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# Comparing Hardening Strategies of Overhead Power Distribution Lines Using SWOT Analysis

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**ABSTRACT:** The disruption of power supply due to extreme weather events has been significantly intensified in recent years by the effect of climate change. These disruptions are mainly caused by the overhead power distribution lines (OPDLs) being exposed to extreme weather events, such as wind storms, freezing rains, and wild forest fires. These weather events either directly affect the OPDLs or the vegetation surrounding them causing power outages. Subsequently, there are massive financial, social, and environmental losses associated with these outages. Therefore, several hardening strategies have been proposed in the literature to mitigate them, such as vegetation management, selective undergrounding, and Multipurpose Utility Tunnels (MUTs). However, each of these strategies has associated costs and benefits, which have not been fully studied and compared. Although undergrounding of OPDLs is a promising solution, which showed its effectiveness in different countries, its high initial costs and potential risks could limit its implementation. This study aims at defining the importance of the conversion process of the OPDLs exposed to extreme weather events from overhead to a more immune environment underground, considering the different factors and challenges. The study uses Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis to compare (1) direct burial, (2) underground duct banks, and (3) multipurpose utility tunnels as the three main underground hardening strategies for the OPDLs. The results of this study will help decision makers determine the most suitable strategy for the conversion process.

## 1. INTRODUCTION

Resilient power distribution networks are essential to ensure a reliable power supply to urban and rural communities. As the demand for more resilient and secure infrastructure increases, there is a critical need for an effective solution to address the ongoing problem of power outages. Several financial and social losses are accrued due to these outages. According to a study performed in Canada, momentary and sustained power outages cost Canadians $8 billion and $4 billion annually, respectively (Zsolt Sepa, 2018). These alarming numbers clearly illustrate the impact of outages, which result in substantial economic and financial losses. Therefore, moving a part of these networks underground is a promising solution that showed its effectiveness in many cities over the world (Martins et al., 2022). Undergrounding Overhead Power Distribution Lines (OPDLs) offers significant advantages in reducing vulnerabilities to weather related events, such as wind storms, freezing rains, wild forest fires, and extreme temperatures, which can disrupt the power supply. As a result, many European counties (e.g. The Netherlands) have either initially constructed their power distribution lines or moved the vast majority of their OPDLs to the underground, which resulted in a positive impact on their reliability [1]. One early example of analyzing the concept of undergrounding existing OPDLs in the USA is mentioned in (Newton, 1916).

Power distribution line hardening strategies can be categorized into two main categories, which are: overhead and underground strategies, as illustrated in Figure 1. Among overhead hardening strategies, vegetation management plays a crucial role in mitigating the risks posed by surrounding vegetation to OPDLs. This approach primarily involves the systematic removal of undesired vegetation along the network's path to minimize disruptions caused by tree contact (Cerrai & Watson, 2019). A study conducted in Quebec, Canada, reported that 40% of power outages in the province result from trees or branches falling on OPDLs due to extreme weather events (Hydro-Québec, 2024). In addition to vegetation management, strengthening existing overhead components and structural systems is another key strategy. This involves reinforcing power poles and elevated distribution lines by improving the durability of network components and incorporating advanced supporting methods, such as spacer cables, to enhance the resilience of OPDLs (Hendrix Aerial Cable Systems, 2007).

While overhead hardening strategies are widely used in large areas, particularly in rural regions, due to their low initial cost, their effectiveness is limited and necessitates ongoing maintenance and repeated interventions to ensure network stability. Therefore, transferring the OPDLs to underground systems can better enhance both the resilience and reliability of the power grids.

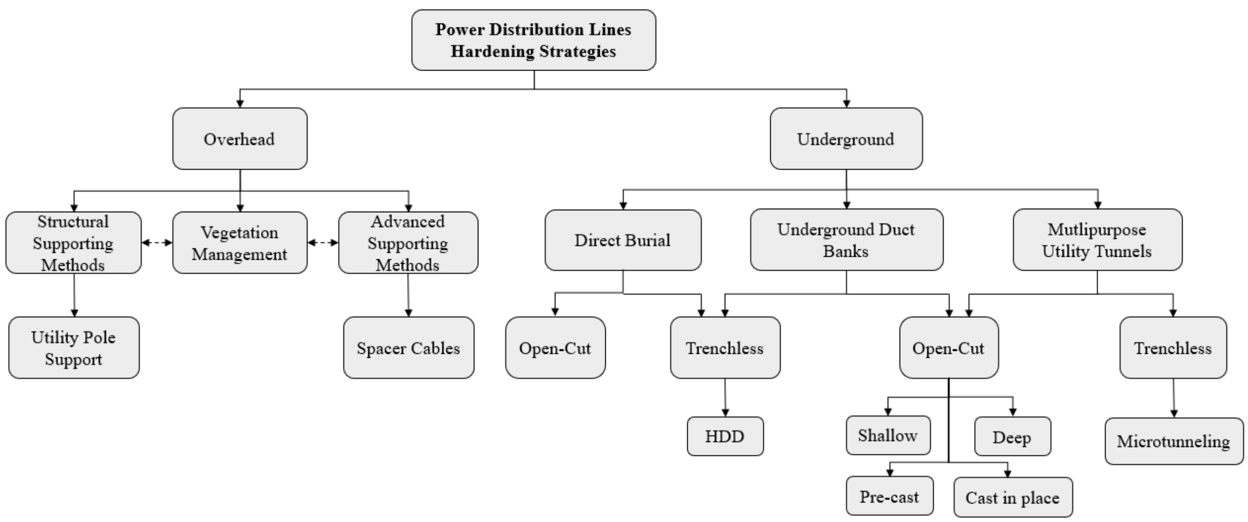


Figure 1: Classification of Power Distribution Lines Hardening Strategies

Underground hardening strategies aim at partial transfer of the OPDLs to the underground (i.e. selective undergrounding) in order to create a more immune environment for the PDLs against extreme weather events. This study aims to provide a comprehensive comparison of the underground hardening strategies including Direct Burial (DB), Underground Duct Banks (UDBs), and Multipurpose Utility Tunnels (MUTs). Each of these underground hardening strategy has different construction method, factors, and associated advantages and disadvantages that are explained in Section 3.

The objectives of this study are: (a) Highlighting the significance of converting OPDLs to a more resilient underground environment; (b) Examining the various factors and challenges that hinder this transition; and (c) Utilizing Strengths, Weakness, Opportunities, and Threats (SWOT) analysis to compare the three primary underground hardening strategies.

## 2. ADVANTAGES AND DISADVANTAGES OF UNDERGROUNDING OPDLS

Transferring the OPDLs to the underground provides numerous benefits, as it provides an ultimate protection for the power distribution lines against weather related events. A study was done by Lawrence Berkeley National Laboratory (Berkeley Lab, 2024) showing the benefits associated with converting the OPDLs to underground in several cases in the USA, Canada, and UK as shown in Table 1. On the other hands, there are some limitations and disadvantages that may limit the use of the undergrounding hardening strategies.

## 2.1 Advantages of undergrounding OPDLs

The advantages of undergrounding the OPDLs are:

**Reliability:** In 1995, the Power and Energy Society (PES) under the Institute of Electrical and Electronics Engineers (IEEE) developed two main indices for measuring the reliability of power systems: (1) *System Average Interruption Frequency Index (SAIFI),* which measures how often do customers experience power outages per year; and (2) *System Average Interruption Duration Index (SAIDI),* which measures the duration of outage that each person experience per year (IEEE, 2012). Both SAIDI and SAIFI are used globally to measure the reliability of the power supply in a specific city, region, or country. It is well proven that the countries that primarily constructed their power distribution lines underground or recently converted their OPDL to underground have higher reliability indexes than these which still rely on the OPDLs (Martins et al., 2022). As an example for the positive effect of undergrounding the OPDLs on the reliability, WSPC has proved that undergrounding OPDLs had improved the SAIDI Index by 95% (Powell et al., 2022; Phil Musser, 2018; WPSC, 2021). Other examples are mentioned in Table 1.

**Resilience:** Undergrounding OPDLs significantly enhances the resilience of the power networks (Brown, 2016; Hunt et al., 2014) through enhancing the four resilience terms: (a) Anticipation: the proactive measures and strategies taken to predict, prevent, or mitigate the impact of potential failures before they occur; (b) Adaptability: The capacity of systems to adjust to changing conditions and challenges; (c) Robustness: The ability of the network to withstand shocks without failing; and (d) Recovery: The speed and efficiency with which systems can return to normal operations after a disruption (Connelly et al., 2017).

**Safety:** Undergrounding OPDLs enhances safety by mitigating risks associated with OPDLs exposed to the weather events, which can lead to structural failures and subsequent electrical hazards (Larsen, 2016a). Additionally, undergrounding OPDLs reduces the likelihood of accidental contact, minimizing risks of electrocution for utility workers and the public. The elimination of exposed medium or high voltage lines also decreases the potential for fire hazards and vehicular collisions with utility poles (HD rink, 2018). Additionally, undergrounding the OPDLs provides an ultimate protection against human-made accidents and terrorist attacks that target the power industry.

**Environment:** Undergrounding OPDLs offers several important environmental benefits. By removing the need for utility poles and the associated tree clearing, it also mitigates the disruption of local ecosystems, helping to preserve habitats and biodiversity (Nationalgrid, 2015). Additionally, underground lines are less susceptible to weather-related damage, such as storms or wildfires, which can otherwise lead to environmental hazards like wild fires and soil erosion that could release harmful pollutants. Although the initial installation of underground lines may involve higher energy and resource input, considering the long-term environmental advantages often justify the investment (Bumby et al., 2010).

**Aesthetics:** Relocating OPDLs to underground enhances the aesthetic appeal of the area, which can positively impact real estate property values (Pabón et al., 2022). This transition eliminates visible suspended wires and cables that may disrupt the visual harmony of the environment and create a perception of insecurity among pedestrians (Sims & Dent, 2005).Reducing visual pollution and preserving natural landscapes and scenic vistas is particularly valuable in areas with significant natural or cultural heritage. Moreover, it significantly enhances the land use by freeing up space and improving the aesthetics of an area. Without the visual clutter of utility poles and wires, the land becomes more versatile, making it suitable for a broader range of uses such as residential, commercial, and recreational developments (Ishigooka et al., 2021).

Table 1: Benefits of Converting OPDLs to the Underground

| Organization | Investment Type | Period | Benefits |
|---|---|---|---|
| Wisconsin Public Service Commission (WPSC) | OPDLs to underground | 2012 - 2021 | 95% improvement in SAIDI index (Powell et al., 2022; M. Phil, 2018; WPSC, 2021) |
| Florida Power & Light (FP&L) | OPDLs to underground | Till 2017 | 20% reduction of power outages (FPL, 2022) |
| VIRGINIA Electric and Power Company (VEPC) | OPDLs to underground | 2016 - 2022 | 99% improvement in SAIFI index |
| | | | 27% reduction in system restoration time (Brown, 2016) |
| | | | Estimated reduction in GDP losses due to outages from $3.6M in 2016 to $270K in 2022 (VSCC, 2023) |
| Pacific Gas and Electric (PG&E) | OPDLs to underground | 2024 | Projected 99% ignition risk reduction during wildfires (PG&E, 2023) |
| Different studies in UK and Montreal, Canada | Conversion of overhead power transmission lines to underground | 1990 - 2000 | Avoided real estate property value losses of about 5-20% (Larsen, 2016b). |

### 2.2 Disadvantages of undergrounding OPDLs

Although undergrounding OPDLs offers several advantages, it also presents significant challenges. The high initial cost of undergrounding compared to overhead hardening strategies remains the primary factor deterring its widespread adoption (Al-Khalidi & Kalam, 2009). Moreover, the initial excavation during the conversion process, and the uncertainty of the underground conditions (e.g. water table level and soil conditions) and the associated risks (e.g. soil erosion, root penetration, and digging activities) are also major challenges. On the other hands, there are some secondary reasons that limit the adoption of the underground hardening strategies for the OPDLs such as harder accessibility, higher complexity, and limited ventilation for medium and high voltage lines. These challenges are considered secondary as they can be overcome through using a suitable underground hardening strategy, as explained in Section 3.

## 3. SWOT ANALYSIS OF THE OPDLS HARDENING STRATEGIES

SWOT analysis is a strategic planning tool used to highlight the strengths, weakness, opportunities, and threats of a certain strategy (Gurl, 2017). The four terms of SWOT analysis in business related studies are commonly defined as follows: (a) Strength: An internal factor that enhances competence, represents a valuable resource, or serves as a beneficial attribute; (b) Weakness: An internal limitation or deficiency that hinders the competence, resources, or attributes essential for success; (c) Opportunity: An external factor that improves performance and can be leveraged or exploited to gain advantages; and (d) Threat: An external factor that impairs performance and poses a risk of diminishing achievements (Capon, 2004). In this study, SWOT analysis is utilized to highlight the advantages, challenges, and threats of converting the OPDLs to underground, then comparing the different underground hardening strategies highlighting the four factors of SWOT analysis for each method. SWOT analysis can either be performed using a field survey considering opinion of experts in the field, internal data based on previous projects or a case study, and finally a review of the literature for the previous research covering the different considered strategies (Leigh, 2010). The SWOT analysis performed in this study relies mainly on the literature review considering the three different underground OPDLs hardening strategies.

### 3.1 Direct Burial (DB)

Direct burial (DB), commonly referred to as shallow burying of the power distribution lines, is an affective alternative for the OPDLs as the power lines are buried underground, providing a better protection to the power lines than the overhead option. In DB installation, cables are placed directly into the soil, often with some insulation or protective layers built into the cables. The cables may be buried in trenches or directly within other types of channels in the ground. The burying depth could vary based on the specification of the project, and the laws and regulations of the location. DB is mainly constructed through the traditional open cut method. A trench to accommodate the desired utility is excavated, followed by placing the utility, then backfilling and restoring the surface.

Although DB is considered the cheapest undergrounding strategy for the OPDLs in terms of the initial cost, it provides a low accessibility to the buried utility what requires repeated excavations in order to access the existing utilities either for maintenance, repair, or modification. Table 2 shows the four Aspects SWOT analysis of the DB strategy.

Table 2: SWOT Analysis of DB

| Category | Details |
|---|---|
| Strengths | **Cost effective**: Lower initial costs, less complex compared to other hardening strategies. |
| | **Fast installation:** Simplified installation process enables faster implementation. |
| Weakness | **Limited protection:** Cables susceptible to damage from environmental factors, such as flooding, soil erosion, root penetration, or digging. |
| | **Difficult accessibility** and complexity of repairs increase the long-term costs and may shorten the lifespan of the cables, which result in less reliability and resilience of the power network. |
| | **Repeated excavations:** Result in financial, social, and environmental losses. |
| Opportunities | **Well-suited for rural areas** with low utility and population density, enabling cost-effective underground power distribution. |
| | **Technological advancements** such as direct burial-rated cables (Thiele, 2024), enhance durability and resistance to environmental factors, though they may lead to higher costs. |
| Threats | **Vulnerable to environmental risks** including soil shifting and water table fluctuations, pose a threat to the integrity of DB systems. |
| | **Regulatory constraints** on burial depth may necessitate deeper excavation, resulting in increased costs. |

### 3.2 Underground Duct Banks (UDBs)

UDBs are structured pathways, typically constructed from concrete or other durable materials (e.g., steel), which host encased conduits designed to accommodate electrical cables and communication lines. The primary purpose of a UDB is to protect and organize these utilities while providing a safe and stable environment for their operation and maintenance. UDBs can be categorized based on several factors, including shape, material, construction method, and the type of utility they house. UDBs may be designed with either straight or bent configurations, depending on the specific routing requirements of the utility. In terms of material, cast-in-place concrete is the most commonly employed due to its cost-effectiveness and flexibility in design modifications. Precast concrete, while offering faster installation and superior quality, incurs higher costs related to transportation and storage. Recently, there has been a shift toward the use of lightweight polymeric duct banks, such as High-Density Polyethylene (HDPE), particularly in environments susceptible to moisture (Vincent, 2021). These materials are favored for their ability to prevent water from reaching underground utilities, thus mitigating potential damages in wet areas and offering an alternative to traditional concrete options. SWOT analysis of the UDBs is presented in Table 3.

Table 3: SWOT Analysis of UDBs

| Category | Details |
|---|---|
| Strengths | **High protection**: As there is no direct contact between the power lines and the surrounding soil and associated hazards. |
| | **Easier maintenance and fault allocation**: Allowing a PDL to be pulled out, maintained, and then returned to its original location without excavation. |
| | **Longevity of power lines**: Encased conduits lead to increased longevity of the hosted cables. |
| Weakness | **Higher initial cost**: UDBs are always associated with higher initial cost than DB. |
| | **Obstacles in maintenance**: While UDBs allow pulling out cables for maintenance and repair, in cases of wire damage, pulling out the cable becomes a problem, often still requiring excavation. |
| | **Voltage limitations**: UDBs are typically restricted to low to medium voltage cables because high voltage lines generate significant thermal energy (Del-Pino-López et al., 2014). |
| Opportunities | **Utility integration**: UDBs allow a limited integration between electricity and telecommunication lines. |
| | **Future modifications**: Adding additional encased conduits during construction allows future modifications and the addition of more utilities without the need for further excavations. |
| Threats | **Limited future expansion**: UDBs limit future improvements, enlargement, or the addition of new utilities. |
| | **Limited Participants**: UDBs can be an expensive solution due to the limited number of participants. |

### 3.3 Multipurpose Utility Tunnels (MUTs)

MUT is an underground tunnel constructed to hold one or more utility types, which can be easily accessible during the operations or maintenance anytime without surface disruption. MUTs are classified based on their shape, depth, type, accessibility and position of installation. MUTs can be classified into three types considering the depth of the cover: (a) Flush Fitting MUTs: the tunnel cover is at ground level, allowing direct access without excavation. These are commonly found in urban areas where frequent maintenance is required; (b) Shallow MUTs: have a cover depth ranging from 0.5 to 2 m, making them relatively easy to access while providing some protection from surface loads and environmental factors; and (c) Deep MUTs: constructed at depths ranging from 2 to 80 m. Deep MUTs are typically used in densely populated cities or for large-scale utility networks where surface space is limited, or where deeper installation provides additional security and protection (Luo et al., 2020). Considering the accessibility, MUTs can be classified as: (a) Searchable: Designed for inspection and monitoring but not necessarily large enough for human entry; (b) Accessible: Large enough for personnel to enter and conduct maintenance manually; and (c) Compartmentalized: Internally divided into separate sections to organize different utilities. Several construction materials are used to construct MUTs such as: Cast-in-place concrete, precast concrete sections, brick and mortar, and High Density Polyethylene (HDPE).

MUTs have a variety of benefits over the other underground hardening strategies. MUTs share the same strengths of UDBs mentioned in Table 3 in addition to their own strengths mentioned in Table 4.

Table 4: SWOT Analysis of MUTs

| Category | Details |
|---|---|
| Strengths | **Higher accessibility**: Facilitate accessibility for maintenance, modifications, and additions of utilities with minimal additional excavation (Canto-Perello & Curiel-Esparza, 2013). |
| | **Cost reduction and cost sharing**: Reduce costs related to repeated excavations (Cano-Hurtado & Canto-Perello, 1999) and allows cost sharing among the different stakeholders participating in a MUT (Alaghbandrad & Hammad, 2020). |
| | **Ultimate protection and accessibility**: Provide ultimate protection and accessibility to PDLs (Jorjam et al., 2024). |
| Weakness | **Higher initial cost**: MUTs have the highest initial cost among the three strategies, which limits selection in certain cases (Hunt et al., 2014). |
| | **Complicated coordination**: Require significant coordination among different utility providers (Genger et al., 2023). |
| | **Complex planning**: Involves complex planning, especially in developing a fair cost-sharing model to attract utility companies (Genger et al., 2023). |
| Opportunities | **Emerging technologies**: MUTs can accommodate emerging technologies like smart sensors for monitoring, operation, and maintenance of utilities (Alaghbandrad & Hammad, 2025). |
| | **Expansion flexibility**: Allow for easy expansion by adding new utilities or enlarging the capacity of the existing utilities with no additional excavation. |
| Threats | **Underground uncertainties**: Underground uncertainties are higher than other alternatives, especially with deeper options. |
| | **Regulatory barriers**: Regulatory barriers, such as government laws, could prevent tunnel construction for security or future development reasons. |
| | **Safety and security:** Criminals, terrorists, and unauthorized persons could gain access to the tunnel to damage infrastructure. |

### 3.4 Hardening strategy selection

Selecting a hardening strategy over another, depends mainly on the unique factors and criteria of each project. The construction method plays a vital role also for the three considered hardening strategies. Each strategy can either be implemented through open-cut traditional construction method or an alternative trenchless method. For DB and UDBs, Horizontal Directional Drilling (HDD) is often selected as an alternative trenchless installation method. HDD is considered the easiest and most common trenchless method as it uses a surface pit that requires no excavation for installing the HDD driller. For MUTs, microtunnelling is a more suitable trenchless method. Even though microtunneling is a pit based and requires excavating and constructing the entry shaft, it is characterised by its high precision and the ability to go deeper. Jorjam et al. (2024) demonstrated that while installing MUTs using trenchless methods in general, and microtunneling in particular, may be more expensive due to the high installation cost, they enable faster installation, significantly reducing the social and economic disruptions associated with excavations. Therefore, advancing the construction method influences the characteristics of the construction process and may affect the selection of the used hardening strategy. Soil condition, water table level, utility density, traffic density, and laws and regulations of each city can also prioritize one underground hardening strategy over another. One important aspect to be considered is the compatibility with future smart cities considering their seamless integration into the city’s infrastructure to ensure efficient maintenance, monitoring, and accessibility. A strategically designed utility network is crucial for supporting smart city initiatives, which prioritize efficiency, sustainability, and technological innovation in urban development. Based on the performed SWOT analysis in this study, a comparison of the undergrounding hardening strategies is presented in Table 5.

Table 5: Comparison of the Underground Hardening Strategies

| Criteria | DB | UDB | MUT |
|---|---|---|---|
| Initial cost | Low | Medium | High |
| Installation speed | High | Medium | Low |
| Resilience | Medium | High | Very High |
| Utility vulnerability | High | Medium | Low |
| Accessibility | Low | Medium | Very High |
| Maintainability | Low | Medium | Very High |

## 4. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

In conclusion, this study provides a comprehensive evaluation of various undergrounding strategies for power distribution lines in response to the increasing frequency and severity of extreme weather events attributed to climate change. Through the application of SWOT analysis, the study comprehensively examined the strengths, weaknesses, opportunities, and threats of direct burial, underground duct banks, and multipurpose utility tunnels as potential solutions for enhancing system reliability and resilience. While undergrounding represents a promising approach to mitigate power disruptions caused by adverse weather, the high initial costs and associated challenges warrant careful consideration. The findings offer valuable insights to guide decision-making, assisting stakeholders in selecting the most suitable undergrounding strategy based on a thorough assessment of resilience, cost-effectiveness, and long-term sustainability, ultimately contributing to the development of a more reliable and resilient power distribution system.

The comparison of underground hardening strategies using SWOT analysis is limited to the traditional open-cut method, without considering alternative construction techniques. Future research should extend this analysis by incorporating trenchless alternatives for each underground hardening strategy. Evaluating methods, such as horizontal directional drilling (HDD) and microtunneling, within the SWOT framework could provide deeper insights into their impact on the conversion process and help mitigate the challenges and side effects associated with excavations for undergrounding power distribution lines. Moreover, the SWOT analysis in this study is primarily based on a review of the literature**.** For future research, conducting a case study, field surveys, and interviews with industry professionals would provide a more robust and data-driven assessment of underground hardening strategies.

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