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Life Cycle Assessment (LCA) of overhead versus underground primary power distribution systems in Southern California

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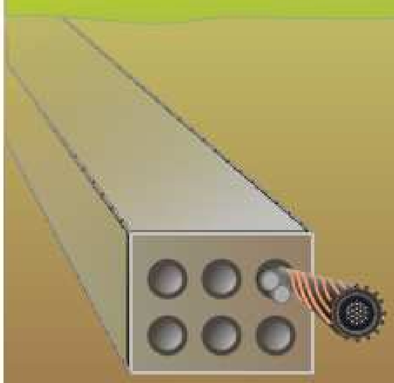

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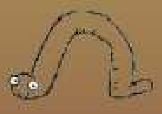

Life Cycle Assessment (LCA) of overhead and underground primary power distribution systems in Southern California

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1. Summary

High electrical power demand has spurred discussion on trade-offs between overhead and underground power distribution systems. Many regions in the United States, European Union, and Australia are considering revising protocol for new power distribution installations and/or converting existing infrastructure to underground mode. Studies generally concur that underground distribution is much more costly to install, but may improve reliability and decrease maintenance costs. Recently, a few comparative environmental assessments of overhead and underground cable production have been conducted. However, current literature lacks a full investigation of the life cycle environmental impacts of both distribution methods, including all infrastructure components. This project thus examines the difference between the potential environmental impacts of overhead and underground primary power distribution systems. It is based on a full Life Cycle Assessment (LCA), which has been conducted using LCA software GaBi 4.3, drawing from a wide range of data sources. The analysis synthesizes detailed information on the use phase, including installation, maintenance, and decommissioning of cable and associated infrastructural components. The study is also specific to Southern California Edison, one of the largest electric utility suppliers in the United States. The results cover a wide range of environmental concerns, such as climate change, photochemical smog, acidification, and toxicity.

2. Introduction

This analysis uses Life Cycle Assessment (LCA) methodology to assess and compare potential environmental impacts of overhead and underground primary power distribution systems in Southern California. The results support decision-makers in managing the expansion or conversion of the electrical grid.

Projections affirm that the supply and demand side of electricity service will face imbalance without procurement of additional resources and efficient use of current resources [1-4]. The policy debate is fueled from overhead systems creating a potential hazard for vehicle collisions, visual obstruction, and increased damage in fires [5-7]. The California Public Utilities Commission's Rule 20 provides undergrounding conversion funds from ratepayer fees and gives priority to congested, civic, and scenic areas [8]. Likewise, other areas within the United States (US), the European Union (EU), and Australia are recommending mandates for installing new underground systems and converting existing overhead infrastructure for aesthetic and safety purposes [5-7].

Many factors contribute to the tradeoff between overhead and underground power distribution. The most widely discussed factors in literature are: aesthetics, safety, cost, and reliability. Underground systems are concealed, thus increasing nearby property values and preserving local aesthetics. Also, underground systems reduce the possibility for live-wire contacts and vehicle accidents from collisions with utility poles [9]. Although installation of underground distribution presents a substantial initial investment, costing four to twenty times more than overhead systems, it may improve reliability and decrease maintenance costs [6, 7, 10]. While underground systems may improve reliability due to fewer outages, the time required to repair an outage event is considerably longer than for overhead systems [5-7, 10]. Thus, the topic of reliability is very contentious and depends significantly on the location of the electrical product system. The above factors have been extensively discussed in literature, but very few studies focus on the environmental impacts of electrical distribution systems. A few LCA studies have examined the environmental impact of different components of the power grid infrastructure [11-14]. No LCA has investigated the entire infrastructure, as well as the cables, for overhead and underground primary power distribution for the sole purpose of analyzing and comparing potential environmental impacts.

SCE delivers power to 13 million people in a 50,000 square-mile service area, which is considered one of the most rapidly developing areas in the US [15]. SCE’s load-growth for 2008-2017 is estimated at 2.22 percent per year (615 megawatts per year) system-wide [16]. This growth will require 564 new distribution circuits of various length, or roughly 56 circuits per year [16]. Focusing on SCE’s service area, this study chose to evaluate cables and infrastructure associated with primary power distribution.

An advantage of choosing the distribution system for this study, as compared to a transmission system, is that it is located in densely populated areas and comprises approximately ninety percent of SCE’s electrical line length [16]. Long distance transmission lines are often through rural and sparsely populated areas, whereas distribution lines deliver power amongst neighborhoods, towns, and in urban centers. It is this urban and suburban area of power delivery where the majority of stakeholders assess the choice between overhead and underground systems. This study provides a basis for more informed decision-making in electricity grid planning and management by adding a new dimension to the discussion, namely environmental impacts of each system drawn from a full comparative LCA.

3. Methods and Data

Electric power transmission and distribution systems generate a wide variety of environmental impacts at all stages of their life cycles. Life cycle assessment (LCA) methodology is therefore ideally suited to quantify and compare the overall environmental impacts of different power distribution systems. More specifically, the cradle-to-grave environmental impacts of overhead and underground primary power distribution systems in Southern California are quantified through LCA. In contrast to other studies, which only assess cable production and end-of-life management [11, 12, 14], the reported research aims at quantifying the environmental impacts from entire power distribution lines throughout their life cycles. The research is based on LCA methodology and terminology as described in ISO 14040/44 (2006) [17].

3.1 Scope and System Boundaries

Scope and boundaries of this study are influenced by a variety of assessment and modeling choices. First, the study focuses on primary MV power distribution. Primary distribution comprises 87% of SCE's total electrical line length and its planning and management involve many stakeholders [18]. Thus, focusing on primary distribution addresses much of the debate on alternative power delivery methods. Second, a line length of one mile was selected as the unit of analysis in order to capture all significant infrastructural components required by each power delivery system. Third, data for the analysis was compiled in collaboration with SCE and their upstream supply chain and downstream waste management companies. The resulting inventory model is thus specific to SCE, which has fairly comprehensive environmental programs and practices in place, and to some extent also to the specifics of its service area. Investigating overhead and underground primary power distribution services, as provided by SCE, compares these systems under Southern Californian conditions and in a relatively eco-efficient setting. Finally, the study focuses only on those materials and processes that are used in new SCE installations. For instance, many utility poles were previously treated with creosote, a coal-tar derivative, and are still in use as part of existing infrastructure. However, SCE has shifted to using pentachlorophenol (PCP) treated poles and thus, only impacts from PCP treated poles were analyzed in this study. In summary, the scope of the overhead and underground life cycle inventory models is one mile of MV distribution line and reflects the specifics and details of new SCE installations.

To provide functional equivalence between the studied distribution systems and help to select their system boundaries, the following functional unit was defined: The distribution of MV power over a distance of one mile and for a duration of one year. The resulting reference flows include cables and infrastructural components to provide the functional unit. The specific overhead and underground cables were selected based on their high-purchase volume and comparable capacity for power delivery. For the chosen cables in a MV distribution system, an overhead electrical circuit requires four cables (three phases and one neutral); while an underground circuit requires only three cables, each includes a copper concentric neutral. The supporting infrastructural components were chosen to match the selected cables. The components and processes required to model each power delivery method from cradle to grave are listed in Table 1.

Environmental impacts associated with the physical and human capital (i.e. the production and maintenance of buildings and vehicles, labor, and associated resources) were not included in the model. It is not viable to allocate and differentiate these capital impacts between overhead and underground systems. Moreover, the impacts would not affect the results of the comparison significantly and thus, they were assumed to be negligible.

In summary, the study's scope and system boundaries ensure a comparable and representative functional unit that covers the life cycle environmental impacts of typical, MV power delivery systems in Southern California.

Table 1. LCA System Boundaries

Materials Required for the Installation of one Circuit Mile (circuit mile)		
Infrastructure Component	**Material**	**Mass (in kg/cmile)**
OVERHEAD		
Cable (4cables)	Aluminum	3,020
	Steel, galvanized	474
Cable Reels (1.85 reels)	Steel, galvanized	336
Utility Poles (25) **Crossarms** (30)	Wood	9,071
	Pentachlorophenol (PCP)	266
Insulators	Polyethylene (PE)	91
Steel castings	Steel, galvanized	420
UNDERGROUND		
Cable (3 cables)	Aluminum	6734
	Copper	2278
	Polyethylene (PE)	7408
Cable Reels (3.96 reels)	Steel, galvanized	2278
Vaults (5.2) **and Duct** (1)	Concrete	1,096,593
Steel Rebar for Vaults	Steel	15,910
Conduits (6)	Polyvinyl chloride (PVC)	66,986

Included Processes		
	Overhead Product System	**Underground Product System**
Production	• Production of all components listed above	
Installation	• Pole hole digging • Aerial lifting • Cable pulling	• Trench excavation • Placing vaults • Concrete mix & pour • Cable pulling
Maintenance	• Tree trimming • Scheduled maintenance	• Vault water pumping • Scheduled maintenance
Decommissioning	• Pole pulling • Cable pulling • Aerial lifting	• Cable pulling • Excavation • Concrete crushing
End of Life Management	• Cable recycling • Reel reuse • Pole assembly landfill	• Cable recycling • Reel reuse • Vault & duct landfill • Conduit landfill
Transportation	• All transportation steps within and between listed processes	

3.2 Reference Flows

Comparing overhead and underground power distribution systems is complicated by the fact that different system components have very different theoretical lifetimes. Additionally, external events affect the lifetimes of the components. Cable segments, in particular, often have to be replaced before they reach the end of their theoretical lifetimes.

Table 2 illustrates how the reference flow masses for the baseline scenario are calculated from the material requirements of installing one circuit mile from Table 1. The reference flow masses denote the amount of materials needed to provide the functional unit, i.e. to distribute MV power over a distance of one mile, for a duration of one year.

Table 2. Functional Unit Mass to Reference Flow Mass Conversion (Baseline Scenario)

Reference Flows	Calculation of Reference Flow Mass (Varied Parameters in Bold Italic)	kg per circuit mile per yr
OVERHEAD		
$\text{MASS}_{\text{OH CABLE}}$	$\frac{\text{FU MASS}_{\text{OH CABLE}}}{\textbf{\textit{TIME}}_{\textbf{\textit{PLANNING HORIZON}}}} + (\text{FU MASS}_{\text{OH CABLE}} * \textbf{\textit{FRACTION}}_{\textbf{\textit{OH CABLE REPLACED}}})$	100.7
$\text{MASS}_{\text{OH CABLE REEL}}$	$\frac{\text{FU MASS}_{\text{OH CABLE REEL}}}{\textbf{\textit{TIME}}_{\textbf{\textit{PLANNING HORIZON}}}} + (\text{FU MASS}_{\text{OH CABLE REEL}} * \textbf{\textit{FRACTION}}_{\textbf{\textit{OH CABLE REPLACED}}})$	9.70
$\text{MASS}_{\text{OH POLE}}$	$\frac{[\text{FU MASS}_{\text{POLE}} - (\text{FU MASS}_{\text{PCP APPLIED}} * \textbf{\textit{FRACTION}}_{\textbf{\textit{PCP LEACHED}}})] \div \text{TIME}_{\text{POLE LIFE}}}{\textbf{\textit{POLE CAPACITY}}}$	186.7
$\text{MASS}_{\text{PCP TO SOIL}}$	$\frac{\text{FU MASS}_{\text{PCP APPLIED}} * \textbf{\textit{FRACTION}}_{\textbf{\textit{PCP LEACHED}}}}{\text{TIME}_{\text{POLE LIFE}}}$	0.00
$\text{MASS}_{\text{INUSLATOR}}$	$\text{FU MASS}_{\text{INSULATOR}} \div \text{TIME}_{\text{POLE LIFE}}$	1.81
$\text{MASS}_{\text{STEEL CASTINGS}}$	$\frac{\text{FU MASS}_{\text{STEEL CASTINGS}}}{\text{TIME}_{\text{POLE LIFE}}}$	8.39
UNDERGROUND		
$\text{MASS}_{\text{UG CABLE}}$	$\frac{\text{FU MASS}_{\text{UG CABLE}}}{\textbf{\textit{TIME}}_{\textbf{\textit{UG CABLE LIFE}}}} + (\text{FU MASS}_{\text{UG CABLE}} * \textbf{\textit{FRACTION}}_{\textbf{\textit{UG CABLE REPLACED}}})$	858.3
$\text{MASS}_{\text{UG CABLE REEL}}$	$\frac{\text{FU MASS}_{\text{UG CABLE REEL}}}{\textbf{\textit{TIME}}_{\textbf{\textit{UG CABLE LIFE}}}} + (\text{FU MASS}_{\text{UG CABLE REEL}} * \textbf{\textit{FRACTION}}_{\textbf{\textit{UG CABLE REPLACED}}})$	119.06
$\text{MASS}_{\text{CONCRETE}}$	$\frac{\text{FU MASS}_{\text{CONCRETE}} / \textbf{\textit{TIME}}_{\textbf{\textit{INFRASTRUCTURE LIFE}}}}{\textbf{\textit{INFRASTRUCTURE CAPACITY}}}$	8900
$\text{MASS}_{\text{PVC CONDUIT}}$	$\frac{\text{FU MASS}_{\text{PVC CONDUIT}} / \textbf{\textit{TIME}}_{\textbf{\textit{INFRASTRUCTURE LIFE}}}}{\textbf{\textit{INFRASTRUCTURE CAPACITY}}}$	535.9

Overhead cable is usually replaced in sections—a length equal to the distance between two utility poles (~69 meters). The rate of cable section replacements depends on frequency of failure events. Statistically, an entire circuit mile of cable may be replaced in pieces in as little as 26 years. The entire circuit mile of overhead cable can be replaced well before the designed cable lifetime. Therefore, the environmental impacts of production and installation of initial mile of cable are distributed over the time the power line is in use. The planning horizon parameter was introduced into the model to reflect this time period. Overhead cable reference flow mass is the sum of the functional unit cable mass divided over the planning horizon plus the cable mass replaced per year. The same approach was used in calculating reference flow masses for components associated with overhead cables (i.e., overhead reels, and diesel requirements for installation and decommissioning of cable).

In contrast, failure frequency is lower in the underground system and thus, the underground cable often reaches its designed lifetime. The reference flow mass for the underground cable is the sum of the functional unit cable mass divided over the underground cable lifetime, plus the cable mass replaced per year. The same approach was used in calculating reference flow masses for components associated with underground cables (i.e., underground reels, and diesel requirements for installation and decommissioning of cable).

These overhead MV line components are replaced only when the utility pole is replaced. Thus, the reference flow mass for each component is the functional unit mass divided over the lifetime of the utility pole. Likewise, impacts of PCP leaching into soil should be distributed over the use time of the utility pole.

These infrastructural components can support more than one power circuit. For example, underground MV distribution systems in the SCE service area are designed to accommodate up to six circuits. Likewise, overhead poles often carry more than one circuit. Therefore, when calculating the reference flow masses for these components, not only their lifetimes but also their capacity must be incorporated. Functional unit masses of these components are divided by their respective lifetimes and by system capacity. The same approach was used in calculating reference flow masses for components, associated with poles, concrete and conduits: Installation and decommissioning requirements for these components were divided by their lifetime and their capacity.

Maintenance includes material and energy requirements for driving and idling during: cable section replacements, routine inspections of both systems, tree trimming for overhead lines, and vault water pumping for underground lines. Reference flow calculations for maintenance associated with cable section replacements are discussed above. The remaining functional unit masses associated with maintenance of both systems are already in annual terms and thus, their reference flows have the same values.

3.3 Parameterization

Several aspects in each power distribution system are subject to significant uncertainty (Table 3). For each of these uncertainties parameters were introduced in the inventory model in order to conduct sensitivity analysis and examine the resulting range of results.

The cable lifetimes are ranges from literature and reflect various designed lifetimes for MV power cables [19]. The designed lifetime of the underground cable is shorter than the overhead cable. This disparity mainly occurs because the plastic insulation of the underground is susceptible to degradation over time or ‘water treeing’. There are no certain values in the literature for rates of pentachlorophenol (PCP) leaching from utility poles. Thus, varying the leaching amount from zero to one-hundred percent captures all possibilities of contaminant release, including the pole’s end-of-life waste management. For both overhead and underground systems, cable recycling rates are associated with some uncertainty. The uncertainty is heightened since the sorted cables are shipped to China for materials recovery and reprocessing. The high recycling value is an international rate whereas, the low value is estimated from material market values to account for the uncertainty of material recovery rates and reprocessing yields overseas [12,20]. While the lifetime of the overhead infrastructure (i.e., wooden utility poles) is fairly well known, that of the underground system infrastructure is not. The oldest underground power delivery infrastructures have been in place for about 100 years and have yet to be decommissioned [21]. Underground infrastructure materials (concrete, steel, and PVC) are extremely durable and long-lasting but not infinite. For these reasons, the underground infrastructure lifetime is assumed to be 125 years with a 20% standard deviation. Another uncertain factor is cable failure frequencies due to external events. The overhead lines are more exposed to forces of wind, fire, ice, and human interaction than underground lines and thus, their failure frequency is higher. The baseline failure frequencies for each system are based on literature values for which a 30% standard deviation was selected for each to account for variation in external influences [19]. Because of the high failure frequency of the overhead cable, the entire circuit mile is often replaced before the cable has reached its designed lifetime. Therefore, the aforementioned planning horizon was introduced into the model. Given the U.S. average of 90 failure events per 100 circuit miles for overhead distribution systems, an entire circuit mile of cable will be replaced in an 26 years. Thus, this value was chosen as the more conservative end to estimate the environmental impacts from the production and installation of the initial mile of cable. Using a planning horizon beyond 100 years, results in impact values that become too small to compare.

Table 3. Parameterized Factors for Cable Product Systems

Parameter	Baseline Scenario Value	Range	Unit	Source
OVERHEAD (OH)				
Cable Lifetime	40	30 - 50	Years	19
Infrastructure Capacity	1	1, 2, 4	Number of Circuits	21
PCP Leaching to Soil	0	0-1	Fraction PCP Mass Leaching to Soil	n/a
Recycling Rate (Including Collection and Recovery)	0.94	± 0.02	Fraction OH Cable Mass Recovered	12, 20
Failure Frequency	0.9	0.63 -1.17	Failure events/circuit mile/year	19
Planning Horizon	63.035	26.07-100	Years over which impacts examined	n/a
UNDERGROUND (UG)				
Cable Lifetime	30	20 - 40	Years	19
Infrastructure Capacity	1	1, 4, 6	Number of Circuits	21
Recycling Rate (Including Collection and Recovery)	0.84	± 0.13	Fraction UG Cable Mass Recovered	12, 20
Infrastructure Lifetime	125	100 -150	Years	21
Failure Frequency	0.1	0.07-0.13	Failure events/circuit mile/year	19

3.4 Life Cycle Inventory

The life cycle inventory models of OH and UG MV power distribution are specific to SCE's situation to the extent possible. Inventory data was therefore gathered in close collaboration with SCE and their primary suppliers and contractors. SCE -specific data was collected using the following methods: site visits, on-site measurements, and personal communications. Sites visited include the cable supplier's manufacturing facilities, SCE service centers, SCE warehouses, and the waste management facilities of SCE's contractors. These methods facilitated measurement, calculation, or robust estimation of SCE-specific values for production, installation, maintenance, decommissioning, and waste management processes. The processes for which no sufficient SCE-specific inventory data could be collected were modeled using process inventories from LCA databases, including GaBi v4.3 and ECOINVENT v2.0, and literature sources. Figures 1 and 2 show material and process flow diagrams of the two products systems. The color coding of processes indicates their data origin.

Figure 1. Overhead System Flow Diagram

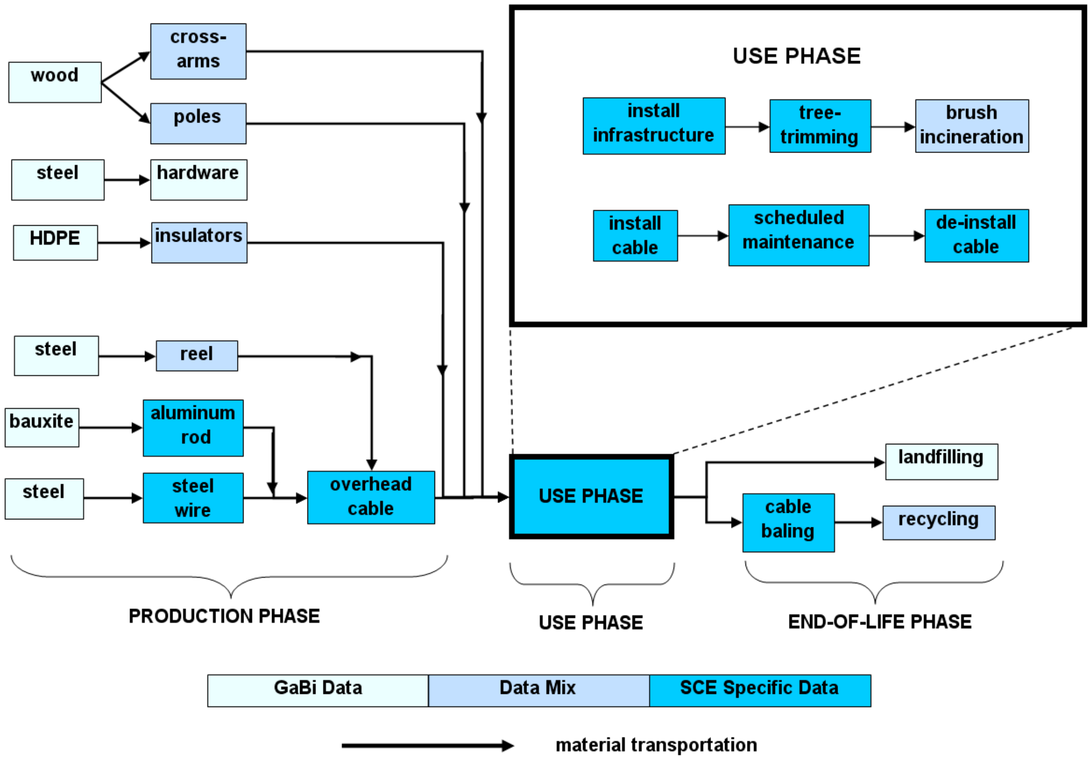
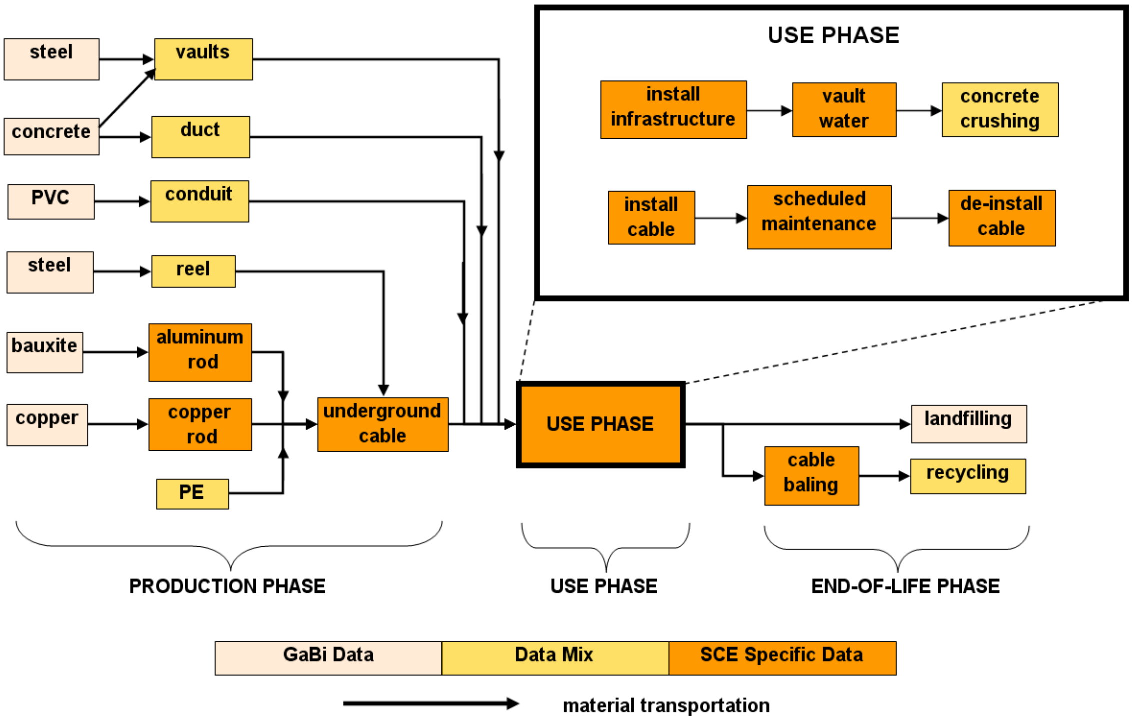


Figure 2. Underground System Flow Diagram



In the production phase, cable production was modeled incorporating the most specific data. The data needed for material and energy requirements of rod production, wire drawing and stranding, and cable extrusion were compiled in close collaboration with SCE's primary cable supplier. These primary data were subsequently modeled by the practitioners in the software and includes aluminum and copper rod production, wire drawing, stranding and testing, and cable extrusion. The remaining processes of cable production, namely material inputs to the cable production, were modeled using industry averages from the GaBi v4.3 and the Ecoinvent v2.0.

The use phase of each product system, including installation, maintenance, and decommissioning, was modeled almost entirely with data calculated from information obtained during communication with SCE specialists. The bulk of use-phase processes consist of using diesel-fueled utility vehicles. Inventory for installation, maintenance, and decommissioning processes included both distances driven by utility vehicles and stationary engine use for activities such as hydraulics and auxiliary work, digging, and pumping.

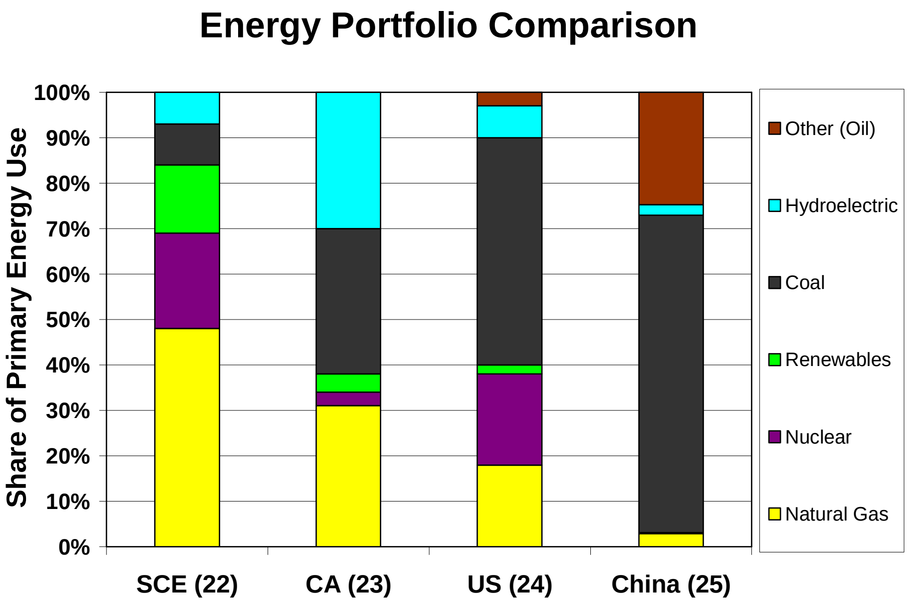
Installation, maintenance, and decommissioning of each product system were modeled based on typical requirements as reported by SCE. The diesel fuel consumption from driving and stationary use during these activities was calculated given average vehicle types, distances, and project durations for SCE. For the overhead system, installation processes include digging holes for poles, setting poles, and stringing the cable; which requires a digger, a cable dolly, an aerial bucket lift, and a cable puller. These same types of vehicles are required to decommission the system. To install the underground system the following activities are typically required: digging the trench, placing vaults and conduits, mixing and pouring concrete, filling the remaining space with backfill, and pulling the cable. The vehicle types needed for these activities are a trencher, a dump truck, a crane, a cable dolly, a cable puller, and a concrete mixer vehicle. Decommissioning for underground requires the same vehicle types except that the concrete mixer is replaced with a machine to crush concrete. Modeling of maintenance accounts for impacts from transportation, replacement of the cable sections due to the failure events, tree trimming for the overhead system and pumping vault water out of the underground infrastructure.

Cables decommissioned from the Southern California Edison service area are sorted and baled by SCE's waste management contractor. The bales are then shipped to China for recycling. Data required for cable sorting, packaging, and chopping processes in the EOL phase were gathered in close collaboration with SCE's cable waste management facility and recycling rates were parameterized in the model using a range of possible values.

Due to the potentially high impact of transportation processes on the comparison results, specific attention was paid to modeling transportation. Transport of materials was modeled using data specific to each trip including: payload capacity and utilization ratio of the vehicle; distance traveled and distance percentage in town, out of town, and on the highway; proportion of sulfur in diesel fuel; and vehicle emission standards. For example, the travel path between specific SCE supply chain facilities and the SCE warehouses and service centers to which the materials are delivered was determined using Google maps. These maps were used to ascertain the distance between facility addresses as well as the distance percentages in town, out of town, and on the highway. Specific distances were not available for steel and concrete raw materials in the production of pre-cast underground vaults. In these cases, local production distances and parameters were assumed to be within 100 kilometers and travel conditions similar to those of the service area.

For an accurate representation of the energy used within Southern California, energy inputs required for the use phase were specific to the SCE utility power profile. Energy inputs required for the Production and EOL phases used a US average profile mix except for cable recycling which occurs in China and thus, uses average China profile mix. The comparison in energy mix profiles used between modeled phases as well as the California mix are illustrated in Figure 3 [22-25].

Figure 3. Energy Portfolio Comparison



Allocation: Allocation is avoided in this model by using consequential system expansion, or the 'avoided burden method'. This method assumes that when a product is recycled, the primary processing of each of the constituent materials is displaced. In this sense, primary production may be seen as a process that generates recyclable materials. However, the environmental impacts of end-of-life processing (i.e., transportation, disassembly, sorting, and secondary processing of constituent materials) are still accounted for in the overall life cycle assessment of the product. Product reuse, in the avoided burden method, displaces the entire production process and thus, avoids all of its associated environmental burdens. Again however, the environmental impacts of collecting and/or treating the re-used product are accounted for in the overall life cycle assessment.

In the overhead and underground distribution product systems, approximately 80% of the steel cable reels are reused. Reel reuse is reflected by subtracting the appropriate fraction of burdens from those of the entire reel production process. The steel from the portion of reels lost from the product system is assumed to be recycled. Reel loss is reflected by subtracting the appropriate fraction of burdens only from those of primary steel production.

Though both the overhead and underground cables are recycled, the recycling rates are uncertain. A range of values was considered to account for this uncertainty. The high value of the recycling rate is an international rate quoted as 95 percent by the Bureau of International Recycling [12]. This high rate is for wire and cable products in general and is appropriate for distribution cable materials if they are efficiently collected and do not change their inherent properties through the recycling process.

The fact that the cables are recycled in China is one reason to consider a lower recycling rate. China's recycling infrastructure has a significant potential for material loss and/or changes in material properties (i.e., downcycling) compared to recycling infrastructures in developed countries. Another aspect to consider is that, while overhead cables are comprised solely of metals, underground cables contain both metals and high density polyethylene and thus, recovery is more complex. The added material complexity of the underground cable increases the likelihood for material loss and downgrading through its recycling process. A devaluation factor was calculated for each cable product to reflect the possibility of lower recycling rates for the cables. This factor accounts for the possible limitations in recycling the product as a whole and/or in the further use of the resulting secondary material(s). Because prices are assumed to best describe the value of a material over the whole material cascade, a preferred method to determine devaluation is by using long-term price averages of primary and secondary materials [26]. Devaluation factors were first calculated for each material in the cable product using long-term price ratios. This method is the same as calculating the Recyclability Index (RI) for a material as proposed by Villalba, et al. [20]. These material RI values were then used to estimate the RI of each cable product. The resulting product RI was then used as a conservative recycling rate for each cable product. Thus, the low value of recycling rate for overhead cable is 91.19 percent and 72.75 percent for the underground cable (Table 4).

Table 4. Calculation of Low Range Recycling Rate for Cables

	Average Value in $/kg for Raw Materials (as cited in 20)			
	Steel	**Aluminum**	**Copper**	**High Density Polyethylene**
Secondary Material (V_{SM})	0.29	1.45	1.67	0.93
Primary Material (V_{PM})	0.29	1.59	1.77	1.1
Product Recycling Rate (RR) Based on Raw Materials' Recycling Indices (RIs)				
Recycling Index ($RI = V_{SM} / V_{PM}$)	1	0.9119	0.9435	0.8454
Low Range RR for OH Cable	$= RI_{steel} * RI_{aluminum} =$ **0.9119**			
Low Range RR for UG Cable	$= RI_{aluminum} * RI_{copper} * RI_{HDPE} =$ **0.7275**			

3.5 Assumptions & Limitations

A few assumptions were made in the model inventory in order to simplify the comparative analysis. First, the system boundaries for this study did not include the transformers required for both product systems. Transformers would be required at the same locations whether the power delivery system is overhead or underground and would perform the same voltage conversions. However, there are some differences in the design between underground and overhead transformers, which were not analyzed in this study.

Second, components encompassing the functional unit were estimated for one mile of straight circuit with no topographical barriers and no obstacles for installation (e.g., roads, hard rocks, hills, corners, etc.). In many cases, geological, terrain, and land use conditions will affect the quantity of infrastructural components needed and energy required for installation, which may significantly change the relative impact of the two systems. For example, assuming no obstacles implies that the underground system does not require landscaping or surface re-pavement after installation.

Third, the truck transportation process inventories were based on EU, rather than US, diesel fuel emission standards. While the current US regulation for *new* diesel vehicles is comparable to EU Euro 5 emission standards, diesel vehicles currently in use in the US are older and the majority of vehicles are below this standard. Therefore, it was estimated that the EU Euro 4 diesel fuel emission standards is the most suitable, conservative assumption for our analysis [27, 28].

Fourth and fifth, land-use issues (e.g. right-of-way, land use change) and the effect of electric magnetic fields (EMFs) were not considered in this study. Both of these topics are quite controversial and there are many competing claims about the possible harm caused by them [9, 29-31]. While the potential harm from EMFs is still an open question, EMF concentrations around primary power distribution lines are mainly defined by distances from the power lines, design of the lines, and the amount of current the line is carrying [32]. Installed underground circuits are closer to the ground's surface whereas overhead lines are farther above. Thus, using underground primary power delivery systems result in higher EMF exposure for power consumers and the general public.

Additionally, due to the complexity of the issue, this study did not include the comparison of power losses between the two cable systems. Power loss is related to the cable's impedance. Impedance in alternating currents will affect the voltage drop along the length of the circuit. Impedance is a function of several factors including: cable separation, conductor size, neutral/shield resistance, and proximity to other cables and ground wires [19].

Finally, the SCE cable supply chain already minimizes material waste in the cable production process and SCE's recycling programs recover nearly all of the materials within the utility's sphere of control. This level of industry efficiency in the studied supply chain should be considered when comparing opportunities in other utilities supply chains and systems.

3.6 Impact Assessment

Impact categories, developed by the Center for Environmental Studies (CML) at Leiden University in the Netherlands, were selected based on their relevance to the project goal and scope (Table 5). The CML database offers a broad range of factors to chose from, has the most current information (revised in December 2007), and uses a mature methodology.

Table 5. Selected Impact Categories and Impact Results

Impact Indicator		Unit	OH Life Cycle Impacts *(per year per mile)*	UG Life Cycle Impacts *(per year per mile)*
ADP	Abiotic Depletion	[kg Sb-Equiv.]	7.00	63.65
AP	Acidification Potential	[kg SO2-Equiv.]	4.01	32.66
EP	Eutrophication Potential	[kg Phosphate-Equiv.]	2.41	3.73
FAETP	Freshwater Aquatic Ecotoxicity Pot.	[kg DCB-Equiv.]	83.57	527.07
GWP	Global Warming Potential (100 years)	[kg CO2-Equiv.]	1402.39	7680.95
HTP	Human Toxicity Potential	[kg DCB-Equiv.]	248.87	1376.11
POCP	Photochem. Ozone Creation Potential	[kg Ethene-Equiv.]	0.44	3.65
TETP	Terrestric Ecotoxicity Potential	[kg DCB-Equiv.]	5.73	29.15

4. Results & Discussion

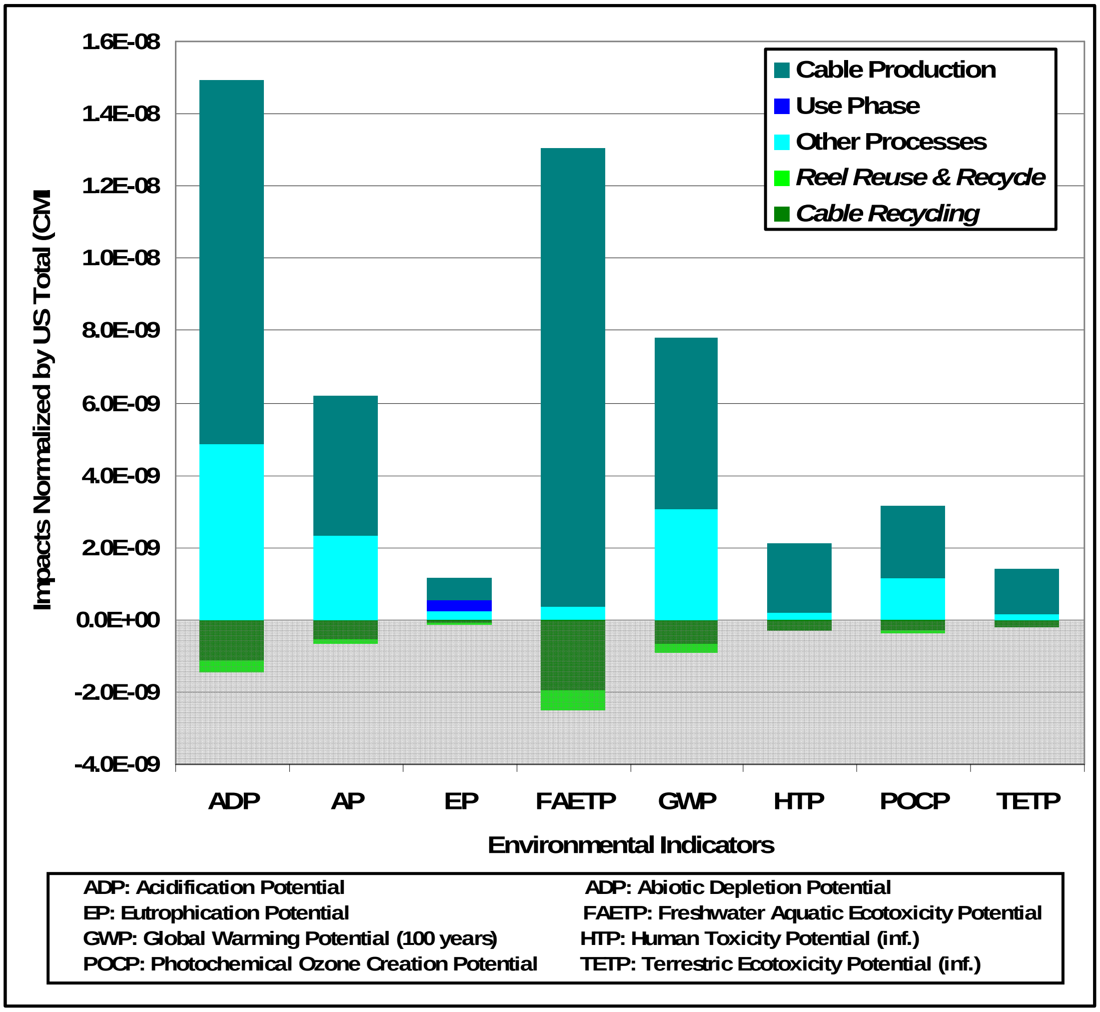
4.1 Technical Analysis

Hotspot Analysis: The hotspot analysis represents the processes that contribute the largest amount of environmental impacts, 25% or greater of the total overall impacts, to the respective system. Negative and positive environmental impacts were analyzed and modeled for each system. The positive environmental impacts, resulting from reuse and recycling, are represented by negative bars in the gray shaded area of the subsequent two figures.

Hotspot Analysis—Underground System: Cable production is the process contributing the most negative environmental impacts in the underground system across all eight indicators (Figure 5). Within cable production, it is the cradle-to-gate process of liquid aluminum production that is responsible for the majority of impacts, especially in FAETP. The “aluminium, primary, liquid at plant” process inventory in the Ecoinvent database includes the electrolysis step of aluminum production. This step is the most energy consuming of aluminum production. As of 2008, electricity use at an aluminum electrolysis plant is approximately 15.6 kWh/kg liquid aluminum, as compared to electricity use for primary copper production, which is 0.55 kWh/kg copper [33]. The mining and resource extraction processes of cradle-to-gate aluminum production also contribute significantly to ADP and FAETP impacts.

The dominant positive environmental impacts are attributed to cable recycling, which takes place in China. Also, the second largest contributor to positive environmental impacts is steel reel reuse and recycling. The steel reels are used to transport the cables to and from SCE and are subsequently either sent back to the supplier or recycled. The steel reels are sent back to the supplier approximately eighty percent of the time, while the remaining twenty percent are recycled.

Figure 5. Underground Hotspot Analysis, Contributing ≥ 25% of Net Impacts
***Main credits shown in grey**

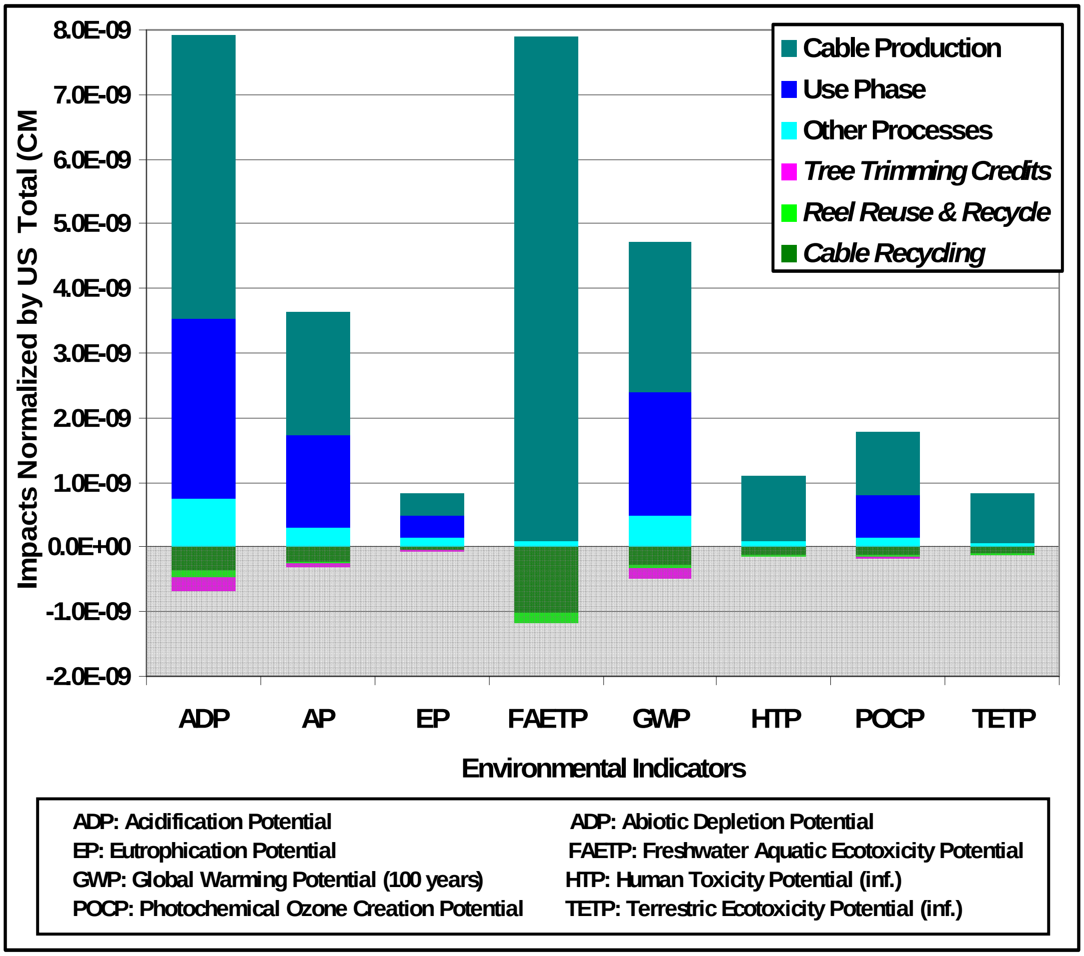


Hotspot Analysis—Overhead System: In the overhead system, production of the cable again dominates all eight environmental impact indicators (Figure 6). The overhead cable modeled is comprised of mostly aluminum. Thus, the “aluminium, primary, liquid at plant” process is responsible for 60-99 percent of the impacts from cable production across all indicators. The amount of aluminum required for the overhead cable is less than half that of underground, as seen in Table 1. This lower material intensity is the reason the associated impacts in the overhead system are an order of magnitude smaller than in the underground system. Even though aluminum cable production is a dominant contributor to all indicators, the methods employed by SCE’s main supplier of cable are very efficient. The primary aluminum is produced adjacent to the aluminum rod plant; therefore, the aluminum can be kept molten up to the rod rolling stage. As a result, less natural gas is required in this facility relative to the amount of natural gas needed for an ordinary metal refinery. In other words, ingot is not purchased and re-melted as can be the case for refined metal products.

The use phase also contributes significantly to net impacts in the overhead system in five out of eight impact indicators (Figure 6). The use phase for the overhead system involves a significant amount of driving large utility trucks to and from installation sites for the purpose of installing cables and infrastructure, scheduled line maintenance, tree trimming, and decommissioning of cables and infrastructure. Following decommissioning, there is subsequent transport of cables and infrastructure to end-of-life processing facilities. Not only was the transportation of these utility trucks modeled, but also the fuel consumption based on truck idling times (i.e., the use of truck engines and auxiliary power), which power equipment to install the infrastructure.

The processes that dominate the positive environmental impacts for the overhead system are the same as the underground system: cable recycling and steel reel reuse and recycling. However, there is an additional dominant process providing positive environmental impacts, "*Tree Trimming Credits*" (Figure 6). Tree trimming credits represent the tree trimmings cut down during scheduled overhead line maintenance. SCE incinerates these tree trimmings to generate heat and electricity that is then utilized within the SCE service area, and thus, is credited to the use phase.

Figure 6. Overhead Hotspot Analysis, Contributing ≥ 25% of Net Impacts
***Main credits shown in grey**



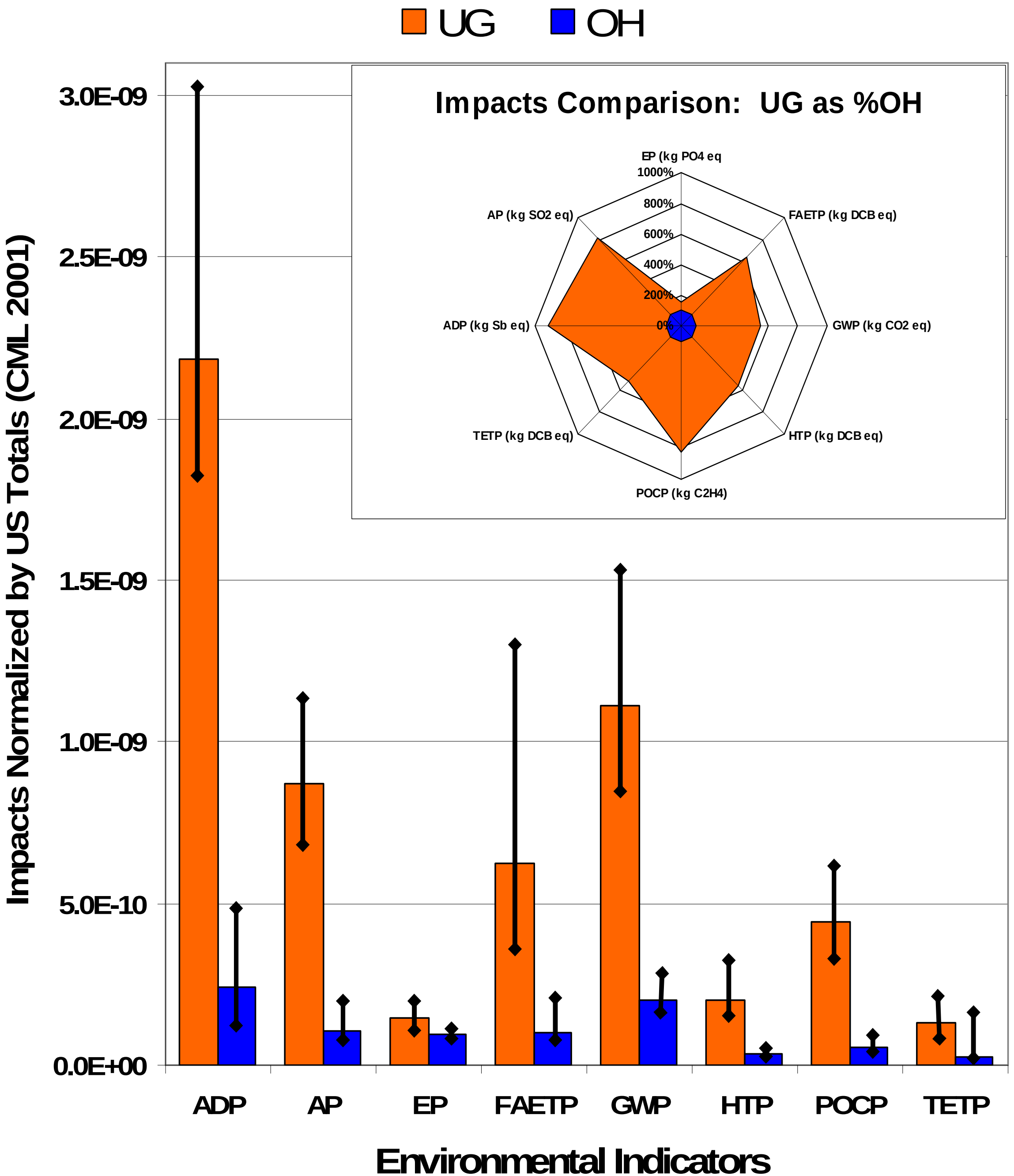
Overall Comparison: The comparison results show that the underground system has higher environmental impact potential than the overhead system in all categories in virtually all scenarios (Figure 7). The baseline scenario values shown in Table 2 were modeled, resulting in the average environmental impact results depicted in the blue and orange bars in Figure 7. This difference is primarily due to the higher material intensity of underground cables. Within the production phase, the main processes contributing to environmental impacts are those of cable production. It is important to note that there is limited flexibility in material selection for cable production due to their physical property requirements and associated economic issues. Placing power delivery systems underground requires additional cable materials. Firstly, when enclosed in tight configuration within the PVC conduits and concrete ducts, heat from the cable does not easily dissipate as it does in open air. Temperature increase in the underground cable would not only pose the risk of melting the plastic insulation layer(s), but would also decrease the conductive properties of the cable. To ensure a safe and efficient temperature range for the underground system, the electrical current density must be decreased. This decrease is achieved by using conductors with larger cross-sectional areas. In other words, a larger mass of aluminum conductor is needed for the underground cable to have the same power delivery capacity as the smaller and bare metal overhead cable. Also, the conductor must be protected from mechanical damage and thus, requires insulating material (i.e., high density polyethylene in this study). In brief, high material intensity of the underground cable is driven by physical conditions, so it is inevitable that delivering primary power underground places higher pressures on the environment.

The Monte Carlo analysis accounts for uncertainties in the parameterized factors for each system. In order to visualize the results of the Monte Carlo analysis, impact indicator values are normalized using overall environmental loads for the United States according to the latest normalization factors developed by the CML (Figure 7). In Figure 7, the error bars indicate the highest and lowest potential impacts in all modeled scenarios. As described in Table 2, the factors included in the scenarios are: underground infrastructure lifetime, overhead planning horizon, PCP leaching from the overhead treated wooden utility poles, cable lifetimes, cable recycling rates, and cable failure frequency for each system. As can be seen in Figure 7, potential environmental impacts of the underground primary distribution system are considerably higher for all impact indicators. However, Monte Carlo analysis suggests that there are two impact indicators in which the overhead system may potentially have higher environmental impacts than the underground system.

For the overhead system, the Terrestric Ecotoxicity Potential (TETP) impacts are significantly increased if 100 percent of the PCP wood treatment chemical leaches into the soil from the utility pole. The fate and transport of PCP leaching from wooden utility poles is not well understood and highly dependent on soil type [34]. It is important to note, however, that 100 percent leaching is a conservative estimate and, according to literature, somewhat unlikely [35, 36]. Accounting for 100 percent PCP leaching brings the impacts of the overhead system in the TETP category into overlap with the TETP range for the underground system. When a majority of the PCP leaches into the soil, the TETP impact for the overhead system is higher than the TETP impact in the underground baseline scenario. However, the underground ‘worst-case scenario’ still has higher environmental impacts in all indicators.

Impact values between the two systems are relatively close in the Eutrophication Potential (EP) indicator and the range of numbers within each system is narrow. For the baseline scenario, the underground system has higher impacts than the overhead system. However, there is some overlap as the 'worst-case scenario' for the overhead system has higher impact than the 'best-case' scenario for the underground.

Figure 7. Overhead vs. Underground: Overall Comparison and Monte Carlo Analysis

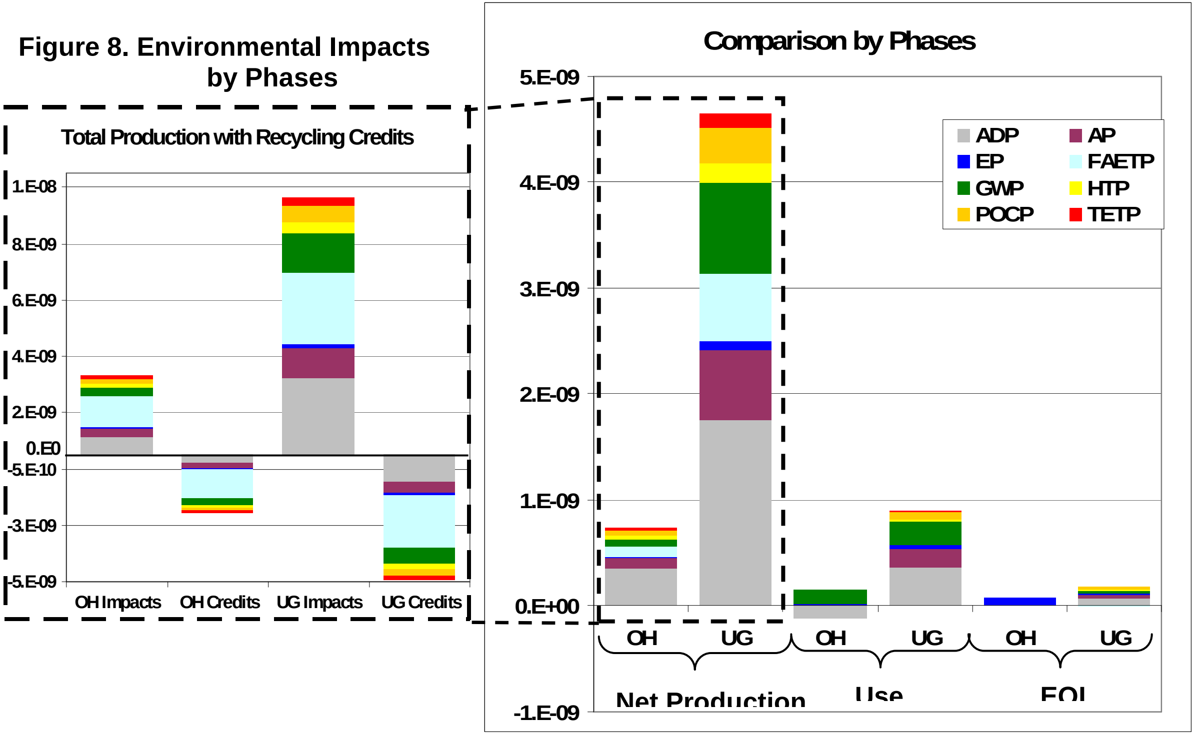


ADP: Acidification Potential **ADP: Abiotic Depletion Potential EP:**
Eutrophication Potential **FAETP: Freshwater Aquatic Ecotoxicity Potential**
GWP: Global Warming Potential (100 years) **HTP: Human Toxicity Potential**
POCP: Photochemical Ozone Creation Potential **TETP: Terrestric Ecotoxicity Potential**

Sensitivity Analysis: A sensitivity analysis was conducted for the model varying each parameter individually. The overhead system impacts lessen most significantly with a decrease in the annual cable replacement mass (i.e., failure frequency). This system's sensitivity to the failure frequency suggests that management practices to reduce the number of failure events per circuit mile are the most effective way to reduce the overall environmental impacts of overhead distribution systems. Additionally, for the overhead system, all impact indicator values increase significantly as the planning horizon shortens. This difference however is not linear – the change in environmental impacts goes down as planning horizon goes up. For the underground system, many of the impact indicator values are affected most significantly by the cable lifetime: a longer cable lifetime significantly decreases many of the impact indicator values. All of the impact indicator values are also sensitive to an increase in cable recovery rates. This sensitivity is especially pronounced in Freshwater Aquatic Ecotoxicity Potential (FAETP) and Abiotic Depletion Potential (ADP) indicators. The best and worst case recovery rates can reduce or increase, respectively, the overall impact values by 30-40%. It is interesting to note that Global Warming Potential (GWP) and Photochemical Ozone Creation Potential (POCP) are the impact indicator values that are most sensitive to changes in the life of the underground infrastructure. Because concrete production has relatively high greenhouse gas emissions and smog production potential, a longer lifetime of the largely concrete underground infrastructure significantly decreases the annual GWP and POCP of the underground distribution system.

Impacts by Phases: Analyzing environmental impacts by phases shows that the EOL phase contributes the least to net impacts. Credits associated with recycling cable materials in the EOL phases are attributed to primary production (i.e., the production phase). Even with these credits attributed, the net production impacts contribute the largest share to overall environmental impacts in both systems (Figure 8).

Figure 8. Environmental Impacts by Phases



ADP: Acidification Potential
EP: Eutrophication Potential
GWP: Global Warming Potential (100 years)
POCP: Photochemical Ozone Creation Potential

ADP: Abiotic Depletion Potential
FAETP: Freshwater Aquatic Ecotoxicity Potential
HTP: Human Toxicity Potential (inf.)
TETP: Terrestric Ecotoxicity Potential (inf.)

4.2 Recommendations

Firstly, the larger environmental impacts associated with delivering power underground should be considered when deciding the mode of new infrastructure for primary power distribution.

Secondly, because the largest environmental impacts of each system come from their production and end-of-life phases, SCE and other electrical utilities must look to Green Supply Chain Management (GSCM) in order to reduce overall impacts. The hotspot and sensitivity analyses show that reducing the amount of cable required per unit of service provided, is the most effective way to reduce the overall environmental impacts throughout the supply chain. In the overhead system, this may be achieved by reducing the frequency of cable failure events. In the underground system, less material is required if the cable lifetime can be extended.

Overhead Cable Failure Reduction

Successful failure reduction programs depend on the quantity and quality of data about what drives cable failures. Thus, improving the data collection for failure events should be a management priority. A number of management practices have been developed to decrease failure rates in power distribution systems. Common programs include: increased inspections and monitoring; tree trimming optimization; infrared feeder inspection; cable replacement optimization; and increased lightning protection. Reports indicate that by using a combination of these management practices, improvements in System Average Interruption Frequency Index (SAIFI) can range from 0 to 47.4 percent [37]. SAIFI reflects the total number of power system interruptions, independently of whether they are caused by cable failure or by a failure of another component. Assuming management practices are able to achieve a 30 percent reduction in cable failure frequency, overall impacts of the overhead system would be reduced by an average of 80 percent across environmental indicators.

Underground Cable Lifetime Expansion

The dominant driver of failure in MV underground cables is mechanical abuse of the insulation system resulting in breach of the insulation wall [19]. Even minor damage of the insulation can result in the exposure of the conductor metal and subsequent cable failure. A few techniques have been developed to address this mechanical abuse. These techniques use liquids with high insulation properties to ‘heal’ the damaged insulation. In one of the techniques, the liquid insulator is added as the cable is produced [38]. The liquid layer is places between two layers of solid cross-linked polyethylene. When the outer insulation layer is damaged, the cable self-repairs with the gel-like layer. Another method is to treat the cables on site during their use [39]. The low molecular weight silicone is injected into the cable around the conductor strands and beneath the insulation. The silicone then diffuses into the insulation layer and gels through a reaction with moisture in the dielectric, thereby replacing water trees with gelled silicone. Both techniques claim significant extensions in cable lifetime [38, 39]. Statistical data on the failure rates recorded for these techniques are still in the collection stage. If this technology is capable of doubling underground cable lifetime, overall impacts of underground power delivery can be reduced significantly. For example, the Freshwater Aquatic Ecotoxicity Potential (FAETP) and the

Human Toxicity Potential (HTP)—both in kg DCB equivalents—could both be reduced by about 25 percent. This improvement would also reduce the Global Warming Potential (GWP) by over ten percent. This estimation, however, does not include the impacts from production of the liquid insulation layer for the first method, or the silicon injection solution and pressure applied for the cable treatment method. The estimation also does not include transportation processes or the effect of these materials on the cable's end-of life phase for either of the techniques.

Use Phase Vehicle Fleet

Within the utility's corporate boundaries, impacts are dominated by diesel fuel production for, and fuel emissions during, the installation, maintenance, and decommissioning of the cable systems, especially for overhead systems. Thus, management and logistics of the service vehicle fleet should be a major consideration in reducing the overall environmental impacts of the use phase in both overhead and underground systems.

4.3 Further Research

This model provides an opportunity to test different scenarios associated with management solutions. Some of these scenarios would require additional process inventories. For example, in order to assess potential improvements in vehicle fleet management, additional inventories for hybrid electric vehicles, flexible-fuel vehicles, and biofuels would be necessary. Next, environmental impacts resulting from physical and human capital were assumed to be negligible and were excluded from the analysis because they would not significantly affect the comparative study results. However, including these impacts into the model using Hybrid LCA methodology could more accurately capture overall environmental impacts of either system

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