Underground Engineering for Sustainable Urban Development (2013)

**Chapter:** 5 Lifecycle Sustainability, Costs, and Benefits of Underground Infrastructure Development

# 5

# Lifecycle Sustainability, Costs, and Benefits of Underground Infrastructure Development

Underground development provides opportunities to use available urban space more effectively, but it requires significant and potentially costprohibitive investment for initial construction as compared to similaruse infrastructure built on the surface. This chapter summarizes the existing knowledge about the lifecycle sustainability, costs, and benefits of underground development.

Literature concerning impacts of underground infrastructure on the lifecycle sustainability of urban development is relatively scant. More is known about monetary lifecycle costs and benefits, while less is known about long-term environmental or social impacts. Even those studies related to economic benefits and costs were primarily to inform assessment of alternatives for proposed projects, such as for the Alaska Way Viaduct in Seattle (Taylor, 2008). Fewer retrospective studies have been conducted to assess actual costs and benefits of underground development.

This chapter does not provide a lifecycle cost assessment for any underground works; rather it identifies factors to be considered in a lifecycle assessment in terms of economic costs and benefits throughout the infrastructure life (construction, operation, and renovation) and environmental and social costs and benefits. Research that would inform better and more comprehensive lifecycle assessments is identified.

## LIFECYCLE SUSTAINABILITY ASSESSMENT

In assessing lifecycle sustainability, a “triple bottom line” analysis is often adopted that considers the economic, environmental, and social impacts of development. Elkington introduced the basic concepts of the approach in 1994 and expanded on them and introduced the term “triple bottom line” in 1997 (Elkington, 1994, 1997). The approach provides a framework for a multiple objective assessment of complex investments. “Full cost accounting” pursues a similar goal of including a wide range of impacts in decision making, but full cost accounting usually focuses on developing monetary estimates of different impacts. A recent example of this approach was the estimate of external costs associated with energy production (NRC, 2010). However, environmental and social impacts are difficult to quantify monetarily and often are beyond the current state of knowledge about underground development because of lack of attention. Accordingly, this chapter is divided into sections that consider the lifecycle economic, environmental, and social impacts of underground development. This review of lifecycle costs and benefits is consistent with the committee’s task to explore how use of the underground could increase sustainability.

### Lifecycle Planning and Assessment

Underground development often involves a relatively long life cycle even when compared with other infrastructure investments. For example, the Circle Line subway in London was originally constructed more than 150 years ago in the mid-nineteenth century (Bobrick, 1981). Although the line has been extended, renovated, and rehabilitated over time, the original investment in underground construction is still paying off and providing travel and other benefits.[1] Similarly, underground pipelines can also last for more than 100 years, especially if in situ inspection, cathodic protection,[2] and rehabilitation are performed (e.g., MWRA, 2006). However, government and private planning horizons are usually fairly short with respect to the useful life of the infrastructure. Metropolitan and statewide long-range transportation plans, for example, often consider the benefits and costs of investment for only a 20-year horizon (DOT, 2007). Such a short planning horizon means that any benefits from underground development that occur after 20 years are not considered in investment decision making.

Underground infrastructure development involves an initial investment to create usable space that provides benefits over an extended period. Long lifetimes of underground infrastructure may be excluded from analyses performed by those with short planning horizons, just as owner and user costs of renovating surface facilities may be excluded from cost analyses, although they may be quite large. Similarly, high discount rates for calculating the present value of future benefits will make those benefits less valuable if provided long into the future. For example, the federal fiscal year 2011 real test discount rate for a 30-year planning horizon was established at 2.7 percent (OMB, 2010). With this discount rate, $1.00 of real benefits received 30 years later would have a 2011 value of 1/1.02730 = $0.45, or less than half. One dollar of benefits received 100 years in the future would either be disregarded as beyond the planning horizon or would have a 2011 value of only $0.07.

A long lifetime in itself also may affect planning for future alternatives. Particular underground development can preclude other uses or make them more expensive to implement. For example, underground transportation tunnels such as the Boston Central Artery project required rebuilding and relocating existing underground utilities in the tunnel right-of-way. Building foundations may make re-use of their underground locations prohibitively expensive, precluding new underground parking, tunnels, or other uses in that location. In effect, underground construction may increase cost and reduce flexibility of options for alternative future uses. Because most underground facilities are left in the ground even after their useful life ends, the extra cost or difficulty of reusing the space continues nearly indefinitely. A comprehensive planning effort would recognize that underground space is a resource that should be used in the best manner possible, rather than letting initial uses preclude later uses. Similar conclusions have been drawn with respect to limiting space debris in orbits around Earth that may prevent use of those orbits for other purposes (e.g., UN, 1999).

In addition to assessing the life cycle of underground infrastructure itself, sustainability suggests that impacts of the infrastructure also be considered for the entire life cycle of a project. Lifecycle assessment "studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave) from raw material acquisition through production use and disposal" (ISO, 1997). Figure 5.1 illustrates a generic supply chain life cycle. For underground infrastructure, the supply chain would include the various materials and processes involved in construction as well as inputs such as energy for lighting and ventilation during facility operation. Closure and decommissioning costs would be included in the disposal phase in Figure 5.1. The landfill phase would be expected to include the costs of providing an engineered landfill for disposal or any costs associated with legacy structures underground.

Metrics to use in assessing sustainable development overall, as well as to assess specific economic, environmental, and social impacts, are still a subject of widespread debate even without consideration of the special circumstances of underground development (Jeon and Amekudzi, 2005). Economic impacts are typically expressed in monetary units, but a variety of impacts may be considered for environmental and social impacts. For example, Reijnders (1996) suggests that broad environmental impacts be considered in preparing a lifecycle assessment including:

- impact on resources (e.g., use of renewable and nonrenewable resources, pollution of resources);
- direct impact on nature and landscape, such as through undesirable change in landscape;
- air pollution and its contribution to climate change, smog, acid deposition, odors, and deterioration of the ozone layer;
- soil pollution, such as solid wastes added to soil, through eutrophication, added toxins, and contributions to groundwater pollution;

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[1] For example, to provide shelter. London subway tunnels were used as bomb shelters during World War II.

[2] Corrosion protection.

- surface water impacts, including biological or chemical discharges with oxygen demand, toxic discharges, surface water warming, and contribution to eutrophication;
- noise;
- electromagnetic radiation or fields; and
- ionizing radiation.

In many environmental lifecycle assessment studies, environmental impact estimates are limited to only a few critical categories of impacts, such as emissions of greenhouse gases and conventional pollutants.

Assessing system interdependencies over the life cycle of underground infrastructure is also an important and challenging part of assessing risk. A variety of analytic tools exist to aid in risk assessment of individual infrastructure systems and interactions. These include Bayesian networks, Monte Carlo simulation, and decision trees (Rinaldi et al., 2001; Haimes, 2004; Weber et al., 2012). Applying such tools may inform decision making by reducing some of the high levels of uncertainty associated with different kinds of risk, especially when dealing with interactions of complex systems.

In this chapter, the committee assembles existing knowledge of the impacts of underground development, recognizing there are numerous knowledge gaps, especially because past studies generally took a narrower view of benefits and costs than is required for a lifecycle sustainability perspective. There is also considerable variation and uncertainty in the performance of underground development, especially with regard to extreme events such as earthquakes or flooding. Moreover, the general advantages and disadvantages for underground facilities described in Chapter 3 necessitate specific evaluations for each type of use and site circumstances.

## LIFECYCLE ECONOMIC BENEFITS AND COSTS

Increasing population, consumption, density, globalization, communication, and other trends suggest an increasing complexity for human society (Boyle et al., 2010). Implementation of technological advancements can have both positive and negative repercussions. It is important that processes to deliver sustainable underground infrastructure be carefully designed to limit negative impacts while gaining the maximum benefit. Indirect impacts of technology advancements also must be considered. Developing underground space provides the opportunity to use surface space for other purposes such as green space for parks or other aboveground development within or closer to urban centers, but quantification of such opportunities is difficult. Low-impact design of infrastructure systems that reduces environmental impacts and transportation costs is now being incorporated into urban development (TRB, 2009). Compact city trends support an underground development concept including a wide range of underground facilities that contribute to an efficient but highly livable environment. In this regard, inherent economic benefits are derived from utilizing the subsurface as part of the provision of housing, transportation, commercial, industrial, and utility facilities.

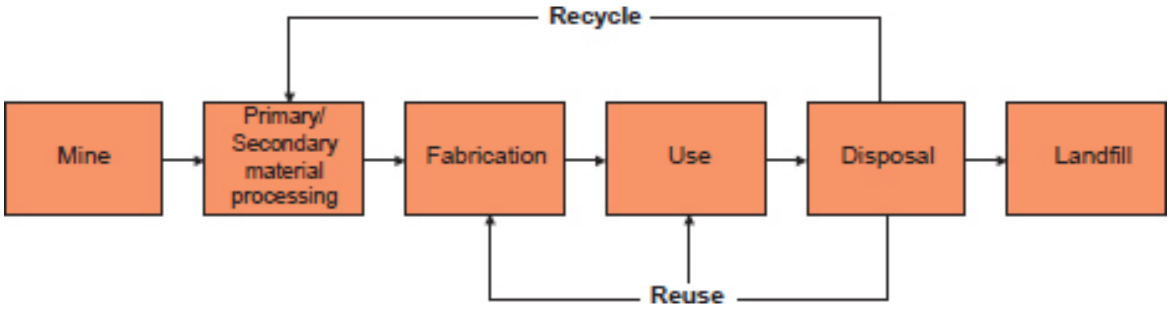

FIGURE 5.1 A generic product cradle-to-grave life cycle. SOURCE: Modified from Hendrickson et al., 2006.

### Intensive Development and the Compact City

There has been a longstanding debate about the benefits and costs of intensive development in the form of compact cities relative to dispersed development and urban sprawl (e.g., Ewing, 1997; Gordon and Richardson, 1997). Compact cities are distinguished by high densities of people per unit land area, a mix of land uses within neighborhoods, one or more high-density centers of employment, and careful spatial arrangement or contiguity of land uses (NRC, 2010). Critics of the compact city note the deleterious effects of more intensive development, including increased traffic congestion, less affordable housing, and higher consumer costs (Gordon and Richardson, 1997; O'Toole, 2009).

A recent NRC study found that compact cities are likely to reduce vehicle miles of travel and both direct and indirect energy consumption and greenhouse gas emissions (NRC, 2010). European experience is similar (Schwanen et al., 2004). Shammin and others (2010) estimated that total energy use is roughly 17 percent lower for urban area residents than for rural or low-density area residents, even when all purchased goods and services are considered. To some extent, these expected benefits from compact cities may arise from self-choice of residents who wish to drive less, but even when attitudinal factors are taken into account,

FIGURE 5.2 Boston Central Artery as an elevated structure and as an underground roadway SOURCE: MADOT, 2012.

less vehicle miles are traveled in compact cities (Handy et al., 2005). Compact development also may reduce infrastructure costs and development pressure on green spaces (Ewing, 1997).

However, higher urban density seems to directly correlate with higher levels of underground space development (Sterling et al., 2012). Many planners believe that underground development and use could enhance the net benefits of intensive development. Use of underground space can reduce traffic congestion and the consumer costs noted by critics of compact cities while simultaneously achieving the travel and energy reductions identified by compact city proponents. Figure 5.2 shows the Boston Central Artery, which was originally built as an elevated structure through downtown Boston but was moved underground in the Big Dig project, resulting in a corridor of open space (NAE/NRC, 2003). The net benefits and indirect effects on long-term development may be significant even though they are difficult to assess on a project-by-project basis.

### Construction Phase Economic Benefits and Costs

Our current “built environment includes buildings, engineering works, and infrastructure such as roads, wastewater and water treatment plants, storm water management systems, power generation facilities, railways, bridges, and even natural systems such as rivers and harbors” (Boyle et al., 2010). Underground development provides an opportunity to place many of these facilities in the

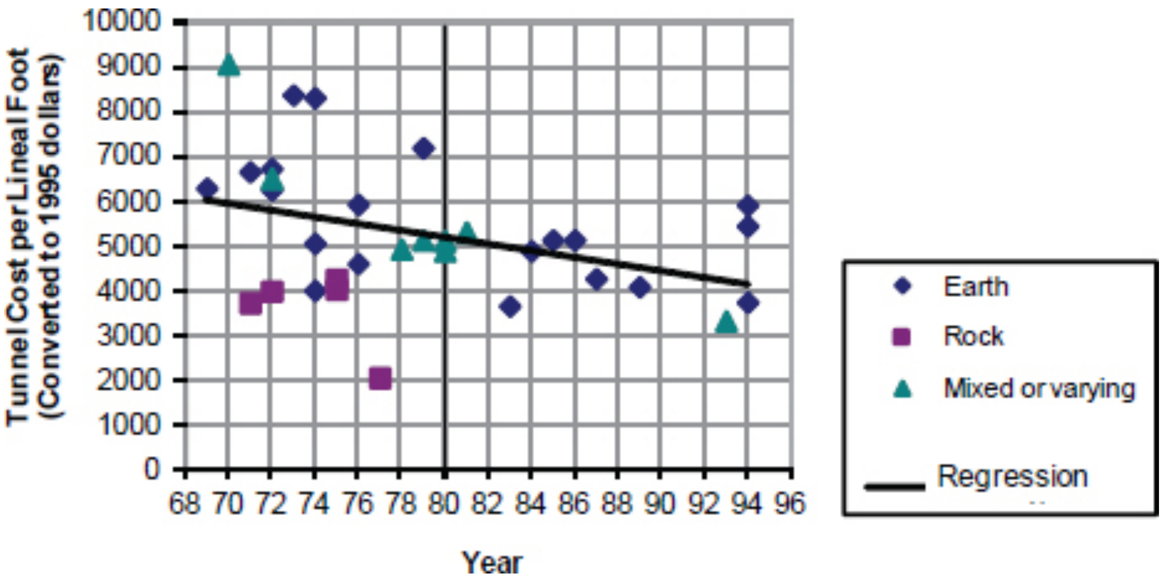

FIGURE 5.3 Cost for mining and lining approximately 20 ft. diameter tunnels for the Washington Metro over the period 1969-1994. SOURCE: R. Sterling, from data supplied by WMATA (courtesy of Walt Mergelsberg). Reprinted with permission of author.

largely available space—real estate—beneath existing surface developments. Sterling (2005) describes the importance of urban underground space planning. Initial costs for underground construction include those related to geological site characterization and management of geologic conditions, finding and relocating utilities, potential disruption to existing infrastructure due to utility strikes, requirements for engineered backfill, and traffic control along a horizontal alignment. A nationwide effort exists to use best practices in underground works in the interest of public safety (CGA, 2008). However, in urban areas, existing structures constrain practical design of underground facilities. Underground facilities must accommodate facility design restrictions and land or easement availability for construction. The time associated with accommodating requirements associated with environmental and safety regulations also must be factored into construction costs.

Figure 5.3, based on data from construction of the Washington Metro from 1969 to 1994, shows a decreasing trend line for raw tunnel construction costs and, equally importantly, a narrowing of the costs range over this 25-year period. Although project costs are highly dependent on specific circumstances, for example, the difficulty of installation of specific sections, this graph could suggest that accumulated knowledge and risk management, investments in research, and adoption of better technologies and contracting practices over the period resulted in cost reductions for actual tunnel construction. Are these cost reductions being seen in the total cost of newer underground construction projects? The answer is probably “no,” because demands for higher safety standards and reduced construction risk and environmental impact for newer projects have increased. In addition, such changes in technical costs may be

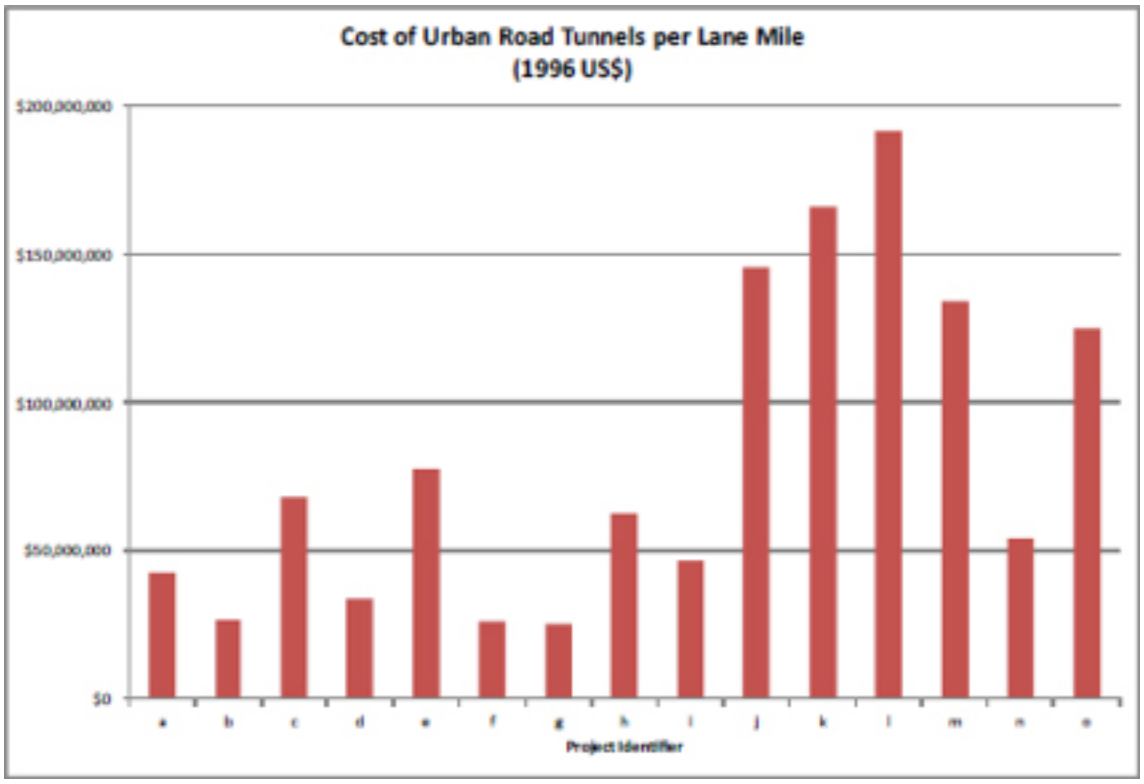

FIGURE 5.4 Variability in urban road tunnel costs based on data from Australia, France, Japan, Sweden, and the United States. Each letter on the x axis represents a different project for which cost data were provided. SOURCE: R. Sterling, from data collected by ITA Working Group 13. Modified with permission of the author.

masked by the wide range in total project costs seen in worldwide projects. For illustration, Figure 5.4 depicts data collected during a study of the costs and benefits of underground transportation facilities undertaken by the International Tunneling and Underground Space Association (ITA) Working Group 13 (ITA WG13, 2004). Cost data on road tunnels from 30 cities in 19 countries were compiled from questionnaire responses and were converted to a common basis in terms of 1996 U.S. dollars for the cost per lane mile of roadway.

Although these costs vary because of what is counted in each project's costs, the variations observed among countries in constructing a lane kilometer of roadway suggest that it would be worthwhile to investigate the reasons for lower costs in some countries as compared to others. Although local geology may have a role, it is not expected to be the only significant reason for the observed variations. Differences in design standards, administrative review processes, public engagement, and streamlining of design and construction processes may be increasingly important. Understanding the reasons for varying costs is important so that the outcomes of projects developed in other countries can be judged according to standards other than high cost and so that factors contributing to high costs can be identified and improved.

Various estimates of the length of water, sewer, and storm water pipelines in the United States can be found in the literature. Table 2.1 lists a total of approximately 3.7 million miles of pipeline including transmission, distribution, and private service connections. More than 480,000 km of underground utilities are estimated to be installed worldwide annually, including water, sewer, gas, electrical, cable television, and telephone (Najafi, 2005). A significant portion of this infrastructure is buried beneath paved surfaces in urban environments. Consequently, more efficient and effective installation and rehabilitation of this vast utility network would provide significant economic benefits due to lower direct cost and a minimal disruption of this surface environment.

Lane closures due to surface construction and the subsequent detours cause traffic delays and have an impact on the cost of fuel (CNRC, 2005). Impacts can be minimized through the selection of suitable construction equipment. Further savings for initial capital equipment may be realized, for example, with trenchless methods, especially in horizontal construction because of reduced use of construction equipment (Woodroffe and Ariaratnam, 2008). In contrast, open-cut excavation requires the use of numerous pieces of equipment including excavators, bulldozers, surface compactors, and haul vehicles.

Now implemented in underground works are alternative contracting mechanisms that provide innovative means for allocating project risks to reduce their effects on bid amounts. These include approaches such as design-build, design-build-own-operate-transfer, and construction manager at risk. Additionally, performance-based specifications are used to promote contractor creativity and reduce construction costs. Incompleteness of performance-based specifications, however, may negatively affect the final product.

There is little comparison of the costs of underground versus aboveground construction (Parker, 2007). Lifecycle cost analyses consider the direct, social, and environmental costs as well as the costs for specialty items such as heating, ventilation, and air conditioning systems over the life cycle. Because they are critical to infrastructure functionality and must be carefully selected and installed during initial construction, these and other operational costs usually are combined with direct capital costs in selecting the best construction alternative.

Safety hazards and risks are inherent in all construction projects and need to be assessed during the design phase. A risk-based safety impact assessment approach was adopted for the construction of a subway line in Seoul, Korea (Seo and Choi, 2008). Open-cut construction also was evaluated for comparison purposes. The goal was to identify and reduce, prior to construction, the risks associated with design items that could cause construction accidents. This is important because subsurface construction is done "out of sight," thereby requiring a high degree of skill and extensive experience on the parts of the designer (often contractually obligated to provide full-time quality control inspection) and the constructor. The design and construction of subsurface infrastructure represent unique scenarios in which design, inspection, and construction functions cannot easily be separated (Kagan et al., 1986).

### Operation Phase Lifecycle Economic Benefits and Costs

As noted earlier, cost benefits accrued from operation of any infrastructure system are difficult to quantify. Benefits may include enhancements to quality of life, reductions in travel and travel time, and increases in productivity. There are, however, inherent benefits related to the operation of underground infrastructure. Johnson (2006) found that the conversion of unsightly overhead electrical lines to underground lines resulted in increased property values and improved aesthetics within neighborhoods. Other lifecycle societal economic benefits include reduced outages, transmission losses, and greenhouse gases; reduced network maintenance costs; fewer electrocutions; and fewer motor vehicle collisions with poles (IFC Consulting, 2003). The average cost of burying existing electrical lines is estimated to be $1 million per mile, which is almost 5 to 6 times (Parsons Brinkerhoff, 2012) or 10 times (Johnson, 2006) the cost of a new overhead line. However, the maintenance and operating costs of underground electrical lines have been reported to be about one-tenth of those of aboveground lines because of reduced transmission losses over the life cycle (IFC Consulting, 2003). In addition, underground cables also may enable increases in power transmission capacity (Al-khalidi and Kalam, 2006).

Chapter 4 describes security issues associated with underground infrastructure but shows that there are inherent security benefits to putting infrastructure underground. Underground systems have a lower risk of disaster failure to earthquakes, hurricanes, tornados, tropical storms, heavy snow events, monsoon winds, and natural disasters, but these systems may be vulnerable to flooding. These lower risks could translate into reduced insurance premiums over the life cycle of the asset (e.g., De Saventhem, 1977).

### Renovation and Replacement Phase Lifecycle Economic Benefits and Costs

Renovation of infrastructure (i.e., asset preservation) often improves operation at a fraction of the cost of full replacement. Consequently, renovation methods such as lining or grouting of pipelines and external face-lifting of buildings are preferred when existing infrastructure is still structurally acceptable but requires renewal to a "like new" condition. Replacement may be deemed necessary because of obsolescence, inflexible design, or irreparability of the existing infrastructure. Surface infrastructure can be replaced with relative ease as compared to underground infrastructure; however, the frequency of the need for repairs and renovations may be less for underground infrastructure because of the protection the underground provides. On the other hand, if underground infrastructure becomes obsolete—for example, the largely abandoned underground freight tunnel system beneath downtown Chicago (see Box 3.7)—it may be difficult to repurpose the space for another use.

Careful planning of underground use for well into the future can minimize the rate at which infrastructure becomes obsolete. Utilidors (described in Chapter 3), for example, provide flexibility to switch out or add utilities when dictated by obsolescence, deterioration, or capacity issues. Utilidors streamline utility easements and provide improved accuracy in locating existing buried utilities, which is advantageous for line maintenance and replacement. Canto-Perello and others (2009) found that utilidors minimize the potential dilemma of mutual interference between utilities and transportation networks. Additionally, placing utilities in utilidors results in minimizing physical damage to surface streets from continual cutting of pavement when installing, inspecting, maintaining, repairing, or replacing lines.

## LIFECYCLE ENVIRONMENTAL BENEFITS AND COSTS

Since 1970, the National Environmental Protection Act (NEPA) has required “federal agencies to integrate environmental values into their decision making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions” (EPA, 2010). As a result, environmental impact statements and analyses have been completed for a wide range of underground developments. However, these impact statements are prospective in nature to inform planning decisions, rather than retrospective assessments of actual environmental impacts from projects as built. For example, whereas many earlier environmental impact analyses did not include greenhouse gas emission effects, recent environmental impact statements address findings such as the 2009 finding by the EPA Administrator that greenhouse gas emissions (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexa-fluoride) threaten public health and the welfare of current and future generations as a result of climate change effects (EPA, 2009). Finally, environmental impact statements typically do not include the supply chain or indirect environmental impacts in the analyses and therefore do not provide a complete lifecycle assessment. For estimating carbon footprint or greenhouse gas emissions, these indirect emissions are termed Tier 3 emissions and often are significant for the provision of goods and services (Matthews et al., 2008). In particular, the production of cement used in underground construction generally results in significant greenhouse gas emissions.

Construction methods play a major role in greenhouse gas emissions. Sihabuddin and Ariaratnam (2009) compared airborne emissions from trenchless versus open-cut pipe replacement on the same project and found that trenchless reduced pollution on the order of 80 percent. Few studies have looked at the effect of underground infrastructure over its entire life cycle or have compared lifecycle assessments of overhead and underground infrastructure delivering the same service (see Box 5.1).

### BOX 5.1

### Environmental Lifecycle Comparison of Overhead and Underground Power Distribution

Bumby et al. (2010) compared buried and overhead power distribution using Southern California Edison designs for medium voltage cables using a process-based lifecycle assessment per guidelines from the International Organization for Standardization.[a] The Figure shows the various process steps involved in the life cycle for the underground power distribution assembly. Their assessment indicates that overhead distribution assemblies as designed by Southern California Edison have lower overall emissions. The values are heavily influenced by the additional material inputs required for cable manufacturing of the underground distribution assembly. Secondary factors include the shorter estimated life for underground cables due to underground heating effects and lost carbon sequestration due to timber production because carbon is captured in the growth of trees. The study also estimated eco-indicator impacts common in Europe (see Guinée, 2002, for standards), including abiotic depletion potential, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity, human toxicity potential, photochemical ozone creation potential, and terrestrial ecotoxicity potential. For reasons similar to those for greenhouse gas emissions, the overhead design had lower environmental impacts in these categories.

The study omitted some categories that require further research. The underground cable had lower resistance, so transmission power losses may be lower underground. The study does not consider land use impacts and the net urban system energy usage or environmental effects given either overhead or underground use. The construction material advantage for power cables may not exist for overhead structures used for other purposes such as carrying vehicles. Moreover, siting overhead power transmission lines often can be difficult for aesthetic reasons. This study demonstrates the difficulty of obtaining comprehensive but rigorous results from triple bottom line analyses. Such analyses can include only the issues for which data are available and are unable to address broader performance, resilience, societal, or environmental issues.

## SOCIAL BENEFITS AND COSTS

This section summarizes some of the social benefit and costs associated with the use of underground space and discusses what additional data or changes in assessment practices might be helpful to making sound investment and operational decisions.

As described in earlier sections, the framework for the economic and environmental lifecycle assessment of project alternatives is reasonably well understood—including how to manage conceptually the combination of quantitative and subjective comparisons. One challenge to lifecycle cost analysis is that some of the strongest advantages of underground structures tend to be more long term and qualitative (including benefits to quality of life or urban resilience), while disadvantages tend to be more readily identifiable and quantifiable (e.g., startup

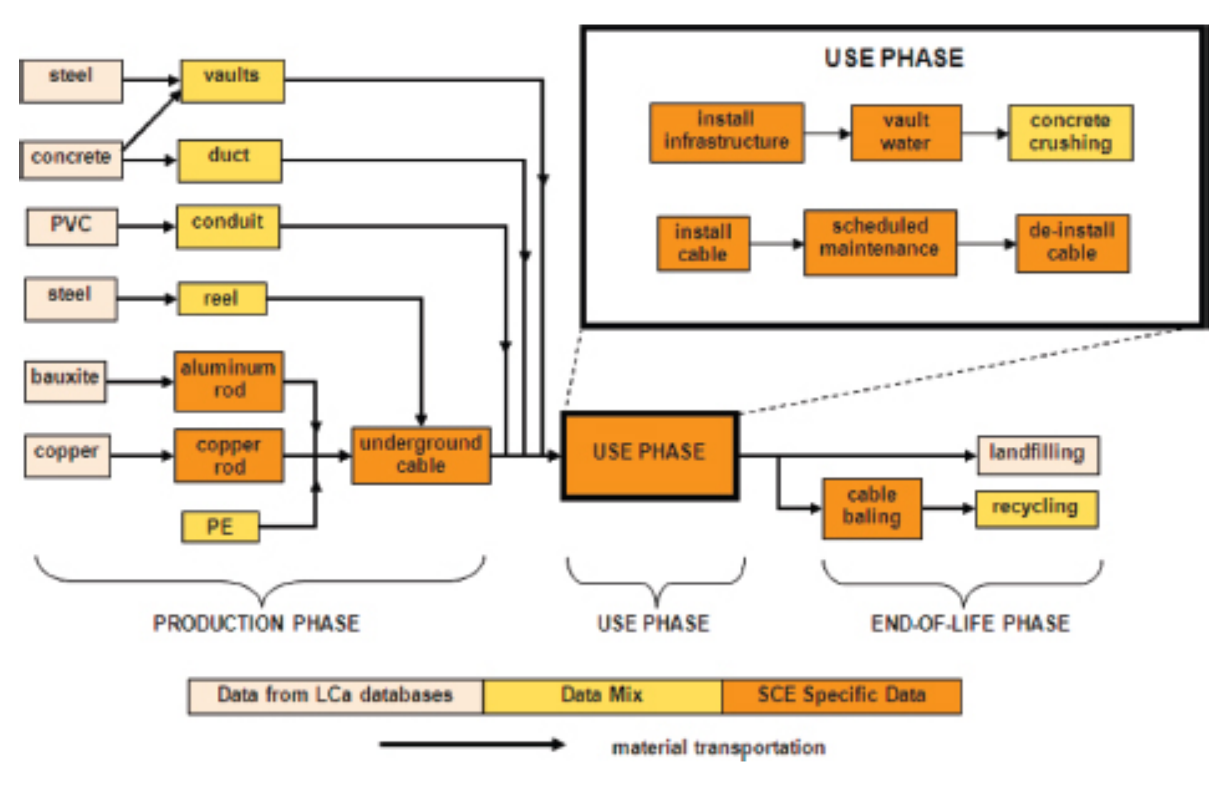

FIGURE Process flow diagram for the underground power distribution assembly. Colors indicate data source as commercial lifecycle assessment databases (pink), Southern California Edison (orange), or a mix of these two sources (yellow). SOURCE: Bumby et al., 2010. Reprinted with permission from American Chemical Society.

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[a] ISO 14044 specifies requirements and provides guidelines for lifecycle assessment including scope, inventory analysis phase, impact assessment phase, interpretation phase (ISO, 2006).

costs). Another challenge is that few individuals are expected to state a preference for being in an underground facility rather than a surface facility for extended periods. In many cases, the benefits come from what the underground facility permits in terms of an improved surface environment, mobility, or services rather than from the superior attributes of the facility itself.

Underground space use, if well planned, permits excellent options for urban transportation and provision of utility services, along with a range of other desired facilities, all with low-impact on the surface environment, heritage, and, potentially, ecology. In other words, well-planned underground construction supports a compact, well-functioning, livable, and sustainable urban environment. The protection and resilience of an underground structure may benefit the project owner, but if it affects the ability of society to function effectively, for example, after a disaster, then it has a much broader societal impact. Likewise, communities are increasingly resisting construction-caused disruption from new infrastructure projects. The project owner may pay some costs attributable to the disruption—such as business loss—but the owner does not pay for traffic delay costs and the diminished livability of the neighborhood due to construction noise, vibration, dust, and diminished air quality. Capturing all of the appropriate costs when comparing project alternatives remains a challenge and a topic for future research.

Multiple papers identify issues to be considered with respect to utility projects (e.g., Gilchrist and Allouche, 2005) and provide case examples of the application of social and indirect costs to project decision making (e.g., Li et al., 2009). However, typically only a few of the key social or indirect costs are considered because of a lack of impacts data or a lack of accepted costing for disturbances effects. Papers that describe analyses of a variety of costs (e.g., Pucker et al., 2006) typically find that traffic delay costs are the most important social cost in urban areas and can rival or exceed the cost of the construction itself for some street utility work. In suburban or rural areas, traffic delays are typically less severe except on key arterial routes.

Local opposition to a project typically is based on the social and indirect costs expected as a result of project construction and operation. Often, these costs can be mitigated through less disruptive construction methods (e.g., trenchless technologies for utility construction and repair, and bored tunnels instead of cut-and-cover tunnels for road and rail projects) and restrictions or modifications to working practices (e.g., limits on working hours, noise, and vibration). As restricted working practices are adopted to accommodate neighborhood opposition, unpaid social costs become hard construction costs and potentially increase construction risks. Least disruptive construction methods are more likely chosen, avoiding the need to calculate social costs.

Another issue worth noting is that construction and operation impacts of major infrastructure projects represent a moving target in terms of acceptable compromises for limiting impacts on neighborhoods. Discussions about transforming a surface or elevated transportation project to an underground alignment, or transforming from cut-and-cover to bored tunnel construction, typically consider noise and air quality impacts at the tunnel portal. In general terms, the shift underground maintains mobility for many people in the urban area and lessens the environmental impact on most of the area through which it passes. However, construction vibrations (e.g., from blasting) and noise and air quality emissions become more localized—making them more bothersome to those in the immediate vicinity, but also more controllable. The drawback is that the increasingly high standards to which underground projects may be held increases their costs relative to surface or elevated alternatives. Critical decisions regarding major infrastructure initiatives for urban areas ride on such concerns. The ability to adequately compare radically different infrastructure alternatives (including the "do nothing" alternative) that potentially change the face of the city for better or worse remains a daunting challenge. In many cases, a strong political decision is finally made in the face of widely different opinions and conflicting cost-benefit analyses.

Accommodating social and human factors issues and improving underground designs are not just window dressing essentially technical projects. How these issues are addressed in the project's design and construction can have profound effects on its cost, acceptance by the public, and impact over its life cycle. There is no single best answer, but it is important to understand the various ramifications. The Stockholm (Sweden) Metro has individualized station designs decorated by artists to make distinctly different environments in each station (Winqvist and Mellgren, 1988). Washington, DC, Metro stations have a similar look that creates familiarity for ease of use. Large station caverns often are used to create an impressive public space underground, but at a cost in terms of initial construction and probably in operation as well (as pointed out by O'Rourke, 1983). Allowing variety in design approaches based on a better understanding of how to create interesting and enjoyable underground spaces without large increases in cost or space requirements remains a challenge, as does quantifying the social costs and benefits over the life cycle of the infrastructure.

## RESEARCH NEEDS FOR LIFECYCLE COSTS AND BENEFITS

As discussed earlier, many factors are incorporated into full lifecycle cost analysis. Consideration of those factors may shift the perception of the feasibility of underground space use—from that of expensive and risky, to wise and most cost-effective in the long term. Largely needed is a better understanding of what aspects of project planning, design, construction, and operation contribute the most to project costs and long-term benefits and performance. The goals of lifecycle cost analysis are to reduce costs where possible through technology enhancements and design and administrative changes, as well as to better articulate the long-term benefits to the urban area—in monetary terms if possible—but, at least through well-documented examples of the positive and negative impacts of underground projects.

Considering the high profile of many underground road and rail projects, it is surprising that comprehensive documentation is hard to find. Planning studies are available, but they lack the retrospective assessment of actual costs and benefits. There is anecdotal or partial evidence of the positive environmental and financial impacts of replacing aboveground transportation structures with underground alignments on neighborhoods worldwide. For example, the Boston Globe reported in 2004 (Palmer, 2004):

> *According to an in-depth review of the City of Boston tax assessing records by the Globe, in the 15 years since the Central Artery tunnel project began, the value of commercial properties along the mile-long strip that this year will become the Rose Kennedy Greenway increased to $2.3 billion, up 79 percent. That's almost double the city-wide 41 percent increase in assessed commercial property values in the same period.*

When adjusted and aggregated over the entire Central Artery alignment, the increase in land values could be of the same order of magnitude as the cost of such a difficult and expensive project. What appears to be lacking in this and other examples is careful and defensible study of the financial and environment changes over, say, a decade following project completion. Retrospective, comparative studies of the costs and impacts of the various types of underground construction projects are needed. To be useful, these studies must be conducted in a comprehensive and scientific manner and must consider economic, environmental, and social impacts.

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