
CHAPTER 2 LIFE-CYCLE INVENTORY

The process of quantifying the inputs (e.g., materials, utilities) and outputs (e.g., emissions, wastes) of a product system is the life-cycle inventory (LCI) phase of a life-cycle assessment (LCA). A product system is made up of the multiple processes that help produce, use, or dispose of the product. Each process has an inventory that consists of input and output flows for that process, and an LCI of a product system consists of several inventories for processes throughout the life cycle of the product. This chapter presents the data collection methodology for each life-cycle stage, in Sections 2.1 through 2.4, followed by the LCI results in Section 2.5.

2.1 Upstream Materials Extraction & Processing Life-Cycle Stages

This section addresses the LCIs related to two major life-cycle stages—materials extraction and materials processing (ME&P)—which together will be referred to as the life-cycle stages that are “upstream” of the product manufacturing (i.e., compounding and extruding) stage.

The purpose of this section is to present the approach used to obtain process-specific inventory data, from primary and secondary sources, related to extraction and processing of the materials needed to produce wire and cable insulation and jacketing compounds. Numerous materials and upstream processes are used to produce wire and cable insulation and jacketing compounds. Therefore, decision rules were used to limit which materials to include in the scope of the LCA. Existing data from secondary sources were used where available. For inventories related to materials extraction and materials processing, various databases with input and output LCI data exist for materials commonly used in the wire and cable industry (i.e., PVC, HDPE, and certain fillers). However, data do not exist for most of the flame retardants, heat stabilizers, plasticizers, and other resins (e.g., FEP) used in the insulation and jacketing compounds. Because of the lack of available secondary LCI data, the WCP sought to collect primary data for these materials.

This section of the report first identifies materials considered for inclusion in the ME&P life-cycle stage. The remainder of the section presents the methodology for collecting upstream data, including data sources, and the limitations to using the upstream data for the WCP.

2.1.1 Materials selection

This section describes the decision process for including materials in the WCP upstream LCI data. The first step in collecting upstream data was to identify those materials that are used in producing the cables, both primary materials and ancillary materials (i.e., fuels and process materials). Bills of materials for the cables in this study are presented in Tables 2-1, 2-2, and 2-3, respectively. (Note that the WCP excluded the conductor from the analysis because the same gauge copper and number of conductors are used in each of the cable alternatives within a given cable type.) The tables present the mass per unit length of each component material in each of the cable alternatives, and their percent mass contribution of the cable with and without the copper conductor. The quantities are based on primary data collected from compounders and manufacturers under confidentiality agreements. The tables show the averages from a total of six different companies.

For each of the three cable types in this study, the bills of materials of lead-stabilized cable (baseline) and the non-leaded alternatives are presented in Tables 2-1, 2-2, and 2-3. A complete bill of materials for CMR zero-halogen cables was not obtained; thus, only limited analyses with these cables are possible. Upstream data selection for the CMR zero-halogen cable alternative is based on general

descriptions of the cables provided by participating companies and limited data provided under confidentiality agreements (Table 2-4).

| Material Name [CASRN] ^b | Function | Baseline Construction | | | Pb-free Alternative Construction | | |
|---|------------------------|---------------------------|---------------------------|------------------------------|----------------------------------|---------------------------|------------------------------|
| | | Mass (kg/km) ^c | Weight % of cable with Cu | Weight % of cable without Cu | Mass (kg/km) ^c | Weight % of cable with Cu | Weight % of cable without Cu |
| Copper (Cu) [7440-50-8] | Conductor ^d | 23.3 | 54% | N/A | 24.2 | 53% | N/A |
| Polyvinyl chloride (PVC) [9002-86-2] | Jacket resin | 7.47 | 17% | 37% | 8.92 | 19% | 37% |
| High density polyethylene (HDPE) [9002-88-4] | Insulation resin | 4.55 | 11% | 23% | proprietary | >5% | >5% |
| Phthalate-based plasticizer | Jacket plasticizer | 2.25 | 5.2% | 11% | proprietary | 1-5% | >5% |
| <i>Non-halogenated flame retardant #1</i> | Jacket flame retardant | proprietary | 1-5% | >5% | proprietary | 1-5% | >5% |
| Polyolefin | Separator | proprietary | 1-5% | 1-5% | proprietary | <1 | 1-5% |
| Trimellitate plasticizer | Jacket plasticizer | proprietary | 1-5% | 1-5% | proprietary | 1-5% | >5% |
| Brominated phthalate | Jacket flame retardant | proprietary | 1-5% | 1-5% | N/A | | |
| <i>Non-halogen FR#2</i> | Jacket flame retardant | 0.466 | 1-5% | 1-5% | proprietary | 1-5% | 1-5% |
| Calcined clay [66402-68-4] | Jacket filler | proprietary | <1% | 1-5% | proprietary | <1% | 1-5% |
| Tribasic lead sulfate [12202-17-4] | Jacket heat stabilizer | 0.351 | 0.81 % | 1.8 % | N/A | | |
| Dibasic lead phthalate [17976-43-1] | Jacket heat stabilizer | proprietary | <1 % | <1 % | N/A | | |
| Calcium-Zinc-based stabilizers [various] | Jacket heat stabilizer | N/A | | | proprietary | 1-5% | 1-5% |
| Unspecified colorants [various] | Insulation colorant | proprietary | <1% | 1-5% | proprietary | <1% | <1% |
| Calcium carbonate (CaCO ₃) [471-34-1] | Jacket filler | proprietary | <1% | <1% | proprietary | 1-5% | 1-5% |
| Polyethylene terephthalate (PET) | Ripcord | proprietary | <1% | <1 % | proprietary | <1% | <1% |
| Stearic acid [57-11-4] | Jacket lubricant | 0.0538 | 0.12% | 0.27% | proprietary | <1% | <1% |
| <i>Proprietary light stabilizer #1</i> | Light stabilizer | proprietary | <1% | <1% | proprietary | <1% | <1% |
| <i>Proprietary lubricant #2</i> | Jacket lubricant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Printing Ink | Ink | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary material #1 | Other | N/A | | | proprietary | <1% | <1% |
| TOTAL CABLE WEIGHT | | 43.3^e | | | 46.0^f | | |

^a Zero-halogen not included as complete cable construction data were not provided.

^b Chemical Abstract Services Registry Number.

^c Metric to English unit conversion: 1 kg/km cable = 0.673 lb/1000 ft cable.

^d Conductor is unshielded twisted pair, 8 conductors in 4 pairs; 23-gauge bare copper. The mass of copper is slightly different due to averaging data from different companies, all of whom did not provide data for both alternatives. Thus, although within a company, the amount of copper was consistent across alternatives, averaging a different number of data sets for each alternative resulted in slightly different mass averages of copper.

^e 94 wt% of the total CMR baseline cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

^f 90 wt% of the total CMR lead-free cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

Note: Percentages without copper that meet the > 1 percent mass cutoff are in bold. Percentages without copper that meet the > 5 percent mass cutoff are in bold and shaded.

Table 2-2

Average CMP Cable Construction Bills of Materials

| Material Name [CASRN] ^a | Function | Baseline Construction | | | Pb-free Alternative Construction | | |
|---|---|---------------------------|---------------------------|------------------------------|----------------------------------|---------------------------|------------------------------|
| | | Mass (kg/km) ^b | Weight % of cable with Cu | Weight % of cable without Cu | Mass (kg/km) ^b | Weight % of cable with Cu | Weight % of cable without Cu |
| Copper (Cu) [7440-50-8] | Conductor ^c | 23.7 | 51% | N/A | 22.5 | 50% | N/A |
| Fluorinated ethylene propylene (FEP) [25067-11-2] | Resin (insulation / separator / filler) | proprietary | >5% | >5% | proprietary | >5% | >5% |
| Polyvinyl chloride (PVC) [9002-86-2] | Jacket resin | proprietary | >5% | >5% | proprietary | >5% | >5% |
| Aluminum trihydrate (ATH) [21645-51-2] | Jacket flame retardant | proprietary | >5% | >5% | proprietary | >5% | >5% |
| Fluoropolymer | Separator | proprietary | 1-5% | >5% | proprietary | 1-5% | 1-5% |
| Proprietary FR#3 | Jacket flame retardant and/or plasticizer | proprietary | 1-5% | 1-5% | proprietary | 1-5% | 1-5% |
| Ammonium octamolybdate [12411-64-2] | Jacket flame retardant and/or plasticizer | proprietary | 1-5% | 1-5% | proprietary | 1-5% | 1-5% |
| Calcined clay [66402-68-4] | Jacket filler | proprietary | <1% | 1-5% | proprietary | 1-5% | 1-5% |
| Brominated phthalate [various] | Jacket flame retardant and/or plasticizer | proprietary | <1% | 1-5% | proprietary | 1-5% | 1-5% |
| Calcium carbonate (CaCO ₃) [471-34-1] | Jacket filler | proprietary | <1% | 1-5% | proprietary | <1% | 1-5% |
| Proprietary plasticizer #1 | Jacket plasticizer | proprietary | <1% | <1% | proprietary | <1% | 1-5% |
| Lead-based stabilizer #1 | Jacket heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Lead-based stabilizer #2 | Jacket heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Calcium-Zinc-based stabilizers [various] | Jacket heat stabilizer | N/A | | | proprietary | <1% | 1-5% |
| Unspecified colorant | Insulation colorant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Unspecified colorant | Jacketing colorant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary FR#4 | Jacket flame retardant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Polyethylene terephthalate (PET) | Ripcord | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Lead-based stabilizer #3 | Jacket heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Zinc borate | Jacket flame retardant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Stearic acid [57-11-4] | Jacket lubricant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary light stabilizer #1 | Light stabilizer | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Proprietary material #2 | Unknown | N/A | | | proprietary | <1% | <1% |
| Barium stearate [6865-35-6] | Jacket lubricant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Printing Ink | Ink | proprietary | <1% | <1% | proprietary | <1% | <1% |
| TOTAL CABLE WEIGHT | | 46.5^e | | | 45.4^f | | |

^a Chemical Abstract Services Registry Number.

^b Metric to English unit conversion: 1 kg/km cable = 0.673 lb/1000 ft cable.

^c Conductor is unshielded twisted pair, 8 conductors in 4 pairs; 23-gauge bare copper. The mass of copper is slightly different due to averaging data from different companies, all of which did not provide data for both alternatives. Thus, although within a company, the amount of copper was consistent across alternatives, averaging a different number of

data sets for each alternative resulted in slightly different mass averages of copper.

^e 92 wt% of the total CMP baseline cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

^f 92 wt% of the total CMP lead-free cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

Note: Percentages without copper that meet the > 1 percent mass cutoff are in bold. Percentages without copper that meet the > 5 percent mass cutoff are in bold and shaded.

| Material Name [CASRN] ^a | Function | Baseline Construction | | | Pb-free Alternative Construction ^b | | |
|--|---------------------------|---------------------------|---------------------------|------------------------------|---|---------------------------|------------------------------|
| | | Mass (kg/km) ^c | Weight % of cable with Cu | Weight % of cable without Cu | Mass (kg/km) | Weight % of cable with Cu | Weight % of cable without Cu |
| Copper (Cu) [7440-50-8] | Conductor ^d | proprietary | >5% | N/A | proprietary | >5% | N/A |
| Polyvinyl chloride (PVC) [9002-86-2] | Resin | 14.4 | 12% | 39% | proprietary | >5% | >5% |
| Proprietary plasticizer #2 | Plasticizer | proprietary | >5% | >5% | N/A | | |
| Paper/bind | Filler | proprietary | 1-5% | >5% | proprietary | 1-5% | >5% |
| Calcium carbonate (CaCO ₃) [1317-65-3] | Filler | 7.2 | 5.8% | 20% | proprietary | 1-5% | >5% |
| Nylon [63428-83-1] | Conductor jacketing resin | proprietary | 1-5% | >5% | proprietary | 1-5% | >5% |
| Non-phthalate plasticizer #1 | Plasticizer | proprietary | <1 % | 1-5% | proprietary | 1-5% | >5% |
| Proprietary plasticizer #3 | Plasticizer | proprietary | <1% | 1-5% | N/A | | |
| Calcined clay [66402-68-4] | Filler | 0.600 | 0.48% | 1.7% | proprietary | <1% | 1-5% |
| Ca/Zn based stabilizer | Stabilizer | N/A | | | proprietary | <1% | 1-5% |
| Omyacarb F Bags | Unknown | N/A | | | proprietary | <1% | <1% |
| Unspecified lubricants | Lubricant | N/A | | | proprietary | <1% | <1% |
| Lead-based heat stabilizer #2 | Heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Unspecified colorants [various] | Colorant | proprietary | <1% | <1% | proprietary | <1% | <1% |
| Phthalate plasticizer #4 | Plasticizer | proprietary | <1% | <1% | N/A | | |
| Phthalate plasticizer #5 | Plasticizer | N/A | | | proprietary | >5% | >5% |
| Lead-based heat stabilizer #1 | Heat stabilizer | proprietary | <1% | <1% | N/A | | |
| Antimony trioxide [1309-64-4] | Flame retardant | 0.085 | 0.07% | 0.23% | proprietary | <1% | <1% |
| Stearic acid [57-11-4] | Lubricant | 0.070 | 0.06% | 0.19% | N/A | | |
| Lubricant #2 | Lubricant | N/A | | | proprietary | <1% | <1% |
| Ink | Ink | proprietary | <1% | <1% | proprietary | <1% | <1% |
| TOTAL CABLE WEIGHT | | 124^e | | | 124^f | | |

^a Chemical Abstract Services Registry Number.

^b Data for the extrusion of the NM-B Pb-free alternative was not provided. The bill of materials was generated assuming the same relative inputs of jacketing, insulation, and other materials as in the baseline.

^c Metric to English unit conversion: 1 kg/km cable = 0.673 lb/1000 ft cable.

^d Conductor is 12-gauge 2-conductor copper with ground wire.

^e 88 wt% of the total NM-B baseline cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

^f 85 wt% of the total NM-B lead-free cable insulation and jacketing is modeled in this analysis (see Table 2-5 for which upstream datasets were not obtained).

Note: Percentages without copper that meet the > 1 percent mass cutoff are in bold. Percentages without copper that meet the > 5 percent mass cutoff are in bold and shaded.

Table 2-4**CMR Zero-Halogen Material Breakdown**

| Material Name | Weight % of Cable Without Copper^a |
|-------------------------------|---|
| Resins FR # 1 | > 5 % |
| FR # 2, 3 | 1 – 5 % |
| Heat stabilizer Lubricants | < 1 % |
| Other | |

^a Materials modeled in this analysis constitute 7 wt% of cable insulation and jacketing.

Decision rules were then applied to the bills of materials in order to determine which materials to focus on during the upstream data collection process. In considering the inclusion of production processes for upstream materials, several factors were considered, including availability of existing data and manufacturers' willingness to participate. Including all of the upstream processes in the scope of the project can unnecessarily lengthen the project period and expend project resources on materials that are unlikely to influence the impact results. The upstream processes included in this analysis were limited to materials contained within the materials found in the final cable constructions. Production processes for materials contained within those cable materials were not included (e.g., production of fluorspar used in FEP production was not considered for inclusion).

The decision criteria provided in Section 1.4.2 were used to assess which upstream processes the scope should include. As per the decision rules, those materials constituting more than 5 percent were given priority, and materials comprising between 1 and 5 percent were evaluated for whether or not upstream inventories were required. Inclusion of materials falling into the 1 to 5 percent range was based on the other decision rule criteria, as well as data availability. Materials of known or suspected environmental or energy significance were included, regardless of their mass contribution. Additionally, materials that were physically unique or functionally significant to a cable alternative (e.g., a Ca/Zn-based stabilizer), as determined by the Core Group, were included to the extent possible if they would have been otherwise eliminated based on the mass cutoff. Because the LCA is comparative in nature, greater emphasis was placed on materials that are physically unique to a cable formulation. In cases where we set out to collect data for a material that met our decision rules and were unsuccessful, in Section 2.1.3 we explain the limitations.

Table 2-5 shows the specific materials for which upstream LCI data were sought, the rationale for their inclusion, and the type of inventory data included in the LCIs. Resins and plasticizers were included because they comprise more than 5 percent of the cable insulation and jacketing compounds by mass. The weight percent of flame retardants ranged from less than 1 percent to greater than 5 percent for the different cable types and alternatives. Any flame retardant comprising greater than 5 percent was included for upstream process data (i.e., ATH), those between 1 and 5 percent were included if secondary data were readily available, and those less than 1 percent were included only if they were greater than 1 percent for a different cable alternative. The lead-based heat stabilizers, which comprise either less than 1 percent or 1 to 5 percent of the insulation and jacketing by mass were included because they are of potential environmental significance. The Ca/Zn-based heat stabilizers were included because they are between 1 and 5 percent and they are physically unique to the alternative formulations compared to the

Pb-based baseline. The fillers and separators were included based on mass. Details about the data are contained in the following sections.

As shown in Table 2-5, primary or secondary data were collected for most of the materials identified using the decision rules. However, data for a few materials, such as some of the flame retardants and other fillers in the compounded jacketing resin (PVC) were not obtained. For the CMR cables, 94 percent of the cable mass is accounted for in the upstream processes for the baseline cable and 90 percent for the lead-free alternative. The zero-halogen CMR cable only accounted for 7 percent of the cable mass. For the CMP cables, 92 percent of the mass is accounted for in both the CMP baseline and lead-free alternative. Finally, 88 percent of cable mass of the NM-B baseline cable is accounted for, and 85 percent of the lead-free NM-B cable. Details of what was and was not included are provided in Section 2.1.2.

Table 2-5
Upstream Materials Selected for Inclusion in LCIs

| Component | Material name | Decision criteria meta | Upstream process data included |
|--------------------------------|---|-------------------------------|---|
| Insulation and jacketing resin | Fluorinated ethylene propylene (FEP) ^a | Mass cutoff | Primary data |
| | High density polyethylene (HDPE) | Mass cutoff | Secondary data |
| | Polyvinyl chloride (PVC) | Mass cutoff | Secondary data |
| | Nylon | Mass cutoff | Secondary data |
| Plasticizer | Phthalate-based | Mass cutoff | Secondary data combined for multiple phthalates |
| | Non-phthalate-based | Mass cutoff | No data obtained |
| Flame retardant | Aluminum trihydrate (ATH) | Mass cutoff | Secondary data |
| | Ammonium octamolybdate (AOM) | Mass cutoff | No data obtained |
| | Antimony trioxide | Mass cutoff | No data obtained |
| | Brominated phthalate | Mass cutoff | No data obtained |
| Heat stabilizer | Pb-based | Environmental significance | Secondary data |
| | Ca/Zn-based | Physical uniqueness | Primary data |
| Filler | Calcined clay | Mass cutoff | Secondary data |
| | Calcium carbonate | Mass cutoff | Secondary data |
| Separator | Polypropylene | Mass cutoff | Secondary data |
| | Polyethylene | Mass cutoff | Secondary data |
| | Fluoropolymer | Mass cutoff | Used primary data of FEP |

^aFEP production, which came from primary datasets, was modeled with 2 industrial precursor chemicals functioning as inputs; PVC and HDPE, both of which came from secondary datasets, were modeled as if all of the materials came from ground (mining of inert or low-toxicity inputs), and did not explicitly include industrial precursor chemicals.

Fuels and electricity are used in various processes in each life-cycle stage. All fuels and electricity contributing greater than 1 percent of total energy sources for each process are included in the LCI. Production inventory data were collected for the following:

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- natural gas,
 - light or distillate fuel oil (fuel oil #2),
 - heavy fuel oil (fuel oil #6), and
 - electricity generation.

No ancillary (process) materials meeting the decision rules outlined in Section 1.4.2 were identified for the compounding or extruding processes; therefore, no upstream data were collected for ancillary materials. For materials that do not meet the decision rules for inclusion as upstream production processes, the materials themselves are still included in the LCI for a cable alternative and are used to calculate impacts as appropriate for each impact category (see Chapter 3).

2.1.2 Data collection

Upstream LCI data were collected from both primary and secondary sources. Primary data are directly accessible, plant-specific, measured, modeled, or estimated data generated for the particular project at hand. Secondary data are from literature sources or other LCAs, but are specific to a product, material, or process used in the manufacture of the product of interest. Where both primary and secondary data were lacking, modeled data or assumptions served as defaults.

Based on input from the Core Group members, a number of companies (many of which participated in the Core Group) were identified as potential sources of primary data for the production of FEP, plasticizers, flame retardants, and heat stabilizers. These included three manufacturers of FEP, five plasticizer manufacturers, two flame retardant manufacturers, and four manufacturers of heat stabilizers. Only a subset of these companies provided data. Primary data for upstream processes were ultimately obtained for FEP resin and Ca/Zn stabilizer production. Any proprietary information collected from primary sources was subject to confidentiality agreements between Abt Associates, Inc. and the participating company. When multiple data sets were collected from the companies for a single process, data were aggregated to generate a single value for each inventory flow. If aggregation was insufficient to protect the confidentiality of the data, then the data were not reported at a process-specific level.

Where primary data for upstream materials were lacking, secondary data were pursued. In addition, data for the fuels and electricity used in the life-cycle processes were obtained from secondary data sources.

Secondary data were collected for manufacturing PVC, HDPE, phthalate plasticizers, selected flame retardants, and filler material. Neither primary nor secondary data were available for lead-based stabilizer manufacturing, but secondary data were collected for lead manufacturing. The following sections detail the primary and secondary data collected for these materials.

2.1.2.1 Resin manufacturing

The resin is the principal component of cable insulation and jacketing. PVC, FEP, and HDPE are the three main resins used in the cables of interest to the WCP. Secondary data were collected for PVC and HDPE, as well as nylon, another resin used in NM-B cables.

Two databases were identified as potential sources of secondary LCI data for PVC, HDPE, and nylon manufacturing:

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- PlasticsEurope (formerly the Association of Plastics Manufacturers in Europe, APME) is an industry body that has published inventory data on HDPE and PVC resin (PlasticsEurope, 2007). These data sets are European-based, of moderate quality, and available free.
 - BUWAL is the Swiss Agency for the Environment, Forests and Landscape (PRé, 2004). This agency has several published reports on LCA. BUWAL 250 is an English version of the agency's LCI database of several common industrial materials. It is a relatively inexpensive database that uses European data collected from secondary sources; therefore, the data quality is marginal.

Secondary LCI data from PlasticsEurope (formerly APME) for the production of suspension-polymerized PVC were used in this study. Originally collected by APME in 1992-1993, this LCI data set was last updated in March 2005 (Boustead, 2005b). Ten separate European PVC plants, which produced a combined 1,730,000 metric tons of PVC in 1993, supplied data for the APME study. The PVC data set begins with the raw materials (i.e., crude oil, natural gas, rock salt, and brine) and includes all operations up to the production of the PVC resin; it does not include the compounding process. For detailed information about PVC manufacturing, see Boustead (2005b).

The WCP chose to use the PlasticsEurope secondary data because the data are publicly available and the data collection process is well documented.⁹ A major shortfall of the PlasticsEurope PVC data is the fact that it ignores the generation of intermediate products such as ethylene dichloride and vinyl chloride. This gap in the data is expected to potentially understate the occupational health impacts inherent in the production of these chlorinated organics. Secondary LCI data from PlasticsEurope also were used for HDPE production. PlasticsEurope collected production data, representing 1999 production, from 24 plants in Western Europe, which produced a total of 3.87 million metric tons (accounting for 89.7 percent of Western European production) of HDPE in 1999 (Boustead, 2005a). The HDPE data set begins with the raw materials (i.e., crude oil and natural gas) and includes all process steps through to the production of HDPE by polymerizing ethylene. For detailed information about HDPE manufacturing, see Boustead (2005).

Primary LCI data for FEP manufacturing were collected for the WCP. Primary data, representing 2005 production, were collected from two of three major manufacturers contacted.

FEP is synthesized from hexafluoropropylene (HFP) and tetrafluoroethylene (TFE) via emulsion polymerization. A 68:32 molar percent HFP:TFE vapor mixture is fed to a heated reactor containing a surfactant, a perfluoropolyether, and deionized water. A free radical initiator solution starts the polymerization, and additional HFP, TFE, and initiator solution are added as the polymerization proceeds. LCI data included in the WCP cover the synthesis of FEP from fluorspar, sulfuric acid, methane, and chlorine. Figure 2-1 shows the steps in the synthesis of TFE, HFP, and FEP (Ring *et al.*, 2002):

⁹ A report prepared for the Plastics Division of the American Chemistry Council (ACC) includes newly developed LCI data for several plastics, including HDPE, PVC and polypropylene (Franklin and Associates, 2007). The report, however, was not available in time for this study. The ACC study described differences between their data and the PlasticsEurope database. They found that the energy impacts of HDPE, PVC and polypropylene based on the ACC database were 9%, 10%, and 13% less than the PlasticsEurope data, respectively. The differences were due to the differences between the North American and European means of forming, transporting, and disposing materials. Thus, the use of PlasticsEurope data could overestimate energy impacts by the percentages noted; and could potentially overestimate other impact categories by unknown amounts. Note: another data source (EcoInvent) was not available for review.

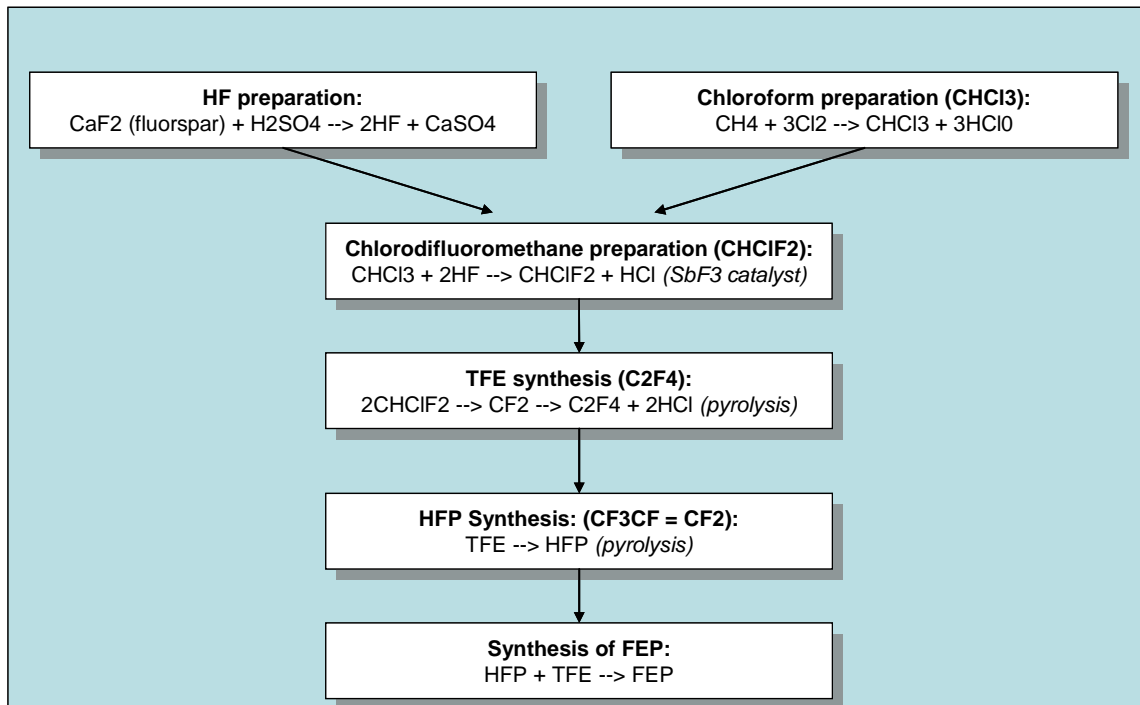


Figure 2-1. Fluorinated Ethylene-Propylene Synthesis

This study included upstream production of major materials in the cables (e.g., FEP) as defined by decision rules described earlier; however, it did not include in its scope upstream production of major materials used to produce the upstream materials (e.g., production of fluorspar, which is used in FEP production, is not included as an upstream process; however, these materials are included in the cable inventories and any impacts associated with those flows are included). However, as a result of secondary dataset boundaries, PVC and HDPE were modeled as coming from ground (i.e., all inputs were mined, bulk precursors). This discrepancy limits the utility of comparisons between FEP and the other resins, especially in impact categories that utilize inputs rather than outputs.

Polypropylene and polyethylene are two resins used in the CMR separators (crosswebs) that meet the mass cutoff decision rules. Secondary data for HDPE described above is used, as well as secondary data available in GaBi 4 for polypropylene. The polypropylene data within GaBi was secondary LCI data derived from the Eco Inventories of the European Polymer Industry (PlasticsEurope). The GaBi 4 documentation does not note the sample size, location, and total mass output of the representative plants. Polypropylene constitutes less than 5 percent of the mass of the cables without copper.

2.1.2.2 Plasticizer manufacturing

The wire and cable industry incorporates plasticizers into PVC in order to make it flexible and workable. The wire and cable industry uses many different plasticizers, most commonly, phthalate esters and trimellitates. For CMR cables, plasticizers represent between 12 and 16 percent by weight of the cable without the copper; for NM-B, between 10 and 40 percent; and for CMP, less than 7 percent. Phthalate esters are the most commonly used type of plasticizers. The wire and cable industry uses many different phthalate esters in PVC compounds. This report does not list the specific phthalate esters that the study partners use, because the compounds' formulations are proprietary. The WCP was unable to collect primary data for plasticizer manufacturing; therefore, secondary LCI data from *Ecobilan* for the

production of the three major phthalate esters—dioctylphthalate or di-2-ethylhexyl phthalate (DOP or DEHP), diisononyl phthalate (DINP), and diisodecyl phthalate (DIDP)—were used as a surrogate in this study (*Ecobilan*, 2001). Eight companies, representing 15 European production plants, provided data for the *Ecobilan* study, which refer to 1998 phthalate ester production, with the exception of some 1999 data.

Phthalate esters are manufactured by reacting phthalic anhydride (PA) with two moles of oxo alcohols to produce the ester (Kattas *et al.*, 2000; *Ecobilan*, 2001). The length and nature of the oxo alcohols (C1 to C13) used to make the esters affects their properties. DEHP is produced from 2-ethylhexanol, DINP is produced from isononyl alcohol, and DIDP is produced from isodecyl alcohol (*Ecobilan*, 2001). The *Ecobilan* study collected primary data for the production of DEHP, DINP, and DIDP; and the main intermediates: phthalate anhydride (PAN), C8 and C9 olefins, synthesis gas, n-butyraldehyde, 2-ethylhexanol, isononyl alcohol, and isodecyl alcohol.

Since the *Ecobilan* data are general to three major phthalate esters, they are used to represent all the phthalate plasticizers in this project. This approach was chosen over excluding upstream data for the plasticizers, which are greater than 10 percent by mass of CMR and NM-B cables.

Trimellitate esters are used as plasticizers in wire and cable compounds in conjunction with phthalate esters. The WCP was unsuccessful in its attempts to collect primary data for the manufacture of trimellitate esters, and no sources of secondary data were identified; therefore, this LCA does not include an LCI dataset for the manufacture of trimellitate esters. However, trimellitate plasticizers represent less than 5 weight percent of the insulation and jacketing for the CMR baseline and less than 7 weight percent for the CMR lead-free alternative. This omission will therefore have a greater effect on the lead-free alternative results than the baseline.

2.1.2.3 Flame-retardant manufacturing

Flame retardants are added to PVC in order to slow the spread of fire, reduce the amount of heat and smoke emitted during a fire, and cause a fire to self-extinguish. Aluminum trihydrate (ATH, aluminum hydroxide) is the most commonly used flame retardant in U.S. wire and cable, comprising 73 percent of the market in 1998 (TURI, 2002). Antimony trioxide/oxide (ATO), ammonium octamolybdate, and brominated phthalates are also used as flame retardants in the cables that the WCP is evaluating.

The WCP was unsuccessful in its attempts to collect primary data for the manufacture of these four flame retardants. Secondary LCI data were available for ATH production, while no secondary data sets were available for ATO, ammonium octamolybdate, or brominated phthalates. ATH represents the majority (by weight) of all flame retardants used in the CMR and CMP alternatives this study is evaluating. The flame retardant in NM-B cables comprises less than 1 percent by weight, and therefore no upstream flame retardant data are included.

A secondary data set for the production of ATH was used in this study, from the SP Swedish National Testing and Research Institute (Andersson *et al.*, 2005). ATH is a heat-absorbing flame retardant that removes heat by using it to evaporate water from its structure (Kattas *et al.*, 2000). It is typically used in flexible PVC formulations in the 20 to 50 phr (parts per hundred parts resin) range (Kroushl, 2004). ATH is typically manufactured from the mineral bauxite, which contains 40 to 60 percent alumina, silica (silicon oxide), iron oxide, and titanium dioxide. In the Bayer process for alumina production, the alumina is dissolved in hot sodium hydroxide solution, and the iron oxide and other oxides are removed as insoluble “red mud.” The solution is then purified, and aluminum trihydrate is precipitated by cooling the purified solution and seeding with aluminum trihydrate crystals (Beck, 2001).

Antimony trioxide (ATO) is a flame retardant synergist that acts to enhance the flame retarding properties of bromine- or chlorine-based flame retardants (Kattas *et al.*, 2000). It is used in PVC-based compounds in the 2 to 3 phr range (Kroushl, 2004). ATO is produced from stibnite ores (antimony trisulfide) or as a by-product of lead smelting and production (IARC, 1989). The manufacture of ATO involves a sublimation reaction of antimony metal with oxygen. Commercial ATO generally contains a maximum up to 0.25 percent of lead and up to 0.1 percent of arsenic contaminants on a weight basis (EFRA, 2006). In cables (in this study) that use ATO, the ATO is less than 3 percent by mass of a length of cable.

2.1.2.4 Heat stabilizer manufacturing

Heat stabilizers are added to PVC in order to prevent its thermal degradation during periods of exposure to elevated temperatures, such as during processing (i.e., extrusion) and during the useful life of the cable (Kattas *et al.*, 2000). The cables the WCP is studying use either lead-based heat stabilizers or mixed metal-based heat stabilizers. Lead-based heat stabilizers have been the predominant heat stabilizers used in wire and cable applications because they have provided cost-effective stabilization while offering excellent electrical insulation properties. However, lead-based heat stabilizers are being replaced by mixed metal-based heat stabilizers because of concerns about the toxicity of lead (Kattas *et al.*, 2000).

The WCP was unsuccessful in its attempts to collect primary data for the manufacture of lead-based heat stabilizers, but a secondary data set for lead manufacturing was available (Primary lead mix, 1997). Because lead-based heat stabilizers are predominantly composed of lead, the lead data set was used as a surrogate for lead-based heat stabilizer manufacturing, by applying the percentage of lead in the lead-based heat stabilizer to the lead data set. Lead sulfates (e.g., tribasic lead sulfate) are inorganic-based stabilizers that are manufactured by reacting lead oxides with sulfuric acid or a sulfate solution (Baitz *et al.*, 2004). Dibasic lead phthalate, an organic-based heat stabilizer, contains 76 percent lead; tribasic lead sulfate contains 83.5 percent lead (Associated Additives, 2007). Since the lead-based stabilizers are included for the potential environmental significance of lead, and comprise only small percentages of the non-copper portion of the cables, the remaining non-lead portion of the heat stabilizers, which constitute even smaller percentages of the cables, are not included as upstream data.

Primary data for calcium/zinc-based heat stabilizer manufacturing were provided by two different companies. Calcium/zinc-based heat stabilizers are simple physical blends; no chemical reactions occur. The stabilizers are manufactured by mixing the components in an electrically powered ribbon blender. Table 2-6 shows a typical formulation for a Ca/Zn based stabilizer.

**Table 2-6
Ca/Zn-Based Heat Stabilizer Formulation**

| Material | Weight |
|-----------------------|---------------|
| hydrotalcite/zeolite | 0.56 kg/kg |
| calcium stearate | 0.18 kg/kg |
| zinc stearate | 0.17 kg/kg |
| proprietary additives | 0.09 kg/kg |

2.1.2.5 Fillers

The primary fillers used in the manufacture of wire and cable are limestone (CaCO_3) and calcined clay. The inventory for the production of both minerals was obtained from secondary data contained within GaBi. The inventory for limestone was based on studies from 1995, 1997, and 1999 documented in German. The source of the inventory for calcined clay, or kaolin, was from 1995 data.

2.1.2.6 Fuels and process materials

The fuel and power inventories were obtained from secondary data sources. The GaBi database inventories of natural gas, fuel oils, and electricity generation were used, and they contain the following processes:

- Electricity generation - Assumes a grid of 52.3 percent hard coal, 22.7 percent nuclear power, 12.4 percent natural gas, 4.2 percent crude oil, 3.5 percent lignite, 3.4 percent hydro, and 1.5 percent other. This process includes the extraction of individual fuels from the ground (e.g., coal, lignite, uranium) and the energy required to extract those fuels. Steam and cogenerated electricity were not modeled as products of the grid, but rather as a burden-less byproduct of using natural gas to generate heat during other processes.
- Natural gas - Exploration, extraction, processing, and distribution (via pipeline or liquefied natural gas [LNG] tanker) to the end customer.
- Light fuel oil (#2) - Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, desulphurization (i.e., medium distillates to hydrofiner), medium distillates mix plant that produces light fuel oil.
- Heavy fuel oil (#6) - Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, residue to fuel mix plant that produces heavy fuel oil.

Table 2-7 summarizes the data sources and data quality information for the secondary fuel and power source inventories used in this study.

2.1.3 Limitations and uncertainties

Upstream data for the primary materials used in wire and cable compounds are not readily available. Primary and/or secondary data sets were collected for 12 of the 16 materials identified for inclusion in the upstream data collection process. Primary data were collected for two of the materials: FEP and Ca/Zn-based heat stabilizers. Secondary data were collected for the remainder (see Table 2-5). For the lead-based stabilizers, while data was unavailable on the compounds themselves, the majority of the compounds are lead, and thus the production process of lead was included and scaled to the amount of lead in the stabilizer compounds. Secondary data sets were also collected for all of the fuels and electricity used in the compounding and extruding processes that met the decision rules.

The limitations and uncertainties associated with the ME&P stage inventories are primarily due to the fact that some of these inventories were unobtainable and others were derived from secondary sources and are not tailored to the specific goals and boundaries of the WCP. Because the secondary data may be based on a limited number of facilities and have different geographic and temporal boundaries, they do not necessarily represent current industry practices in the geographic and temporal boundaries defined for the WCP (see Chapter 1). These limitations and uncertainties are common to LCA, which strives to evaluate the life-cycle environmental impacts of entire product systems and is, therefore, limited by

resource constraints that do not allow the collection of original, measured data for every unit process within a product life cycle.

Table 2-7

Data Sources and Data Quality for Fuel and Power Inventories Used In Various Life-Cycle Stages

| Materials | Year of data | Geographic boundaries | | Primary data sources ^a | Data quality description |
|------------------------|--------------|--|---------------|-----------------------------------|--|
| | | Extraction | Processing | | |
| Natural gas | 1995 | Canada, Mexico, United States, Algeria | United States | b, c | GaBi4 states the data quality is "...good. The important flows are considered. Natural gas supply is representative." |
| Light fuel oil (#2) | 1994 | Unclear (various country-based data sources cited) | Germany | d, e | GaBi4 describes the data quality as "good." It is average industrial data from 1994. |
| Heavy fuel oil (#6) | 1994 | Unclear (various country-based data sources cited) | Germany | d, e | GaBi4 describes the data quality as "good." It is average industrial data from 1994. |
| Electricity generation | 1995 | Multiple countries, fuel dependent | United States | Not available | GaBi describes the data quality as "good," claiming to use consistent statistics and a comparable information basis for every state. |

^a All primary data sources are available within the GaBi4 database (PE&IKP, 2003).

^b ETH Zuerich. oekoinventare Energiesysteme. Schweiz, 1996 (in PE&IKP, 2003).

^c U. Fritsche *et al.* Gesamt- Emissions- Modell Integrierter Systeme (GEMIS) Version2. Darmstadt, 1992 (in PE&IKP, 2003).

^d ETH Zuerich. oekoinventare Energiesysteme. Schweiz, 1996 (in PE&IKP, 2003).

^e K. Weissermehl; H.J. Arpe. Industrielle Organische Chemie. 5. vollst. ueberarb. Auflage. Weinheim, 1998 (in PE&IKP, 2003).

Specific to the secondary PVC and HDPE inventories, a major assumption is that European-based data for production of these resins is similar to U.S.-based process data. For PVC, chlorinated intermediate materials such as ethylene dichloride and vinyl chloride were not provided in the inventory, which will affect occupational inputs (see Chapter 3). For the lead-based heat stabilizer inventory, a major assumption is that the production of lead adequately represents the upstream impacts associated with lead-based stabilizer manufacturing. Specific to the electric grid inventory, uncertainties exist in the weighting values applied to the various fuel sources from which the power is generated for the U.S. electric grid. The factors were based on a reference year of 1995, and, thus, may vary given the volatility of the oil supply and the current U.S. energy policy.

Other, specific limitations include the following:

- For the primary data sets (i.e., FEP and Ca/Zn production), 2 companies provided data for each process. While a greater number of companies would have been preferred, those providing data likely represent a large market share of the products.
- Data for phthalate esters were not directly available; thus the *Ecobilan* data, which combines the production of several phthalate esters into one data set, was used to represent all phthalate plasticizers identified for the cables being studied in this project. It is unknown what the

implications of this limitation would be on the results; however, those alternatives using a smaller amount of plasticizers will have less uncertainty associated with this limitation.

- Upstream process data for trimellitate plasticizers (used for CMR and NM-B cables) were not included in the LCIs for this study; however, these plasticizers are used in lower amounts than the phthalate plasticizers.
- Upstream data for some flame retardants were not available; however, those for which data were lacking only constitute small amounts of the cable insulation and jacketing by mass.
- FEP production data does not include extraction and processing of fluorspar and many other post-mining precursors, in contrast to PVC and HDPE. However, this only affects the results to the extent there are differences in the amount of FEP used in the lead versus the lead-free alternatives (the baseline uses under 10 percent more FEP by weight).
- Secondary data are not all US-specific; however, it is unknown how this affects the results, except that it contributes to uncertainty.

In general, although some upstream data have been excluded from the LCIs despite meeting the mass cutoff, what is most important about how they affect the results is how different the quantities are for the alternatives being compared. For example, if CMP, lead-stabilized cables use nearly the same amount of a certain material, there will be less impact on the results.

2.2 Manufacturing Life-Cycle Stage

This section addresses the LCIs related to the product manufacturing life-cycle stage of cables. The cable manufacturing life-cycle stage includes two distinct processes: the compounding of the insulation and jacketing resins, where applicable, and cable manufacturing, which includes extrusion of insulation and jacketing.

The purpose of this section is to present the approach for obtaining process-specific inventory data related to the manufacturing stage (i.e., compounding, crossweb manufacturing, and extruding) of three cable types: Category 6 CMR- and CMP-rated telecommunications cables, and low-voltage power (i.e., NM-B) cables. LCI inputs for the manufacturing stage of the WCP include primary materials used in the insulation and jacketing compounds and in the cable extrusion process, ancillary materials used to manufacture the compounds and extrude the cables, and energy and other resources consumed in the manufacturing of the compounds and extrusion of the cables. LCI process output flows include primary products; co-products; and releases to air, water, and land.

2.2.1 Data collection

Primary data were collected through site visits or through the distribution of data collection forms for all of the processes associated with the manufacturing life-cycle stage. Site visits were conducted at four facilities, representing two compounders, two extruders, and one crossweb manufacturer (one facility performs both compounding and extruding).

Data collection forms were developed by the Abt Associates, Inc. research team and approved by the Core Group to most efficiently collect and organize inventory data needed for the LCA (Appendix A). Data forms were completed during site visits or directly by companies when site visits were not possible. Collected data included brief process descriptions; primary and ancillary material inputs; utility inputs (e.g., electricity, fuels, water); air, water, and waste outputs; and product outputs. Quantities of inputs and

outputs provided by companies were converted to mass per unit of product produced, which was later scaled to the mass per one kilometer of cable length to conduct the analyses on a common functional unit basis. Transport of materials to and from the manufacturing facility was excluded from the data collection process for this study, because it was assumed that impacts from transportation would be similar for all alternatives within each product type.

During each site visit, Abt Associates, Inc. researchers and company personnel completed a data collection form similar to those completed by facilities that were not visited. Each site visit took approximately half a day and included an extensive tour of the processes, interviews with process personnel, and a period of time spent completing and reviewing the data on the collection form for accuracy. Data either had been previously measured or collected by the facility, or were estimated with the assistance of process personnel with appropriate experience and process knowledge. Data were collected, when possible, on a per mass of compound or cable produced basis.

Data collected from the processes were then scaled to represent the mass of the material required per functional unit, which for the WCP is one kilometer (3,281 feet) of cable. Process data collected based on volume were converted to mass using the product's density. In cases where data collected covered the processing of more than one type of compound or cable (e.g., monthly energy consumption for a process producing multiple compounds or cable types), data were allocated to the various compound or cable types based on the mass of product produced. Other data were allocated to the compounds or cables using appropriate conversions, where applicable. Multiple data sets collected for a single process were aggregated before being used for analyses in the study. Data were aggregated to generate a single value for each inventory item, to represent an industry average and to protect the confidentiality of individual data points. The one variation to this approach (for CMR/CMP extrusion energy data) is described in Section 2.2.4.

2.2.2 Telecommunications cables

The WCP is evaluating two types of telecommunications cables: Category 6 riser-rated cable (CMR) and Category 6 plenum-rated cable (CMP). These cables consist of four pairs of insulated copper conductors that are separated by a crossweb and encased in a plastic jacket. Primary data for the manufacturing life-cycle stage were collected from compounders, crossweb manufacturers, and extruders through a series of facility site visits and through the distribution of data collection forms. Data were collected for the standard (i.e., baseline) and alternative formulations for both cable types (see Section 2.1.1). Although these processes vary slightly by manufacturer and cable type, the overall process for manufacturing telecom cables follows a similar series of process steps. Figure 2-2 displays a flow diagram for both CMR and CMP cable manufacturing. The diagram depicts the primary process steps for which manufacturing LCI data were collected. (Note that the wire drawing process was excluded from this study.)

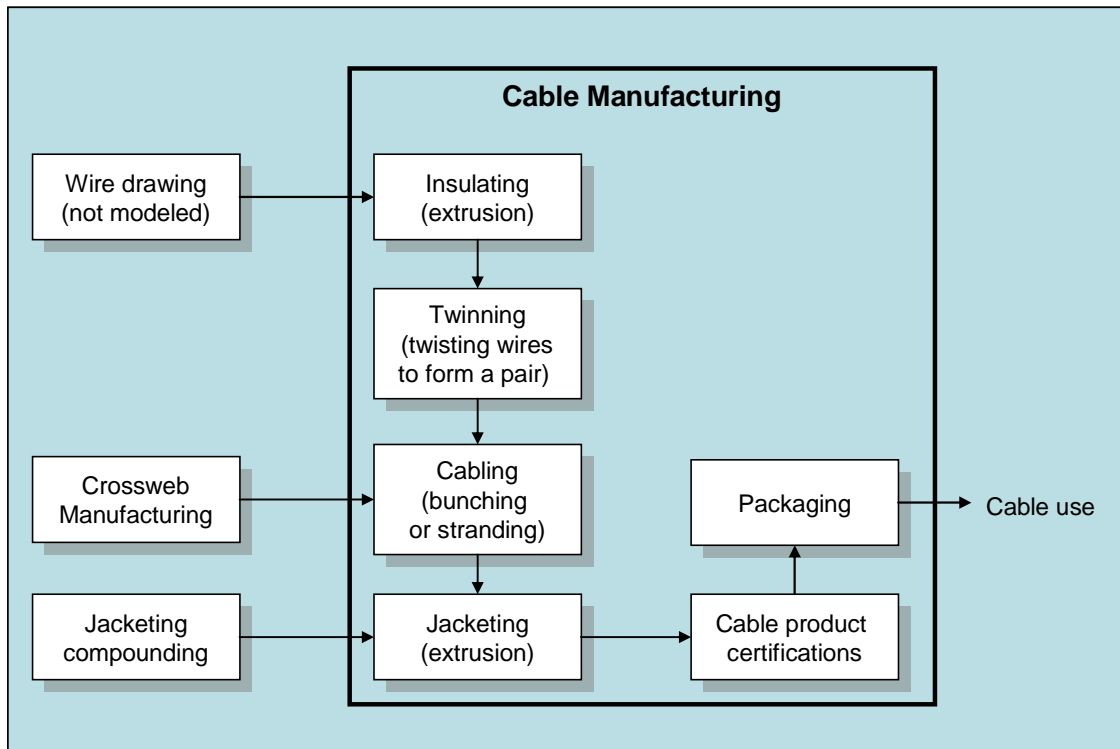


Figure 2-2. Manufacturing Process Diagram for CMR- and CMP-rated Telecommunications Cables

Compounding, a preliminary step in the manufacturing stage, involves the blending of the base jacketing resin (PVC) with various additives in order to impart desired characteristics (e.g., flame retardancy, flexibility) in the resin. Within the wire and cable industry, compounding is conducted either by custom compounders or by the cable manufacturers themselves. Crosswebs, which typically consist of only the base insulation resin (i.e., HDPE or FEP), are manufactured by extrusion. Cable manufacturing is a multi-step process that involves extruding insulation onto the conductors, twinning two insulated conductors to form a pair, bunching or stranding multiple twisted pairs (cabling), extruding a jacket over the bunched pairs, and packaging the cable for sale.

Primary data were collected for the three processes—compounding, crossweb manufacturing, and extruding—that comprise the manufacturing life-cycle stage for telecom cables. The following subsections describe these processes and the associated data collected for them.

2.2.2.1 Compounding

PVC, which is used as a jacketing for CMR and CMP cables, is given its desired properties (e.g., flexibility, resistance to thermal degradation, flame retardancy) by compounding the base PVC resin with a variety of additives—plasticizers, heat stabilizers, and flame retardants—at an elevated temperature. Although each individual PVC compounder uses its own proprietary mix of additives, they all employ a similar PVC compounding process.

PVC compounds are prepared in a batch process using blenders that allow precise temperature control. The compounding process involves high-intensity blending of resin and additives to form a dry blend powder, which is then compounded using compounding equipment, such as a Farrell Continuous Mixer (FCM), a Buss Kneader, or twin screw and other machines. The compounded mixture is then

pelletized. The pellets are spherical or cylindrical, with diameters averaging 1 to 5 mm (Barry and Orroth, 2000).

Electricity is the main energy source used in the compounding process; it is used to power the blenders and roll mills. The compounding process also uses fuel oil or natural gas to produce steam, which provides heat to the blenders.

Primary data for manufacturing the baseline and alternative CMR and CMP jacketing compounds of interest to the WCP were collected directly from the compounders participating in the project. A total of six primary datasets were received for compounding CMR jackets: three for lead-stabilized compounding, two for Ca/Zn-stabilized compounding, and one for halogen-free CMR jacket compounding. Four primary datasets were received for compounding CMP jackets: two for lead-stabilized compounding and two for Ca/Zn-stabilized compounding.

2.2.2.2 Crossweb manufacturing

The Category 6-rated CMR and CMP unshielded twisted pair (UTP) telecom cables of interest to this study contain a crossweb or pair separator. Crosswebs provide physical and electrical separation of the twisted conductor pairs, which improves the cable's crosstalk performance. (Crosstalk is the unwanted interference signal that comes from coupling between one conductor pair and another; see d'Allmen, 2000.) Although the specific design of the crossweb varies by manufacturer, the material used in the crossweb is typically chosen so that it mimics the insulation material used in the cable as closely as possible. The crosswebs used in the cables of interest to this study generally consist of virgin or postindustrial recycled PE (for CMR cables) or FEP (for CMP cables). Postindustrial sources of FRPE and FEP include resin that does not meet specification, and bleeder scrap (i.e., the plastic that cable manufacturers generate during the start-up of their extrusion lines). Postconsumer cable scrap (i.e., plastic collected from cable chopping operations) is currently not usable as a feedstock for crosswebs because the plastic contains an unacceptable level of copper fines.

Crosswebs are manufactured by a basic extrusion process. The extruder line consists of a hopper to hold the resin, a screw extruder, a cooling bath, a puller (to pull the crossweb through the process), and a reel for winding the final product. Electricity, which is used to heat the extruder, is the main energy source used during the crossweb manufacturing process. FEP-based crosswebs require more energy to extrude than PE-based crosswebs because FEP has a higher melting temperature than PE; therefore, a higher temperature is required in the extruder.

Primary data for CMR and CMP crossweb manufacturing were collected directly by one crossweb manufacturer participating in the project.

2.2.2.3 Cable manufacturing

Cable manufacturing is a multistep process. The conductor material (e.g., copper wire) is first drawn to the specified diameter. The bare wire is then transferred to the wire coating line, where electrical insulation material (HDPE for CMR cables, FEP for CMP cables) is extruded onto the conductor using a single-screw extruder. The wire coating line typically consists of an unwinding roll for the wire followed by a tension controlled input capstan, possibly a wire straightener, and a wire preheater, which improves the adhesion of the plastic to the conductor. The wire proceeds from the preheater to the extruder's crosshead die, where the melted plastic insulation is applied. Processing temperatures in the die average 400° F (204° C) for HDPE and 650 to 700° F (343 – 371° C) for FEP. The coated wire continues through a water bath and/or air-cooling system, spark tester, gauge controller, tension output

capstan, and tension controller, and is then wound onto a bobbin or reel. Output rates for extruding the wire insulation average approximately 550 m/min (1,800 ft/min) for FEP and 1,500 m/min (5,000 ft/min) for HDPE (Tyler, 2007).

After the insulation has been applied, two conductors are twisted together (paired) in a process called twinning. The number of twists per foot is precisely controlled during the twinning process, and each of the four pairs is twisted differently (i.e., different number of twists per foot) in order to limit crosstalk between pairs in the final cable. Twinning lines use two motors: one to feed insulated wire to the process and one to take up the twisted conductor pairs. The next step is cabling, in which four of the twisted pairs are bunched or stranded together with a crossweb separating the twisted pairs. A jacket, which protects the conductors from mechanical damage and provides fire retardancy, is then extruded over the core using a process similar to the one used to apply the wire insulation. Any markings are printed onto the cable jacketing during this step. Jacketing proceeds at an average speed of 400 to 500 feet per minute (120-150 m/min); temperatures in the die average 320 to 350° F (160 – 177° C). Both the CMR and CMP cables use compounded PVC for the jacketing. The final cable product is tested for adherence to electrical parameters and then packaged into customer-desired lengths.

The primary wastes from the cable manufacturing process (excluding waste from the copper drawing process) are scrap cable, and insulation and jacketing resins. Any insulation or jacketing that is bled from the extruding lines during start-up or shut-down is collected and recycled to the process. Preconsumer PVC waste is relatively easy for PVC compounders and cable extruders to recycle and reuse as an equivalent for virgin PVC, because the composition is known. Scrap cable from the process is sent to cable chopping operations for recycling (see Section 2.4).

One dataset was collected for CMR Pb-stabilized cable manufacturing, two datasets were received for CMR Ca/Zn-based cable manufacturing, and no datasets were received for halogen-free CMR cable manufacturing. For CMP cable manufacturing, one dataset was received for Pb-stabilized CMP cables and two datasets were received for Ca/Zn-stabilized CMP cables.

2.2.3 Low-voltage power cables

The WCP is evaluating one type of low-voltage power cable—nonmetallic-sheathed cable (NM-B)—that is primarily used in residential wiring as branch circuits for outlets, switches, and other loads. There are numerous types of NM-B cables available because both the conductor gauge and number of conductors can be varied. The WCP chose to focus on 12-2 NM-B cables because they are the most commonly used NM-B cables. 12-2 NM-B cables consist of two insulated copper conductors and a paper-wrapped ground wire, all of which have a diameter of 12 AWG (American Wire Gauge). The entire assembly is wrapped with a paper filler, then encased in a plastic jacket.

Primary data for the manufacturing life-cycle stage were collected from compounders and extruders through facility site visits and through the distribution of data collection forms. Data were collected for baseline and alternative formulations for 12-2 NM-B cables. Although the compounding and extruding processes vary slightly by manufacturer, the overall process for manufacturing low-voltage power cables follows a similar series of process steps. Figure 2-3 displays a flow diagram for the manufacture of NM-B cables. The diagram depicts the primary process steps for which manufacturing LCI data were collected. (Note that the wire drawing process was excluded from this study.)

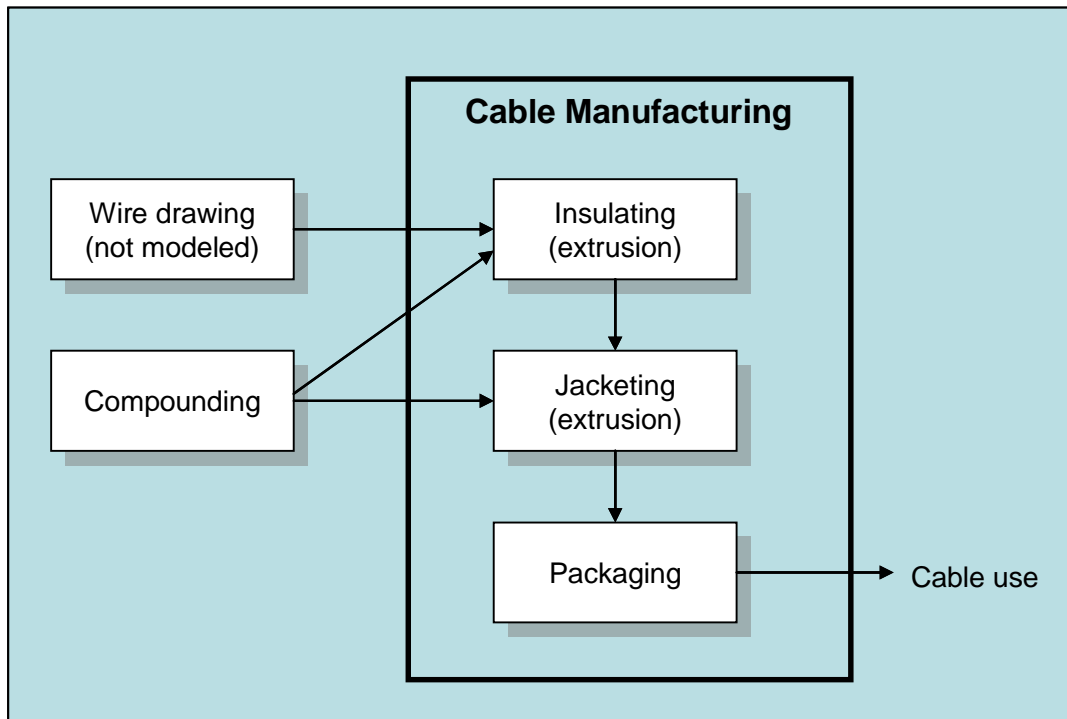


Figure 2-3. Manufacturing Process Diagram for Nonmetallic-sheathed Low-voltage Power Cable

Similar to the communication cables, compounding is the first step in the manufacturing life-cycle stage. Compounding involves the blending of a base resin (i.e., PVC) with various additives in order to impart desired characteristics (e.g., flame retardancy, flexibility) to the resin. Within the wire and cable industry, compounding is conducted either by custom compounders or by the cable manufacturers themselves. Cable manufacturing (primarily involving extruding) is a multi-step process that involves extruding insulation onto the conductors, applying the paper filler to the ground wire, wrapping the entire construction with a paper filler, extruding a jacket over the three wire assembly, and then packaging the cable for sale.

Primary data were collected for compounding and extruding of low-voltage power cables, which are described in the following subsections.

2.2.3.1 Compounding

PVC is used as insulation and jacketing for NM-B cables, is given its desired properties (e.g., flexibility, resistance to thermal degradation, flame retardancy) by compounding the base PVC resin with a variety of additives—plasticizers, heat stabilizers, and flame retardants—at an elevated temperature. Although each individual PVC compounder uses its own proprietary mix of additives, all employ a similar PVC compounding process.

As described above in Section 2.2.2.1, which discusses CMR and CMP cables, PVC compounds are prepared in a batch process using blenders that allow precise temperature control. The compounding process involves high-intensity blending of resin and additives to form a dry blend powder, which is then compounded using compounding equipment, such as a Farrell Continuous Mixer (FCM), a Buss Kneader,

or Werner-Pfleiderer PK-400 machines. The compounded mixture is then pelletized using a twin-screw extruder. The pellets are spherical or cylindrical with diameters averaging 1 to 5 mm (Barry and Orroth, 2000).

Electricity is the main energy source used in the compounding process; it is used to power the blenders and compounders. The compounding process uses fuel oil, natural gas, and propane to produce steam, which provides heat to the blenders.

Three primary datasets were received for NM-B Pb-stabilized insulation compounding; only one dataset was received for compounding the Pb-stabilized jacket. For the Ca/Zn-stabilized compounds, two datasets were received for the insulation and one was received for the jacketing.

2.2.3.2 Cable manufacturing

Cable manufacturing (primarily involving extruding) is a multistep process. The copper conductors and ground wire are first drawn to the specified diameter. The conductors are then transferred to the wire coating line, where the electrical insulation is extruded onto the conductors using a tandem extruder. The tandem extruder first extrudes the PVC-based electrical insulation compound onto the bare wire and then immediately extrudes a nylon jacket onto the PVC. Color concentrates are added to the PVC in the extruder. The wire coating line typically consists of an unwinding roll for the wire followed by a tension-controlled input capstan, possibly a wire straightener, and a wire preheater, which improves the adhesion of the plastic to the conductor. The wire proceeds from the preheater to the extruder's crosshead die, where the melted plastic insulation is applied. Processing temperatures in the die average 320 to 350 °F (160 – 177 °C). If required by the customer, the specifications are then printed on the conductor. The coated wire continues through a water bath and/or air-cooling system, spark tester, gauge controller, tension output capstan, and tension controller, and is then wound onto a roll. Output rates for extruding the wire insulation average 4,000 feet per minute (1,300 m/min) (Barry and Oroth, 2000; Rosato, 1998).

Spools of the insulated conductors and uncoated ground wire are mounted at the beginning of the jacketing line. Two spools of paper, which are approximately one to two inches wide, are also mounted at the beginning of the jacketing line. The ground wire is first wrapped with paper, rather than being insulated with plastic, because paper is less expensive than plastic. The insulated conductors and paper-wrapped ground wire are then laid parallel, with the ground wire between the conductors, and the entire assembly is wrapped with a paper filler. A PVC-based jacket, which protects the conductors from mechanical damage and provides fire retardancy, is then extruded onto the cable using a process similar to the one used to apply the wire insulation. Jacketing proceeds at an average speed of 400 to 500 feet per minute (120-150 m/min); temperatures in the die average 320 to 350 °F (160 – 177 °C). An inkjet printer prints the specifications onto the jacketing before the cable is cooled in a water bath. The finished cable is then coiled, spooled, or reeled, depending upon the customers' needs, and packaged for delivery.

Electricity is the main energy source used during the cable manufacturing process. It is used for wire drawing, to melt the plastic in the extruder, and to drive machinery that moves the wire around the facility.

The primary wastes from the cable manufacturing process (excluding waste from the copper drawing process) are PVC and nylon. These materials are primarily generated as bleeder scrap (i.e., insulation and jacketing that is bled from the extruding lines during startup). A majority of the bleeder scrap is repelletized and reused in the process, but that which is not recyclable is sent to landfills. Scrap

cable is sent to cable chopping operations for recycling. (See Section 2.4 for more information about the cable chopping process.)

One primary dataset was received for NM-B Pb-stabilized cable manufacturing; no datasets were received for Ca/Zn-stabilized cable manufacturing.

2.2.4 Data collection summary

Table 2-9 shows the number of primary datasets received for the major processes associated with the cable manufacturing life-cycle stage. Primary data were collected for the major processes associated with the manufacturing life-cycle stage for telecom and low-voltage power cables. These data were collected directly from eight cable compounders and manufacturers through site visits and through the distribution of data collection forms. These data represent a total of 30 data sets for the manufacturing life-cycle stage of the three cable types.

Table 2-9

Total Primary Datasets Received for the Cable Manufacturing Life-cycle Stage

| Cable type/alternative | Crossweb manufacturing | Compounding | | Cable manufacturing | Total |
|------------------------|---------------------------|-------------|-----------|------------------------|-------|
| | | Insulation | Jacketing | | |
| CMR Pb-stabilized | 1 | n/a | 3 | 1 | 5 |
| CMR Ca/Zn-stabilized | 1 | n/a | 2 | 2 | 5 |
| CMR halogen-free | 0 | n/a | 1 | 0 | 1 |
| CMP Pb-stabilized | 1 | n/a | 2 | 1 | 4 |
| CMP Ca/Zn-stabilized | 1 | n/a | 2 | 2 | 5 |
| NM-B Pb-stabilized | n/a | 3 | 2 | 1 | 6 |
| NM-B Ca/Zn stabilized | n/a | 2 | 2 | 0 | 4 |

Multiple data sets for a process were averaged to represent the industry average. In one case, a large discrepancy existed, and the simple averaging approach was modified as necessary. That is, for CMR and CMP cables, electricity is the main energy source used during the cable manufacturing process. It is used for wire drawing, to melt the plastic in the extruder, and to drive machinery that moves the wire around the facility. The modeling of the extrusion of *lead-free* CMR/CMP cable drew upon data sets from two companies. Utilities information from these data sets suggested that the use of electricity during the extrusion process varies highly from company to company. The modeling of the extrusion of the *baseline* CMR/CMP cable drew on data from only one of these companies. Consequently, the aggregated lead-free value from the two companies was divergent from what would be expected as an aggregated value for the baseline (as verified by the companies supplying the data). In light of this, a proxy energy value for the baseline CMR/CMP cable was created. The proxy value was generated by applying the ratio of the extrusion energy of the lead-free extrusion energy data points to the lead case. Thus,

$$\text{PROXY}_{\text{base},2} = (E_{\text{Pb-free},2} / E_{\text{Pb-free},1}) E_{\text{base},1}$$

2.2.5 Limitations and uncertainties

Limitations and uncertainties related to the data collection process include the fact that companies were self-selected, which could lead to selection bias (i.e., those companies that are more advanced in

terms of environmental protection might be more willing to supply data than those that are less progressive). Companies providing data also may have a vested interest in the project outcome, which could result in biased data being provided. Where possible, multiple sets of data were obtained for this project to develop life-cycle processes. The peer review process and employment of the Core Group as reviewers in this project is intended to help identify and reduce any such bias. Additional limitations to the manufacturing stage inventory are related to the data themselves. Specific data with the greatest uncertainty include the utility data for multiple processes that were scaled to the specific process or processes of interest to the WCP. The greatest source of variability in the data was the CMR/CMP cable extrusion energy, described in the preceding section.

2.3 Use Life-Cycle Stage

The use stage encompasses installation, use, maintenance, repair, and reuse of the standard and alternative cables. During these activities any input flows such as materials, fuels, and electricity are assumed to be the same for each alternative within a cable type, and therefore do not affect the comparative analyses in this study. Further, no direct outputs would be anticipated. While installers could be exposed to dust recirculated within an existing installation site from aging cable insulation and jacketing, these exposures are expected to be the same regardless of the alternative and therefore also would not affect the study's comparative analyses.

2.3.1 Installation

For installation during new construction, CMP communications cable is placed within the plenum space, typically using a J-hook or a tray to secure it. The cable is mechanically connected and left in place for use. The ceiling acoustic tiles are then secured. When additional cable is installed, a few ceiling tiles are removed and new cable is added (Dawson, 2007). CMR communications cable is placed in conduits or secured to existing structures with ties during installation. The cable is left in place for use after being mechanically connected.

NM-B cable is used primarily in residential wiring as branch circuits for outlets, switches, and other loads. The cable is typically installed during residential construction through holes drilled into studs where the cable is pulled through. If additional cable is added, holes are drilled in the wall and the cable inserted (Sims, 2007).

Within each cable type, installation procedures are the same for each cable alternative, which supports the scoping decision to exclude the use stage from the LCI.

Although concern has been raised about the existence of lead dust during installation of new cables (Wilson, 2004), any existing dust would be the same for any alternative, provided installation occurs at the same time for each alternative. For example, if lead-free CMP cable is compared to lead-stabilized CMP cable, installation would occur at the same time and installers would have the same exposure to existing dust, regardless of the resin cable being installed. Differences would occur at EOL when cables are removed and dust is generated from either the leaded or lead-free alternative.

2.3.2 Use, maintenance, and repair

Communications cable and electrical cable are used in temperature-controlled environments where the temperatures are well below those known to release chemicals of concerns from cable insulation or jackets under normal conditions. (Catastrophic events such as fires are addressed in the end-of-life, Section 2.4). Communications cable has built-in redundancy; therefore, there is no planned

maintenance and repair during cable life, and the cable's technical obsolescence is the usual driver for replacement (Dawson, 2007). NM-B electrical cable has a 25 to 40 year useful life with typically no maintenance or repair. The cable installed at construction is usually used throughout the building life (Sims, 2007). For this analysis, there is no difference among the standard and alternative cable types for use, maintenance, and repair.

2.3.3 Reuse

Communications cable is typically replaced when it is obsolete (Dawson, 2007) and there is little domestic market for reuse. Any reuse in developing world markets is outside the scope of this analysis. Electrical cable, with a life span of 25 to 40 years, is not reused either, often due to electrical codes (Sims, 2007). However, the copper conductor in both types of cable is likely to be recovered (as discussed in Section 2.4).

2.3.4 Limitations and uncertainties

The use stage has not been included in the WCP LCIs. Since the focus of the analyses in this project is comparing functionally equivalent alternatives, and no differences among alternatives are anticipated during the use stage, no limitations are foreseen. Potential exposure to workers removing cables is discussed in Section 2.4, although the WCP does not quantify such exposures. Because this life-cycle stage is excluded, care must be taken not to interpret results as the full life cycle of an individual alternative, but rather as a comparison of differences among alternatives.

2.4 End-Of-Life

EOL issues are of growing interest to cable manufacturers, building owners, and building tenants, due to the National Electrical Code's requirement that all accessible abandoned copper and fiber optic cabling be removed from buildings. It is important to note that although the copper conductor material is an essential component of cable wire and contributes to life-cycle impacts, this project focuses on the insulation and jacketing resins, and follows disposition of these materials through the end of life.

This section describes the issues associated with EOL cables (i.e., cables that have been used for their initial, intended purpose and are no longer intended to be used), and the approach used to evaluate the EOL life-cycle stages of CMR, CMP, and NM-B cables for the WCP. This approach includes developing scenarios to represent reasonable EOL alternatives, and collecting LCI data for the EOL alternatives.

2.4.1 Background

Based on 2002 data, U.S. sales of CMR-rated cables average approximately 1.2 billion ft/yr and account for 15 percent of the total U.S. communications network cable market. CMP-rated cable sales total approximately 6.0 billion ft/yr, accounting for approximately 75 percent of the U.S. communications network cable market (CRU, 2002). Category 6 cables held approximately a 45 percent share of the unshielded twisted pair (UTP) market in 2005, with rapidly increasing growth (Glew, 2005). An estimated 2.7 billion ft/yr of Cat 6 CMP-rated cable, and 0.54 billion ft/yr of Cat 6 CMR-rated cable, is installed annually in the U.S.¹⁰

¹⁰ This assumes that the breakdown of CMP- and CMR-rated cables (75% and 15%, respectively) holds true for Cat 6 cables: $6.0\text{B ft/yr} \times 0.45 = 2.7\text{B ft/yr}$ of Cat 6 CMP cable, and $1.2\text{B ft/yr} \times 0.45 = 0.54\text{B ft/yr}$ of Cat 6 CMR cable.

In 2005, the annual U.S. market for NM-B rated cable was estimated at 800 million to 1 billion pounds (7.3 to 9.2 billion feet)¹¹ (Sims, 2005). Information on projected sales of communications and low-voltage power cables or on amount of cable installed (current and projected) was not available.

Cables are long-life products; therefore, there is a considerable time lag between when the cables are manufactured and installed and when they reach end-of-life. For example, communications cables have an expected lifetime of 10 to 15 years, due to obsolescence resulting from technological advancements. In addition, low-voltage power cables have a useful life of approximately 25 to 40 years. As a result of this time lag, current EOL generation patterns of cables are not correlated with their contemporary production (Mersiowsky, 2002). A large quantity of PVC waste is not expected to hit the market until 2010 because PVC did not achieve significant market shares until the 1970s (Plinke *et al.*, 2000).

The removal of abandoned cabling is expected to generate in excess of 300 million pounds of plastic waste over the “next several years” (Realcomm Advisory, 2006). EOL cables are generated in small quantities from disperse sources. This may change over time as more EOL cable becomes available due to stricter regulations, such as the Abandoned Cable Provision of the National Electrical Code (Realcomm Advisory, 2006).

Projected amounts of EOL cable in the U.S. were not found (e.g., the amount of communications EOL cable in 10 and 15 years; and the amount of low-voltage power EOL cable in 25 and 40 years).

2.4.2 Materials Recovery

2.4.2.1 Copper

End-of-life communications and low-voltage power cables are valuable because they consist of approximately 50 percent copper by weight, which sold for \$4,800 to \$7,400/ton in the last year (June 2006 to June 2007) (COMEX, 2007). According to the Bureau of International Recycling (BIR), this historically high price of copper ensures that an estimated 95 percent of EOL cable and wire is recycled (Bartley, 2006). EOL cables are highly sought after by copper consumers in North America and overseas, and overseas competition, especially from China, is often cited as a source for changes that have greatly affected the wire and cable recycling sector in recent years. Foremost among the changes has been a willingness among export brokers representing consuming companies in China to pay more for copper-bearing wire and cable scrap than many North American consumers will pay (Taylor, 2005). China’s seemingly insatiable demand resulted in a shortage of copper cable for U.S. scrap cable processors in 2003 (Taylor and Toto, 2003); however, in 2004, customs, trade, and environmental regulations in China slowed down the pace of EOL cable sales to China and helped to re-establish the U.S. wire chopping market (Taylor, 2004).

2.4.2.2 Polymer fraction

Traditionally the polymer fraction (i.e., insulation, jacketing, and crossweb) of EOL cables has been landfilled because it is regarded as a waste product with little value; however, it does have value and can be recycled (Hagström *et al.*, 2006). The types of products the polymer fraction can be used for are typically limited because it consists of a mix of plastics (i.e., compounded PVC, HDPE, and FEP), whereas plastics extruders typically require a pure feedstock. Because these polymers are all

¹¹ Using an average net weight of 109 lbs/1,000 ft (0.109 lbs per foot for 12-gauge 3-conductor copper NM-B with ground wire, i.e., typical Romex building wire).

thermoplastics, they can be remelted during recycling and used as a substitute for virgin materials in general plastic products (e.g., industrial flooring, car floor mats and mud flaps, shoe soles, sound barriers, and garden hoses), concrete products (e.g., parking blocks, speed bumps, and large planters), and/or wood products (Plinke *et al.*, 2000).

The potential to collect and recycle installation wastes (i.e., cut-offs from installing cables) also exists; however, this cable waste is often mixed with other construction waste and would have to be separated prior to recycling (Plinke *et al.*, 2000).

Fluorinated ethylene propylene

While the high cost of virgin fluoropolymers provides a greater incentive to recycle the FEP from EOL cables, the small volumes that are available and the difficulty of separation make the recycling of FEP from EOL cables problematic (Ring *et al.*, 2002). However, several companies are developing technologies to effectively recycle fluoropolymer cable. For example, DuPont, Inc. has implemented a copper cable recycling program to develop new cable products containing recycled plastics. The program recycles the plastics from EOL communications cables into separate streams for each plastic material. DuPont notes that an average Category 6 enhanced plenum cable could contain over 3 lbs per 1,000 foot-box of recycled fluoropolymer (DuPont, 2006). In addition, some manufacturers of cable recover 100 percent of their waste FEP to manufacture pair separators used in Category 6 plenum cables (Uniprise, 2006).

Polyvinyl chloride

The amount of EOL PVC insulation and jacketing that is recycled is limited due to technical, economic, and logistical constraints (UNEP, 2002). Plinke *et al.* (2000) identify two primary technical constraints:

- PVC is a compounded material; an average cable jacket consists of a mixture of 50 percent plasticizers, heat stabilizers (often lead-based), flame retardants, and other additives, and 50 percent PVC resin.
- Different cable applications (i.e., CMR, CMP, and NM-B) use different PVC-based compounds, including different plasticizers, stabilizers, and flame retardants. Furthermore, different cable manufactures use their own unique compounds, so even within the same cable type, the compounds differ. These formulations also change over time, which can cause additional problems for a long-life product such as cable.

Because the overall PVC industry is large, many potential markets exist for the recovery of PVC materials. If the recycled PVC is to be used to produce new PVC products, its composition must meet the specifications of the new product, which may be achieved through additives to gain or enhance the needed properties (Bennett, 1990). However, the technical constraints noted above make it difficult to identify the composition of the post-consumer EOL PVC insulation and jacketing, and, for post-consumer PVC waste, to make a one-to-one substitution of recycled PVC for virgin PVC (Plinke *et al.*, 2000).

Based on a European source (Plinke *et al.*, 2000), EOL cables are collected primarily to recover the valuable copper conductor. Therefore, from an economic standpoint, the recycling of the PVC fraction starts at the cable recycler and does not include the collection and treatment of the cables. As with other waste streams, the decision to recycle the plastic fraction is based on whether the cost to transport and recycle the material, minus any revenue for the recovered plastic, is less than the costs of landfilling or incineration. In addition, the profitability and demand of PVC recycling depends on the

fluctuating cost of virgin PVC (Plinke *et al.*, 2000). As of 2000, PVC recovered from EOL cables was considered the only post-consumer PVC waste for which recycling is profitable (Plinke *et al.*, 2000).

Logistical constraints are largely related to the fact that EOL cables are generated in small quantities from dispersed sources, making collection less efficient. This may change over time as more EOL cable becomes available due to stricter regulations, such as the Abandoned Cable Provision of the National Electrical Code.

The presence of heavy metals, such as lead, and other potentially toxic substances in PVC is of potential concern because these materials will be dispersed into the variety of products that are made from the recycled PVC. However, because these toxic materials are fixed in the PVC matrix, the risk of exposure to humans and the environment is often considered low (Plinke *et al.*, 2000). According to Wilson (2004), there is, however, some concern that removing abandoned cables could result in lead exposure because, as the plasticizer leaches out of the compound over time, the PVC becomes brittle and the lead could potentially migrate to the surface, leaving behind dust with a high lead content. Lead dust in the plenum space, for example, could reach building occupants or workers removing the abandoned cables. However, studies have shown that the aged PVC cables perform extremely well in regards to physical properties, precluding embrittlement from occurring (Dini, Fabian, and Chaplin, 2006).

In 1997, 0.2 million kilograms (0.5 million pounds) of PVC were recovered from EOL wire and cable and recycled (Principia Partners, 1999). However, we do not have the breakdown of how much is pre- and post-consumer waste.

Polyethylene

Polyethylene (PE), when used as the insulation for CMR cables, is typically not compounded (i.e., the insulation consists of 100 percent PE). Therefore, PE could potentially be recovered and reused. In many mechanical recycling operations, however, it is difficult to obtain the clean streams of recycled PE that are required for it to replace virgin PE (Hagström, *et al.*, 2006). BASF, on a pilot scale, has tested a thermolysis process (in which PE is decomposed into ethylene using heat) for chemically recycling PE; however, the cost of the recovered ethylene from thermolysis was higher than the cost of virgin ethylene produced from fossil fuel (Hagström *et al.*, 2006).

2.4.3 Regulations covering EOL communications and building cables

2.4.3.1 Abandoned cable provision of National Electrical Code (NEC)

The National Fire Protection Association (NFPA) estimates that there are approximately 60 billion feet of communications cables installed in the United States, many of which are abandoned (Network Cabling, 2005). Section 800.2 of the NEC defines abandoned cable as “installed communications cable that is not terminated at both ends at a connector or other equipment and not identified ‘For Future Use’ with a tag.” Abandoned cabling poses a substantial risk to health and safety because it increases the amount of combustible material in concealed spaces (i.e., risers and plenum spaces), may generate toxic fumes when subjected to fire, can affect air flow in ceiling plenums, and generates a significant amount of smoke (Fishman, 2006; DuPont, 2007). In order to address the growing concern over abandoned cable, the NFPA added a new provision to the NEC in 2002 that mandates the removal of all accessible abandoned copper and fiber optic cabling from buildings. (The 2005 NEC also contains this abandoned cable provision.) Although the NEC itself is not codified as law, any jurisdiction that has adopted the 2002 or the updated 2005 NEC (which incorporates the 2002 NEC) into its building code can enforce the abandoned cable provision (BOMA, 2006).

2.4.3.2 Basel Convention

The Basel Convention addresses the production, management, and international transport of certain hazardous wastes, including metal cables with plastic insulation containing lead stabilizers. The convention states that regulated wastes are not exportable without the consent of the government of the receiving country. These wastes include “waste metal cables coated or insulated with plastics containing or contaminated with coal tar, PCB, lead, cadmium, other organohalogen compounds” or other constituents regulated by the convention (Annex VIII, Basel Convention, 1992).

Waste metal cables using plastics that do not contain coal tar, PCB, lead, cadmium, or other toxic components are not regulated by the convention as long as they are disposed of via operations “which do not lead to the possibility of resource recovery, recycling, reclamation, direct re-use or alternative uses”; or “operations involving, at any stage, uncontrolled thermal processes, such as open burning” (Basel Convention, 1992). FEP is listed in the convention as a substance that is unregulated in its pure form, but PVC and PE are not explicitly mentioned anywhere in the treaty (Annex IX, Basel Convention, 1992).

The convention issued technical guidance regarding plastic coated cables in 2002, stating that “open burning is not an environmentally acceptable solution for any kind of waste” and that it “must not be applied to processing of cable scrap” (UNEP, 2002). Cable chopping and stripping are recommended as the most economical and environmental methods of recycling cable scrap, especially if the cable is pre-sorted so that the separated plastic insulation will be relatively pure. The guidance goes on to recommend incineration in state-of-the-art furnaces as the only environmentally responsible method of burning cable waste, and that energy should be recovered whenever possible (ENS, 2002).

Though the United States is a party to the convention, which took effect in 1992, the U.S. Senate has not yet ratified it. An amendment that bans the export of hazardous waste from developed to developing countries for purposes of final disposal or recycling was adopted in 1995, but has not been ratified by a sufficient number of countries to come into force.

2.4.3.3 Landfill restrictions

The NEC does not address the *disposal* of abandoned cabling that has been removed from buildings. Given the likely presence of lead stabilizers in PVC jacketing in the abandoned cable, some municipalities may be concerned about its disposal in construction and demolition (C&D) landfills or municipal solid waste (MSW) landfills. After reviewing the types of hazardous materials (HAZMAT) that are in the waste stream for landfills, some municipalities are beginning to route the heavy metal wastes from the unlined C&D landfills to the lined HAZMAT waste facilities. This may in turn increase the costs of disposal for abandoned cable (Bisbee, undated).

2.4.4 EOL disposition options

The major EOL dispositions for cables that are removed from the structure in which they were installed include recycling, incineration, and landfilling. In addition to the EOL dispositions that would occur when a cable is physically removed, a fire could cause a cable to reach its end of life. The WCP considers reuse to be part of the use stage, so reuse is not discussed here. Also, while post-industrial cable scrap generated by manufacturers could follow the same dispositions as EOL cables, this is not included under the EOL discussion. The following sub-sections qualitatively examine the EOL options for communications cables and low-voltage power cables.

2.4.4.1 Recycling

Recycling of copper cables is motivated by the high value of copper. The first step of recycling is to separate the conductor from the insulation and jacketing. The copper is then sent to a copper smelter for reprocessing. The remaining resins are either disposed of or also reprocessed. As the focus of the WCP is on the resin systems, we do not describe the copper smelting process.

Separation

BIR (2006) reports that there are two primary, economically viable and environmentally sound methods for separating the plastic insulation and jacketing from the metal conductor of EOL cable: chopping and stripping. According to UNEP (2002), these methods have been able to prevail worldwide due to the development of pre-sorting techniques and the expanded chopping capacity, plus the concurrent development of a better technique for separating tailings. Developed countries primarily recover the metal from cable scrap using automated cable chopping operations. Developing countries typically use cable stripping machines, which are less expensive than cable chopping operations, but have a much lower throughput (BIR, 2006). One advantage of cable stripping over cable chopping is the improved purity of the recovered jacketing and insulation materials. According to UNEP (2002), the recovered materials are claimed to be completely free of conducting metal, and with careful segregation of the cable scrap prior to processing, the recovered materials can consist of one type of polymer. Cable stripping often results in a waste plastic stream that is more than 99.5 percent pure, which facilitates recycling of the plastic waste. In contrast, a cable chopping operation that uses a pre-segregated feedstock of EOL cable and an electrostatic process to remove all residual metal from the plastic fraction produces a plastic stream that is 90 to 95 percent pure. Both metal and polymer tailings, therefore, are more easily recyclable using cable stripping (UNEP, 2002).

Cable chopping

In North America, an estimated 55 facilities (51 in the United States) were operating one or more cable chopping lines in 2003 (Taylor and Toto, 2003). Systems vary in size from 225 to 680 kg/hr (496 to 1499 lb/hr) to 4,770 to 5,455 kg/hr (10,516 to 12,026 lb/hr), and costs (based on 1997 prices) vary from \$150,000 for small chopping machinery to \$1.8 million for larger machines. U.S. cable choppers typically operate lines with capacities reaching at least 5.5 tons/hr (5 metric tons/hr). Cable chopping typically involves the following steps (BIR, 2006; Finlay, 2004; UNEP, 2002):

- *Pre-sorting* involves the separation of long cable sections by type of insulation and jacketing (e.g., PVC, FEP, or PE), by conductor diameter, or as plated or unplated conductor; the separation of densely baled cables; and the separation of pieces of ferrous and non-ferrous metal, which can be fed directly into a metal shredder, from loose cable. One of the most important functions of pre-sorting is the separation of copper cable from aluminum cable.

Pre-sorting is the most important step in the cable chopping process, because it allows maximum value to be obtained for the recovered metal scrap and it makes further separation of plastics easier. Long cable sections are sheared into lengths of about one yard so that they can be fed into a granulator, whereas densely baled cable is broken up into loose streams. Material not well-suited to such automated systems (e.g., superfine wire and grease or tar-filled cables that can obstruct the system) can be separated out manually beforehand.

- *Cable chopping* is used to reduce long cable sections into an acceptable size for the granulator. It is commonly performed in large operations but is optional at smaller facilities.

-
- *Granulation* uses primary and secondary granulators to strip the plastic insulation and jacketing from the metal conductor. These machines process cables from about three inches diameter to thin cable of about 26-gauge (0.016 in). A secondary granulator reduces the cable lengths to about 0.6 cm (0.24 in.), which typically liberates most of the metal from the plastic; however, small amounts of metal will remain imbedded in the plastic fraction.
 - *Screening* is often used in cable chopping operations to enhance the recovery of metal by yielding the desired chop size. Smaller chop sizes allow for more-efficient removal of the metal. Oversize material can be reprocessed in the granulator. Fines, which contain metal, plastics, fibers, and dirt, drop through the bottom of the screen. Metal particles are recovered from the fines by removing lighter, non-metallic particles and dust using an aspirator.
 - Separation techniques, such as gravity or air density tables, washing systems, and fluidized bed separators, are used to separate the metal fraction from the plastic residue. The metal content of residue streams can vary from less than 1 percent to more than 15 percent, depending on the separation technique employed. Some cable processors have installed dry electrostatic systems, which can reduce the metal content of tailings to less than 0.1 percent, thereby increasing the value of the recovered plastic.

Cable stripping

Cable stripping is a less expensive method for recovering the copper from EOL cable, but it has much lower throughput than cable chopping. Cable stripping equipment is designed to handle only single strands of cable waste at rates up to 60 m/min (197 ft/min) or 1,100 kg/hr (2425 lb/hr) with cable as thin as 1.6 mm (0.06 in.) or as thick as 150 mm (5.9 in.). Based on 1997 prices, machines that operate at 24 m/min (78.7 ft/min) sell for about \$5,000, whereas small tabletop machines that operate at rates of only 8 m/min (26.2 ft/min) sell for as little as \$1,800 in the United States and Europe (BIR, 2006). Developing countries typically prefer cable stripping machines rather than the more expensive cable chopping machines; cable stripping machines are also used in most developed countries by utilities, cable manufacturers, cable chopping companies, and metal scrap dealers.

Separation by incineration

Cable scrap can be incinerated to obtain the conductor metal using authorized controlled atmosphere furnaces that seek to prevent the formation of persistent organic pollutants (POPs). Only a few such furnaces have been authorized in the world. Plans to build new incinerators or to expand the capacities of existing facilities are often met with public resistance, often due to concerns about PVC incineration, which generates a large amount of hydrogen chloride and potentially forms dioxins and furans (Braun, 2002). Recovery of the metal fraction of EOL cable using incineration is less preferable than chopping or stripping because burning can oxidize the metal, thus decreasing its value. State-of-the-art furnaces, however, are better able to control the combustion conditions and avoid oxidizing the metal (UNEP, 2002).

Other separation methods

Cables are often exported to developing countries for reuse or recycling. According to UNEP (2002) about 30 percent of the total amount of EOL cables is reused rather than recycled. For cables exported annually from the United States, Japan, and Europe to developing countries, and which are not reused, the copper (and aluminum) conductors have a sale value to smelter operators, but the PVC or PE

insulation and jacketing is frequently disposed of, often by open burning (Lemieux *et al.*, 2004; *Recycling Today*, 2002).¹²

Polymer recycling

Due to its high value, the copper in cables is often recovered and recycled; however, only in some cases is the plastic material recycled. In order to increase their value and expand their reuse options, mixed plastic tailings from both cable chopping and cable stripping operations are often further separated into a clean PE fraction and a clean PVC fraction using either sink and float (hydrogravimetric) or cryogenic processing (UNEP, 2002). Sink and float processing, which employs a liquid medium, separates lower density plastics (i.e., PE), which float on the liquid, from higher density plastics (i.e., PVC), which sink (Hagström *et al.*, 2006). Cryogenic processing uses liquid nitrogen to freeze the mixed plastic tailings. At liquid nitrogen temperatures, PVC shatters into small particles when it is impacted; polyethylene and some other plastics do not. The relatively small PVC particles are then screened from the other larger plastics to produce a purer PVC fraction (UNEP, 2002).

The separated polymers can then be recycled using either mechanical or chemical processes. Currently four different chemical processes—cracking, gasification, hydrogenation, and pyrolysis—are being considered for chemical recycling, which is the conversion of polymers back into short-chain chemicals for reuse in polymerization or other chemical processes (Braun, 2002). Mechanical recycling processes use mills and extruders to convert the separated plastic fractions into re-granulates of a defined size and composition (Plinke *et al.*, 2000).

PVC recycling

One method of reprocessing the PVC fraction of cable waste is the The Solvay Vinyloop® process. According to a representative at Vinyloop® in Ferrara, Italy, the primary feedstock to the Vinyloop® process from the wire and cable industry is end-of-life PVC-based cable insulation that is generated by copper reclaiming operations. More than 90 percent of the PVC-based insulation that the Vinyloop® process recycles is from EOL building cables; less than 10 percent of the cable scrap is from EOL communications cables (Leitner, 2006). According to Hagström *et al.* (2006), however, the Vinyloop® process is better suited to the recycling of pre-consumer production scrap because the input material conforms to today's environmental requirements. EOL cables, in contrast, are likely to contain additives that were permitted some years ago, but may not be so freely used today, thus contaminating the final recycled PVC product. For economic reasons, the Vinyloop® plant in Ferrara, Italy, is designed for processing waste with an average minimum PVC content of 85 percent. Plastic scrap with a PVC content of 50 to 60 percent requires a triboelectric step, which separates other polymers and makes a waste containing at least 85 percent PVC (Hagström *et al.*, 2006; Scheirs, 2003).

The Vinyloop® process selectively dissolves the PVC in a solvent, such as tetrahydrofuran or methylethylketone; separates the PVC from insoluble or secondary materials, including polyethylene, copper, and other elastomers; and then precipitates the regenerated PVC compound, including all components of the original formulation (i.e., heat stabilizers, plasticizers, flame retardants, and colorants), as microgranules for resale. The regenerated PVC can be reprocessed by extrusion, injection, or calendaring (continuous extrusion between a pair of cylinders). The solvent is fully recovered and

¹² The *Recycling Today* article did not specify the type of burning (e.g., controlled or uncontrolled), or who burns the waste insulation and jacketing; while Lemieux *et al.* specified that open burning occurs. (See *Smouldering of Copper Cables*: http://www.pops.int/documents/meetings/bat_bep/2nd_session/egb2_followup/draftguide/6LCopperCablesDRAFT.pdf.)

recycled within the process. A study by PE Europe did not detect dioxin formation when the Vinyloop® process was used to recycle scrap PVC cables (Kreissig *et al.*, 2003). Solvay has a demonstration plant operating in Ferrara, Italy, and opened a commercial-scale facility in Chiba, Japan, in May 2006 (Glew and Grune, 2004; Vinyloop, 2006).

The Stignæs Plant in Denmark also has a process for recycling PVC waste. The plant, owned by RGS 90, uses a two-step chemical process to recycle all types of PVC waste. First, PVC is hydrolyzed to an inorganic (chlorine) fraction and an organic (hydrocarbon) fraction. Then the organic fraction is post-heated. Salt (NaCl), a fluent oil fraction, and a sandblasting material are the products from the process. The capacity of the plant is approximately 50,000 metric tons per year, and the gate fee is in the range of \$200 to \$300 per metric ton (Hagström *et al.*, 2006). As of 2005, RGS 90 has been forced to stop accepting PVC waste while they consider other options for the plant. Technical difficulties and an inability to compete with other options, especially landfills, on price led to the suspension of operations (Vinyl 2010, 2006). Currently, a feasibility study is underway to build a Vinyloop® facility in the United States (Vinyloop, 2007).

FEP recycled into cross web

Since FEP does not have the additives that PVC has, it can more easily be reprocessed into product. Thus, FEP is sometimes reprocessed as crossweb for CMP communications cables by extruding the scrap FEP. However, the small volumes and difficulty of separation makes the recycling of FEP from EOL cables problematic (Ring *et al.*, 2002). As noted previously, some cable manufacturers recover 100 percent of their pre-consumer waste FEP to manufacture pair separators used in Category 6 plenum cables (Uniprise, 2006).

Other recycling methods

There are other methods that are mentioned here only briefly, as they are not believed to constitute common practices. However, if they become more prevalent in the future, they may be applicable to the EOL disposition of the cables studied in this project once they finally reach their end of life. These methods include:

- Low Smoke-PVC from plenum jacketing recycled and blended with virgin PVC for new riser jackets (Glew & Grune 2004).
- Center for Research into Plastic Materials (CEREMAP) is a plastics recycling company based in France. CEREMAP recovers mixed plastic material into “low-value” products that are adapted for regional markets (e.g., palettes, boxes, outdoor furniture, building materials, etc.) (Ecolink, 2003).
- Japanese microwave radiation technique to assist in the separation of the wire and insulation materials (Glew & Grune 2004).

2.4.4.2 Waste-to-energy (WTE) incineration

Incineration with energy recovery is a viable option for treating the polymer fraction of EOL cables because of the high energy content that is liberated upon combustion of polymers. Polyethylene has a heat of combustion of 46 MJ/kg and generates only water and carbon dioxide upon combustion at temperatures typical of WTE incineration (1,000°C). PVC, which has a heat of combustion of 18 MJ/kg, consists of carbon, hydrogen, and chlorine, and generates hydrochloric acid upon combustion. The PVC and PE fractions are typically separated prior to incineration because the hydrochloric acid formed by

burning PVC requires special measures (Hagström *et al.*, 2006). FEP, on the other hand, generates very little energy: its heat of combustion is 5.1 MJ/kg (Plastech, 2007). Although FEP does not burn easily, it emits hydrogen fluoride, a highly toxic gas (Wilson, 2004). Comparatively, the heat of combustion for automotive gasoline is about 44 MJ/kg (DOE, 1997).

2.4.4.3 Landfilling

According to Scheirs (2003), landfilling is the predominant means for disposing of PVC waste throughout the world. There is a concern that, over time, the PVC matrix will break down under landfill conditions, allowing the additives to leach from the PVC. Mersiowsky *et al.* (2001) found that, after 28 months under simulated landfill conditions, a lead-stabilized PVC cable lost around 40 percent of its original content of a secondary phthalate-based plasticizer; the content of the primary plasticizer, diisodecyl phthalate (DIDP), did not change. This study also found that none of the PVC samples underwent changes in molecular weight distribution, nor was vinyl chloride detectable in the biogas of the sample vessels (Mersiowsky *et al.*, 2001).

Lead stabilizers are primarily immobilized in the PVC matrix, which ensures that leachability into the environment is extremely low; however, the increased surface area of finely divided PVC waste from cable chopping operations might facilitate extraction under certain landfill conditions (e.g., acidic leachate conditions; see Scheirs, 2003). Leachate rates for lead from CMR cables are estimated to be between 1 to 2 percent if the cable has not been chopped/stripped significantly, and approximately 10 percent for smaller, chopped cable particles (personal communication with Dr. Townsend, University of Florida, 2007). These leachate rates would apply to a 100-year lifetime of a landfill.

According to Hagström *et al.* (2006), combustion as a high-grade fuel is the only technical, economical, and environmentally acceptable method currently available for dealing with the PE fraction of the polymer waste from EOL cable.

According to Scheirs (2003), “On the basis of the available research and evidence, the landfilling of end-of-life PVC seems to be environmentally acceptable when mechanical recycling and thermal treatment processes are not possible. The overall conclusion of the most recent studies is that PVC products do not constitute a substantial impact on toxicity of landfill leachate and gas.”

2.4.4.4 Fire scenario

A building fire could cause a cable to reach the end of its life prematurely. While CMR and CMP cables are primarily installed in commercial and educational buildings, NM-B cable is found in the vast majority of buildings, including residential, agricultural, and industrial structures. Further discussion on frequency estimates are provided below in section 2.4.5.1.

2.4.5 LCI Methodology

Modeling the EOL stage required two key steps: (1) estimating the EOL distribution among the disposition options (i.e., recovery, incineration, and landfilling), and (2) estimating the inventory flows for each disposition option. These steps are described in detail below.

2.4.5.1 Distribution Estimates of EOL

Figure 2-4 presents the major disposition options for EOL cable. The schematic shows that a certain fraction of the resins can end up in a variety of final dispositions, including recovery, landfilling, and incineration. As noted previously, although most cable reaches the EOL stage after the end of its

useful life, some may reach this stage prematurely through a building fire. A conservative upper-bound estimate for the annual frequency of fires in buildings is about 1.1 percent for those buildings that have CMR and CMP cabling and approximately 0.5 percent for buildings with NM-B cabling (however, due to the lack of complete life-cycle data the NM-B analysis did not ultimately use include the EOL scenarios). Appendix B provides the methodology for making these assumptions, which used National Fire Protection Association Data and U.S. census data.

There was not, however, sufficient quantitative information regarding the percent of cable burned in a fire to empirically determine a central estimate. Thus, we applied a default estimate: 10 percent of the cables contained in a building where a fire has occurred are assumed to have been consumed in the fire (based on best professional judgment, which considered the fact that cable fires occur but are expected to occur at relatively low frequencies). This estimate was varied in the uncertainty analysis, assuming complete uncertainty for this parameter (see Section 3.4). The default estimate recognizes that fire protection methods would skew actual burn percentages toward the lower end. In addition, it should be noted that the percent of CMP cables burned would likely be lower than the percent of CMR cables burned, due to different fire safety standards; however, either percent would be in the range of the uncertainty analysis. Further, the CMR is not being compared to the CMP, precluding any effect on the analyses in this LCA. Based on the above considerations, the point estimate calculations conducted in this LCA used a value of 0.11 percent of CMR and CMP cables that reach the EOL stage through fires.

Estimates for the distribution of cable after its useful life were not readily available; however, wire and cable recycling for copper recovery is currently estimated at 95 percent (Bartley, 2006). We assume that this includes the proportion that is sent overseas, and that the estimate recognizes that a proportion of what is sent for recycling is sometimes first re-used. However, we still assume that the ultimate disposition (after it is reused) is to recycle the cables for the copper content. Provided the value of copper continues to remain high, we expect recycling to continue to be prevalent at the time when the cables produced now reach their end-of-life (e.g., 10 or 15 years for communications cables, and 25 or 40 years for the low-voltage power cables).

The cables sent for recycling could either undergo wire chopping, wire stripping, or burning to separate the copper from the plastic material. Data is limited, however, on the distribution of recovered cable amount associated with these separation options. Although cable chopping may be more prevalent in North America, as stated earlier, there may be a large amount of EOL cables going to developing countries where stripping and burning might be more established. However, as noted above, the UNEP Basel Convention has restricted the shipment of plastic insulated cables for uncontrolled burning (Basel Convention, 1992). For the analysis in this study, we assumed 100 percent of the recovered cable undergoes chopping, given the lack of LCI data on the other separation options.

Once the copper and plastics fraction are separated, the copper is sent to a copper smelter and the plastics fraction is either recycled or disposed. Because the copper smelting process is beyond the scope of this study, our analysis focuses on the plastics fraction that is sent for recycling versus disposal. The percent of chopped resin that is recycled is very uncertain. A European Commission study completed in 2000 (Plinke, 2000) provides an upper estimate that 20 percent of resin in cables sent for recycling is sent to thermoplastic recycling.¹³ We assumed an arbitrary midpoint of 10 percent of the resins going to thermoplastic recycling. This parameter was then varied in the uncertainty analysis presented in Section 3.4.

¹³ Note that this estimate is from a historical point in time and other factors such as different recycling rates, international shipping of wires and cables, and the introduction of new technologies since the study was done could affect the accuracy of this bounding estimate.

The remainder of the chopped resin is assumed to be incinerated or landfilled (at the same MSW percentage split described below). Any conclusions regarding recycling rates should be understood in the context of probable future progress in the area of recovery technology (e.g., Vinyl2010, 2006).

As illustrated in Figure 2-4, EOL cables that are not recycled are landfilled or incinerated. Given the limited data on the distribution of EOL cable, our analysis assumes that the plastics content disposed follows the same distribution as U.S. municipal solid waste to landfills (81 percent) and incinerators (19 percent) (U.S. EPA, 2005). Accordingly, we estimate that of the 5 percent of EOL cables not recovered, approximately 4 percent is disposed in a C&D landfill and 1 percent is incinerated. After chopping for recovery of copper, of the estimated 90 percent of plastics disposed (i.e., not sent for thermoplastic recycling), 17 percent would be incinerated and 73 percent would be sent to a MSW landfill.

Finally, in addition to identifying the percentage distribution for the EOL cable, distinguishing among the alternatives at the EOL stage is of particular interest for the LCA. For example, since we are comparing alternatives within a cable type, we assume transportation is equivalent and therefore do not incorporate these inventory flows in the analysis. In addition, given the limited information available, we assume that the distributions among the cable types are alike. However, there are differences in the amount of NM-B cable that are disposed as a result of a larger percentage assumed to end in a fire. The EOL analysis in this study did not include unregulated or uncontrolled burning.

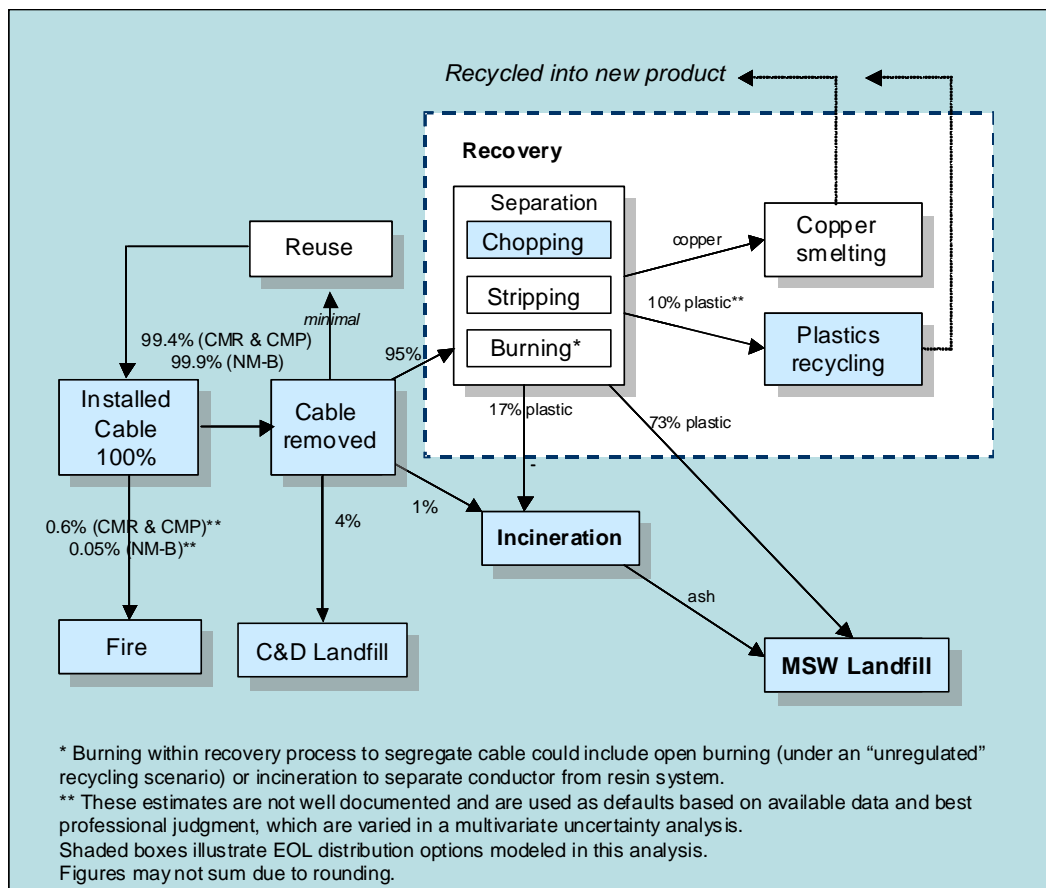


Figure 2-4. Illustration of EOL Distribution Options: Baseline and Lead-free Alternative

2.4.5.2 EOL Inventory for Disposition Options

To model the EOL LCI, the analysis relied on primary data for cable chopping and thermoplastic recycling and secondary data (Simonson *et al.* 2001) to identify the emissions and inventory flows for landfilling, incineration, and structure fires.

Simonson, *et al.* (2001) conducted an LCA to compare the impacts resulting from cable fires of two cable constructions: (a) PVC jacketing over PVC insulation, and (b) PE jacketing over PE insulation. Fire tests were performed on both cable constructions using two temperatures (350° C and 650° C) and two oxygen concentrations (5 percent and 21 percent), and the emissions were analyzed. Accordingly, the outputs for the study are primarily based on the PVC plastics, PE plastics, and the copper conductor. Because our analysis does not include the copper component, and the cable types we are addressing in this analysis include PVC jacketing, we used inventory data for the PVC plastics from the Simonson *et al.* study. However, the cable types in the WCP also include other materials (e.g., FEP) and other compounds and resins, thus the EOL inventory flows from these materials are not captured. An earlier study conducted by DuPont (Leung and Kasprzak, 1999) looked at the combustion products likely to be emitted during the burning of cable at temperatures expected to be reached during building fires (350 to 450° C). This study was not used to identify combustion products due to lack of clarity about the jacketing and insulation formulations, but will potentially be used to inform further study of the wire and cable fire EOL disposition.

The Simonson *et al.* assessment studied the outputs resulting from both ventilated and vitiated PVC cable fires, where no spreading of the fire beyond the cable occurs. We chose to use the vitiated fire data as it better represents a secondary fire (i.e., one that originates away from the cables), which is the only type expected given the placement of fire retardancy features of the cables.

The Simonson *et al.* study also provided emissions data on a per kilometer of cable basis for landfilling and incineration. Since their data did not have lead emissions from the PVC cable emissions associated with the baseline alternative were incorporated from other sources. For example, based on estimates provided by the University of Florida, discussed above (Section 2.4.4.3), we assume a leachate rate of 1.5 percent for removed cable disposed in a C&D landfill. For the incineration and the fire scenarios, we assumed 98.5 percent of the lead content is disposed of with the ash to a landfill and 1.5 percent is released to the air (Chang-Hwan, no date, and Abanades, 2002, cited in Geibig and Socolof, 2005). Of the lead assumed to be disposed of in a MSW landfill, we assumed the higher leachate rate of 10 percent, given that the cable is disposed of in smaller, chopped pieces. Given the uncertainty in these estimates, the leachate rates were varied in the multivariate uncertainty analysis (Section 3.4).

Primary data were collected for two cable recycling facilities: cable separation (i.e., chopping) and PVC recycling (i.e., Vinyloop® process). Only one facility for each process supplied inventory data. Following are key assumptions for each disposition option based on available primary and secondary data:

- *Landfill:* Emission data for landfilling lead-free cables are based on a time period of 100 years. The analysis assumes that a “minor” part of the emissions will be released during this period, whereas the majority of materials will remain in the landfill and will be broken down over time. Accordingly, the model assumes that only 3 percent of the original polymer materials will be broken down during the first 100 years. However, it assumes that 80 percent of the plasticizers in the PVC cable will decompose (Simonson *et al.*, 2001, page 114). These data were supplemented with lead leachate data for the baseline cables.

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- *Incineration*: The study assumes that incineration occurs in “standard waste incinerators with a relatively high degree of flue gas cleaning” (Simonson *et al.*, 2001, page 117). Typically, cables are only part of the total waste flow to the incinerator. Therefore, where possible, emissions outputs are calculated directly from the material content (e.g., carbon dioxide and hydrochloric acid). However, emissions related to combustion conditions in a typical incinerator are allocated to the cable material. For example, carbon monoxide emissions are allocated based on the carbon content of the materials in the cable (Simonson *et al.*, 2001). These data were supplemented with assumptions about the lead releases to air and to landfill as ash.
 - *Recycling (Separation)*: As noted previously, the inventory data for the separation stage is based on a small cable recycling facility employing a mechanical, cable chopping operation. Although the recycler primarily accepts cable to extract the valuable copper component, it also recycles much of the plastic component of the cable.
 - *Recycling (Thermoplastics)*: As noted previously, more than 90 percent of the PVC-based insulation recycled is from EOL building cables (e.g., low-voltage power cables); and less than 10 percent of the cable scrap is from EOL communications cables (Leitner, 2006). However, our analysis assumes the energy and material input and output flows to be the same per unit of PVC recycled for power cable and telecom cables.
 - *Fire*: Simonson *et al.* (2001) included fire inventory data for both ventilated and vitiated fires. The latter represents an oxygen deficient fire, which they assume represents a secondary fire (i.e., are not started with the cable but capable of consuming the cable and not spreading beyond the cable). Our analysis includes data for only vitiated fires, which represent the most probable scenario for CMR/CMP cable fires. In addition, the analysis uses a default of 10 percent of the cables are burnt during the fire.

2.4.5.3 Limitations and Uncertainties

Assumptions about the disposition percentages may not truly represent the actual dispositions. For example, our analysis currently assumes that the dispositions of the EOL cables (after any fires) for all three cable types will be the same once the cable is removed. However, it is likely that each cable has different percentages of the plastic component that are recovered. In addition, estimates of the distribution between landfilling and incineration were based on processing MSW rather than specifically on processing cable. Sensitivity analyses, which vary these assumptions, can be conducted if results show enough impacts at EOL to warrant further analysis.

Furthermore, the analysis does not give credit for open loop recycling of mixed plastics into other non-recyclable material/products. That is, this analysis does not account for environmental savings from the recycled content of materials/products created from the recycled plastics from the cables. In addition, although the recovery of FEP follows more of a closed-loop process, the LCA only accounts for this in the data received by crossweb manufacturers whose data incorporated recycled FEP in their process estimates.

With respect to the LCI data for the GaBi analysis, as noted above, our analysis primarily relied on secondary data from the Simonson *et al.* (2001) study. Although this study was useful in providing estimates of emission outputs for PVC for the EOL disposition options, it did not include data to account for the other material in the cable wire we assessed (e.g., FEP, PE, plasticizers, resins). Therefore, differences in the outputs for each cable type were primarily based on the amount of PVC per unit length

for each cable type. In addition, the Simonson *et al.* study did not include estimates for emissions resulting from lead content. Thus, lead outputs from landfilling were estimated based on leachate rates for the metal. In addition, although the recovery of plastics using the Vinyloop® process was based on primary data, our analysis does not account for the triboelectric step, which is necessary to separate plastic scrap with a PVC content of 50 to 60 percent (Hagström *et al.*, 2006; Scheirs, 2003).

2.5 LCI Summary

The LCIs of each cable alternative are the combinations of the upstream, manufacturing, and EOL data described in the preceding sections. Presented under each subsection below are figures showing all the processes modeled for each cable alternative, followed by the total inventories. The total input and output mass inventory data are summarized by general categories of flows (e.g., emissions to air, emissions to water). When possible, given proprietary restrictions, more detailed breakdowns of the inventory are also provided, such as the top contributing processes to the total inventory, and the top contributing inventory flows associated with the modeled life cycle of each cable alternative.

This section presents only the mass flows. Energy inputs are presented in Chapter 3 under the energy impact category (Section 3.2.2). For the remaining impact categories included in the WCP analyses, the mass inventory data are then used as the basis of the other impact assessment calculations in Chapter 3.

2.5.1 CMR LCIs

Figures 2-5 and 2-6 show the processes modeled for the CMR baseline (lead-stabilized) and CMR lead-free cables from materials extraction through to the end of life. Figure 2-7 shows the processes modeled for the zero-halogen CMR cables. Incomplete data on the zero-halogen extrusion process resulted in only a cradle-to-gate analysis comparing the lead and lead-free CMR cables to the zero-halogen cables in Chapter 3.

In the flow charts below, the “cable installation/use” process is shaded in gray, showing that inventory data were not included for this stage, except to set the functional unit to 1 kilometer of linear length of cable. Processes in bold represent those for which primary data were collected. For the zero-halogen alternative, the jacketing and insulation extrusion process is in hash marks to show it is a mostly incomplete dataset. The processes noted in parentheses next to each upstream (ME&P) process indicates the process to which the upstream process feeds. For example, “electricity (cmpdg)” indicates the inventory from the generation of electricity that is needed for the compounding process. This notation is used so that subsequent figures showing top contributing processes can be identified with the linked downstream process. When confidentiality agreement restrictions prohibited the presentation of an individual process contribution, some processes have been combined as needed.

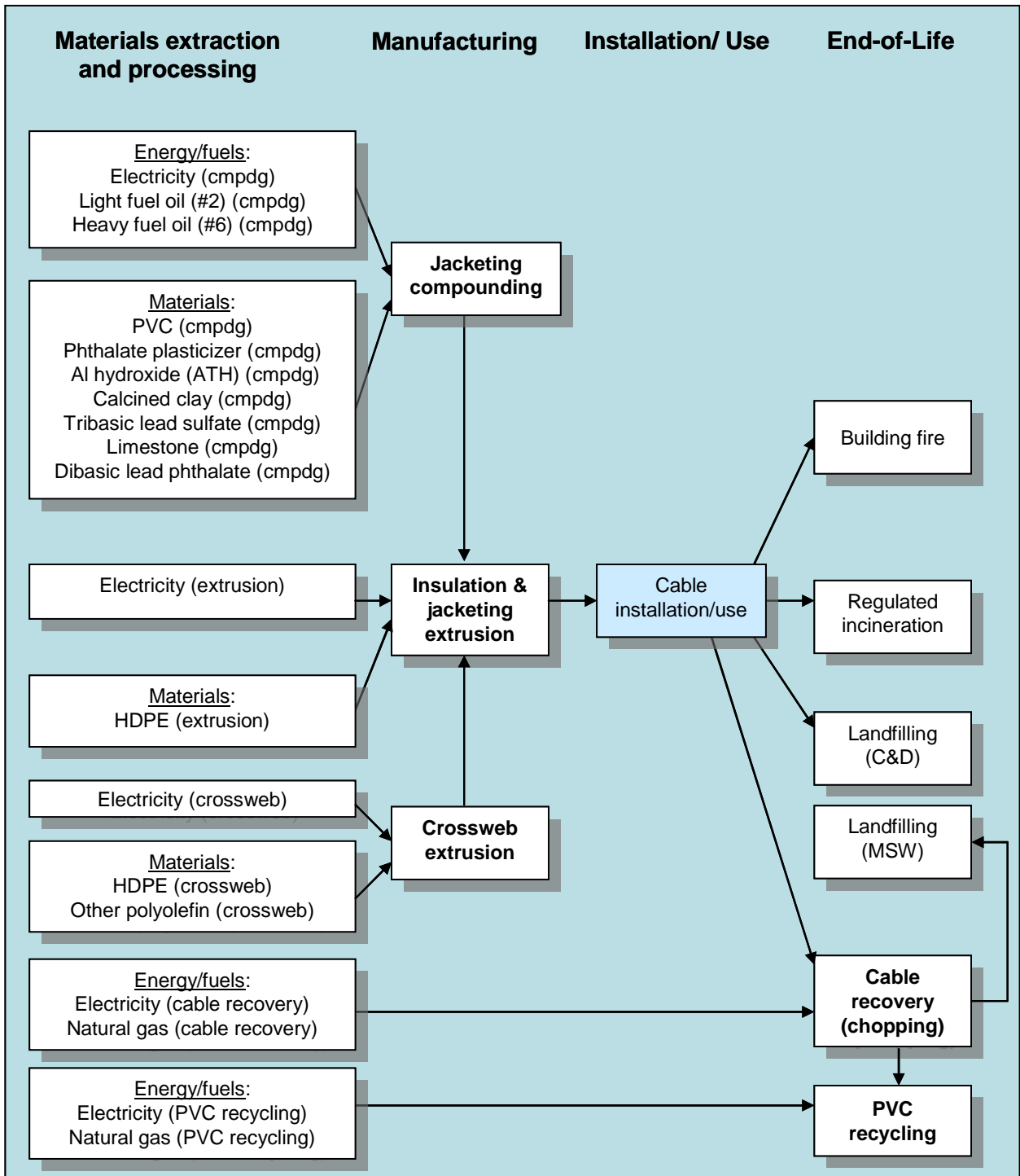


Figure 2-5. CMR Baseline (Lead-Stabilized): Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

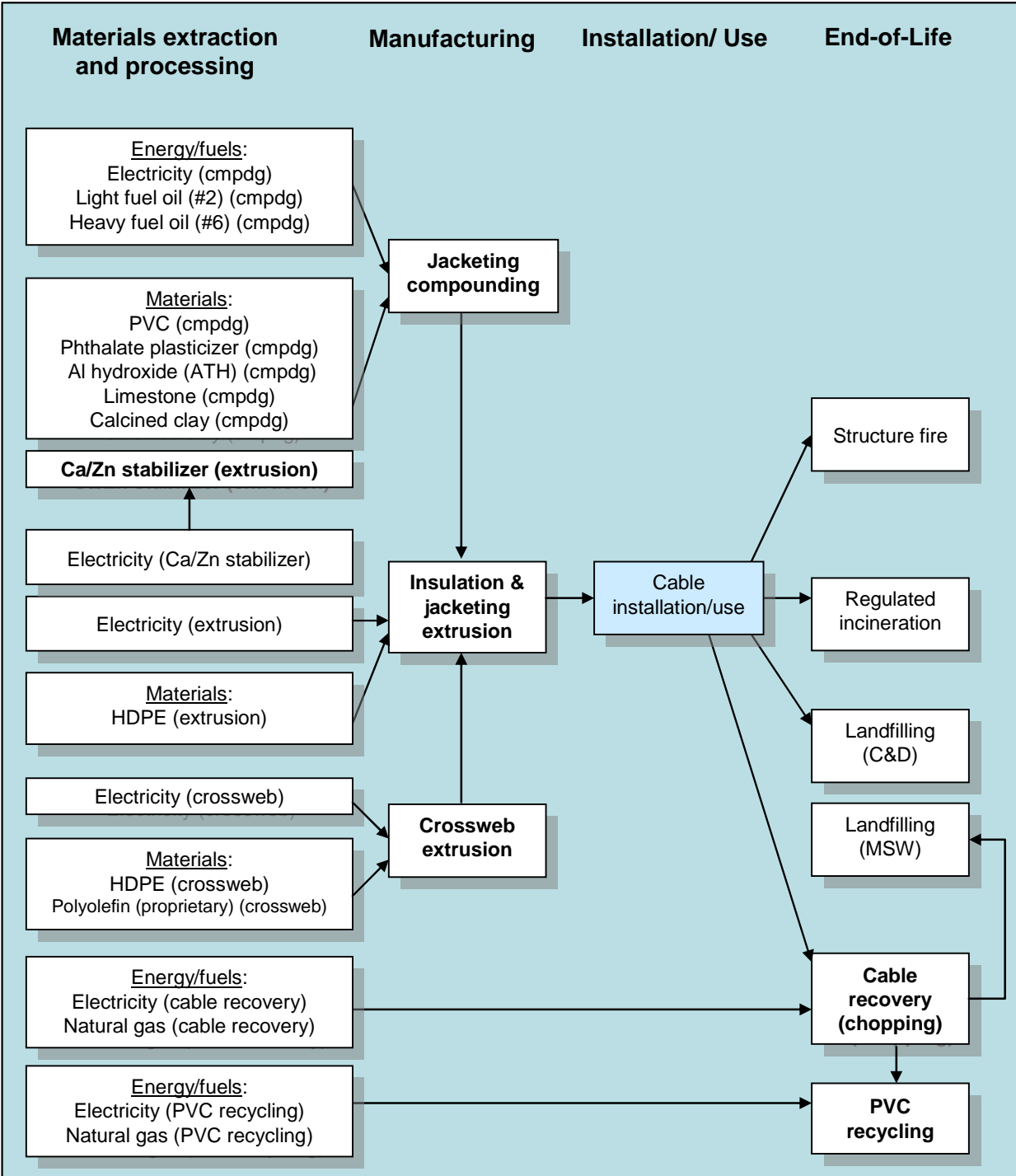


Figure 2-6. CMR Lead-Free Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

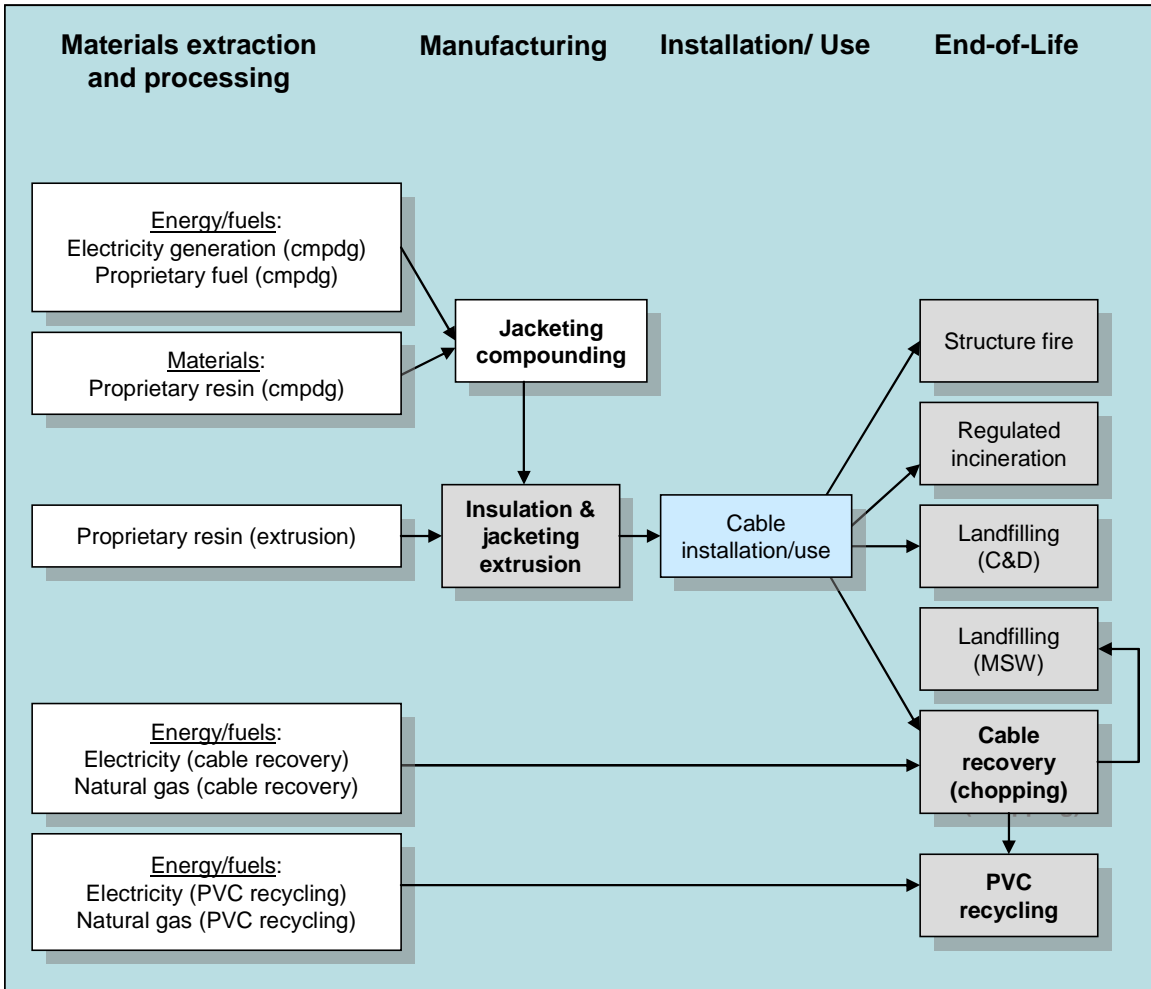


Figure 2-7. CMR Zero-Halogen Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

Figures 2-8 through 2-10 compare the mass inputs for the baseline and the lead-free CMR alternatives. Figure 2-8 presents the total mass inputs and Figures 2-9 and 2-10 provide a breakdown of the processes and individual flows that contribute greater than 1 percent to the total mass inputs. The total mass inputs for CMR are 19 percent greater for the baseline than the lead-free alternative (3,156 kg/km cable and 2,641 kg/km cable, respectively). For both alternatives, water is 88 percent of the total inputs, and the process that contributes greatest to each alternative's mass inputs is electricity production used for cable extrusion (69 percent for the baseline and 65 percent for the lead-free alternative) (Figures 2-9 and 2-10). To protect confidentiality, Figure 2-9 combines the mass inputs from all upstream electricity generation.

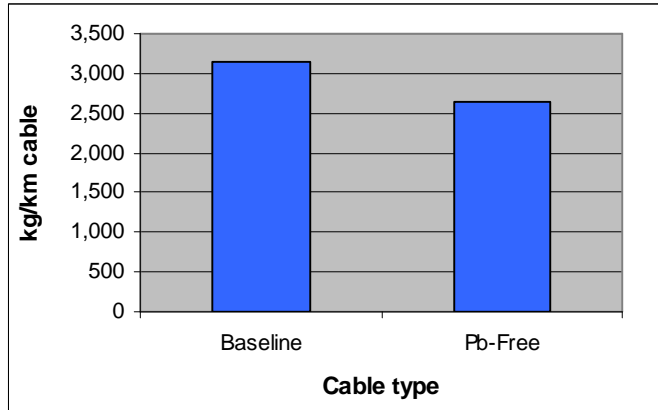


Figure 2-8. CMR Total Mass Inputs

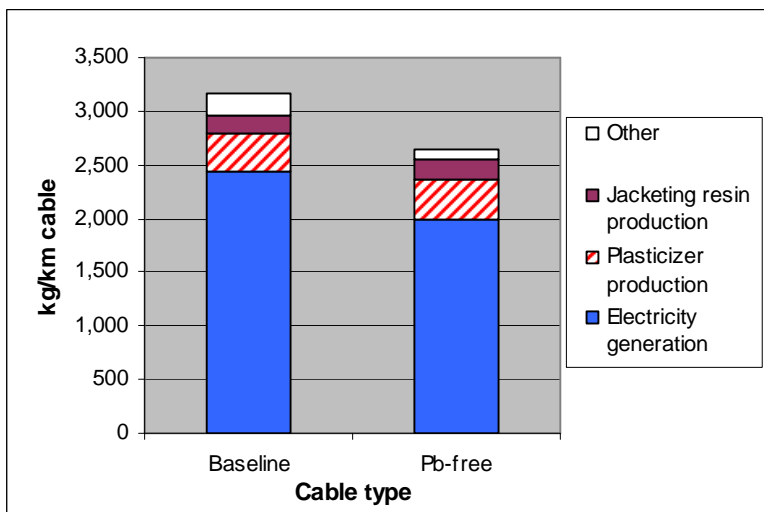


Figure 2-9. CMR Mass Inputs – Top Contributing Processes

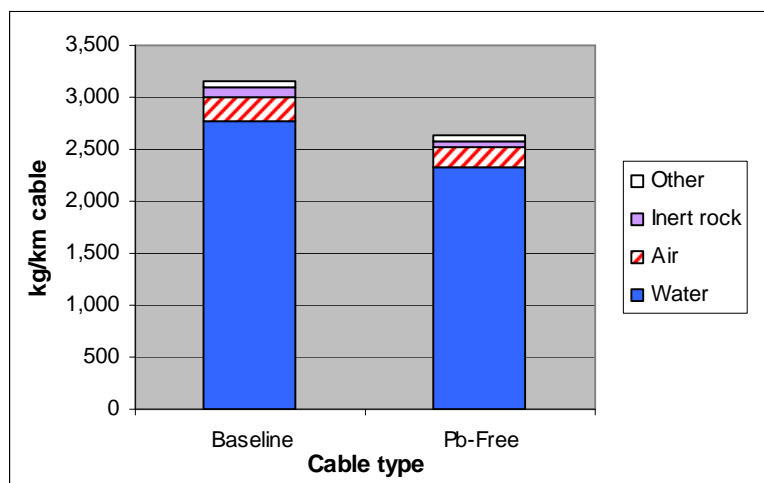


Figure 2-10. CMR Mass Inputs – Top Contributing Flows

The mass outputs are presented in Figures 2-11 through 2-13. Outputs include: deposited goods, which include consumer waste, hazardous waste and stockpile goods (e.g., overburden¹⁴); production residues, which include hazardous and non-hazardous waste for disposal; and substances such as intermediate products (e.g., PVC). Note also, emissions to water include the total mass of wastewater itself, as well as pollutants contained therein. Since data for the zero-halogen alternative were incomplete, similar comparative inventory results are not shown. The mass outputs are 23 percent greater for the baseline compared to the lead-free cable (2,542 and 2,073 kg/km cable, respectively). The mass outputs are mostly releases to fresh water (79 percent for both leaded and lead-free cables). 86 percent and 83 percent of the mass outputs are from the production of electricity needed for the cable extrusion and compounding processes for the lead and lead-free alternatives, respectively. To protect confidentiality, Figure 2-12 combines the mass outputs from all upstream electricity generation. The figures indicate that water from electricity generation contributes the most to the mass inputs and outputs for both the baseline and lead-free alternatives.

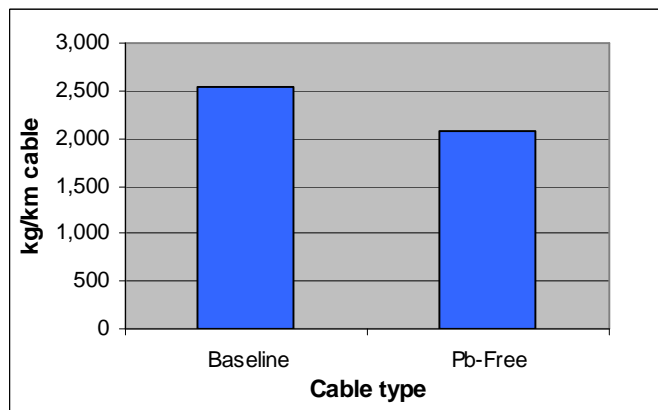


Figure 2-11. CMR Total Mass Outputs

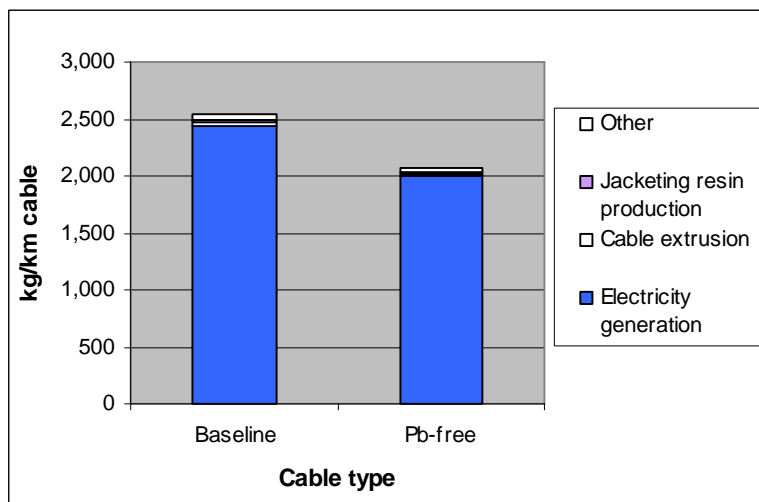


Figure 2-12. CMR Mass Outputs – Top Contributing Processes

¹⁴ Surface soil that must be moved away to access coal seams and mineral deposits.

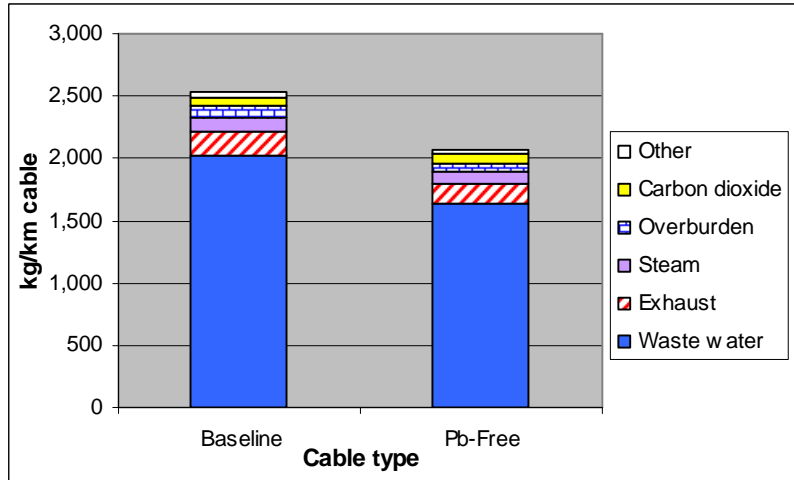


Figure 2-13. CMR Mass Outputs – Top Contributing Flows

The halogen-free alternative did not have complete data to compare the full life cycles of the alternatives. The only comparison that could be made for the zero-halogen (X-free) alternative is comparing the compounding process and the production of electricity and fuels associated with compounding. This comparison found that the zero-halogen process had greater mass inputs and outputs compared to the baseline (lead) (Figures 2-14 and 2-15). This does not account for any differences in the production processes of the additives in the compounded resin.

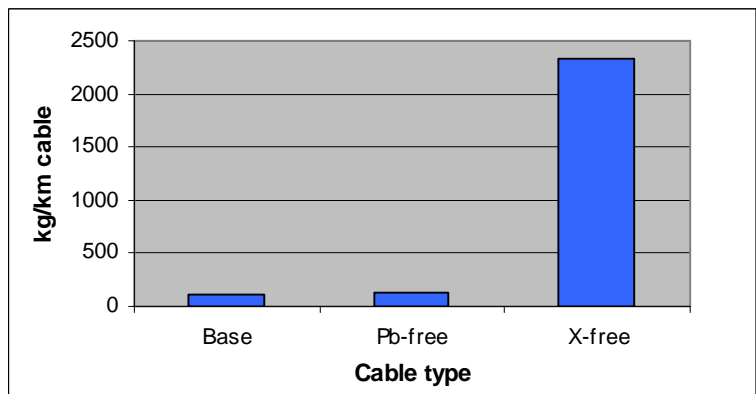


Figure 2-14. CMR 3-way Cradle-to-gate Mass Inputs

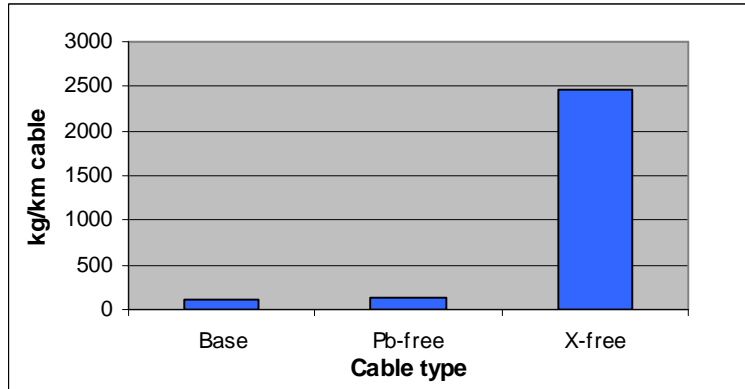


Figure 2-15. CMR 3-way Cradle-to-gate Mass Outputs

The primary explanation for the discrepancy in the halogen-free cable cradle-to-gate mass inputs and outputs compared to the baseline and lead-free alternatives is the difference in energy use as well as the mass of cable jacket per unit length, which is far higher than the two other types of cable (see Table 1-2).

2.5.2 CMP LCIs

Figures 2-16 and 2-17 show the processes modeled for the CMP baseline (lead-stabilized) and CMP lead-free cables from materials extraction through to the end of life. As in the CMR flow charts, the inventory data for the “cable installation/use” process were not included, the functional unit is set to 1 kilometer of linear length of cable, and processes in bold represent those for which primary data were collected.

Figures 2-18 through 2-20 compare the mass inputs for the baseline and the lead-free CMP alternatives. Figure 2-18 presents the total mass inputs while Figures 2-19 and 2-20 provide a breakdown of the processes that contribute greater than 5 percent to the total mass inputs and the individual flows that contribute greater than 1 percent to the total mass inputs, respectively. The total mass inputs for CMP are 9 percent greater for the baseline than the lead-free alternative (4,480 kg/km cable and 4,123 kg/km cable, respectively). The top contributing process for both alternatives is the generation of electricity for use in the cable extrusion process (Figure 2-19). To protect confidentiality, Figure 2-19 combines the mass input from all upstream electricity generation. Water is the greatest individual flow contributing to the mass input for both alternatives (Figure 2-20). Figure 2-19 includes the processes that contribute >5 percent of the total impacts, which represent 93 and 87 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 2-20 includes individual flows that contribute >1 percent to the total impacts and represents 95 percent of the total input mass for both the baseline and lead-free alternatives. The overall differences in mass input between the cables are primarily a function of the differences in energy use, as electricity generation uses substantial amounts of water. Energy inputs are presented in Section 3.2.2 under Energy Impacts.

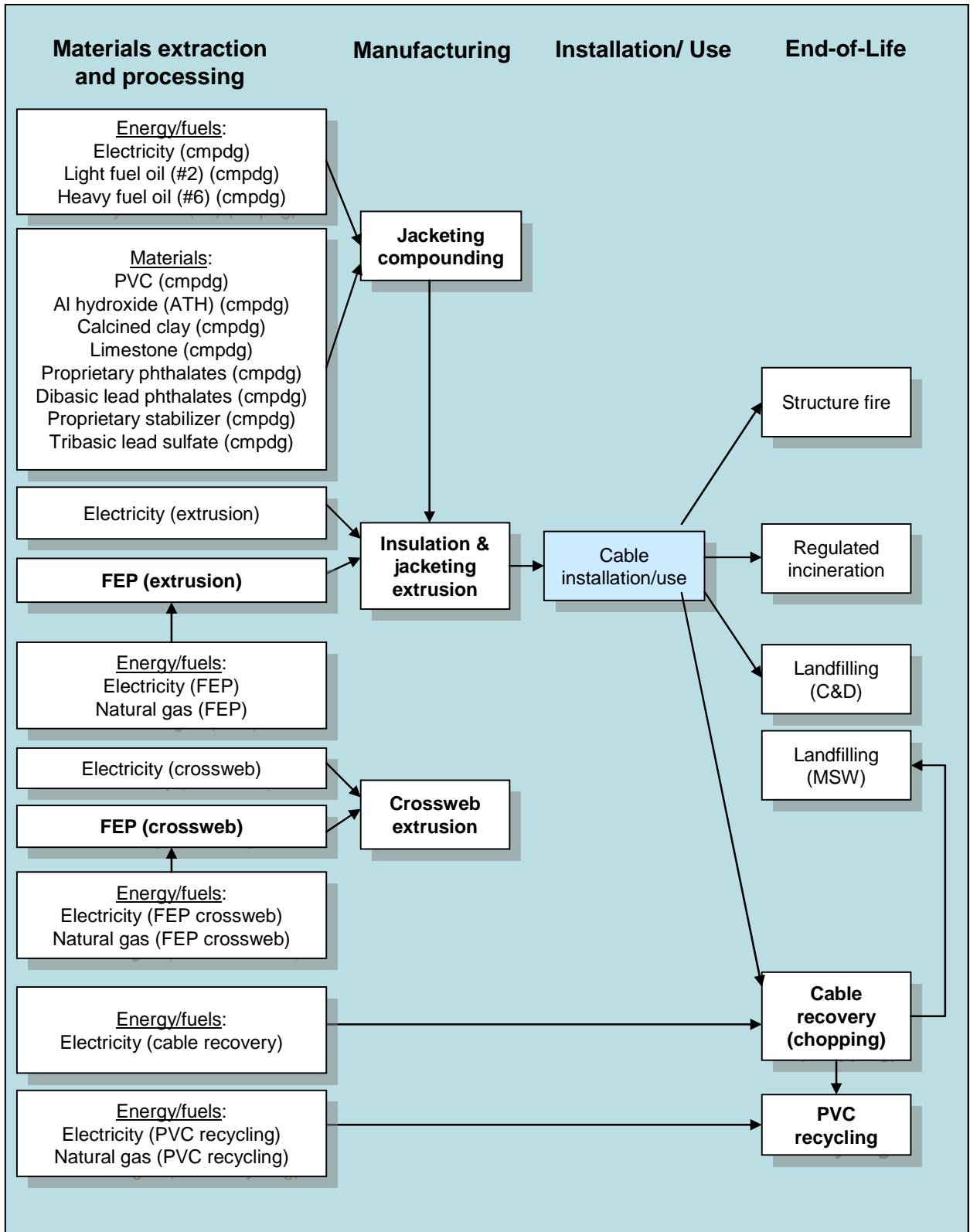


Figure 2-16. CMP Baseline (Lead-Stabilized): Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

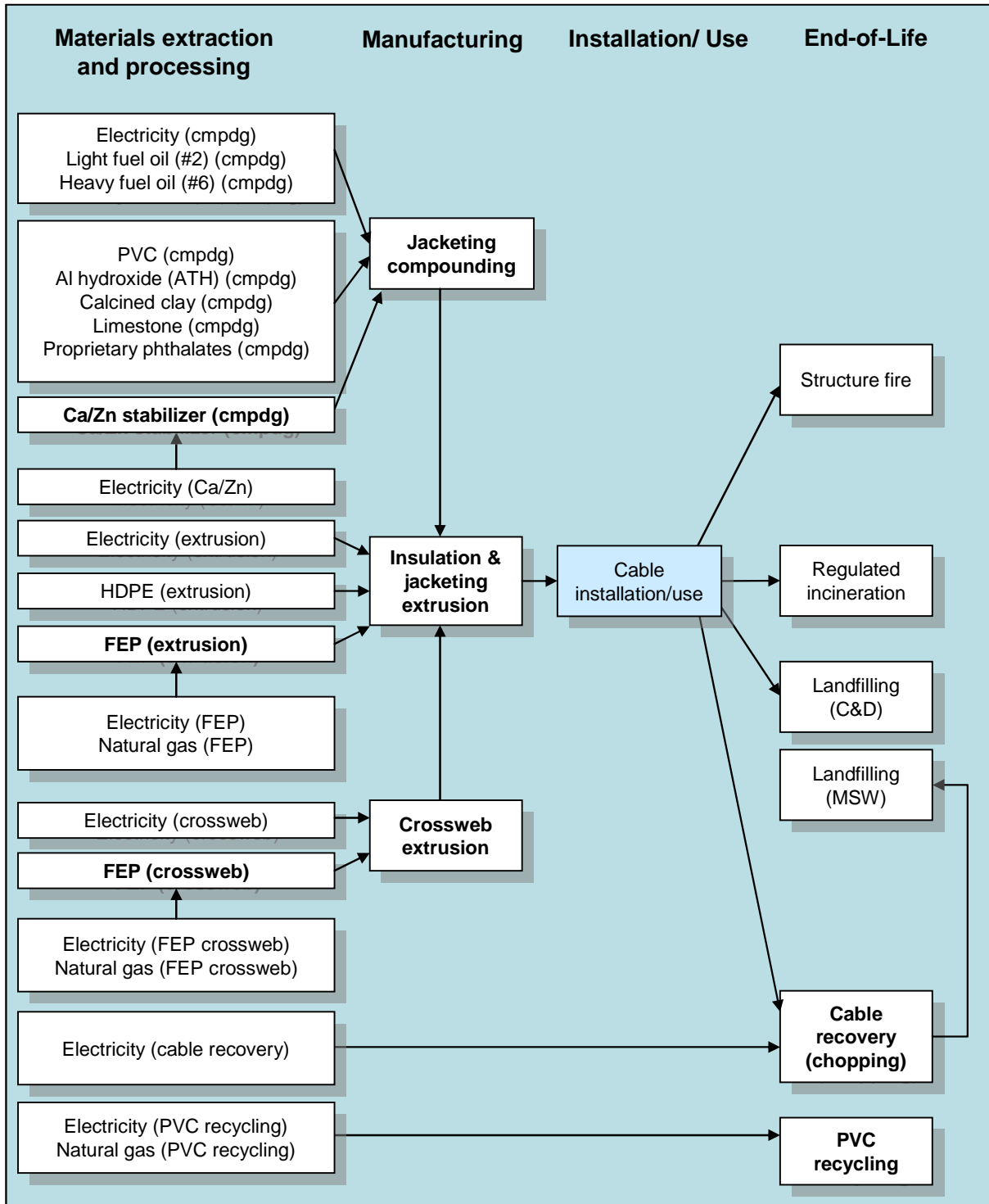


Figure 2-17. CMP Lead-Free Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

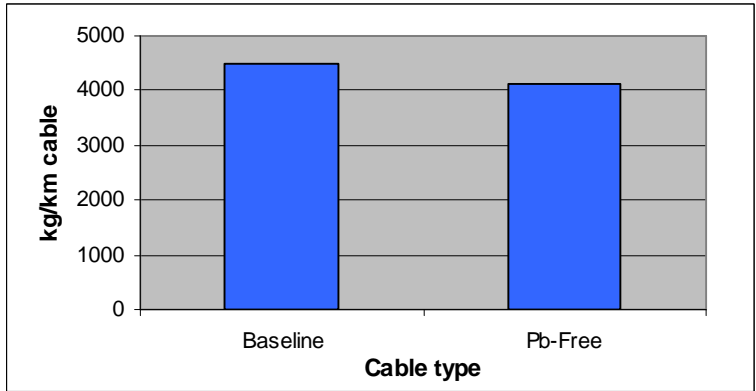


Figure 2-18. CMP Total Mass Inputs

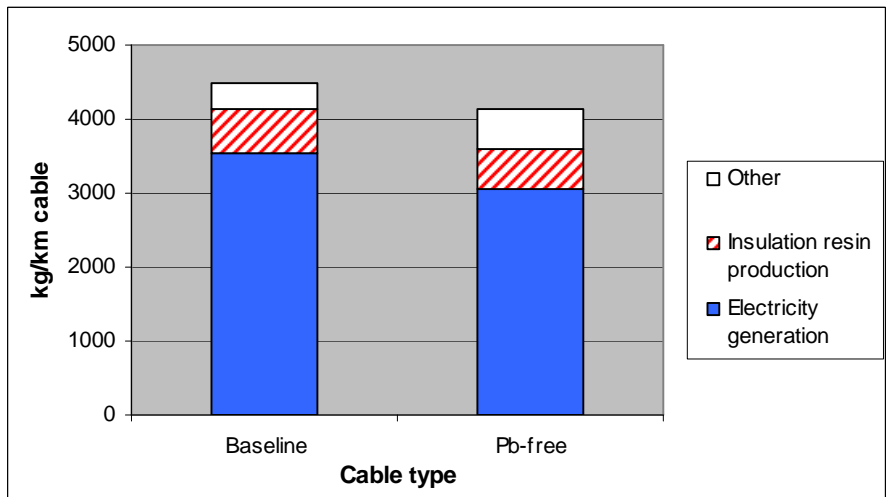


Figure 2-19. CMP Mass Inputs – Top Contributing Processes

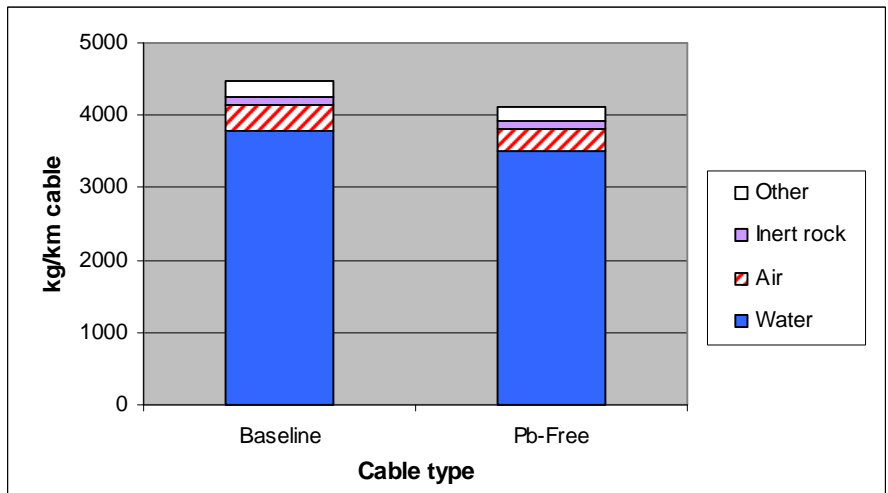


Figure 2-20. CMP Mass Inputs – Top Contributing Flows

Similar to the inputs, the mass outputs are presented in Figures 2-21 through 2-23. The baseline cable generates 10 percent more mass output than the lead-free alternative, which is shown in Figure 2-21. The top contributing process for both alternatives is the generation of electricity for use in the cable extrusion process (Figure 2-22). To protect confidentiality, Figure 2-22 combines the mass output from all upstream electricity generation. Wastewater is the greatest individual flow contributing to the mass output for both alternatives (Figure 2-23). Figure 2-22 includes the processes that contribute >3 percent of the total mass output, which represent 98 and 97 percent of the total impacts for the baseline and lead-free alternatives, respectively. Figure 2-23 includes individual flows that contribute >1 percent to the total impacts, and represents 98 percent of the total output mass for both the baseline and lead-free alternatives. The overall differences in mass output between the cables are primarily a function of the differences in energy use, as electricity generation generates substantial amounts of wastewater.

The total water outputs are tallied separately from individual constituents in the water that might be considered hazardous or toxic. The impacts associated with those are translated into appropriate impact categories as presented in Chapter 3.

The inventory is used to generate impact results, as described in Chapter 3. Further details, such as the inventories for specific processes are not provided for reasons of confidentiality.

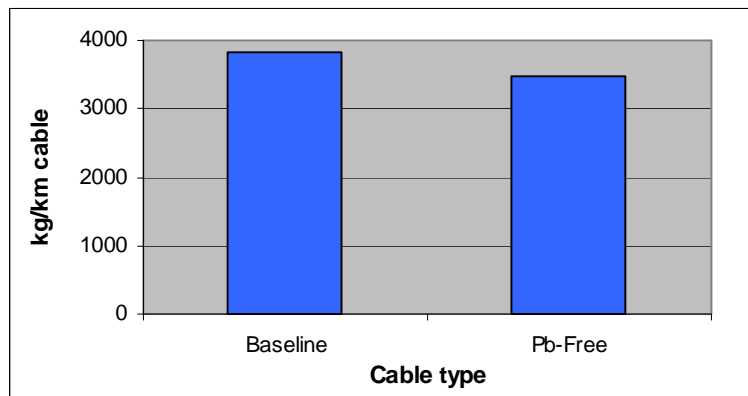


Figure 2-21. CMP Total Mass Outputs

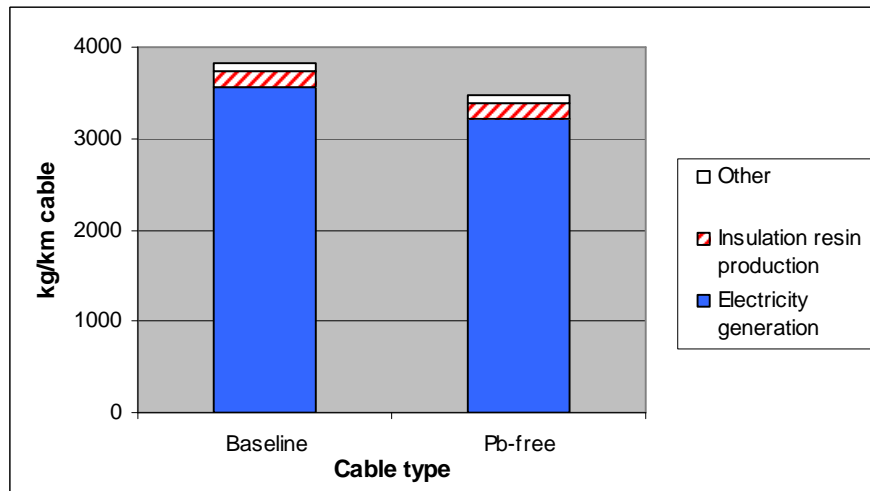


Figure 2-22. CMP Mass Outputs – Top Contributing Processes

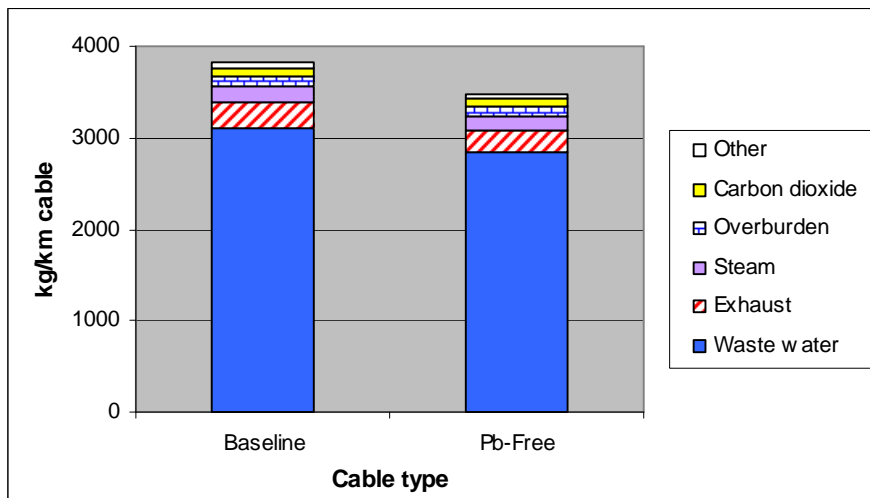


Figure 2-23. CMP Mass Outputs – Top Contributing Flows

2.5.3 NM-B LCIs

Figures 2-24 and 2-25 show the processes modeled for the NM-B baseline (lead-stabilized) and NM-B lead-free cables from materials extraction through to the end of life. Note that the lead-free alternative only represents materials extraction up to compounding, while the baseline includes materials extraction through EOL (thus in the LCIA results in Chapter 3, the NM-B comparisons are only based on the upstream through compounding processes). As in the CMR and CMP flow charts, the inventory data for the shaded process boxes (e.g., “cable installation/use”) are not included in the inventory, the functional unit is set to 1 kilometer of linear length of cable, and processes in bold represent those for which primary data were obtained.

Figures 2-26 through 2-28 compare the cradle-to-gate mass inputs for the baseline and the lead-free NM-B alternatives. Energy inputs are presented in Section 3.2.2 under Energy Impacts. Figure 2-26 presents the total cradle-to-gate mass inputs, while Figures 2-27 and 2-28 provide a breakdown of the processes that contribute greater than 5 percent to the total cradle-to-gate mass inputs and the individual flows that contribute greater than 1 percent to the total cradle-to-gate mass inputs, respectively. The total cradle-to-gate mass inputs for NM-B are 11 percent greater for the baseline than the lead-free alternative (1,836 kg/km cable and 1,657 kg/km cable, respectively). For both alternatives, the production of plasticizers is the greatest contributing process (59 percent of the total inputs for the baseline and 63 percent for the lead-free alternative) and the top contributing input flow is water, which contributes 93 percent of the total inputs for the baseline and 94 percent for the lead-free alternative. To protect confidentiality, Figure 2-27 combines the cradle-to-gate mass input from all upstream electricity generation.

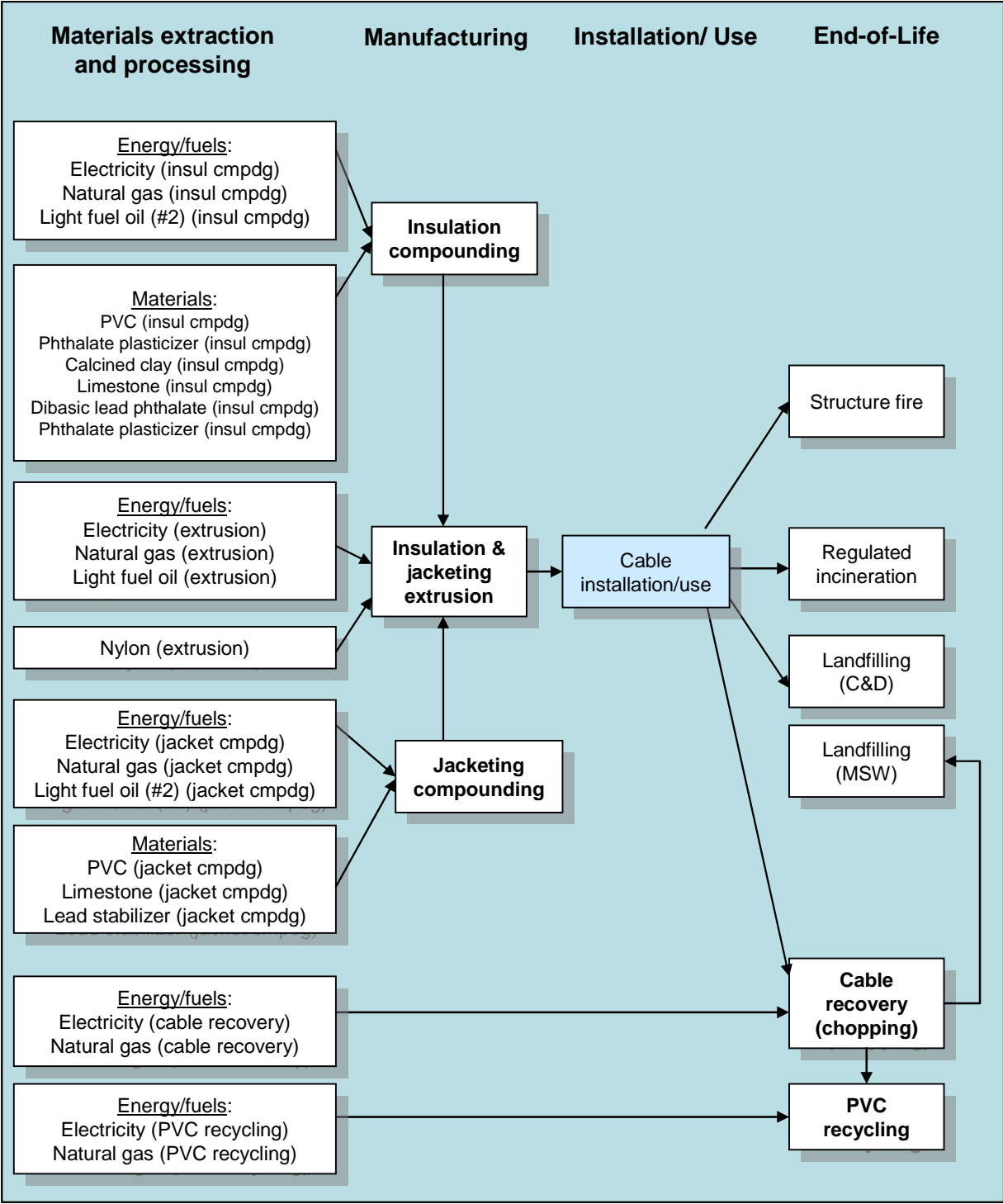


Figure 2-24. NM-B Baseline (Lead-Stabilized): Processes Modeled for the NM-B LCI

Note: Shaded boxes indicate no inventory data included for that process. Bold text indicates primary data collection for that process.

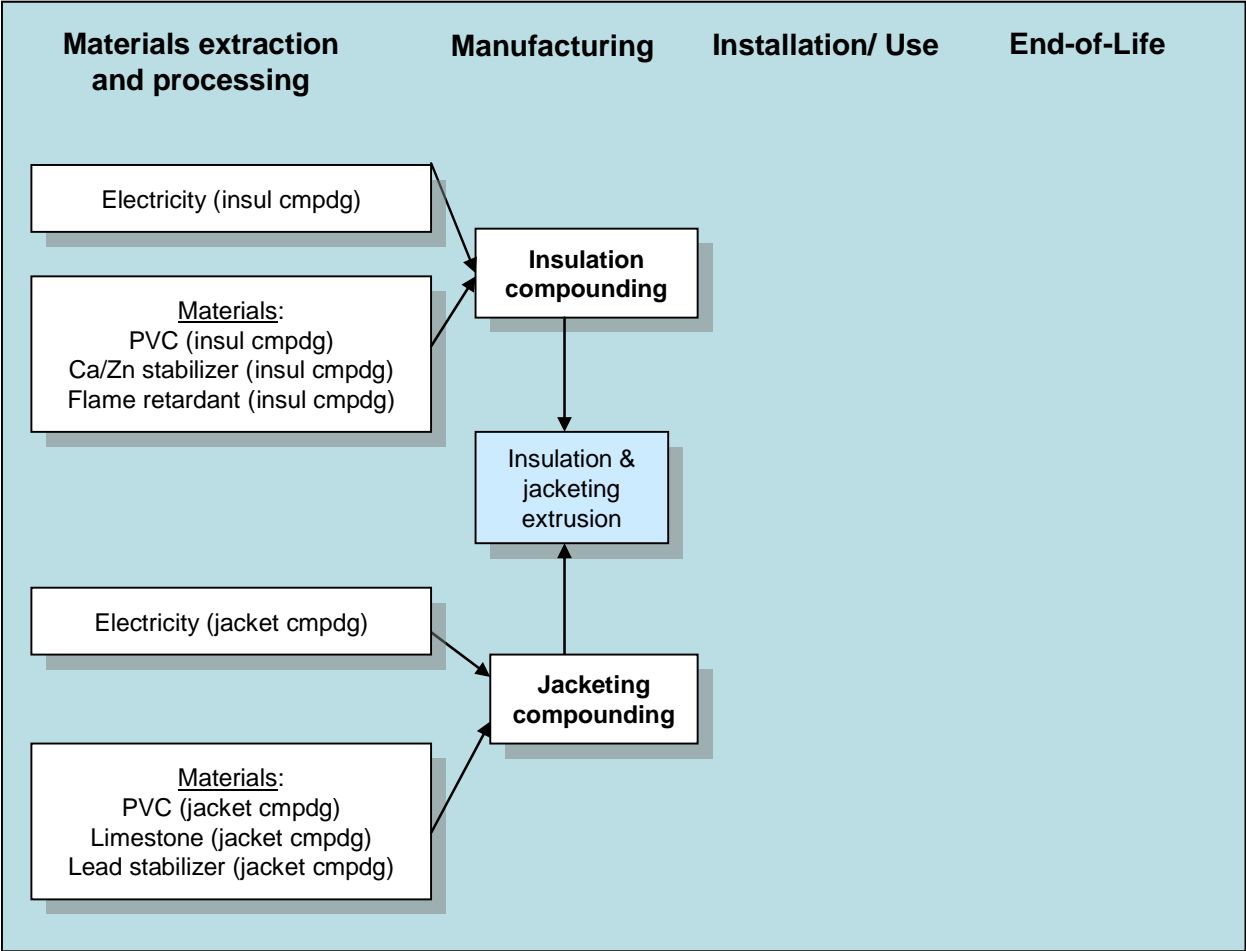


Figure 2-25. NM-B Lead-Free Cables: Processes Modeled for the WCP Comparative LCA

Note: Shaded boxes indicates no inventory data included for that process. Bold text indicates primary data collection for that process.

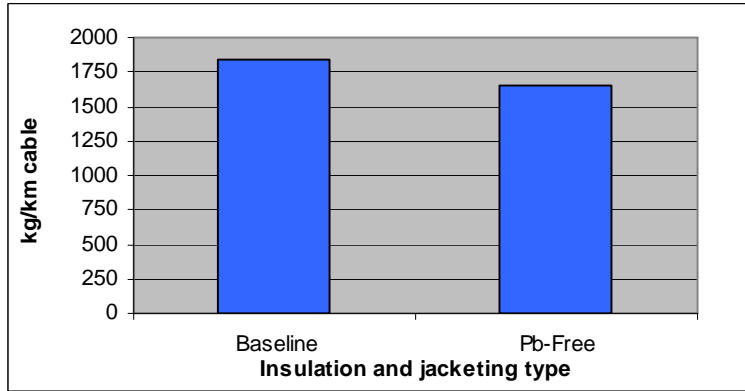


Figure 2-26. NM-B Total Mass Inputs – Partial Life Cycle

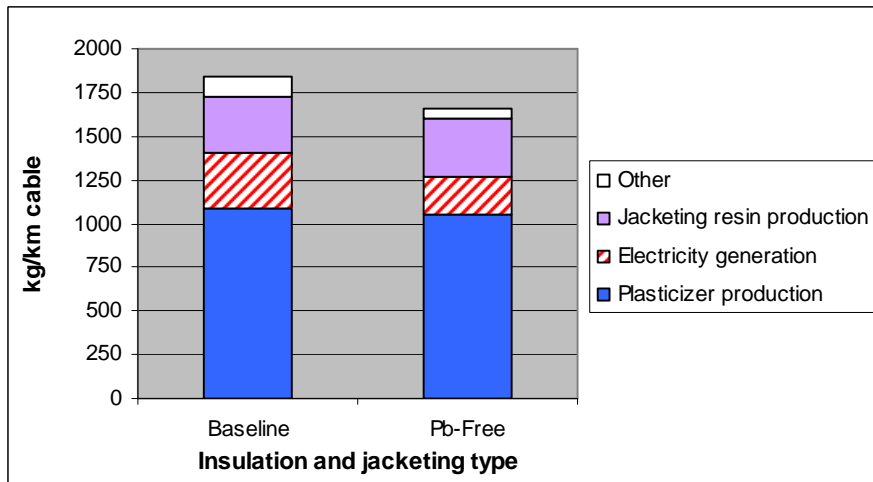


Figure 2-27. NM-B Mass Inputs – Top Contributing Processes – Partial Life Cycle

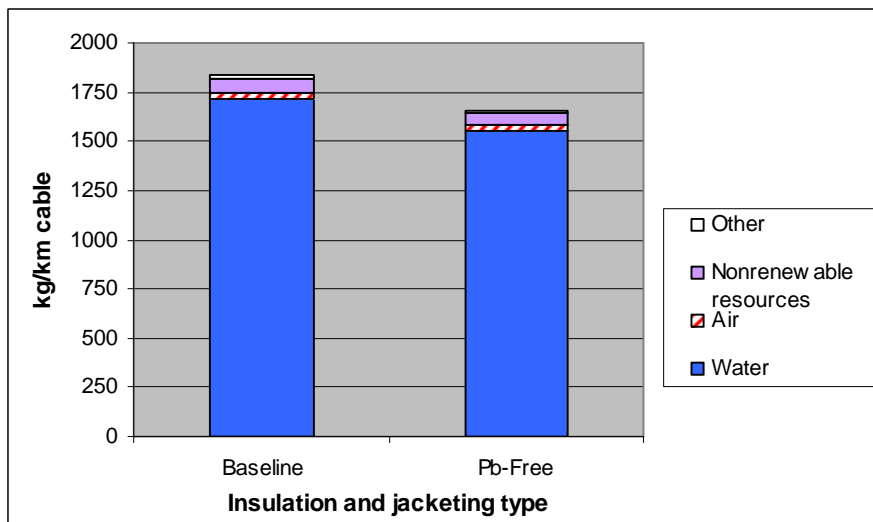


Figure 2-28. NM-B Mass Inputs – Top Contributing Flows – Partial Life Cycle

The baseline NM-B cable generates 35 percent more cradle-to-gate mass output than the lead-free alternative, which is shown in Figure 2-29. The top contributing process for both alternatives is the generation of electricity for use in the compounding of cable insulation and jacketing (Figure 2-30). To protect confidentiality, Figure 2-30 combines the cradle-to-gate mass output from all upstream electricity generation. Wastewater is the greatest individual flow contributing to the cradle-to-gate mass output for both alternatives (Figure 2-31). Figure 2-30 includes the processes that contribute >5 percent of the total mass output, which represent 94 and 96 percent of the total cradle-to-gate mass output baseline and lead-free alternatives, respectively. Figure 2-31 includes individual flows that contribute >1 percent to the total impacts, and represents 101 and 108 percent of the total cradle-to-gate output mass for both the baseline and lead-free alternatives (the fact that they account for greater than 100 percent is due to the aggregation of mass inputs and outputs in the calculation of totals). The overall differences in cradle-to-gate mass output between the cables are primarily a function of the differences in energy use, as electricity generation generates substantial amounts of wastewater.

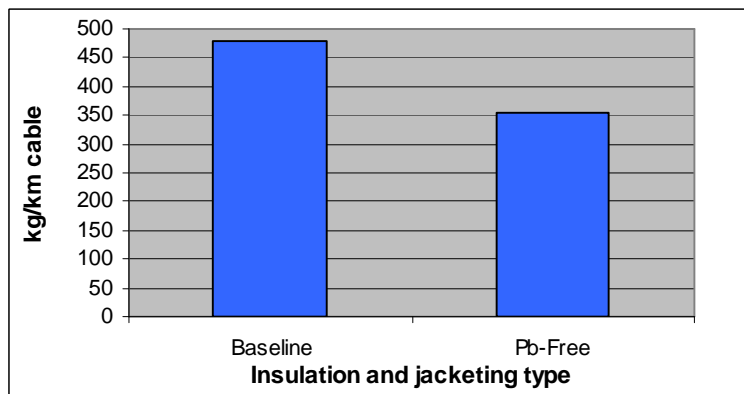


Figure 2-29. NM-B Total Mass Outputs – Partial Life Cycle

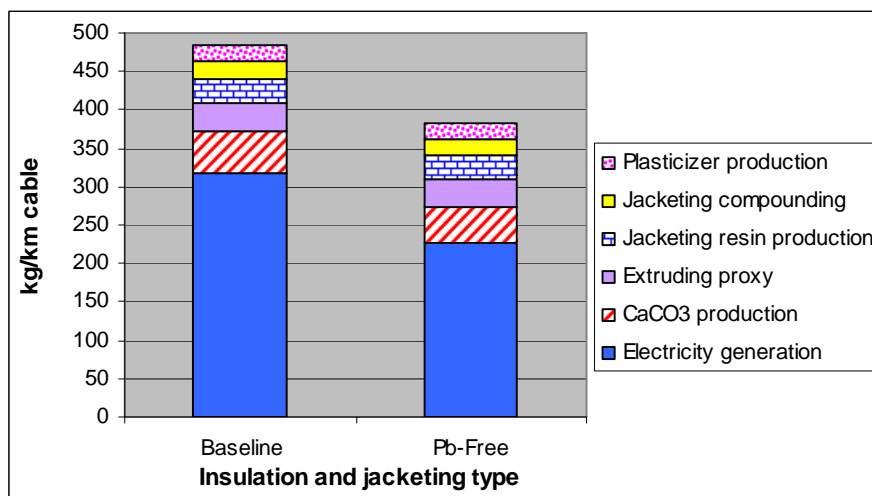


Figure 2-30. NM-B Mass Outputs – Top Contributing Processes – Partial Life Cycle

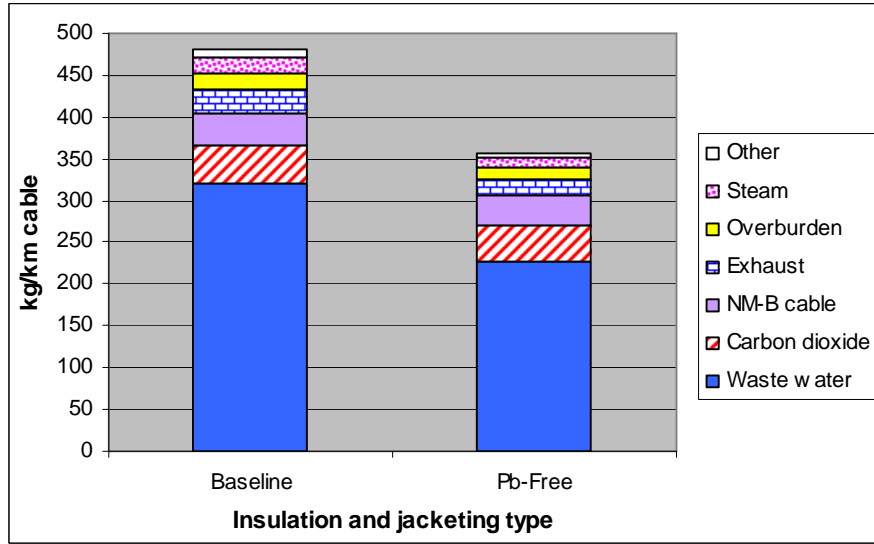


Figure 2-31. NM-B Mass Outputs – Top Contributing Flows – Partial Life Cycle