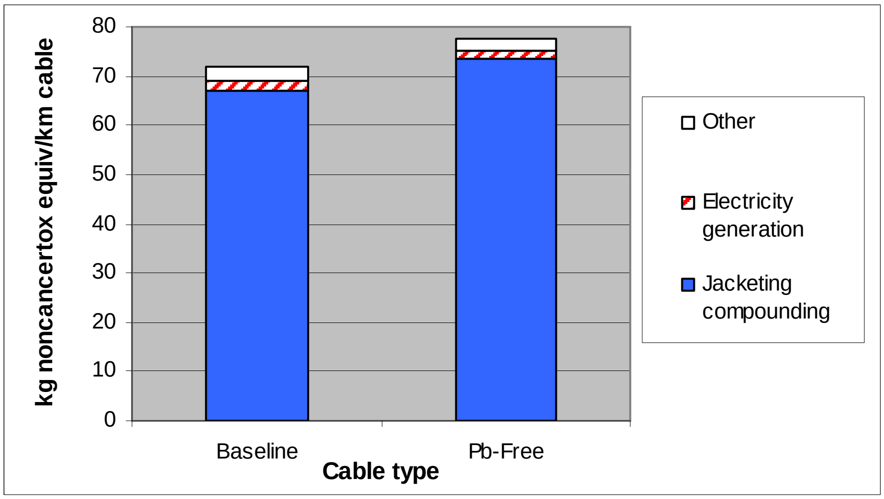

Figure 3-84. Top Contributing Processes to Potential Occupational Non-cancer Toxicity Impacts – CMR Full life cycle

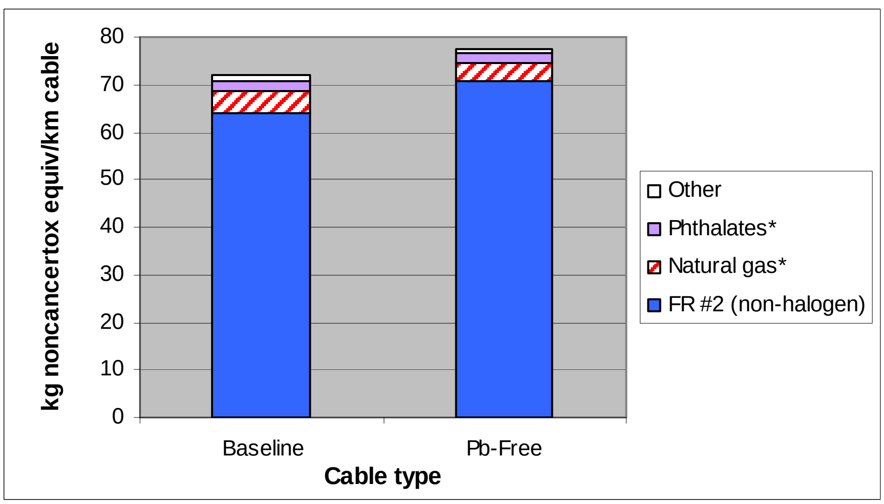

Figure 3-85. Top Contributing Flows to Potential Occupational Non-cancer Toxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

Potential Occupational Cancer Toxicity Impacts (CMR)

The lead-free alternative has a 5 percent greater impact on potential occupational cancer toxicity than the baseline cable, which is shown in Figure 3-86. The top contributing process for the baseline cable and lead-free alternative is the cable jacketing compounding process (Figure 3-87). The top contributing flow for both the baseline and lead-free alternatives is phthalates (Figure 3-88). Figure 3-87 includes the processes that contribute >3 percent of the total impacts, which represent 99 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-88 includes individual flows that contribute >3 percent to the total impacts, and represents 97 and 94 percent of the total potential occupational cancer toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-88, some material flow has been given a default hazard value due to lack of toxicological data

The overall differences between the cables are primarily a function of the differences in jacketing compounding and non-lead stabilizer production. An uncertainty analysis was conducted to address the uncertainty in extrusion and EOL data (Section 3.4). As that analysis did not take into consideration differences in jacket compounding or product formulation, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the relatively small differences between the cables remained for the potential occupational cancer toxicity impact category (see Section 3.4). Modifications to the jacket compounding process could have the largest potential to reduce impacts for both alternatives.

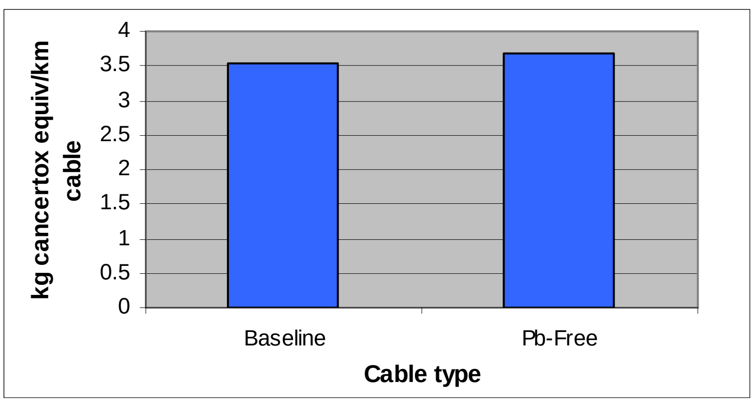

Figure 3-86. Total Potential Occupational Cancer Toxicity Impacts – CMR Full life cycle

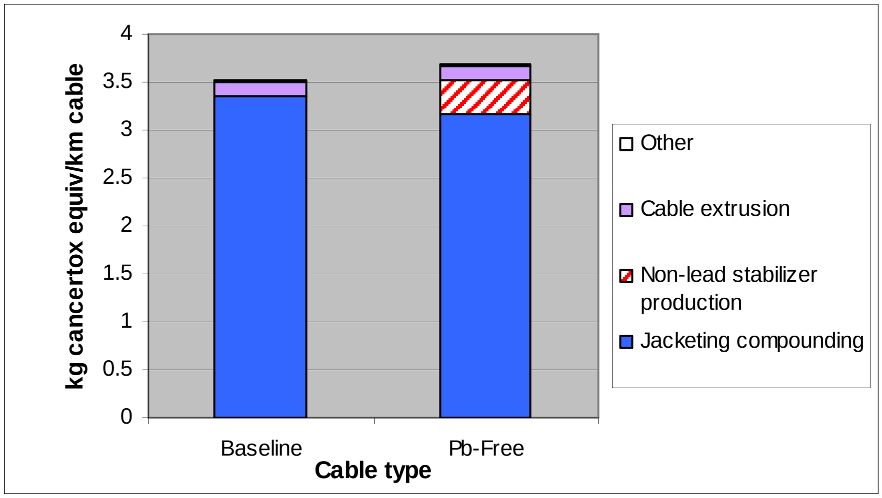

Figure 3-87. Top Contributing Processes to Potential Occupational Cancer Toxicity Impacts – CMR Full life cycle

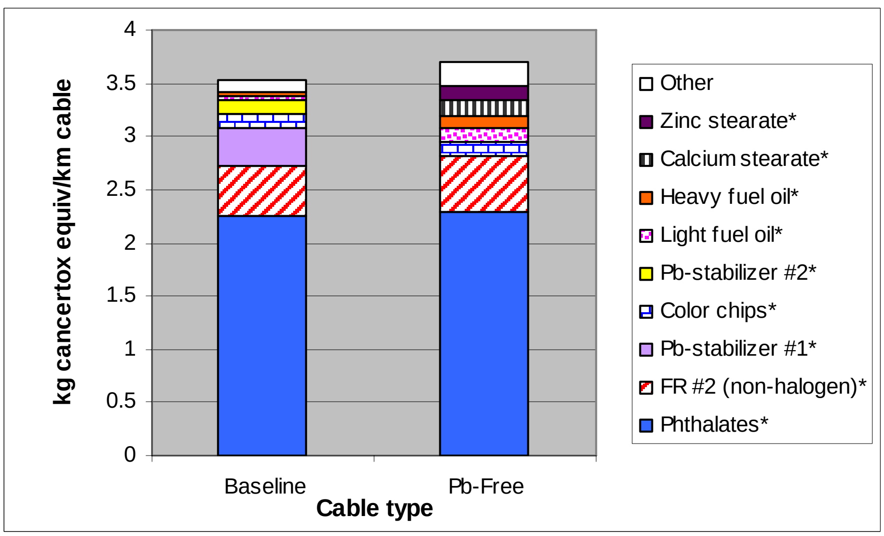

Figure 3-88. Top Contributing Flows to Potential Occupational Cancer Toxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.10.3 CMP results

Potential Occupational Non-cancer Toxicity Impacts (CMP)

The baseline cable has a 5 percent greater impact on potential occupational non-cancer toxicity than the lead-free alternative, which is shown in Figure 3-89. The top contributing process for the baseline cable and lead-free alternative is the production of natural gas (Figure 3-90). To protect confidentiality, Figure 3-90 combines the potential occupational non-cancer toxicity impacts from all upstream natural gas production. The top contributing flow for both the baseline and lead-free alternatives is natural gas (Figure 3-91). Figure 3-90 includes the processes that contribute >5 percent of the total impacts, which represent 89 and 90 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-91 includes individual flows that contribute >0.5 percent to the total impacts, and represents 98 percent of the total potential occupational non-cancer toxicity impacts for both the baseline and lead-free alternatives. As noted in Figure 3-91, natural gas was given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in insulation (FEP) production and natural gas production. As the uncertainty analysis did not take into consideration uncertainties in these processes, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the relatively small differences between the cables remained for the potential occupational non-cancer toxicity impact category (see Section 3.4).

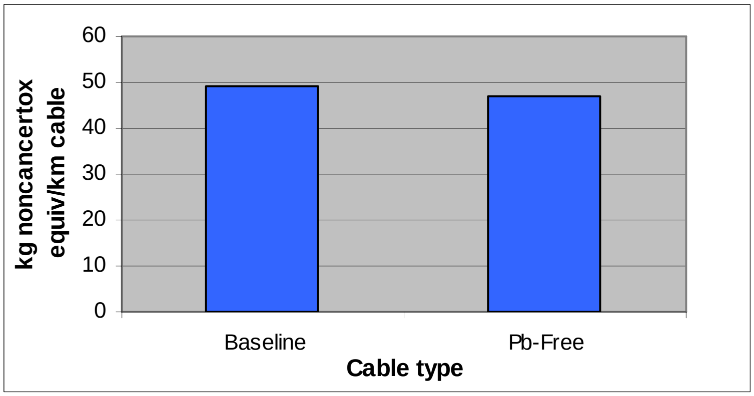

Figure 3-89. Total Potential Occupational Non-cancer Toxicity Impacts – CMP Full life cycle

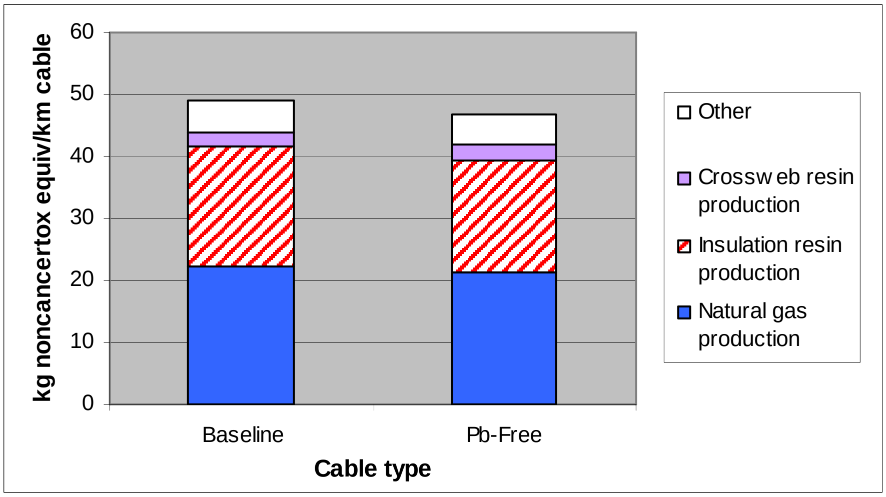

Figure 3-90. Top Contributing Processes to Potential Occupational Non-cancer Toxicity Impacts – CMP Full life cycle

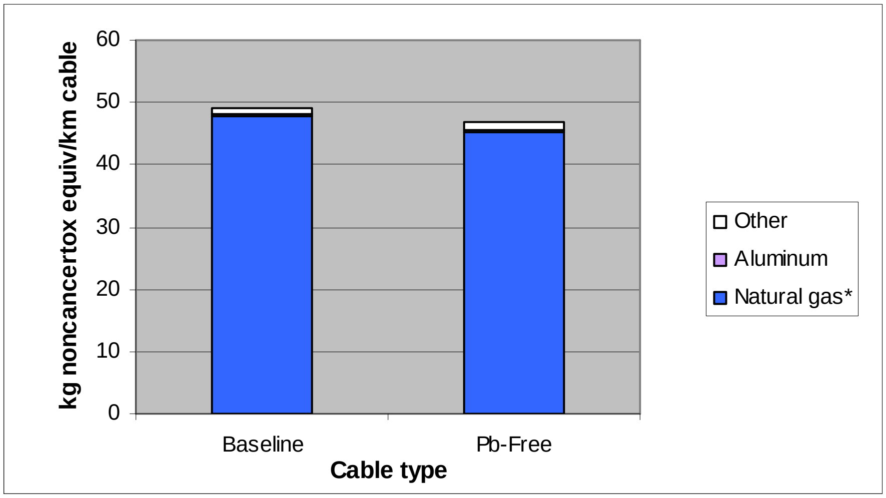

Figure 3-91. Top Contributing Flows to Potential Occupational Non-cancer Toxicity – CMP full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

Potential Occupational Cancer Toxicity Impacts (CMP)

The lead-free cable has a 3 percent greater impact on potential occupational cancer toxicity than the lead-free alternative, which is shown in Figure 3-92. The top contributing process for the baseline cable and lead-free alternative is the compounding of the cable jacketing (Figure 3-93). The top contributing flow for both the baseline and lead-free alternatives is fire retardant #3 (Figure 3-94). Figure 3-93 includes the processes that contribute >5 percent of the total impacts, which represents 96 and 91 percent of the total impact for the baseline and lead-free alternatives, respectively. Figure 3-94 includes individual flows that contribute >5 percent to the total impacts, and represents 89 and 81 percent of the total potential occupational cancer toxicity impact for the baseline and lead-free alternatives, respectively. As noted in figure 3-94, all of the material flows have been given a default hazard value due to lack of toxicological data.

The greatest contributor to occupational cancer toxicity impacts is jacketing compounding. An uncertainty analysis was conducted to address the uncertainty in extrusion and EOL data (Section 3.4). As that analysis did not take into consideration differences in jacket compounding, it was not expected to impact this finding. The uncertainty analysis showed that despite the variance of multiple model parameters, the relatively small differences between the cables remained distinguishable for the potential occupational cancer toxicity impact category (see Section 3.4). Modifications to the jacket compounding process could have the largest potential to reduce impacts for both alternatives.

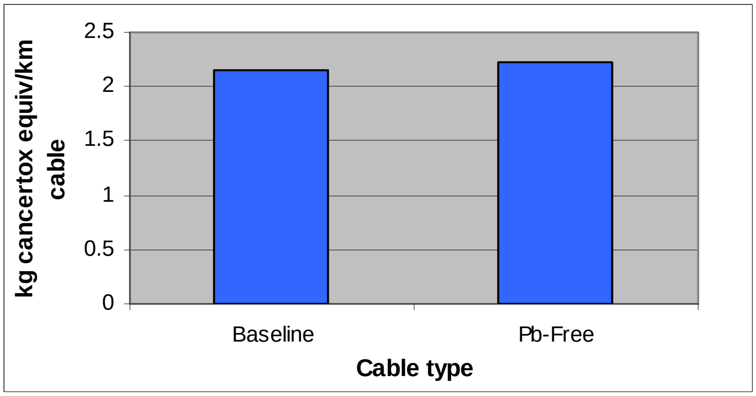

Figure 3-92. Total Potential Occupational Cancer Toxicity Impacts – CMP Full life cycle

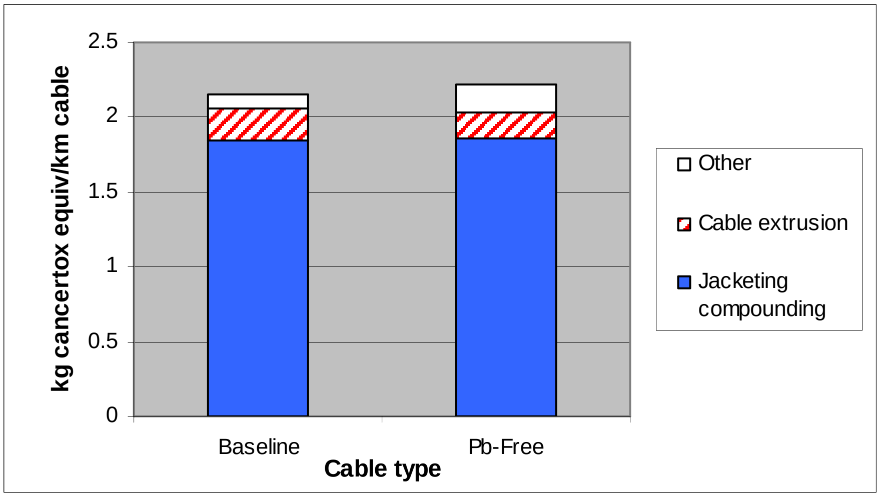

Figure 3-93. Top Contributing Processes to Potential Occupational Cancer Toxicity Impacts – CMP Full life cycle

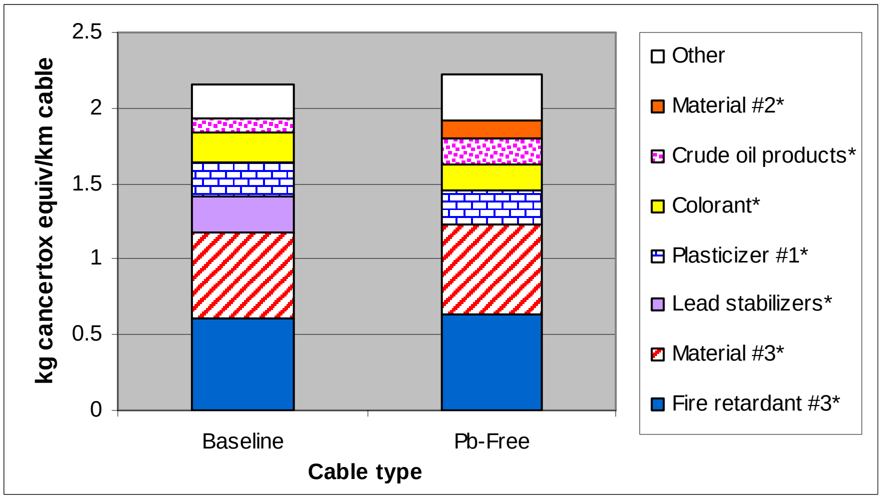

Figure 3-94. Top Contributing Flows to Potential Occupational Cancer Toxicity – CMP Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.10.4 NM-B results

Occupational Non-cancer Toxicity Impacts (NM-B)

In the NM-B cradle-to-gate analysis, the lead-free alternative generates 33 percent greater occupational non-cancer toxicity impacts than the baseline (leaded) cable, which is shown in Figure 3-95. The top contributing process is cable insulation compounding for both alternatives (Figure 3-96). Non-halogenated fire retardant #2 is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-97). Figure 3-96 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 98 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-97 includes individual flows that contribute >1 percent to the total impacts, which represent 99 and 98 percent of the total occupational non-cancer impacts for the baseline and lead-free alternatives, respectively.

The flow primarily responsible for causing the lead-free cable to have greater impacts than the baseline cable is a phthalate plasticizer. In addition, the greater amount of the non-halogenated flame retardant #2 (name withheld to protect confidentiality) contributed to greater burden on occupational toxicity for the lead-free cable. As noted in figure 3-97, some material flow has been given a default hazard value due to lack of toxicological data.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that insulation compounding contributes greatest to occupational non-cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts if insulation and plasticizers are reduced. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., non-halogenated flame retardants).

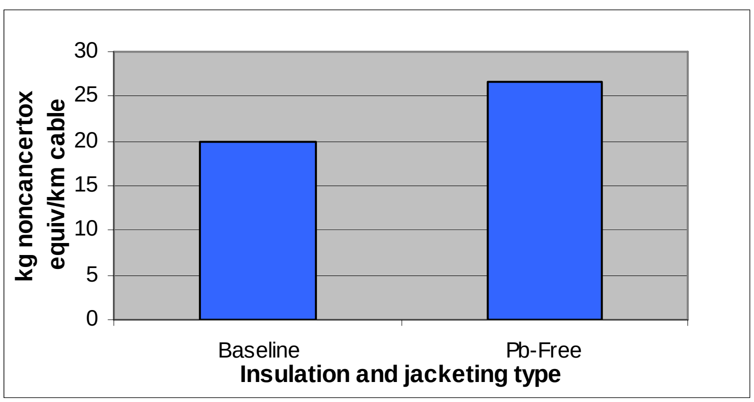

Figure 3-95. Total Potential Occupational Non-Cancer Impacts – NM-B Partial life cycle

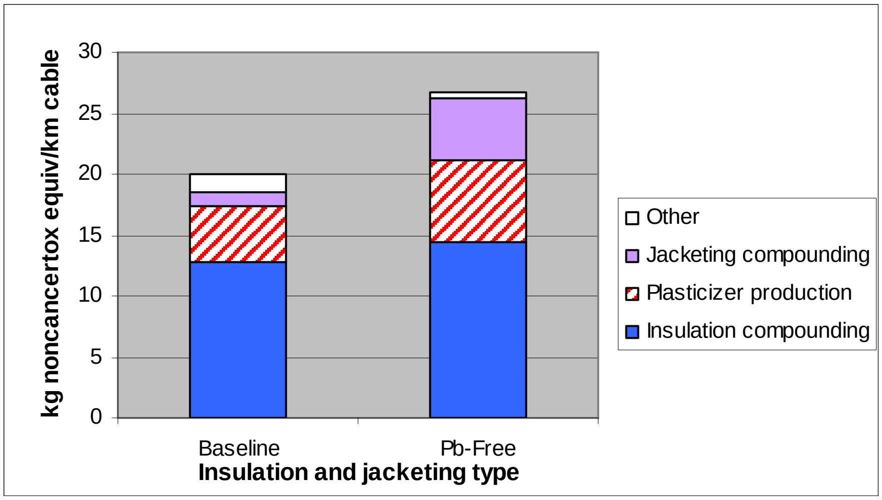

Figure 3-96. Top Contributing Processes to Potential Occupational Non-Cancer Toxicity Impacts – NM-B Partial life cycle

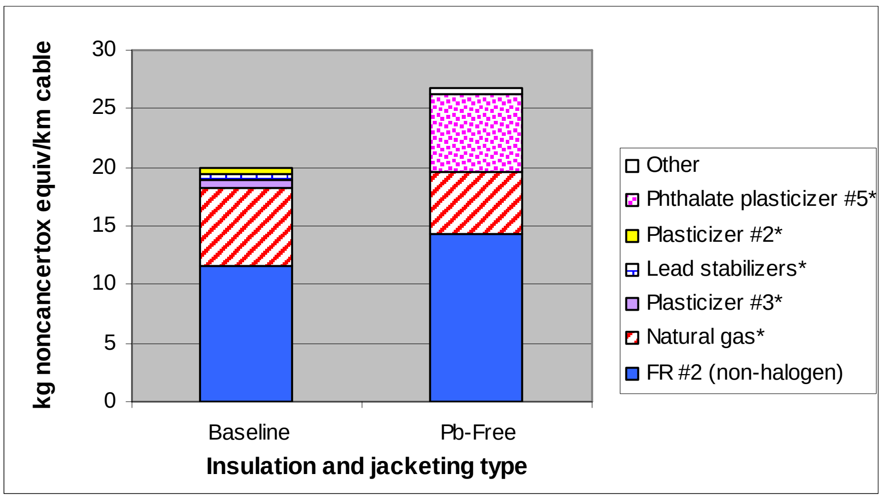

Figure 3-97. Top Contributing Flows to Potential Occupational Non-Cancer Toxicity Impacts – NM-B Partial life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

Potential Occupational Cancer Toxicity Impacts (NM-B)

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 16 percent higher potential occupational cancer toxicity impacts than the lead-free alternative, which is shown in Figure 3-98. The top contributing process is cable jacketing compounding for both alternatives (Figure 3-99). The top contributing flow for the baseline cable is plasticizer #2, and for the lead-free alternative it is phthalate plasticizer #5 (Figure 3-100). Figure 3-99 includes the processes that contribute >5 percent of the total impacts, which represent >99 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-100 includes individual flows that contribute >1 percent to the total impacts, which represent >99 and 98 percent of the total potential occupational cancer impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-100, some material flow has been given a default hazard value due to lack of toxicological data.

Care should be taken when interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that jacketing compounding contributes greatest to potential occupational cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts if electricity use is reduced. Another opportunity for reducing impacts to the greatest extent would be to focus on reducing the greatest contributing flows (i.e., plasticizers).

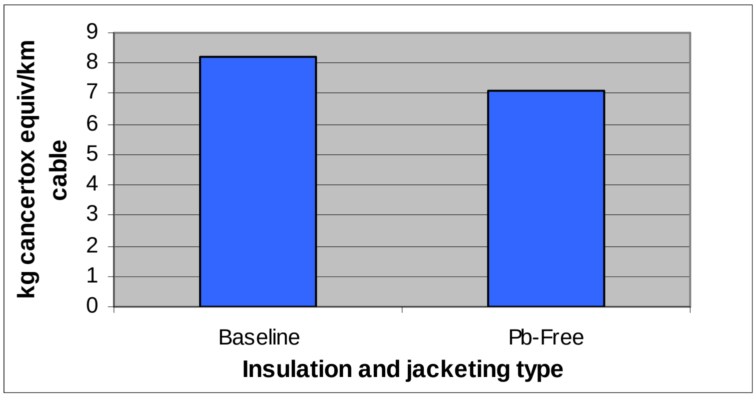

Figure 3-98. Total Potential Occupational Cancer Impacts – NM-B Partial life cycle

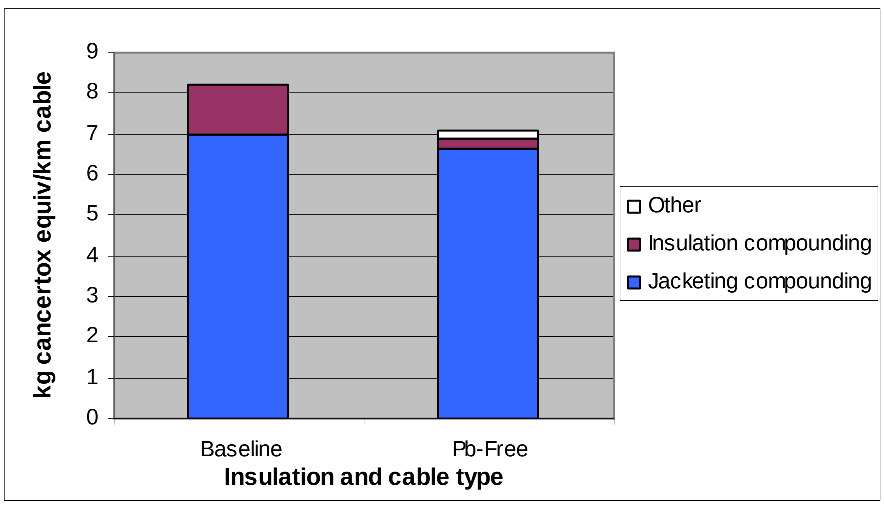

Figure 3-99. Top Contributing Processes to Potential Occupational Cancer Toxicity Impacts – NM-B Partial life cycle

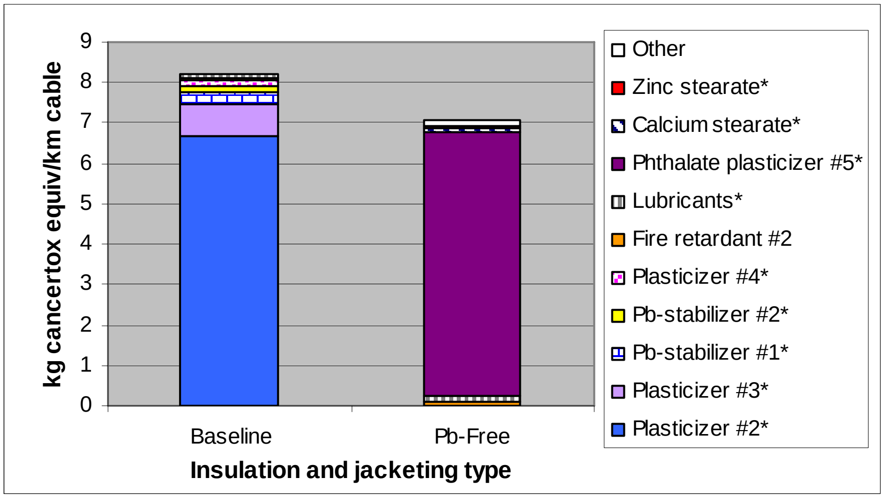

Figure 3-100. Top Contributing Flows to Potential Occupational Cancer Toxicity Impacts – NM-B Partial life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.10.5 Limitations and uncertainties

Most of the limitations and uncertainties associated with the chronic human health results presented here and in Section 3.2.12 can be grouped into three categories:

1. *Structural or modeling limitations and uncertainties* associated with the accuracy of the toxic chemical classification method and the chemical scoring approach used to characterize human health effects.
2. *Toxicity data limitations and uncertainties* associated with the availability and accuracy of toxicity data to represent potential human health effects.
3. *LCI data limitations and uncertainties* associated with the accuracy and representativeness of the inventory data.

Each of these is discussed below:

Structural or modeling limitations and uncertainties. The chemical scoring method used in the human health effects impact characterization is a screening tool to identify chemicals of potential concern, not to predict actual effects or characterize risk. A major limitation in the method is that it only measures relative toxicity combined with inventory amount. It does not take chemical fate, transportation, or degradation into account. In addition, it uses a simple surrogate value (e.g., inventory amount) to evaluate the potential for exposure, when actual exposure potential involves many more factors, some of which are chemical-specific. The LCIA method for toxicity impacts also takes the most toxic endpoint to calculate a hazard value, regardless of the route of exposure (e.g., inhalation or ingestion); therefore, this approach does not model true potential exposures, but rather the relative toxicity as compared to other chemicals, to compare life-cycle results among alloys. This is addressed further in Section 3.2.11.5 with respect to public health impacts.

Other sources of uncertainty include possible omissions by the WCP researchers in the impact classification process (e.g., potentially toxic chemicals not classified as such) or misrepresentation of chemicals in the impact characterization method itself (e.g., misrepresenting a chemical as a small contributor to total impacts, because of missing or inaccurate toxicity data). Some of these limitations and uncertainties also may be considered limits in the toxicity data which are discussed further below.

It should be noted, however, that because LCA involves analyzing many processes over the entire life cycle of a product, a comprehensive, quantitative risk assessment of each chemical input or output cannot be done. Rather, LCA develops relative impacts that often lack temporal or spatial specificity, but can be used to identify materials for more detailed evaluation.

<u>Toxicity data limitations and uncertainties</u>. Major uncertainties in the impact assessment for potentially toxic chemicals result from missing toxicity data and from limitations of the available toxicity data. Uncertainties in the human health hazard data (as typically encountered in a hazard assessment) include the following:

- Using dose-response data from laboratory animals to represent potential effects in humans.
- Using data from homogenous populations of laboratory animals or healthy human populations to represent the potential effects on the general human populations with a wide range of sensitivities.
- Using dose-response data from high dose toxicity studies to represent potential effects that may occur at low levels.
- Using data from short-term studies to represent the potential effects of long-term exposures.
- Assuming a linear dose-response relationship.
- Possibly increased or decreased toxicity resulting from chemical interactions.

Uncertainty is associated with using a default HV (i.e., assuming average toxicity for that measure when a chemical could be either more or less toxic than average) for missing toxicity data; however, the use of neutral default values for missing data reduces the bias that typically favors chemicals with little available information. Use of a data-neutral default value to fill data gaps is consistent with principles for chemical ranking and scoring (Swanson and Socha, 1997). Of the top contributing flows to the occupational *non-cancer* toxicity impacts, only a few chemicals had toxicity data (flame retardant #2, chlorine, aluminum, and plasticizer #2). All the others used the default HV of unity to represent potential relative toxicity. For the occupational *cancer* toxicity impacts, all top contributing flows represented in previous figures were based on default hazard values where no toxicity data were available (e.g., WOE classification or slope factor). Therefore, none of the top material contributors to the occupational cancer impacts that are known or suspected human carcinogens have slope factors. The occupational cancer impacts, therefore, are largely distributed among the material inputs used in the greatest quantity in the cable life cycles, but the relative carcinogenicity of these materials is uncertain.

<u>LCI data limitations and uncertainties</u>. For the CMR results, jacketing compounding followed by electricity generation (as used to fuel the manufacturing processes) were the major contributing processes to both non-cancer and cancer toxicity. The compounding process for the baseline CMR cables had the largest number of primary data sets (i.e., 3) and is believed to be of good quality. The compounding process for the lead-free CMR cables were averaged from 2 primary datasets, which are believed to be of good quality, but somewhat more limited by the smaller sample size. Any limitations resulting from selection bias (e.g., companies choosing to provide data might represent more progressive health and

environmental protection activities) would be consistent across alternatives being compared; therefore, this is not considered a large limitation.

The CMP results were mostly affected by the FEP production process, which was derived from 2 companies providing data, and are also believed to be of good quality, however, are limited by the small sample size and the fact that the dataset had different boundaries than other modeled resins. As a result of secondary dataset boundaries, PVC and HDPE were modeled as coming from ground (i.e., all inputs were mined, bulk precursors), whereas FEP was modeled with industrial chemical intermediates as inputs. This discrepancy may limit the utility of comparisons between the impacts of FEP and the other resins, especially in impact categories that utilize inputs rather than outputs (e.g., energy use). Natural gas production and electricity production (used in manufacturing processes) were the second and third greatest contributors to CMP results and used secondary data (see Section 2.1.2.6).

NM-B results were highly impacted by the compounding process and to a lesser degree the plasticizer production process. Compounding of insulation and jacketing for NM-B was based on 2 or 3 data sets (refer to Table 2-9), and are expected to be of good quality, again limited by the small sample size. The plasticizer production process was based on secondary data, which were averaged data for several plasticizers, introducing a limitation to these data.

Based on the LCIA methodology and the LCI data, the occupational non-cancer toxicity category is given an overall relative data quality rating of “medium” for all cable types, and the cancer toxicity category is given a “medium to low” since the results are primarily based on chemicals without toxicity data (and were thus given default values).

3.2.11 Public Toxicity Impacts

This section presents the LCIA characterization methodology and the LCIA results for the public human health impact category. General information that is common to all the toxicity impact categories (i.e., occupational human health, public human health, and ecological toxicity) was presented in Section 3.2.10 and is applicable to this section. For chronic public health effects, the impact scores represent surrogates for potential health effects to residents living near a facility from long-term repeated exposure to toxic or carcinogenic agents. Impact scores are calculated for both cancer and non-cancer effects, and are based on the identity and amount of toxic chemical outputs with dispositions to air, soil and water.[16] As stated previously, inventory items do not truly represent long-term exposure, instead impacts are relative toxicity weightings of the inventory.

The scores for impacts to the public differ from occupational impacts in that inventory outputs are used as opposed to inventory inputs. This basic screening level scoring does not incorporate the fate and transport of the chemicals. The public human health impact results presented in this section include two impact categories: public non-cancer impacts and public cancer impacts.

3.2.11.1 Characterization

Section 3.2.10.1 (Potential Human Health Impacts) provides a general discussion of the human health characterization approach in this LCIA. Below are the specific equations used to calculate impact scores for potential public non-cancer and cancer impacts.

---

[16] Disposition to soil includes direct, uncontained releases to soil as could occur from unregulated disposal. It does not include solid or hazardous waste disposal in a regulated landfill. Disposition to water, however, could include groundwater if a landfill model shows releases to groundwater, for example.

Potential Public Toxicity Impact Characterization: Non-cancer

The chronic public health effects impact score for non-cancer effects is calculated by:

$$(IS_{CHP\text{-}NC})_i = (HV_{NC} \times Amt_{TCoutput})_i$$

where:

$IS_{CHP\text{-}NC}$ equals the impact score for chronic non-cancer effects to the public for chemical *i* (kg non-cancertox-equivalent) per functional unit;

HV_{NC} equals the hazard value for chronic non-cancer effects for chemical *i* (based on either inhalation or oral toxicity, see Section 3.2.10.1); and

$Amt_{TC\ output}$ equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit.

More detail on the HV_{NC} is provided in Section 3.2.10.1. Accounting for the inventory and characterization methodology and data, the potential public chronic non-cancer toxicity impact category is given a "medium" data quality measure.

Potential Public Toxicity Impact Characterization: Cancer

The chronic public health effects impact score for cancer effects is calculated as follows:

$$(IS_{CHP\text{-}CA})_i = (HV_{CA} \times Amt_{TCoutput})_i$$

where:

$IS_{CHP\text{-}CA}$ equals the impact score for chronic cancer health effects to the public for chemical *i* (kg cancertox-equivalent) per functional unit;

HV_{CA} equals the hazard value for carcinogenicity for chemical *i* (based on either inhalation or oral carcinogenicity, see Section 3.2.10.1); and

$Amt_{TC\ output}$ equals the amount of toxic inventory output of chemical *i* to air, water, and soil (kg) per functional unit.

Potential public cancer toxicity is given a "medium to low" rating, given that most inventory flows contributing to potential cancer toxicity did not have cancer toxicity data, and were thus based on default hazard values.

3.2.11.2 CMR results

Potential Public Non-cancer Toxicity Impacts (CMR)

The baseline cable has a five-fold greater impact on the potential public chronic non-cancer toxicity than the lead-free alternative, which is shown in Figure 3-101. The top contributing process for the baseline cable is the landfilling of chopped waste cable, and for the lead-free alternative it is the electricity used during cable extrusion (Figure 3-102). To protect confidentiality, Figure 3-102 combines the public non-cancer toxicity impact from all upstream electricity generation. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is sulfur dioxide (Figure 3-103). Figure 3-102 includes the processes that contribute >5 percent of the total impacts, which represent 97 and 93 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-103 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 99 percent of the total potential public non-cancer toxicity impacts for the baseline and lead-free alternatives, respectively.

The overall differences between the cables are primarily a function of the differences in composition: The use of lead in the baseline cable potentially increases the public non-cancer risk substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential public non-cancer toxicity impact category (see Section 3.4).

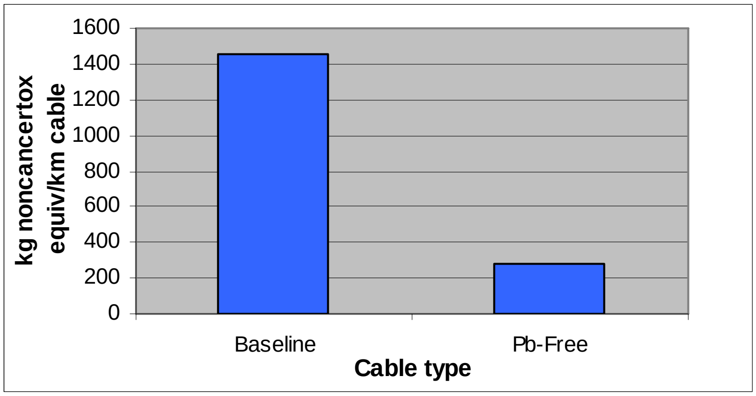

Figure 3-101. Total Potential Public Non-cancer Toxicity Impacts – CMR Full life cycle

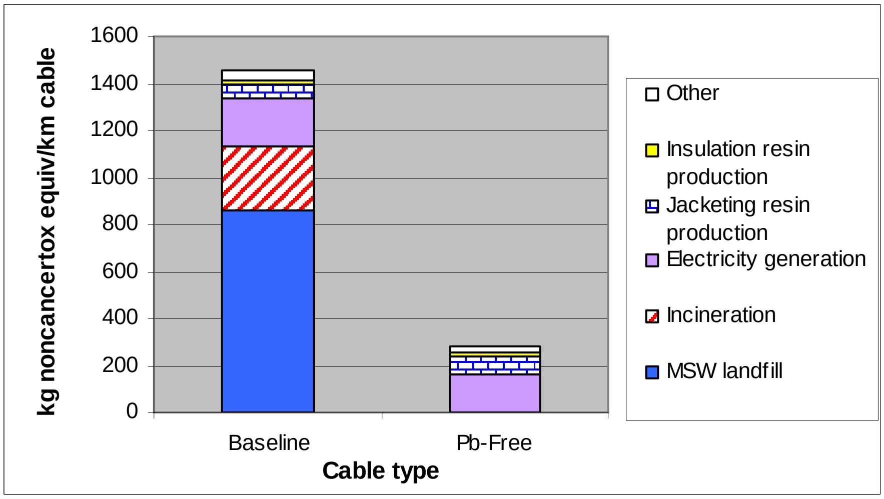

Figure 3-102. Top Contributing Processes to Potential Public Non-Cancer Toxicity Impacts – CMR Full life cycle

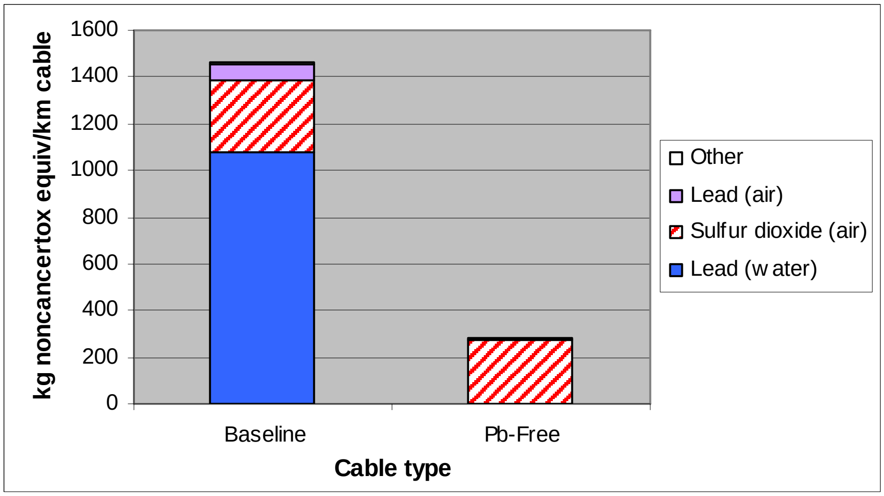

Figure 3-103. Top Contributing Flows to Potential Public Non-Cancer Toxicity Impacts – CMR Full life cycle

Potential Public Cancer Toxicity Impacts (CMR)

The lead-free alternative has a 1 percent greater impact on the potential public cancer toxicity than the baseline cable, which is shown in Figure 3-104. The top contributing process for the baseline cable is the landfilling of chopped waste cable, and for the lead-free alternative it is the production of jacketing resin (Figure 3-105). To protect confidentiality, Figure 3-105 combines the public cancer toxicity impact from all upstream electricity generation. The top contributing flow for the baseline cable and the lead-free alternative is methane (Figure 3-106). Figure 3-105 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 93 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-106 includes individual flows that contribute >1 percent to the total impacts and represents 97 percent of the total potential public cancer toxicity impacts for both the baseline and lead-free alternatives. As noted in figure 3-106, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are a result of a number of factors including energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the potential public cancer toxicity impact category (see Section 3.4).

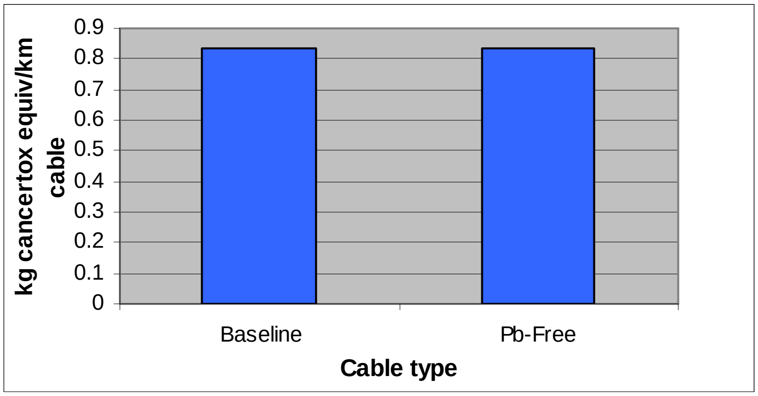

Figure 3-104. Total Potential Public Cancer Toxicity Impacts – CMR Full life cycle

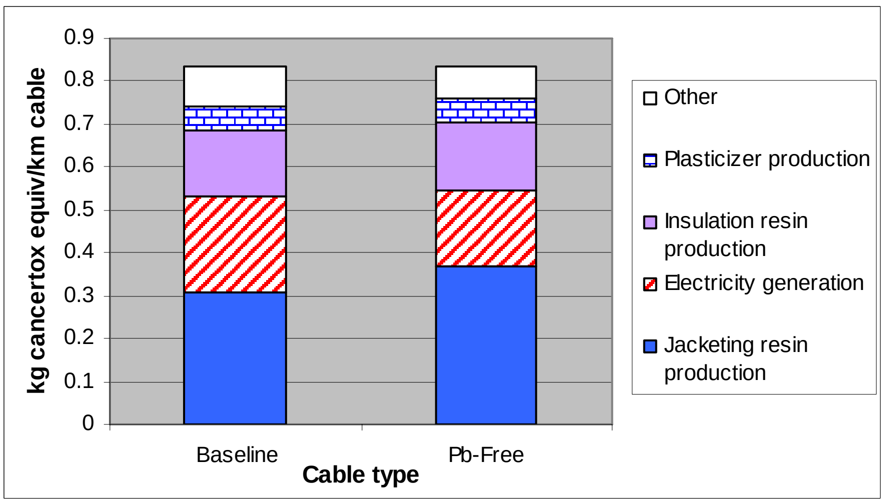

Figure 3-105. Top Contributing Processes to Potential Public Cancer Toxicity Impacts – CMR Full life cycle

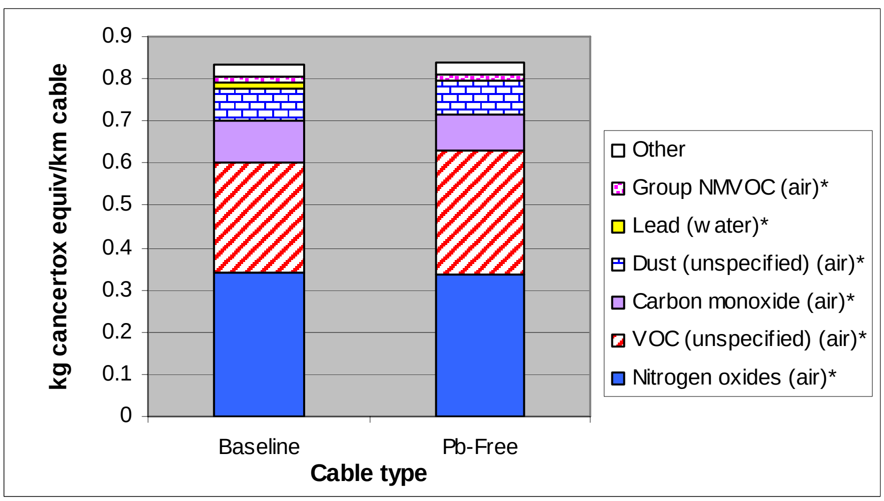

Figure 3-106. Top Contributing Flows to Potential Public Cancer Toxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.11.3 CMP results

Potential Public Non-cancer Toxicity Impacts (CMP)

The baseline cable has an approximately 2.5-fold greater impact on the potential public chronic non-cancer toxicity as the lead-free alternative, which is shown in Figure 3-107. The top contributing process for the baseline cable is the landfilling of chopped waste cable, and for the lead-free alternative it is the electricity used during cable extrusion (Figure 3-108). To protect confidentiality, Figure 3-108 combines the public non-cancer toxicity from all upstream electricity generation and natural gas production. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is sulfur dioxide (Figure 3-109). Figure 3-108 includes the processes that contribute >5 percent of the total impacts, which represents 97 percent of the total impact for both the baseline and lead-free alternatives. Figure 3-109 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 99 percent of the total potential public non-cancer toxicity impacts for the baseline and lead-free alternatives, respectively.

The overall differences between the cables are primarily a function of the differences in composition. The use of lead in the baseline cable potentially increases the public non-cancer risk substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential public non-cancer toxicity impact category (see Section 3.4).

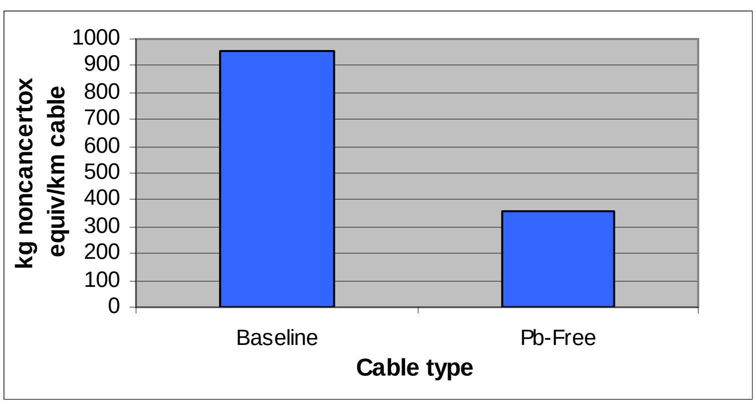

Figure 3-107. Total Potential Public Non-cancer Toxicity Impacts – CMP Full life cycle

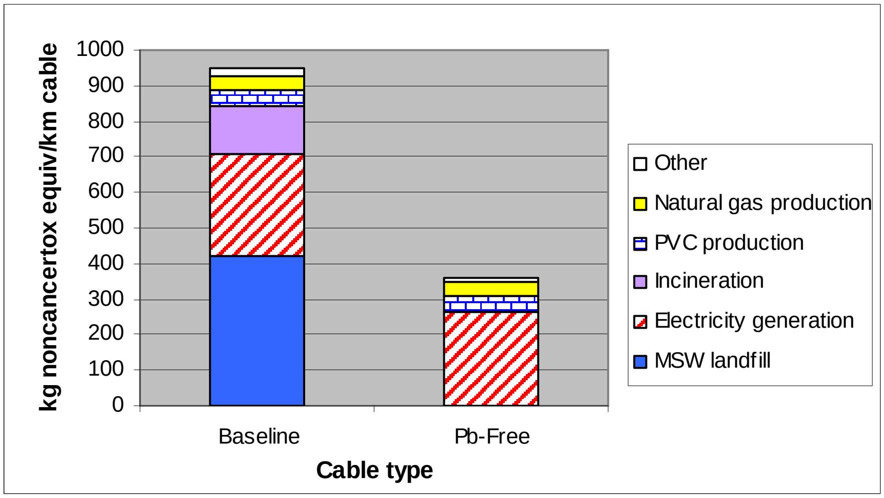

Figure 3-108. Top Contributing Processes to Potential Public Non-cancer Toxicity Impacts – CMP Full life cycle

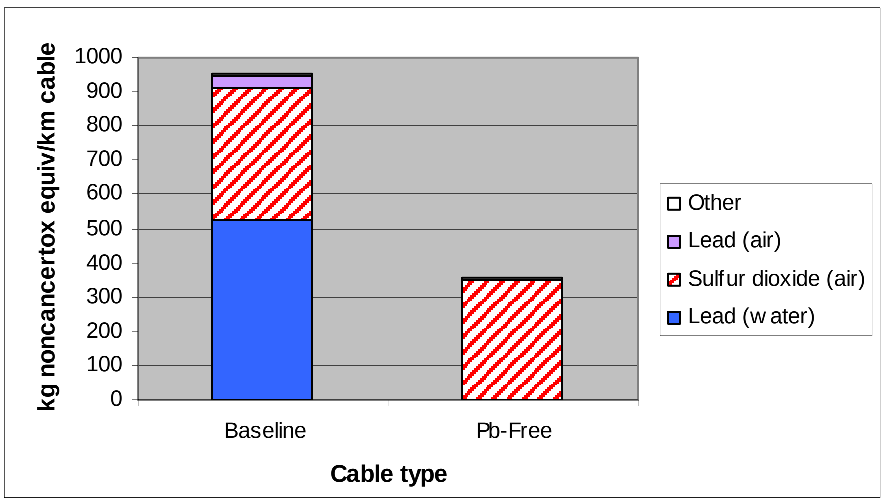

Figure 3-109. Top Contributing Flows to Potential Public Non-Cancer Toxicity Impacts – CMP Full life cycle

Potential Public Cancer Toxicity Impacts (CMP)

The baseline cable has a 5 percent greater impact on the potential public cancer toxicity than the lead-free alternative, which is shown in Figure 3-110. The top contributing process for the baseline cable and lead-free alternative is the generation of electricity for cable extrusion (Figure 3-111). To protect confidentiality, Figure 3-111 combines the public cancer toxicity impacts from all upstream electricity generation. The top contributing flow for both alternatives is nitrogen oxides (NO_x) (Figure 3-112). Figure 3-111 includes the processes that contribute >5 percent of the total impacts, which represent 85 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-112 includes individual flows that contribute >1 percent to the total impacts and represents 93 and 94 percent of the total potential public cancer toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-112, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in energy use. Due to the uncertainty associated with the extrusion energy inventory data (see Section 2.2.4), an uncertainty analysis was conducted which showed that by varying the extrusion energy across the range of primary data obtained, the differences between the cables was not greatly distinguishable for the potential public cancer toxicity impact category (see Section 3.4).

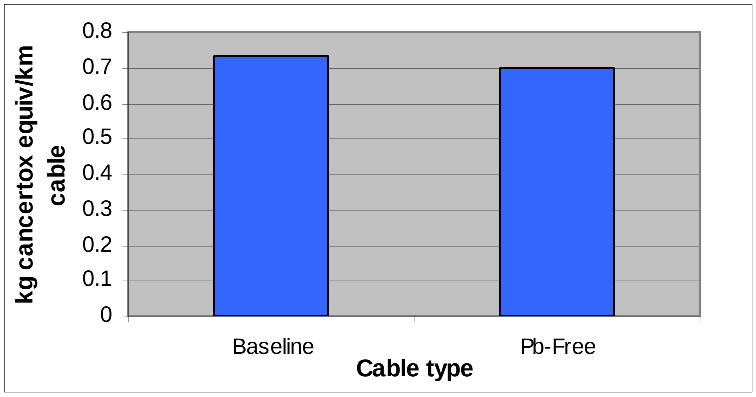

Figure 3-110. Total Potential Public Cancer Toxicity Impacts – CMP Full life cycle

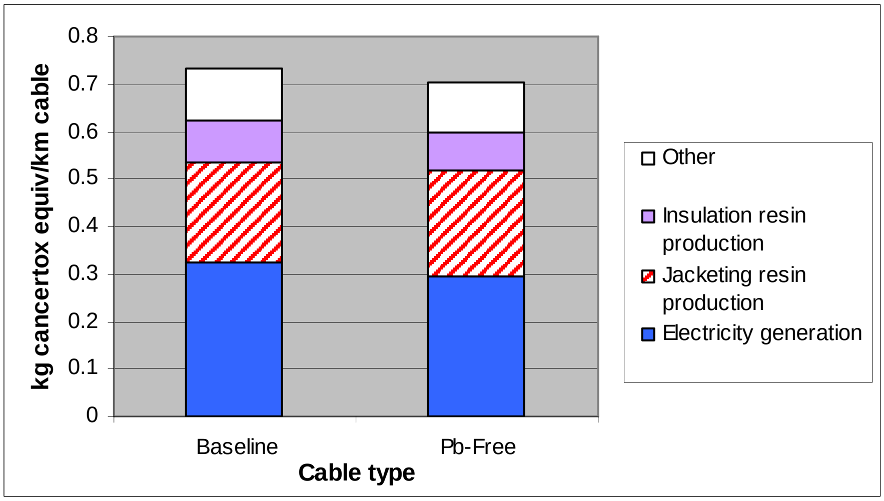

Figure 3-111. Top Contributing Processes to Potential Public Cancer Toxicity Impacts – CMP Full life cycle

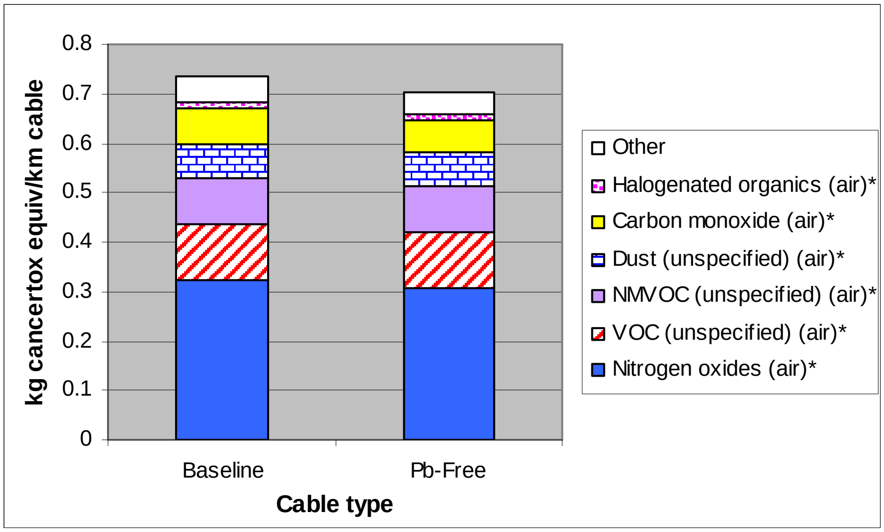

Figure 3-112. Top Contributing Flows to Potential Public Cancer Toxicity Impacts – CMP Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.11.4 NM-B results

Potential Public Non-cancer Toxicity Impacts (NM-B)

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 11 percent higher potential public chronic non-cancer toxicity impacts than the lead-free alternative, which is shown in Figure 3-113. The top contributing process is jacketing resin production for both alternatives (Figure 3-114) and sulfur dioxide is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-115). Figure 3-114 includes the processes that contribute >5 percent of the total impacts, which represent 92 and 99 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-115 includes individual flows that contribute >1 percent to the total impacts, which represent 98 and 99 percent of the total potential public non-cancer impacts for the baseline and lead-free alternatives, respectively.

Of note is that the impacts for both the leaded and lead-free constructions are driven by sulfur dioxide, which is in contrast to the CMR and CMP results, which included EOL. When EOL was included, the leaded cables had much greater burdens due to lead released to the environment primarily at the EOL stage. Therefore, it is likely that if the full life cycle were considered for NM-B these results would be driven by other processes and chemicals. Since we expect EOL to be a large driver of impacts to this category, the potential public non-cancer toxicity category for NM-B is given a "medium-to-low" quality rating (ratings are summarized in Chapter 4, Table 4-6).

As alluded to, care should be taken in interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to potential public non-cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of PVC used. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to this category to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce sulfur dioxide emissions).

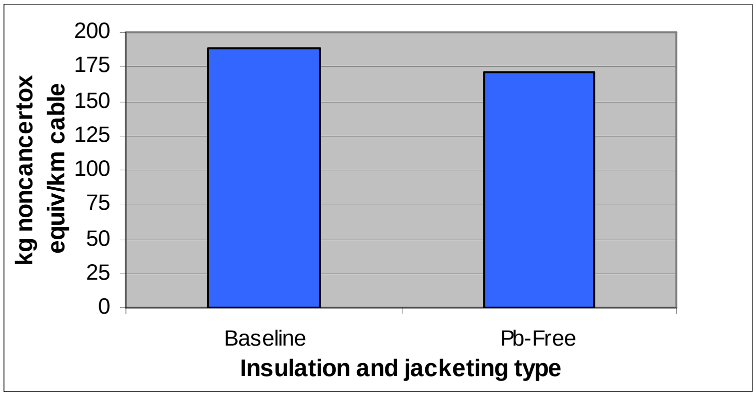

Figure 3-113. Total Potential Public Non-Cancer Toxicity Impacts – NM-B Partial life cycle

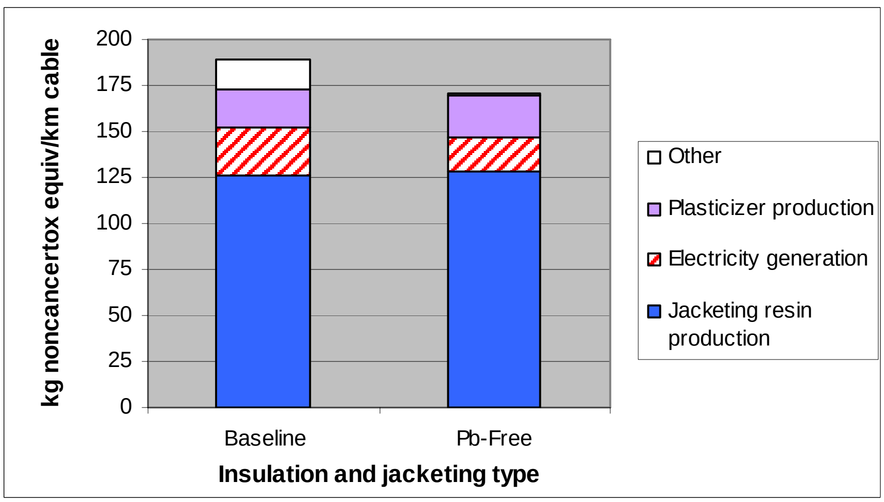

Figure 3-114. Top Contributing Processes to Potential Public Non-Cancer Toxicity Impacts – NM-B Partial life cycle

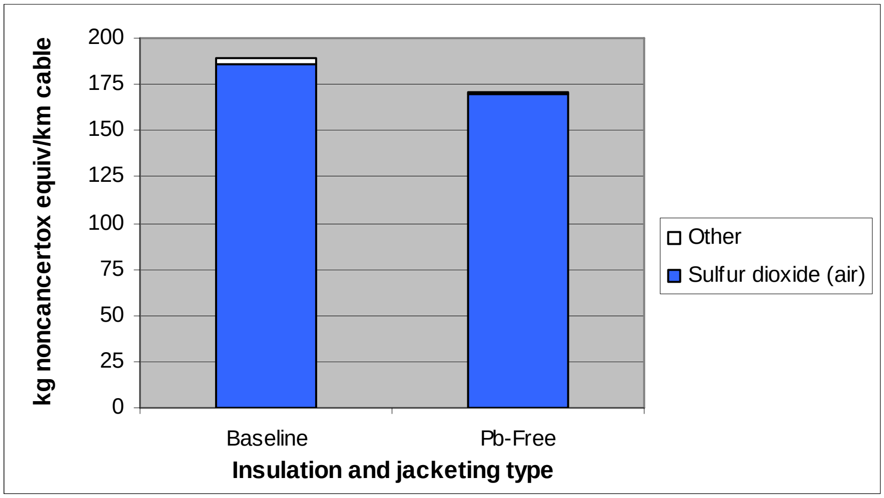

Figure 3-115. Top Contributing Flows to Potential Public Non-Cancer Toxicity Impacts – NM-B Partial life cycle

Potential Public Cancer Toxicity Impacts (NM-B)

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 4 percent higher potential public cancer toxicity impacts than the lead-free alternative, which is shown in Figure 3-116. The top contributing process is the PVC jacketing resin production for both alternatives (Figure 3-117). Nitrogen oxides (NO_x) is the greatest individual flow contributing to the impact of the baseline cable, and unspecified volatile organic compounds (VOCs) are the greatest individual flow contributing to the impact of the lead-free alternative (Figure 3-118). Figure 3-117 includes the processes that contribute >5 percent of the total impacts, which represent 96 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-118 includes individual flows that contribute >1 percent to the total impacts, which represent 96 and 98 percent of the total potential public cancer impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-118, some material flow has been given a default hazard value due to lack of toxicological data.

Care should be taken in interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that PVC jacketing resin production contributes greatest to potential public cancer toxicity impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of PVC used. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to this category to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce nitrogen oxide emissions). It should also be noted that the output flows contributing to the potential public cancer toxicity category are not any known carcinogens. Chemicals lacking data on carcinogenicity remain in the analysis as potential carcinogens.

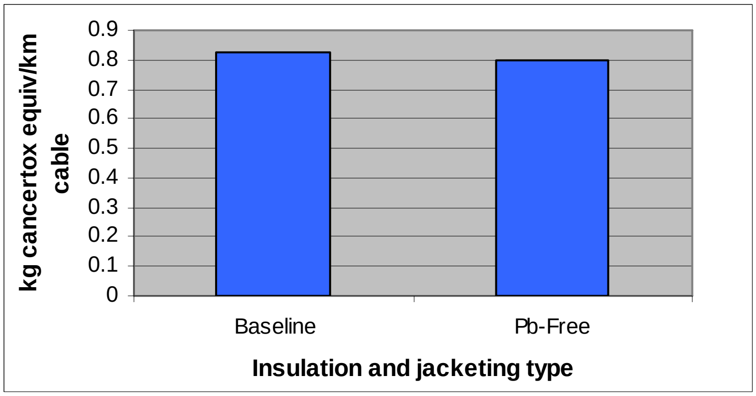

Figure 3-116. Total Potential Public Cancer Toxicity Impacts – NM-B Partial life cycle

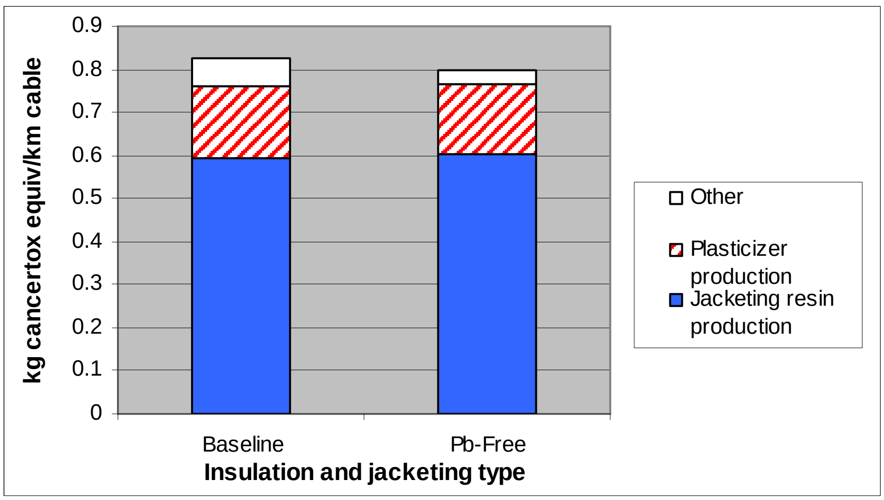

Figure 3-117. Top Contributing Processes to Potential Public Cancer Toxicity Impacts – NM-B Partial life cycle

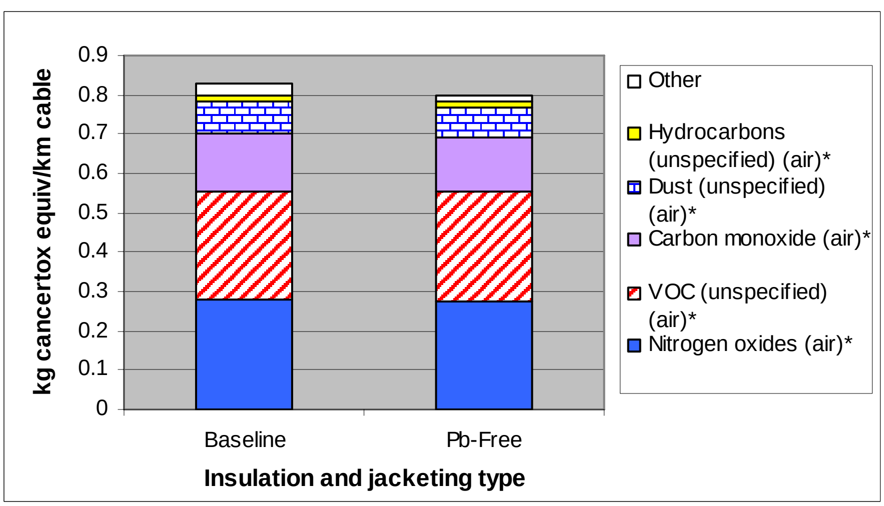

Figure 3-118. Top Contributing Flows to Potential Public Cancer Toxicity Impacts – NM-B Partial life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.11.5 Limitations and uncertainties

This section summarizes the limitations and uncertainties associated with public non-cancer and cancer health impacts. The public health LCIA limitations and uncertainties that address (1) structural or modeling limitations and (2) toxicity data limitations, are identical to those for occupational health impacts. For a detailed discussion, refer to Section 3.2.10.5. For example, much of the public *cancer* impact results are driven by a lack of toxicity data, rather than known carcinogenic hazards. Of the top contributing flows to the public *non-cancer* toxicity impacts presented in preceding figures, all the chemicals had HVs based on available toxicity data. For the occupational *cancer* toxicity impacts, all top contributing flows except for lead (in CMR public cancer toxicity results) were based on default hazard values where no toxicity data were available (e.g., WOE classification or slope factor). Therefore, most of the public cancer impacts are based on materials that lack data on their carcinogenicity, and similar to the occupational impact results, the public cancer impacts are largely distributed among the material inputs used in the greatest quantity in the cable life cycles, but the relative carcinogenicity of these materials is uncertain.

The LCI data limitations for public health impacts in many cases are similar to those described in Section 3.2.10.5. LCI data limitations pertinent to public health impacts are summarized below.

For the CMR and CMP results, the baseline results were driven by landfilling (e.g., lead leaching from the landfill), followed by incineration and then electricity production (for manufacturing processes). The impacts from the lead-free alternative, however, were driven by the electricity production. There is uncertainty in the leachate estimate used in the analysis, which was therefore varied in the multivariate uncertainty analysis (Section 3.4). As the uncertainty analysis revealed, a significant difference between the alternatives is likely, even given the defined range of uncertainty (see Section 3.4). Since the landfill leachate data were an important aspect of the public toxicity impacts, further refinement of the potential exposure, through more sophisticated exposure analysis and fate and transport analysis, as well as leachability studies, are warranted. In addition to lead output uncertainties, there are EOL uncertainties related to the assumptions about EOL dispositions (e.g., 4 percent of cables go directly to landfilling, and 73 percent go to landfilling after chopping for copper recovery). This is discussed in greater detail in Chapter 2. For incineration, secondary literature was used to estimate outputs and additional secondary sources were reviewed to make assumptions about lead releases and partitioning to various environmental media, which introduces uncertainty into the incineration outputs.

The NM-B analysis, which did not include EOL modeling were driven by PVC production for both non-cancer and cancer toxicity impacts. As explained in previous sections, PVC production data are secondary data. It is also important to note that the secondary data set that was used for this process does not include any vinyl chloride monomer inputs or outputs. As discussed in Chapter 1, vinyl chloride is a known carcinogen. Given that there is potential occupational exposure to the vinyl chloride monomer during production, and potential public exposure from any environmental releases of the monomer, the cancer impact results are further limited. Therefore, the differences in PVC use across alternatives could drive cancer impacts in the same direction. Because PVC production was a large contributor to NM-B results, the M-B results would likely be affected to the greatest extent. However, CMR and CMP results would also be affected as PVC is used in both of these cables as well.

As lead released to water (via landfill leaching) is a large proportion of impacts, further investigation into the hazard and exposure to lead from landfills is warranted. And although lead-free constructions are gaining market share, further investigation into the exposure and risk from landfill disposal is important to address existing leaded-cables that have not yet reached their end-of-life dispositions.

Based on the LCIA methodology and the LCI data, the public non-cancer toxicity category is given an overall relative data quality rating of “medium” for all cable types, and the cancer toxicity category is given a “medium to low” rating since the results are primarily based on chemicals without toxicity data (and were thus given default values), and there is no consideration for vinyl chloride in the PVC production process.

3.2.12 Potential Aquatic Ecotoxicity Impacts

3.2.12.1 Characterization

Ecotoxicity refers to effects of chemical outputs on non-human living organisms. Impact categories could include both ecotoxicity impacts to aquatic and terrestrial ecosystems. The method for calculating terrestrial toxicity, however, would be the same as for the chronic, non-cancer public toxicity impacts described above, which is based on mammalian toxicity data. As the relative ranking approach of the LCIA toxicity method does not modify the toxicity data for different species or for fate and transport, both human and terrestrial LCIA impacts are the same; therefore, only aquatic toxicity, which uses a different methodology, is presented below.

Toxicity measures for fish are used to represent potential adverse effects to organisms living in the aquatic environment from exposure to a toxic chemical. Impact scores are based on the identity and amount of toxic chemicals as outputs to surface water. Impact characterization is based on CHEMS-1 acute and chronic hazard values for fish (Swanson *et al.*, 1997) combined with the inventory amount. Both acute and chronic impacts comprise the aquatic ecotoxicity term. The HVs for acute and chronic toxicity are based on LC_{50} (the lethal concentration to 50 percent of the exposed fish population) and NOEL (no-observed-effect level) (or NOEC [no-observed-effect concentration]) toxicity data, respectively, mostly from toxicity tests in fathead minnows (Pimephales promelas) (Swanson *et al.*, 1997). The acute fish HV is calculated by:

$$(HV_{FA})_i = \frac{1/(LC_{50})_i}{1/(LC_{50})_{mean}}$$

where:

HV_{FA} equals the hazard value for acute fish toxicity for chemical *i* (unitless);

LC_{50} equals the lethal concentration to 50 percent of the exposed fish population for chemical *i*; and

$LC_{50\,mean}$ equals the geometric mean LC_{50} of available fish LC_{50} values in Appendix E (mg/L).

The chronic fish HV is calculated by:

$$(HV_{FC})_i = \frac{1/\ NOEL_i}{1/\ NOEL_{mean}}$$

where:

HV_{FC}	equals the hazard value for chronic fish toxicity for chemical *i*;
NOEL	equals the no-observed-effect level for fish for chemical *i*; and
$NOEL_{mean}$	equals the geometric mean NOEL of available fish NOEL values in Appendix E (mg/L).

For chemicals that do not have chronic fish toxicity data available, but do have LC_{50} data, the LC_{50} and the log K_{ow} of the chemical are used to estimate the NOEL. Based on studies comparing the LC_{50} to the NOEL (Kenega, 1982; Jones and Schultz, 1995, and Call *et al.*, 1985) as reported in Swanson *et al.* (1997), NOEL values for organic chemicals within a certain range of log K_{ow} values are calculated using the following continuous linear function:

For organics with 2 # log K_{ow} < 5:

$$NOEL = LC_{50}/(5.3 \, x \log K_{ow} - 6.6)$$

Organic chemicals with high log K_{ow} values (i.e., greater than 5) are generally more toxic to fish and are not expected to follow a continuous linear function with K_{ow}, thus, they are estimated directly from the LC_{50}. In addition, inorganic chemicals are poorly fat soluble and their fish toxicity does not correlate to log K_{ow}. The NOEL values of the inorganic chemicals were, therefore, also based on the fish LC_{50} values.

For inorganics or organics with log K_{ow} ∃5:

$$NOEL = 0.05 \, x \, (LC_{50})$$

For organics with log K_{ow}<2, which are poorly fat soluble but assumed to have a higher NOEL value than those with higher K_{ow} values or than inorganics, the NOEL is estimated as follows:

For organics with log K_{ow} <2:

$$NOEL = 0.25 \, x \, (LC_{50})$$

Once the HVs are calculated, whether from NOEL data or estimated from the LC_{50} and the K_{ow}, the aquatic toxicity impact score is calculated as follows:

$$(IS_{AQ})_i = [(HV_{FA} + HV_{FC}) \, x \, Amt_{TCoutput,water}]_i$$

Accounting for the inventory and the characterization method, we have assigned a “medium” data quality measure for the aquatic ecotoxicity impact category results.

3.2.12.2 CMR results

The baseline cable has an approximately 150-fold greater impact on the potential aquatic toxicity than the lead-free alternative, which is shown in Figure 3-119. The top contributing process for the baseline cable is the landfilling of chopped cable, and for the lead-free alternative it is the generation of electricity for cable extrusion (Figure 3-120). To protect confidentiality, Figure 3-120 combines the aquatic toxicity impact from all upstream electricity generation. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is dissolved chlorine (Figure 3-121). Figure 3-120 includes the processes that contribute >5 percent of the total impacts, which represent 99 and 91 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-121 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 97 percent of the total potential aquatic toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-121, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in composition. The use of lead in the baseline cable potentially increases the aquatic toxicity impact substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential aquatic toxicity impact category (see Section 3.4).

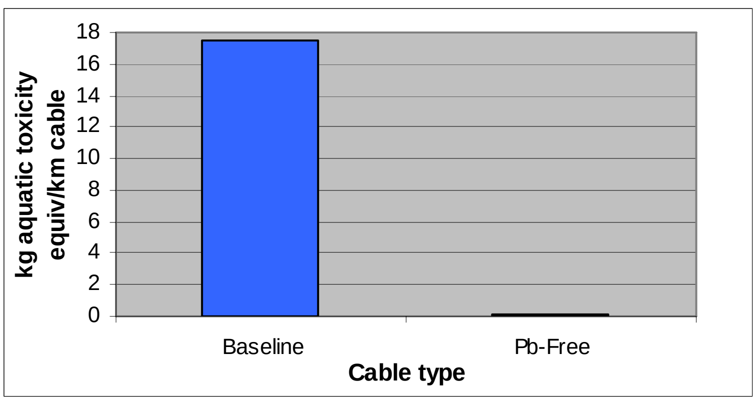

Figure 3-119. Total Potential Aquatic Ecotoxicity Impacts – CMR Full life cycle

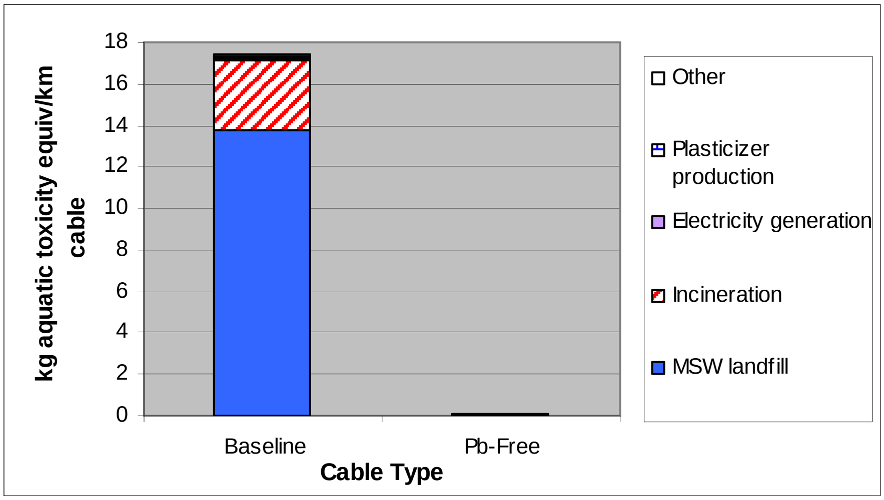

Figure 3-120. Top Contributing Processes to Potential Aquatic Ecotoxicity Impacts – CMR Full life cycle

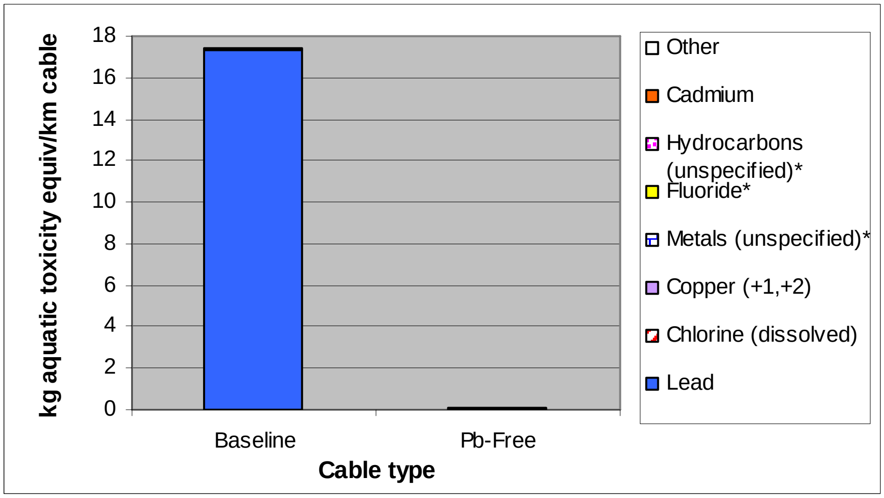

Figure 3-121. Top Contributing Flows to Potential Aquatic Ecotoxicity Impacts – CMR Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.12.3 CMP results

The baseline cable has an approximately 55-fold greater impact on the potential aquatic toxicity than the lead-free alternative, which is shown in Figure 3-122. The top contributing process for the baseline cable is the landfilling of chopped cable, and for the lead-free alternative it is the generation of electricity for cable extrusion (Figure 3-123). To protect confidentiality, Figure 3-123 combines the aquatic toxicity impacts from all upstream electricity generation. The top contributing flow for the baseline cable is leached lead, and for the lead-free alternative it is dissolved chlorine (Figure 3-124). Figure 2-123 includes the processes that contribute >5 percent of the total impacts, which represent 99 and 94 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 3-124 includes individual flows that contribute >1 percent to the total impacts and represents >99 and 96 percent of the total potential aquatic toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in figure 3-124, some material flow has been given a default hazard value due to lack of toxicological data.

The overall differences between the cables are primarily a function of the differences in composition. The use of lead in the baseline cable potentially increases the aquatic toxicity impact substantially. Due to the uncertainty associated with the leaching of lead from landfills (see Section 2.4.5.2), an uncertainty analysis was conducted which showed that by varying the proportion of leachate released into the environment, the differences between the cables was still substantial for the potential aquatic toxicity impact category (see Section 3.4).

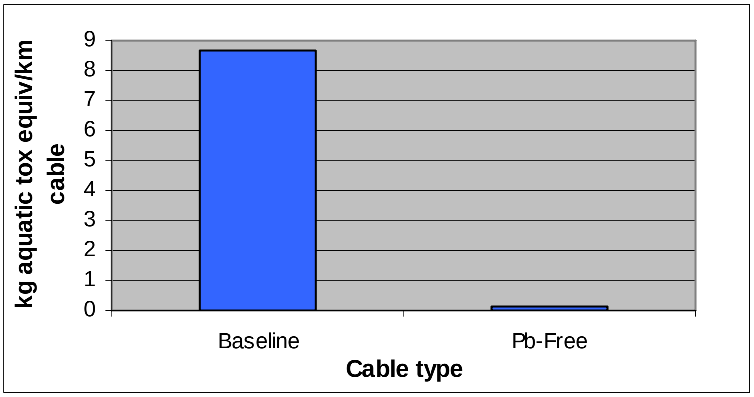

Figure 3-122. Total Potential Ecotoxicity Impacts – CMP Full life cycle

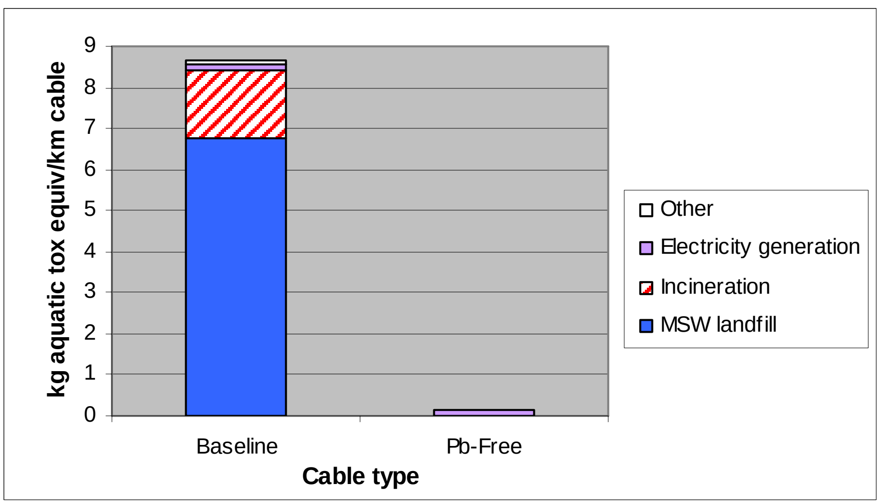

Figure 3-123. Top Contributing Processes to Potential Aquatic Ecotoxicity Impacts – CMP full life cycle

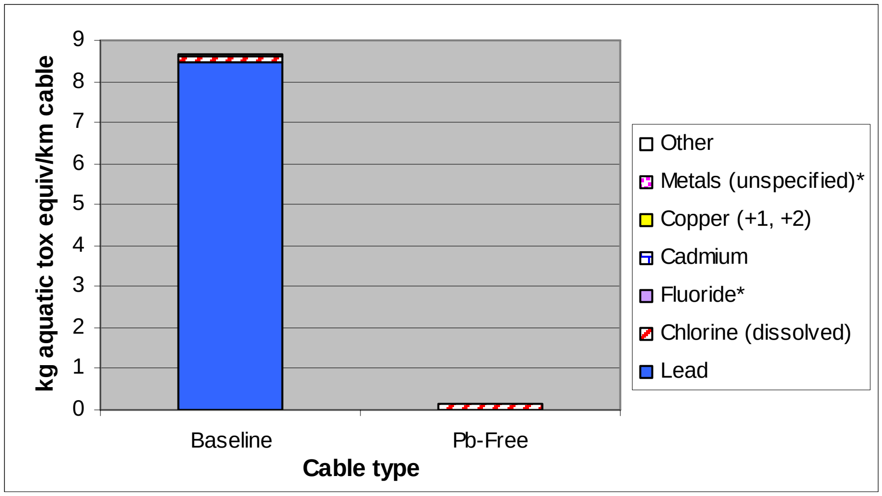

Figure 3-124. Top Contributing Flows to Potential Aquatic Ecotoxicity Impacts – CMP Full life cycle

* Material flow has been given a default hazard value due to lack of toxicological data

3.2.12.4 NM-B results

In the NM-B cradle-to-gate analysis, the baseline (leaded) cable generates 43 percent higher potential aquatic toxicity impacts than the lead-free alternative, which is shown in Figure 3-125. The top contributing process is phthalate plasticizer production for both alternatives (Figure 3-126) and copper (1+, 2+) is the greatest individual flow contributing to the impacts for both alternatives (Figure 3-127). Figure 3-126 includes the processes that contribute >5 percent of the total impacts, which represent 96 percent of the total impacts for both the baseline and lead-free alternatives. Figure 3-127 includes individual flows that contribute >1 percent to the total impacts, which represent 99 and 98 percent of the total potential aquatic toxicity impacts for the baseline and lead-free alternatives, respectively. As noted in Figure 3-127, some material flow has been given a default hazard value due to lack of toxicological data.

Of note is that the impacts for both the leaded and lead-free constructions are driven by plasticizer production process, and the top contributing flow was copper ions. This is in contrast to the CMR and CMP results, which included EOL. When EOL was included, the leaded telecommunication cables had much greater burdens due to lead released to the environment primarily at the EOL stage. Therefore, it is likely that if the full life cycle were considered for NM-B these results would be driven by other processes and chemicals. Since we expect EOL to be a large driver of impacts to this category, the potential aquatic ecotoxicity category for NM-B is given a “medium-to-low” quality rating (ratings are summarized in Chapter 4, Table 4-6).

As alluded to, care should be taken in interpreting these results, as they do not represent the full life-cycle impacts. Nonetheless, when focusing on insulation and jacket compounding and the associated upstream processes for NM-B cables, understanding that phthalate production contributes greatest to potential aquatic ecotoxicity impacts for both alternatives could provide the opportunity to reduce these impacts by reducing the amount of phthalates used. However, any substituted material would need to be examined for tradeoffs in the other impact categories. Another opportunity for reducing impacts to this category to the greatest extent would be to focus on reducing the greatest contributing flow (i.e., reduce copper emissions).

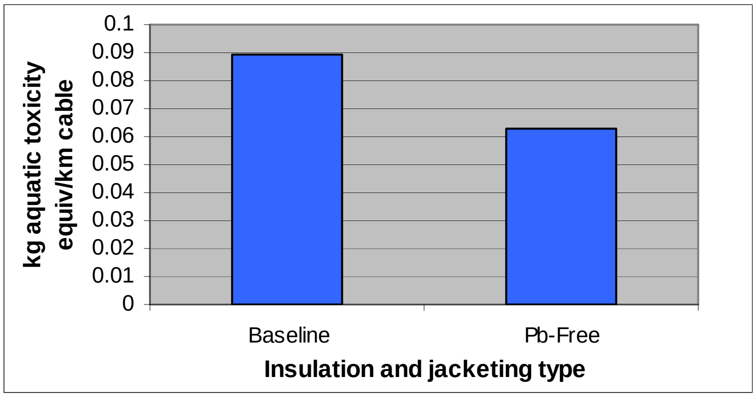

Figure 3-125. Total Potential Aquatic Ecotoxocity Impacts – NM-B Partial life cycle

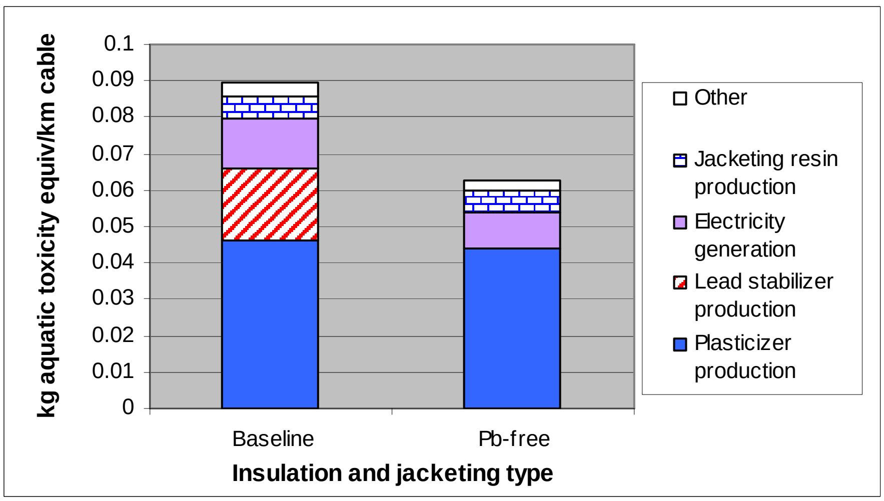

Figure 3-126. Top Contributing Processes to Potential Aquatic Ecotoxicity Impacts – NM-B Partial life cycle

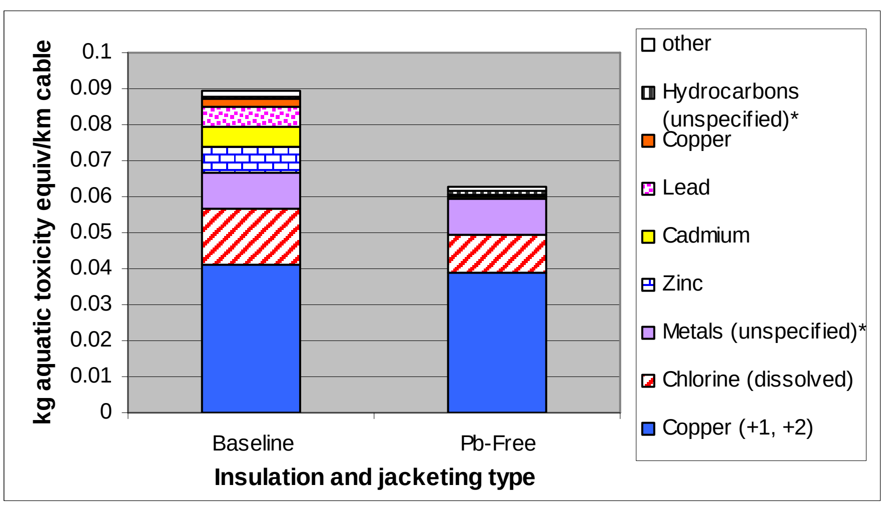

Figure 3-127. Top Contributing Flows to Potential Aquatic Ecotoxicity Impacts – NM-B Partial life cycle
* Material flow has been given a default hazard value due to lack of toxicological data

3.2.12.5 Limitations and uncertainties

The LCIA methodology for potential aquatic ecotoxicity impacts is subject to the same structural or modeling limitations and toxicity data limitations discussed previously for the occupational and public health impact categories. For a detailed discussion, refer to the *Structural or modeling limitations and uncertainties* subsection of Section 3.2.10.5. One important distinction is that more toxicity data tend to be available for aquatic effects than for human carcinogenic effects. Specifically, toxicity data were available for lead outputs, which drive the aquatic ecotoxicity differences between CMR and CMP alternatives. For NM-B, the top contributing flows differed from the CMR/CMP results; however, ecotoxicity data were also available for those chemicals.

The LCI data limitations also are similar to those described in preceding sections. For the CMR and CMP results, the baseline results were driven by landfilling (e.g., lead leaching from the landfill), followed primarily by incineration and then electricity production (for manufacturing processes). The impacts from the lead-free alternative, however, were driven by the electricity production. There is uncertainty in the leachate estimate used in the analysis, and this estimate was varied in the multivariate uncertainty analysis (Section 3.4). As the uncertainty analysis revealed, a significant difference between the alternatives is likely, even given the defined range of uncertainty (see Section 3.4). Since the landfill leachate data were an important aspect of the public toxicity impacts, further refinement of the potential exposure, through more sophisticated exposure analysis and fate and transport analysis are warranted.

The NM-B analysis, which did not include EOL modeling was driven by phthalate plasticizer production, which used secondary data. Based on the LCIA methodology and the LCI data, the aquatic ecotoxicity category is given an overall relative data quality rating of "medium" for all cable types.

3.3 Summary of Life-Cycle Impact Analysis Characterization

This section presents an overview of the characterization methods and the life-cycle impact results for the different cable types. Section 3.3.1 provides the equations for each impact category that are used to calculate impact scores; Section 3.3.2 describes the LCIA data sources and data quality; and Section 3.3.3 provides the limitations and uncertainties associated with the LCIA methodology.

The WCP LCIA methodology does not perform the optional LCIA steps of normalization (calculating the magnitude of category indicator results relative to a reference value), grouping (scoring and possibly ranking of indicators across categories), or weighting (converting indicator results based on importance and possibly aggregating them across impact categories). Grouping and weighting, in particular, are subjective steps that depend on the values of different individuals, organizations, or societies performing the analysis. Since the WCP involves a variety of stakeholders from different geographic regions and with different values, these more subjective steps were intentionally excluded from the WCP LCIA methodology. Normalization also was intentionally not included as there are not universally accepted normalization reference values for all the impact categories included in this study. Furthermore, one of the primary purposes of this research is to identify the relative differences in the potential impacts among cable alternatives, and normalization within impact categories would not affect the relative differences among alternatives within the impact categories.

3.3.1 Impact Score Equations

Table 3-112 summarizes the impact categories, associated impact score equations, and the input or output data required for calculating natural resource impacts. Each of these characterization equations is a loading estimate. For a more detailed discussion of loading estimates, refer to Section 3.1.2.

Table 3-112

Summary of natural resources impact scoring

		Data required from inventory (per functional unit)	
Impact category	**Impact score approach**	**Inputs**	**Outputs**
Use/depletion of non-renewable resources	$IS_{NRR} = Amt_{NRR} \times (1 - RC)$	Material mass (kg)	None
Energy use, general energy consumption	$IS_E = Amt_E$ or $(Amt_F \times H/D)$	Energy (MJ) (electricity, fuel)	None
Landfill space use	$IS_L = Amt_W / D$	None	Mass of waste (hazardous and solid waste combined) (kg) and density (e.g., volume, m^3)

Abbreviations: RC=recycled content; H=heat value of fuel *i*; D=density of fuel *i*.

The term abiotic ecosystem refers to the nonliving environment that supports living systems. Table 3-113 presents the impact categories, impact score equations, and inventory data requirements for abiotic environmental impacts to atmospheric resources.

Table 3-113

Summary of atmospheric resource impact scoring

		Data required from inventory (per functional unit)	
Impact category	**Impact score approach**	**Inputs**	**Outputs**
Global warming	$IS_{GW} = EF_{GWP} \times Amt_{GG}$	None	Amount of each greenhouse gas chemical released to air
Stratospheric ozone depletion	$IS_{OD} = EF_{ODP} \times Amt_{ODC}$	None	Amount of each ozone depleting chemical released to air
Photochemical smog	$IS_{POCP} = EF_{POCP} \times Amt_{POC}$	None	Amount of each smog-creating chemical released to air
Acidification	$IS_{AP} = EF_{AP} \times Amt_{AC}$	None	Amount of each acidification chemical released to air
Air quality (particulate matter)	$IS_{PM} = Amt_{PM}$	None	Amount of particulates: PM_{10} or TSP released to air [a]

[a] Assumes PM_{10} and TSP are equal; however, using TSP will overestimate PM_{10}.

Table 3-114 presents the impact categories, impact score equations, and required inventory data for abiotic environmental impacts to water resources.

Table 3-114

Summary of water resource impact scoring

Impact category	Impact score approach	Data required from inventory (per functional unit) Inputs	Outputs
Water eutrophication	$IS_{EUTR} = EF_{EP} \times Amt_{EC}$	None	Amount of each eutrophication chemical released to water

Table 3-115 summarizes the human health and ecotoxicity impact scoring approaches. The impact categories, impact score equations, the type of inventory data, and the chemical properties required to calculate impact scores are presented. The human health effects and ecotoxicity impact scores are based on the scoring of inherent properties approach to characterization. For a more detailed discussion of characterization methods, refer to Section 3.1.2.

Table 3-115

Summary of human health and ecotoxicity impact scoring

Impact category	Impact score equations	Data required from inventory (per functional unit) Inputs	Outputs	Chemical properties data required
Chronic human health effectsC occupational, cancer	$IS_{CHO\text{-}CA} = HV_{CA} \times Amt_{TCinput}$	Mass of each primary and ancillary toxic chemical	None	WOE or SF
Chronic human health effectsC occupational, noncancer	$IS_{CHO\text{-}NC} = HV_{NC} \times Amt_{TCinput}$	Mass of each primary and ancillary toxic chemical	None	Mammal NOAEL or LOAEL
Chronic human health effectsC public, cancer	$IS_{CHP\text{-}CA} = HV_{CA} \times Amt_{TCoutput}$	None	Mass of each toxic chemical released to air and surface water	WOE or SF
Chronic human health effectsC public, noncancer	$IS_{CHP\text{-}NC} = HV_{NC} \times Amt_{TCoutput}$	None	Mass of each toxic chemical released to air and surface water	Mammal NOAEL or LOAEL
Aquatic ecotoxicity	$IS_{AQ} = (HV_{FA} + HV_{FC}) \times Amt_{TCoutput,water}$	None	Mass of each toxic chemical released to surface water	Fish LC_{50} and/or fish NOEL

Individual impact scores are calculated for inventory items for a certain impact category and can be aggregated by inventory item (e.g., a certain chemical), process, life-cycle stage, or entire product profile. For example, global warming impacts can be calculated for one inventory item (e.g., CO_2 releases), for one process that could include contributions from several inventory items (e.g., electricity generation), for a life-cycle stage that may consist of several process steps (e.g., product manufacturing), or for an entire profile (e.g., a functional unit of a cable).

3.3.2 LCIA Data Sources and Data Quality

Data that are used to calculate impacts come from: (1) equivalency factors or other parameters used to identify hazard values; and (2) LCI items. Equivalency factors and data used to develop hazard values presented in this methodology include GWP, ODP, POCP, AP, EP, WOE, SF, mammalian LOAEL/NOAEL, fish LC_{50}, and fish NOEL. Published lists of the chemical-specific parameter values exist for GWP, ODP, POCP, AP, and EP (see Appendix D). The other parameters may exist for a large number of chemicals, and several data sources must be searched to identify the appropriate parameter values. Priority is given to peer-reviewed databases (e.g., Health Effects Assessment Summary Tables [HEAST], Integrated Risk Information System [IRIS], Hazardous Substances Data Bank [HSDB]), next other databases (e.g., Registry of Toxic Effects of Chemical Substances [RTECS]), then other studies or literature, and finally estimation methods (e.g., structure-activity relationships [SARs] or quantitative structure-activity relationships [QSARs]). More details are provided in Appendix E.

The sources of each parameter presented in this report and the basis for their values are presented in Table 3-116. Data quality is affected by the data source itself, the type of data source (e.g., primary versus secondary data), the currency of the data, and the accuracy and precision of the data. The sources and quality of the LCI data used to calculate impact scores were discussed in Chapter 2. Data sources and data quality for each impact category are discussed further in Section 3.2, LCIA Results.

Table 3-116

Data sources for equivalency factors and hazard values

Parameter	Basis of parameter values	Source
Global warming potential	Atmospheric lifetimes and radiative forcing compared to CO_2	IPCC, 2001 (see Appendix D)
Ozone depletion potential	The change in the ozone column in the equilibrium state of a substance compared to CFC-11	UNEP, 2003; WMO 1999 (see Appendix D)
Photochemical oxidant creation potential	Simulated trajectories of ozone production with and without VOCs present compared to ethene	Heijungs *et al.*, 1992; EI, 1999 (see Appendix D)
Acidification potential	Number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to SO_2	Heijungs *et al.*, 1992; Hauschild and Wenzel, 1997 (see Appendix D)
Nutrient enrichment/eutrophication potential	Ratio of N to P in the average composition of algae ($C_{106}H_{263}O_{110}N_{16}P$) compared to phosphate (PO_4^{3-})	Heijungs *et al.*, 1992; Lindfors *et al.*, 1995 (see Appendix D)
Weight-of-evidence	Classification of carcinogenicity by EPA or IARC based on human and/or animal toxicity data	EPA, 1999; IARC, 1998 (see Appendix E)
Slope factor	Measure of an individual=s excess risk or increased likelihood of developing cancer if exposed to a chemical, based on dose-response data	IRIS and HEAST as cited in RAIS online database (see Appendix E)
Mammalian: LOAEL/NOAEL	Mammalian (primarily rodent) toxicity studies	IRIS, HEAST and various literature sources (see Appendix E)

Table 3-116

Data sources for equivalency factors and hazard values

Parameter	Basis of parameter values	Source
Fish lethal concentration to 50 percent of the exposed population (LC_{50})	Fish (primarily fathead minnow) toxicity studies	Various literature sources and Ecotox database (see Appendix E)
Fish NOEL	Fish (primarily fathead minnow) toxicity studies	Literature sources and Ecotox database (see Appendix E)

IRIS = Integrated Risk Information System; HEAST = Health Effects Assessment Summary Tables; RAIS = Risk Assessment Information System.

3.3.3 General LCIA methodology limitations and uncertainties

This section summarizes some of the limitations and uncertainties in the LCIA methodology in general. Specific limitations and uncertainties in each impact category are discussed in Sections 3.2.2 through 3.2.12 with the LCIA results for the WCP.

The purpose of an LCIA is to evaluate the relative potential impacts of a product system for various impact categories. There is no intent to measure the actual impacts or to provide spatial or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts.

In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA also is limited by the availability and quality of the inventory data. Data collection can be time-consuming and expensive, and confidentiality issues may inhibit the availability of primary data.

Uncertainties are inherent in each parameter described in Table 3-112 through 3-115. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects), resulting in a high degree of uncertainty. Sources for each type of data should be consulted for more information on uncertainties specific to each parameter.

Uncertainties exist in chemical ranking and scoring systems, such as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk. Uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. In addition, when LOAELs were not available but NOAELs were, a factor of ten was applied to the NOAEL to estimate the LOAEL, thus introducing uncertainty. The human health and ecotoxicity impact characterization methods presented in the WCP LCIA are screening tools that cannot substitute for more detailed risk characterization methods; however, the methodology is an attempt to consider chemical toxicity at a screening level for potentially toxic materials in the inventory.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires and other limitations identified during inventory data collection. These uncertainties are carried into the impact assessment. Uncertainties in the inventory data include, but are not limited to, the following:

- missing individual inventory items;
- missing processes or sets of data;
- measurement uncertainty;

- estimation uncertainty;
- allocation uncertainty/working with aggregated data; and
- unspeciated chemical data.

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is assured that some missing data still exist. The remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data). The limitations and uncertainties in the inventory data were discussed further in Chapter 2.

3.4 Uncertainty and Sensitivity Analyses

As was stated in Section 3.3.3, uncertainty is inherent in all of the parameters involved in the calculation of product life-cycle impacts. Uncertainty and sensitivity analysis were both used to examine the effect that parameter uncertainty had on the impact category results. Uncertainty analysis addressed the magnitude of the sum of parameter uncertainty, and sensitivity analysis was used to address each parameter's contribution to the overall uncertainty. Uncertainty and sensitivity analysis were performed on the CMR and CMP full life-cycle comparisons, and not on the CMR three-way (baseline/lead-free/halogen-free) and NM-B cradle-to-gate comparisons.

3.4.1 Uncertainty Analysis

3.4.1.1 Methodology

Monte Carlo statistical methods were used to examine the contribution of uncertainty in various life-cycle processes to each impact category result. Monte Carlo methods describe the generation of a distribution of model results based on the specification of one or more distributions to represent model parameters. As values are iteratively chosen from uncertain model parameters, a distribution of outcomes is created that represents the effect of this uncertainty. A built-in Monte Carlo function found in the GaBi4 software package (PE & IKP, 2003), which provides two built-in distributions, Gaussian and uniform, was used to generate probabilistic impact results.

Four parameters within the life-cycle processes were chosen as highly uncertain and given uniform distributions representing the degree of uncertainty surrounding them. The majority of the parameters selected as highly uncertain came from end-of-life processes. Uniform distributions were chosen to represent these parameters as they allow parameters to assume extreme bounds without presuming any more knowledge about the actual parameter distribution. Choosing a Gaussian distribution to represent the parameter uncertainty would have expressed the highest confidence in values surrounding the mean, something justifiable only in the presence of a larger number of parameter data points.

The parameter representing the percentage of cable consumed in fire was selected as highly uncertain due to the lack of information about building cable burned in fire. As mentioned before, the frequency of fires in buildings containing the cables of interest was known, thus the natural extreme bounds were that anywhere from 0 percent to 100 percent of the cable contained in these buildings would burn in the fire (equivalent to 0-1.1 percent of all cable installed in the case of CMP and CMR). A number of factors complicate this picture. Communication cables are contained behind fire resistant walls and are protected by sprinkler systems. They are formulated using effective flame retardants. Finally, out of all of the fires reported in the U.S., it is likely that a high proportion are minor and do not cause extensive damage to the whole structure. Thus, the extreme values stated above do not reflect an accurate bounding of the likely value of the percentage of cable consumed in fire. The bounding values chosen were 0 percent and 20 percent of the cable contained in buildings that have fires being burned. These values were chosen as somewhat arbitrary reductions of the natural extreme bounds in response to the recognition that fire protection methods would skew actual burn percentages toward the lower end.

The percentage of cable resins going to recycling was another source of substantial uncertainty in the end-of-life. As noted previously, a report for the European Commission stated that 20 percent of thermoplastics going to recycling was a justifiable high-end estimate. Using this European estimate as a surrogate for U.S.-specific data, the expected extreme bounds of 0 percent and 20 percent of the chopped cable resins being recycled were chosen.

As described earlier, the parameter representing the percentage of lead leached into the ground assumed that 0-100 percent of the leachate would ultimately escape any landfill lining and leachate collection system (equivalent to 0-1.5 percent of total lead escaping for cable directly landfilled or equivalent to 0-10 percent of total lead escaping for cable resins landfilled after chopping). As there was no other information to narrow the uncertainty bounds, the natural extreme bounds were used to model parameter uncertainty.

The final uncertainty distribution represented a data discrepancy for extruding energy data for the CMR and CMP cables. Inconsistent and highly divergent energy values used in the cable extrusion process led to high uncertainty for the extruding data. Large inter-company variation in extrusion energy combined with small numbers of data sets for each cable type resulted in a need to create proxy values for the energy of extrusion of the CMR and CMP baseline cable types, which both had only one contributing data point. Thus, the range of the data sets collected as primary data, or, in cases where there was only one data point, the range spanning the data point and the proxy data point, was used to set the bounds of the uncertainty analysis, given that none of the data could be identified as anomalous. A uniform distribution was used to bound the energy used in the leaded and lead-free cable extrusion inventories.

In the Monte Carlo analysis, the parameters described above were varied simultaneously, to observe the distribution of the LCIA indicator results given the ranges of uncertainties in all four parameters. The parameters varied were only applicable to the CMR and CMP full life-cycle analyses. Five thousand simulations were run (i.e., five thousand combinations of uncertain parameter values were chosen) to generate a distribution of the LCIA indicator results represented as the mean and various percentile ranges around the mean.

3.4.1.2 Uncertainty Analysis Results

Tables 3-117 through 3-120 present the uncertainty analysis results for the CMR and CMP lead and lead-free cable alternative analyses. Results are presented as means and 10th/90th percentiles of the impact distribution (i.e., the values below which 10 percent and 90 percent of the Monte Carlo iterative results fell). These results give a sense of the magnitude of uncertainty in the impact categories resulting from model parameter uncertainty. The majority of the impact categories' 10th and 90th percentile ranges overlap for both the CMP and CMR lead versus lead-free comparisons, revealing few major differences between the alternatives. An example of this can be seen in the non-renewable resources impact category from the CMR comparison. The baseline cable 10th-90th percentile range is 98.6-185 kg of non-renewable resources used/km of cable, which overlaps the lead-free range of 87.1-155 kg of non-renewable resources used/km of cable. The overlap implies that, given the lack of precision in the uncertain parameters, it cannot definitively be stated that the lead-free cable alternative uses less non-renewable resources. Chapter 4 summarizes these results in terms of the overall LCA results.

Table 3-117

CMR Baseline LCIA Uncertainty Analysis Results

LCIA Results	Units per km Cable	Mean	10th Percentile	90th Percentile
NRR	kg	141	98.6	185
Energy	MJ	2410	2020	2820
Landfill space	m^3	0.0166	0.0163	0.0168
Global warming	kg CO_2-equiv.	90.1	69.3	111
Ozone depletion	kg CFC 11-equiv.	5.89E-06	3.55E-06	8.26E-06
Smog	kg ethene-equiv.	0.125	0.117	0.133
Acidification	kg SO_2-equiv.	0.730	0.563	0.899
Air particulates	kg	0.0781	0.0682	0.0881
Eutrophication	kg phosphate-equiv.	0.00899	0.00564	0.0124
Pot. occ. non-ca	kg cancertox-equiv.	71.8	70.8	72.8
Pot. occ. cancer	kg noncancertox-equiv.	3.53	3.52	3.54
Pot. public non-ca	kg noncancertox-equiv.	1470	770	2170
Pot. public cancer	kg cancertox-equiv.	0.832	0.741	0.923
Pot. Aq. ecotox	kg aqtox-equiv.	17.7	6.44	28.7

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity

Table 3-118

CMR Lead-free LCIA Uncertainty Analysis Results

LCIA Results	Units per km Cable	Mean	10th Percentile	90th Percentile
NRR	kg	121	87.1	155
Energy	MJ	2360	2050	2680
Landfill space	m^3	0.0181	0.0179	0.0183
Global warming	kg CO_2-equiv.	83.7	67.3	100
Ozone depletion	kg CFC 11-equiv.	4.98E-06	3.11E-06	6.81E-06
Smog	kg ethene-equiv.	0.134	0.127	0.140
Acidification	kg SO_2-equiv.	0.680	0.547	0.810
Air particulates	kg	0.0816	0.0737	0.0893
Eutrophication	kg phosphate-equiv.	0.00760	0.00492	0.0102
Pot. occ. non-ca	kg cancertox-equiv.	77.6	76.9	78.4
Pot. occ. cancer	kg noncancertox-equiv.	3.69	3.69	3.70
Pot. public non-ca	kg noncancertox-equiv.	280	216	343
Pot. public cancer	kg cancertox-equiv.	0.836	0.765	0.908
Pot. aq. ecotox	kg aqtox-equiv.	0.113	0.0786	0.148

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity

The results from the uncertainty analysis for the CMR baseline and lead-free cable alternatives display substantial variability in a number of the impact categories. For the leaded cable results, the categories with high variability were non-renewable resource use, potential public chronic non-cancer toxicity, potential aquatic ecotoxicity, ozone depletion potential, and eutrophication potential, whose standard deviations were 22 percent, 35 percent, 47 percent, 29 percent, and 27 percent of their means, respectively (not reported in Tables 3-117 and 3-118). For the lead-free cables, the results also show substantial variability in a number of impacts: non-renewable resources, potential aquatic ecotoxicity, ozone depletion potential, and eutrophication potential, whose standard deviations were 20 percent, 22 percent, 27 percent, and 25 percent of their means, respectively.

Table 3-119

CMP Baseline LCIA Uncertainty Analysis Results

LCIA Results	Units per km Cable	Mean	10th Percentile	90th Percentile
NRR	kg	237	200	273
Energy	MJ	3940	3600	4280
Landfill space	m^3	0.0132	0.0124	0.0140
Global warming	kg CO_2-equiv.	181	163	198
Ozone depletion	kg CFC 11-equiv.	1.16E-03	1.16E-03	1.16E-03
Smog	kg ethene-equiv.	0.0885	0.0814	0.0956
Acidification	kg SO_2-equiv.	0.877	0.732	1.02
Air particulates	kg	0.0746	0.0660	0.0830
Eutrophication	kg phosphate-equiv.	0.0125	0.00961	0.0154
Pot. occ. non-ca	kg cancertox-equiv.	49.2	48.3	50.0
Pot. occ. cancer	kg noncancertox-equiv.	2.16	2.15	2.17
Pot. public non-ca	kg noncancertox-equiv.	951	606	1300
Pot. public cancer	kg cancertox-equiv.	0.736	0.658	0.813
Pot. aq. ecotox	kg aqtox-equiv.	8.63	3.22	14.1

NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity

Table 3-120

CMP Lead-free LCIA Uncertainty Analysis Results

LCIA Results	Units per km Cable	Mean	10th Percentile	90th Percentile
NRR	Kg	219	187	252
Energy	MJ	3740	3440	4050
Landfill space	m^3	0.0144	0.0137	0.0150
Global warming	kg CO_2-equiv.	171	155	187
Ozone depletion	kg CFC 11-equiv.	0.00110	0.00110	0.00111
Smog	kg ethene-equiv.	0.0869	0.0807	0.0932
Acidification	kg SO_2-equiv.	0.819	0.693	0.947
Air particulates	Kg	0.0726	0.0651	0.0802
Eutrophication	kg phosphate-equiv.	0.0114	0.00890	0.0140
Pot. occ. non-ca	kg cancertox-equiv.	46.8	46.0	47.5
Pot. occ. cancer	kg noncancertox-equiv.	2.22	2.21	2.23
Pot. public non-ca	kg noncancertox-equiv.	358	297	420
Pot. public cancer	kg cancertox-equiv.	0.702	0.633	0.771
Pot. aq. ecotox	kg aqtox-equiv.	0.151	0.118	0.185

NRR = non-renewable resource use; Pot. = Potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity

The CMP baseline and lead-free cable alternatives display less relative variability (measured as standard deviation normalized by the mean) than those of the CMR cable alternatives overall. However, the potential public chronic non-cancer toxicity and potential aquatic ecotoxicity indicators still display substantial variability in the baseline case (standard deviations are 27 percent and 47 percent of their means, respectively; not shown in Tables 3-119 and 3-120). The lead-free cable results show substantially less relative variability than those of the baseline cable, with no impact indicators' standard deviations exceeding 20 percent of their mean.

3.4.2 Sensitivity Analysis

The variance of results from the Monte Carlo analysis emanated from the concurrent variation of four parameters. Therefore, a sensitivity analysis was necessary to assess the magnitude of each parameter's contribution. A built-in sensitivity analysis function from the GaBi4 software was used to determine the amount of variance in each impact category attributable to each of the dynamic parameters.

The sensitivity analysis was used to probe the contributions to overall impact uncertainty from each of the stochastic parameters. Results of the analysis, shown in Table 3-121, give the largest contributing parameter along with the percent variance in the impact result attributable to this dominant parameter.

It is evident from Table 3-121 that one parameter is responsible for most of the variation in impacts for each cable type: the energy used for cable extrusion. However, for the CMR and CMP leaded cables, the uncertainty in the public chronic non-cancer toxicity and the aquatic ecotoxicity categories are dominated by the landfill leachate parameter, and for all cables, thermoplastic recycling dominates the landfill space use indicators.

Table 3-121

LCIA Sensitivity Analysis Results [a,b]

Impact Category	CMR		CMP	
	Baseline	Lead-free	Baseline	Lead-free
NRR	E (98)	E (98)	E (98)	E (97)
Energy	E (>50)[c]	E (>50)[c]	E (>50)[c]	E (>50)[c]
Landfill space	TR (63)	TR (65)	TR (88)	TR (86)
Global warming	E (98)	E (97)	E (99)	E (98)
Ozone depletion	E (98)	E (98)	E (98)	E (98)
Smog	E (99)	E (99)	E (99)	E (99)
Acidification	E (94)	E (92)	E (92)	E (92)
Air particulates	E (98)	E (98)	E (98)	E (98)
Eutrophication	E (98)	E (98)	E (98)	E (98)
Pot. occ. non-ca	E (97)	E (96)	E (96)	E (95)
Pot. occ. cancer	E (98)	E (97)	E (97)	E (97)
Pot. public non-ca	L (83)	E (98)	L (78)	E (97)
Pot. public cancer	E (86)	E (96)	E (90)	E (96)
Pot. aq. ecotox	L (90)	E (98)	L (90)	E (98)

[a] Results are reported as the dominant parameter (percentage of the overall impact result variance for which it is responsible).
[b] TR = Percentage of cable going to thermoplastics recycling; L = percentage of lead lost from landfill; E = Variance of extrusion energy; NRR = non-renewable resource use; Pot. = potential; occ. = occupational; aq. ecotox = aquatic ecotoxicity
[c] Actual percentage withheld to protect confidentiality.