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Systematic Review

Reliability-Oriented Underground Cable Planning in Power Distribution Networks: A Systematic Review of Modeling Approaches and Decision Factors

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Abstract

Reliability-oriented planning of power distribution networks is becoming increasingly important as utilities face aging infrastructure, extreme weather conditions and rising expectations for service reliability. Overlooking relevant factors in this planning process may contribute to power failures and their associated economic and service impacts. An evaluation of reliability-focused power distribution network design is provided in this systematic literature review by examining the principal modeling approaches used for planning underground and mixed overhead–underground cable configurations. The studies were chosen according to previously defined eligibility criteria and then screened for relevance to power distribution networks, to underground or hybrid line configurations and to reliability or planning. A literature search was carried out using Compendex and Google Scholar, with the final search completed in August 2026. The review incorporates insights from 79 included empirical and analytical studies and provides an overview of the related modeling approaches, methodological trends and the classification of commonly considered input and output variables relevant to underground cable planning and reliability improvement. The findings highlight the importance of considering environmental, network-design, operational and economic factors when developing sustainable, reliability-oriented distribution network planning strategies. The review may not capture relevant studies indexed only in databases other than those searched.

Keywords: power distribution; reliability; resilience; sustainable distribution network planning; underground cable; undergrounding; asset management

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1. Introduction

Electric power distribution networks face cumulative stress due to infrastructure degradation, extreme weather events and evolving service demands. Accordingly, reliability improvement and the implementation of comparative measures to assess power grid performance are considered major planning concerns. In addition to studying the various factors that impact performance, determining the appropriate distribution of power lines between overhead and underground configurations has become a challenge when considering both performance indices and financial metrics. Particularly in regions where

severe climate conditions or risks imposed by vegetation exist, decision-making on power cable distribution and identifying the impact of specific covariates have become important planning priorities. By considering the effects of these factors, the analyst can define objectives more clearly and effectively when assessing the system's overall performance. While taking the aforementioned actions into account, it is useful to examine the fundamental design of such networks in order to obtain the intrinsic reliability that a system may exhibit in its best-case scenario. At this point, it should be noted that some preliminary actions are required in the grid design before proceeding to activities such as preventive or proactive maintenance planning and other restoration activities. Thereafter, following the implementation of an appropriate network design, the system performance may be further improved by implementing measures such as maintenance planning or reducing patrol response time when dealing with outages. Among the high-priority factors impacting the reliability of these networks, power-line configuration plays an important role in network design, specifically when considering overhead (aerial) and underground power cables. Undergrounding power lines, while reducing exposure to outage causes such as ice storms, vegetation, animal contact and vandalism, offers potential improvements in system reliability, but at the same time, is more costly in terms of initial capital investment, as discussed by Abdullah et al. [1].

This study builds on the existing literature to provide a systematic literature review of modeling approaches for reliability-oriented power distribution network design, with particular emphasis on underground cable placement strategies. Overhead power lines are examined in a complementary work by Yaghoubi et al. [2] through a bibliometric analysis considering reliability and resilience, modeling approaches, variable utilization and research trends. The present review extends this line of investigation toward underground and mixed overhead–underground configurations. It further identifies and categorizes the input and output variables considered in previous studies. In addition, the review examines methodological trends and the application of these variables across underground and mixed overhead–underground network studies. The contribution of this review is a synthesis that is aimed at guiding decision-making, not simply a collection of studies on underground cables. It compares the applicability and limitations of the principal modeling families, links the recorded input and output variables to planning and restoration requirements and determines the research priorities needed to coordinate reliability, resilience and cost under changing operating conditions.

The remainder of this article is organized as follows. Section 2 presents the review methodology and literature selection process. Section 3 reviews the principal modeling approaches for underground cable placement and grid reliability planning. Section 4 categorizes the identified variables, examines their prevalence and analyzes the evolution of the reviewed methodological approaches. Section 5 discusses the findings, their implications and future research directions, while Section 6 concludes the study.

2. Methodology

A systematic literature review approach was adopted in this study, with the literature identification, screening and selection process conducted in accordance with the PRISMA 2020 guidelines [3]. The completed PRISMA 2020 checklist is provided in Supplementary Material S2. The selected studies were examined based on their modeling approaches, and the identified input and output variables were grouped into broader categories, with their frequency of occurrence in the reviewed literature also evaluated. Based on the objective of cable placement strategies and to address reliability modeling and grid architecture, a dataset of 79 studies was gathered and examined. Firstly, the inclusion criteria focused on studies comparing the undergrounding strategy of power lines with

other policies, i.e., overhead or mixed configurations in power distribution networks, along with the associated key reliability metrics (e.g., SAIDI, SAIFI, operation and maintenance costs). The literature review was conducted using the Compendex and Google Scholar bibliographic databases. The final literature search was conducted in August 2026.

An effective approach to decision-making is analyzing how different factors affect grid components. The importance of precise design planning is that the probability of not meeting the performance targets is reduced and hence the competitive abilities of corporations are significantly improved. The design optimization problems have been addressed using several techniques such as statistical models, simulation approaches and machine learning techniques. However, these models vary based on the size and environmental conditions of the areas in which the grids are located. Moreover, conventional models that consider only total costs as a single objective, or are proposed as a general framework, necessitate additional constraints in their formulation. They should consider competitive performance metrics such as customer satisfaction resulting from fewer power outages and should be specifically tailored according to the regional location of the installations. With the application of recent methodologies for classification and prediction using the associated data, the precision of such designs has been substantially enhanced.

The methodology is provided in a flowchart following the PRISMA guidelines, as shown in Figure 1.

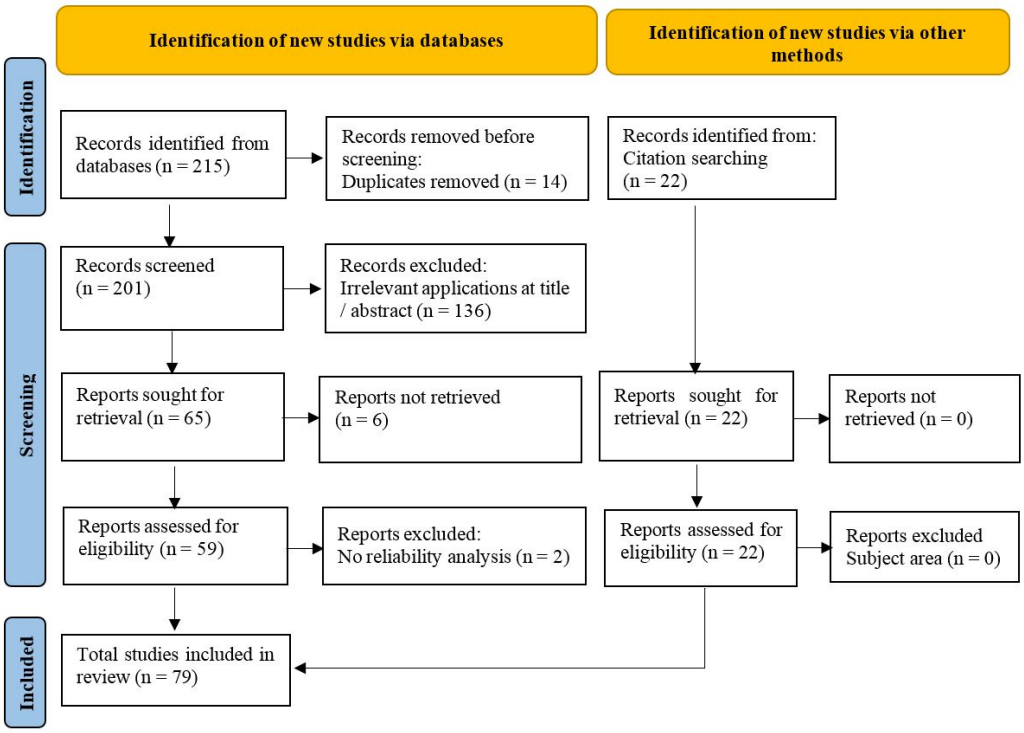


Figure 1. Literature identification and screening process adapted from the PRISMA 2020 framework [3].

(1) Our search terms include the following: ("Power Distribution" OR "distribution network" OR grid) + (resilience OR reliability) + (Undergrounding OR "Underground cable" OR "Underground power line").
(2) Based on the flowchart, the articles identified through the approach were limited to studies published between 1980 and 2026. Accordingly, 237 related publications were obtained and downloaded through an institutional academic account.
(3) After excluding the studies irrelevant to our objective, 79 studies remained for inclusion in this review.

Inclusion and exclusion criteria were predefined and used to determine the eligibility of the studies, with regard to the study scope, power distribution network application, underground or hybrid line configurations and relevance to reliability or planning. Studies were excluded when they did not address power distribution applications, underground or mixed line configurations or reliability-related or planning-related outcomes. Before the screening process, duplicate records were removed, and the titles, abstracts and introductions were screened by one author according to the predefined eligibility criteria. In the following step, the full texts of the studies that might have been eligible were evaluated, and final eligibility was decided on the basis of the same pre-established criteria. Data were extracted only from those studies which satisfied the eligibility criteria, and data extraction was performed by one author.

Given the methodological heterogeneity of the reviewed literature, including simulation, optimization, statistical, economic and computational approaches, no single formal risk-of-bias assessment tool was considered suitable for all studies. For each included study, information including publication year, modeling approach, distribution-line configuration, as well as the input and output variables considered in the analysis was extracted. A study-by-study summary of these characteristics for the 79 included studies is provided in Supplementary Table S1. The identified variables and methodologies were then grouped into broader categories, and their frequencies of occurrence were calculated to examine the main research trends across the reviewed literature. The studies were placed in the appropriate synthesis categories based on the modeling approach they employed, the configuration of their distribution line and the input and output variables that they considered. Terms that referred to the same concepts were combined into a single, more general category. The synthesis was descriptive and qualitative and was supplemented by a quantitative frequency analysis of the variables and methodological approaches identified. This systematic review was not prospectively registered, and no separate review protocol was prepared. The 79 included sources comprise 38 journal articles (48.1%), 30 conference proceedings (38.0%) and 11 other source types (13.9%), such as reports, theses, preprints, books and related publications. The complete reference list also contains contextual and methodological sources cited outside the screened corpus; these sources are not counted among the 79 included studies or in the variable-frequency analysis. This categorization refers to the origin of the sources and not to their methodological quality. Differences in study design, validation and applicability are therefore relevant to the interpretation of specific findings, while the reported variable-use frequencies remain descriptive and are not weighted according to the quality of the evidence.

Finally, this article addresses the following main questions:

(1) What are the principal methodologies for assessing grid performance in the context of underground power line distribution diagnostics? (Section 3).
(2) What are the most common input and output variables used in reliability modeling for underground power cable placement strategy in power distribution networks? (Section 4).
(3) What are the future directions for improving the currently applied techniques used by power utilities? (Section 5).

3. Review of Modeling Approaches for Planning Underground Cable Placement in Grid Reliability Design

The following two subsections categorize the reviewed literature according to the methodological approaches and applications used to assess the planning and deployment of underground or mixed cable strategies as part of grid infrastructure design. The methods are classified based on article summaries, which allow for the identification of each

method's strengths, limitations and application context across the analyzed studies. The objectives and methodologies of each article are discussed in detail in the following sections. In interpreting these methodological approaches, it is also important to distinguish between the concepts of reliability and resilience.

Reliability and resilience describe different aspects of performance in power distribution systems. Reliability refers to the ability of the network to provide continuous service under certain operating conditions. Resilience describes how well a power system can adapt to and recover from major disruptions, including severe weather events, wildfires and other extreme conditions. For undergrounding decisions, both concepts are relevant because underground cables can reduce exposure to external hazards while introducing different challenges.

3.1. Traditional Methods

The methodological approaches discussed in this section include statistical analysis, optimization and financial modeling. These methods quantify the relationships between grid architecture covariates, such as the percentage of underground lines, consumer density and vegetation and key reliability indices, including SAIFI, SAIDI and operation and maintenance costs, with respect to the objective of power cable undergrounding.

3.1.1. Statistical Analysis

Root Cause Identification and Reliability Metrics

Statistical approaches are used in several studies to identify critical factors that affect distribution network reliability. Root causes of poor performance in medium-voltage feeders are analyzed by Choma et al. [4], highlighting the principal roles of distribution lines and underground cables. They proposed a predictive assessment method to reduce outage durations.

Similarly, Al Mamun et al. [5] examined ten years of outage and weather data from 116 circuits in southeastern North Carolina. The statistical evaluation of SAIDI and related metrics in their work revealed the primary contributors to power interruptions, namely vegetation and transmission failures, which offer insights into grid vulnerability under extreme weather conditions. Their analysis also distinguished frequent vegetation-related and equipment-related outages from less frequent transmission or generation failures and reported a substantial proportion of unclassified causes. Inconsistencies in reliability reporting practices across U.S. utilities were further examined by Warren et al. [6]. Differences in outage definitions and in the calculation and reporting of indices such as SAIDI and SAIFI were identified as important limitations when comparing performance across utilities.

Underground Cables and Cost-Reliability Trade-Offs

Undergrounding as a resilience strategy received significant attention across various contexts. Ken Hall [7] evaluated the cost-reliability implications of undergrounding distribution and transmission systems in the U.S., revealing that although underground networks experience fewer and shorter outages during storms, their cost is substantially higher, up to five times for transmission infrastructure. Lvov et al. [8] examined this balance using an approach that considered both life-cycle cost and reliability. They suggested that underground cables can reduce long-term expenses even though installation is more costly. In a separate analysis, Mariut et al. [9] modeled underground-cable life under combined thermal, humidity and vibration stresses using Arrhenius–Weibull relationships to illustrate the effects of multiple stresses on estimated cable lifetime and support condition-based maintenance planning.

Statistical and Stochastic Reliability Modeling

Reliability assessment is enriched by several contributions that apply statistical modeling tools. To assess the reliability of power distribution components, Kannan et al. [10] made a comparison between exponential, Weibull and Markov models and illustrated how operating-condition-adjusted failure rates and Weibull shape parameters influence component reliability estimates. The authors acknowledged that their illustrative results were not exact in the absence of real statistical data. In another study and with an objective of finding a balance between maintenance costs and system reliability, Lefebvre and Yaghoubi [11] examined optimal inspection frequencies that consider stochastic degradation processes. The study extended previous research by integrating continuous-time Markov chains and dynamic programming in the modeling. In a related application of dynamic programming, a stochastic queueing problem was also considered in a study by Lefebvre and Yaghoubi [12], in which operational decisions are optimized while both system performance and control costs are taken into account. These studies provide general mathematical formulations for maintenance and queueing control rather than direct evaluations of underground-cable placement. In addition, Nemati et al. [13] used a Weibull proportional-hazards model based on historical cable inventory and failure records. Their analysis demonstrated that accounting for recurrent failures in repairable cables can change failure-rate estimates and maintenance rankings. Valenzuela et al. [14] proposed a heuristic approach and clustering algorithms to plan georeferenced underground distribution networks through transformer allocation, network routing and tie-point placement while considering construction costs and network configuration. In another approach, instead of assuming constant reliability rates, Khan et al. [15] developed a continuous-time Markov process framework for underground distribution systems to represent the degradation of components due to thermal effects. Failure rates based on temperature and load were incorporated to provide a more realistic representation of the reliability and also the availability of underground infrastructure.

Diagnostics, Condition-Based Maintenance and Failure Trends

In order to identify aging-related faults, Pultrum et al. [16] analyzed the Dutch underground cable network, which highlighted the value of condition-based maintenance for fully underground grids. In a similar work, Reder et al. [17] demonstrated the benefits of reliability-centered maintenance in underground systems. In their feeder case study, repairs at 40% of the recommended locations were associated with a 40% improvement in SAIFI. These studies clearly show how performance and cost-efficiency in underground networks can be optimized by predictive and condition-based strategies. In another study, and in order to provide decision support for maintenance optimization and system resilience improvement, Gaha et al. [18] proposed an asset management framework that integrates risk assessment. This approach uses asset behavior models, Monte Carlo simulation and Value of Lost Load to evaluate maintenance strategies for electrical utilities. Lin et al. [19] also proposed a condition-monitoring framework for underground transmission cable systems that incorporates reliability information. Their work combines a health index, an operating factor and a reliability index in a dynamic evaluation model to support preventive maintenance of cable assets.

Multi-Hazard Resilience

Several studies explored resilience under multi-hazard conditions, focusing on underground cable placement. In one study, and in order to inform repair prioritization post-earthquake, Rehman et al. [20] proposed a resilience-based criticality index and created fragility curves for underground cables. Calcara et al. [21] presented a resilience-assessment

framework incorporating empirical relationships for underground cable-joint failures associated with overheating and damage models for cables exposed to earthquakes. The use of these models within a decision-support system was also illustrated. Eddy [22] contributed a regulatory perspective for at-risk infrastructure by examining wildfire risks in Western Canada and concluded the need for stronger enforcement, transparency and mandatory mitigation measures. Venkateswaran et al. [23] developed a probabilistic earthquake-hardening framework combining underground cables and resilient energy storage with demand-side home battery inverters and their communication infrastructure. The analysis evaluated their combined contribution to system resilience under the modeled seismic scenarios. In another study, and to optimize underground line deployment, Taheri et al. [24] extended disaster resilience modeling and proposed a stochastic MILP framework. Their modeling revealed that considering underground infrastructure results in greater load restoration compared with conventional planning. Piansky et al. [25] evaluated wildfire-focused undergrounding investments against additional hazard scenarios using a synthetic Texas transmission network. They found that investments selected for one hazard need not provide comparable resilience benefits under other hazards, motivating future multi-hazard co-optimization rather than demonstrating that such a co-optimization had already been performed.

Environmental Stressors

Power grid reliability can be significantly influenced by environmental and climatic factors. In a study by Maliszewski et al. [26], multivariate regression was used to examine relationships between residential outages and environmental, infrastructural and spatial factors in Phoenix, Arizona, including interactions between weather conditions and distribution infrastructure. Sun et al. [27] also proposed a dataset to statistically evaluate nationwide underground infrastructure in the U.S. Their analysis identified regional disparities and associations between underground distribution rates, household income, urbanization and exposure to natural hazards, highlighting potential equity considerations in infrastructure planning. Moreover, Jun et al. [28] highlighted the operational importance of grounding strategies and recommended an effective grounding approach in areas with a high concentration of underground cables to improve reliability under fault scenarios. Morissette et al. [29] combined asset integrity management and resilience to evaluate transmission and distribution networks during extreme weather. They showed that grid resilience can be improved by combining the evaluation of system weaknesses with planning measures to reduce their impacts during severe weather. Arora [30] considered extreme weather events to identify where the power system is most vulnerable and assess possible strategies for reducing these risks. In this study, risk analysis was combined with outage forecasting to assess the resilience of the power system. Arora and Ceferino [31] carried out a comparison between undergrounding and the use of distributed energy resources as well as peer-to-peer energy sharing in the context of hurricane scenarios. Their analysis showed that energy communities could lead to considerable reductions in the duration of outages while at the same time offering lower household costs than the undergrounding option in the situations under examination.

Policy Implications and Public Perception

From a policy perspective, Mueller et al. [32] compared underground and overhead high-voltage transmission-line projects in Germany by examining public attitudes. They found no substantial differences between the two project sites in residents' risk expectations, attitudes or protest behavior, although residents in the underground project area reported feeling less affected by grid expansion. In addition, a methodology based on

historical outage records under hypothetical undergrounding scenarios was developed by Ahmad et al. [33], which quantifies the resilience benefits of an undergrounding strategy.

Synthesis and Limitations

The statistical methods under review offer complementary evidence instead of providing a direct ranking of the various undergrounding options. Historical outage data show the causes and patterns of interruptions [5], utility surveys reveal the inconsistencies in reporting [6] and degradation and failure models describe cable life and recurrent failures [9,13]. Although counterfactual analysis can be used to estimate the possible benefits of undergrounding [33], the transferability of these estimates depends on the observation period, local conditions, the availability of data and the modeling assumptions. As a result, statistical findings should be used to help estimate and verify the inputs for undergrounding decisions rather than be interpreted as standalone investment optimization results.

3.1.2. Optimization

Decision-makers have increasingly contributed optimization techniques for improving the resilience and reliability improvement of power distribution systems. Accordingly, with a particular focus on the integration of underground cables, this section reviews optimization-based approaches addressing various aspects of distribution network performance under stress.

Predictive Maintenance and Replacement Planning

To reduce failure-related costs and improve reliability, Mirshekali et al. [34] formulated a multi-objective underground-cable replacement problem using mixed-integer programming and an ϵ-constraint approach. The formulation balances interruption indices, outage costs and the number of replaced cables under budget constraints. Some studies have proposed bi-level optimization models to support resilience investments in power distribution systems that are exposed to natural hazards. Another model was proposed by Nait-Belaid et al. [35], which uses mixed-integer linear programming. The results showed that integrated restoration planning improves both critical load recovery and connectivity in communications in comparison with conventional restoration methods. As an extension of this work, the allocation of resilience investments between utilities and consumers was investigated by Wu et al. [36] using linear programming for optimizing decisions related to battery installations and undergrounding under increasing outage risks. In a recent study, Chatterton and Steele [37] examined cable replacement by performing a life cycle assessment. Their work showed that the service life of aged underground cables can be extended through rejuvenation, while reducing environmental impacts and life-cycle greenhouse gas emissions and improving reliability performance. In another study, to demonstrate the potential of predictive analytics in enhancing cable reliability and optimizing resource allocation, Abdullah and Gobal [38] developed a machine learning model for predicting failures in 11 kV underground cables to support predictive maintenance. Their model uses historical inspection and maintenance data, failure records, cable characteristics and geospatial information. The Selangor pilot indicated an accuracy of 80% in predicting cable failures and a separate assessment reported an accuracy of 93% along with an F1-score of 74%. However, these results do not prove the model's performance following nationwide deployment.

Spatial Risk Assessment and Planning

Advancing this line of research, a decision analysis was employed by Von Winterfeldt et al. [39] to evaluate alternative strategies for reducing potential electromagnetic-field risks associated with power lines. The study showed how this analysis can support planning decisions, especially when undergrounding is used to reduce power failures. A geo-analytical and fuzzy-logic risk-assessment approach for underground cables was developed in a study by Mortensen and Shaker [40], in which fault vulnerability and network-performance consequences are integrated to aid the prioritization of maintenance activities. The proposed method examines cable-related risks rather than optimizing new underground-line locations. Using a mixed-integer linear programming formulation, Velini et al. [41] assessed weather-informed network reconfiguration by adjusting component failure and repair parameters under adverse-weather scenarios. Reliability indices were used to evaluate alternative network topologies rather than to optimize the installation of new underground lines. Similarly, in order to optimize reserve-power planning in rural underground cable networks, Haakana et al. [42] proposed a methodology that considers alternative network configurations for supply restoration improvement.

Synthesis and Limitations

Optimization-related studies address different decision levels and are not interchangeable undergrounding models. They range from georeferenced routing [14] and multi-objective cable replacement [34] to stochastic underground-line siting [24]. Other methods focus on utility, such as consumer investment [36], communication-aware restoration [35], weather-dependent reconfiguration [41], reserve-power planning [42] and maintenance prioritization [40]. These approaches should therefore be compared according to their decision variables, planning horizon and data requirements. Further integration of deterioration, investment timing and hazard-dependent restoration remains needed [24,34].

3.1.3. Financial Analysis and Econometric Approaches

Economic and econometric analyses provide valuable insights into the financial feasibility, long-term cost evaluations and regulatory effects of undergrounding power distribution infrastructure through quantifying the economic effects of grid reliability improvements. Both policy development and infrastructure investment decisions are supported by these methods and strategies.

Cost-Effectiveness of Undergrounding

A comparative analysis of data from 163 U.S. utilities was conducted by Fenrick and Getachew [43] to examine the cost and reliability effects of undergrounding, while controlling for potential confounding factors. A greater share of underground lines was associated with shorter outage durations and lower operation and maintenance expenses. However, damaged underground lines may require longer restoration times. Similarly, Shaw Consultants International [44] estimated that undergrounding all overhead mainline primary distribution facilities in Washington, D.C. would cost approximately USD 1.1 billion and prevent 65% of the overhead customer outages recorded in the study baseline. These were projected results of the proposed strategy rather than outcomes measured after implementation. Another assessment of the feasibility of statewide undergrounding was carried out by the Virginia State Corporation Commission [45]. The implementation cost was estimated at over USD 80 billion. The report concluded that the benefits considered were insufficient to offset the construction costs of a comprehensive conversion programme. In a recent preprint case study, Dennin [46] examined the benefit–cost performance of

targeted overhead-to-underground conversions in Michigan at the circuit level. The results indicated that selective conversion could yield positive net benefits, although the economic outcomes differed considerably among circuits. In a cost–benefit analysis regarding undergrounding investments, Larsen [47] developed an analysis framework to evaluate the costs and benefits of undergrounding transmission and distribution lines. The results indicated that broad conversion could result in a net social loss under the assumptions examined, whereas targeted undergrounding could be economically feasible if certain conditions were met.

Econometric Modeling of Reliability and Regulation

In order to assess the relationships among severe weather, utility spending and long-term electricity reliability, Larsen et al. [48] applied an econometric framework using historical data from U.S. utilities. The findings suggest that utilities with a larger share of underground lines experience fewer power interruptions, although the relationship with interruption duration remained inconclusive. In another study with an objective of analyzing the incentive regulation on service quality and its effects on U.S. utilities, Ter-Martirosyan et al. [49] used a generalized least squares model. They found that the SAIDI metric is significantly worsened without mandatory service quality standards, while operation and maintenance (O&M) costs decreased.

Valuation of Infrastructure and Community Preferences

McNair et al. [50] analyzed the influence of underground power distribution on suburban property values using a regression model. The findings showed that underground networks increase property prices and that undergrounding may provide economic benefits beyond reliability improvements. Bohman [51] quantitatively compared resilience strategies such as undergrounding, automation and distributed energy resources. The results showed that the choice of resilience measures should reflect local needs and regional characteristics.

Synthesis and Limitations

Economic methods provide evidence at different decision levels. Utility-level econometric studies examine associations among infrastructure, spending, regulation and reliability [43,48,49], while project- and system-level studies compare construction and life-cycle costs with avoided interruptions and other benefits [44–47,50]. The researchers' findings cannot be directly applied to other planning scales or areas since the results are based on local cost structures, discount rates, the lifespan of assets, levels of customer density and tolerance for interruptions. It is therefore necessary for economic evaluations to separate utility costs from societal benefits and to compare different investment options against the local reliability and environmental conditions [46,47].

3.2. Computational Intelligence (CI) Methods

The growing complexity of power distribution systems has accelerated the adoption of computational intelligence in both academia and industry. In addition, the development of CI techniques has made them a key component of the Industry 4.0 framework. This section provides a comprehensive review of the literature in the domain of power distribution network reliability, covering a wide range of CI models, including the following methods: machine learning, simulation and analytical modeling, metaheuristic optimization and Internet of Things (IoT)-based real-time monitoring.

3.2.1. Machine Learning

Machine learning has become an important computational intelligence approach that employs a variety of techniques such as artificial neural networks, support vector machines, random forests, reinforcement learning and others. The patterns in reliability data are used to enhance fault detection, predictive maintenance and reliability planning under changing environmental conditions for underground cable infrastructure. These insights further support decision-making under uncertain grid conditions, although strong predictive models still require a large dataset. The following studies address topics relevant to the current research.

Fault Detection and Localization

A supervised learning approach was proposed by Eze et al. [52] for fault detection in subsea power cables. This study integrated several models such as decision trees and Gaussian Naïve Bayes to classify faulty and non-faulty cable conditions using measurements obtained from protection relays. More recently, fault detection and localization techniques were reviewed by Sudhagar and Marimuthu [53] for underground distribution cables, including machine learning and deep learning approaches. Their review results indicated an increasing application of intelligent models, such as artificial neural networks, to improve fault classification and localization.

Environmental and Seasonal Failure Prediction

The importance of climate-informed diagnostics has been highlighted in recent studies of underground cable networks. Bosisio et al. [54] analyzed joint failure trends in Italian underground cables and revealed that high summer temperatures and thermal stress related to loads are the main contributors to joint failures. The authors also mentioned the use of an offline machine-learning diagnostic tool for identifying critical cables and spoke of various initiatives aimed at digitizing joint-installation and maintenance activities; these measures were included as part of the utility's wider strategy for improving reliability and resilience. In another work, the environmental topic was broadened by Alhusin et al. [55] through observing failures in underground power cable joints. The analysis identified associations between cable-joint failures, high temperatures and heavy rainfall. K-means clustering was applied to the failure-weather data, while several time-series models were developed to forecast failure rates. However, the authors acknowledged uncertainty in the rainfall data and difficulties in forecasting daily failures, highlighting the importance of data resolution and quality.

Synthesis and Limitations

The reviewed machine-learning applications address different asset-management tasks: fault classification from measured signals [52], weather-informed failure forecasting [55] and utility-focused cable prioritization using inspection, maintenance and failure records [38]. Their performance therefore depends on the available data and evaluation context; for example, the subsea-cable study is not directly representative of distribution feeders [52], while weather forecasting was affected by rainfall-data uncertainty [55]. Predictive accuracy alone does not establish undergrounding benefits, so planning use also requires consideration of network consequences, intervention costs and transferability.

3.2.2. Simulation and Analytical Modeling

Among existing computer-aided evaluation methods, simulation-based techniques are widely used for replicating the scenarios and failure behavior of power grids under different

combinations of conditions. Through modeling the interactions between components of the grid, consumer demand, environmental factors, failure mechanisms, etc., this approach helps in evaluating system performance and predicting future outcomes.

Monte Carlo simulation is a commonly applied stochastic simulation technique within this class of methods and is used for modeling system performance under uncertainty in the contributing factors. Some advantages of this method are fault propagation evaluation and system reliability assessment based on related metrics, as applied at Hydro-Québec by Gaha et al. [56]. In addition, numerous studies have focused on grid and network design to influence network efficiency by taking into account the effective factors, including the strategy of power cable undergrounding. A categorized overview of the mentioned studies is provided below. In a recent study, Zhang et al. [57] proposed a framework for flood risk mitigation and recovery planning. In this work, different flood scenarios are considered, and a resilience assessment framework is developed. Finally, flood depth data are combined with equipment and line damage models to quantitatively evaluate the system's resilience and to detect vulnerable components through the simulation results. In order to capture the stochastic nature of component failures, Iqbal et al. [58] used a Monte Carlo simulation for reliability evaluation of underground transformer vaults. They considered wear-out mechanisms of components in distribution systems, and the proposed framework offered more realistic reliability estimates than deterministic approaches and identified underground cables as the primary contributors to system failures and downtime. Voltage and current measurements were used by Nithya et al. [59] to estimate fault distance in underground cables. The proposed method was intended to locate faults more quickly and reduce restoration time.

Digital Twin Approaches

In distribution networks, a virtual representation of the physical assets of the grid can be provided by digital twin approaches for modeling and analysis. These models can support simulation, system evaluation and planning by combining several contributing factors such as electrical, spatial and operational information.

For low-voltage distribution networks with underground cables, accurate representation of cable geometry and impedance was found to be important for reliable digital twin simulations. Cleenwerck et al. [60] reached this finding by testing the model on a realistic feeder with smart meter data. Another study related to the operation and maintenance of power cables was conducted by Li et al. [61], who proposed a digital twin for underground utility tunnels. Spatial geometry, electrical characteristics and maintenance information are modeled using a long short-term memory (LSTM) network for monitoring. The findings show its application to real-time monitoring and fault diagnosis, with high accuracy in anomaly identification. In order to examine protection coordination and the response of protection devices under possible network conditions, another digital twin model was introduced for distribution networks by Gómez-Luna et al. [62], which uses real-time simulation. The proposed digital twin environment also assesses fault removal times and protection device response. In another study, a network digital twin was developed in a case study considering both overhead and underground networks by Fernandes et al. [63] for an electrical distribution system. The Brazilian utility case demonstrates three-dimensional network and asset representation and its use in field operations. IoT data and AI-based functions are discussed as part of the broader digital-twin concept rather than as measured undergrounding reliability benefits. More recently, the integration of artificial intelligence and digital twin technologies in power systems was reviewed by Rahmani-Sane et al. [64]. Their study highlighted the potential of digital twins to support AI-based monitoring, fault detection and decision-making by creating a link between information from the physical

system and virtual models. This is a review of broader power-system applications and does not constitute independent field validation of underground-cable investments.

Wildfire Risk and Strategic Undergrounding

Recent studies based on simulation modeling have increasingly focused on the impact of wildfires on power system reliability and the choice of undergrounding to reduce these risks. Sohrabi et al. [65] combined wildfire spread simulation with network power-flow analysis to identify vulnerable lines and nodes in a georeferenced IEEE 30-bus case. Nematshahi et al. [66] subsequently used potential wildfire damage to develop a prioritization list for undergrounding high-voltage transmission spans. Neither study demonstrates a distribution-feeder reliability improvement after undergrounding. Nematshahi et al. [67] evaluated the wildfire ignition and associated financial risk of transmission lines using environmental, weather and grid information. The study provides risk assessment to inform mitigation priorities, rather than a measured post-undergrounding resilience or cost outcome. A related integrated model by Nematshahi et al. [68] combines wildfire simulation and the valuation of environmental, structural and grid-asset damages to map line-level financial exposure. This identifies potential mitigation priorities rather than directly calculating the realised return from undergrounding.

Financial Risk and Customer Impact Modeling

Motta et al. [69] proposed a probabilistic customer-outage-cost method and illustrated it with a rural Finnish dairy-farm case. Its customer-specific findings should not be presented as measured costs for all customer categories. Shin et al. [70] compared three underground low-voltage secondary-substation configurations through power-flow analysis and an economic assessment involving construction costs and the value of lost load. The study concerns the configuration of underground secondary substations rather than a general overhead-to-underground conversion optimization. Krstivojević and Stojković Terzić [71] combined Monte Carlo reliability assessment with investment-option selection under budget constraints, accounting for uncertainty in component reliability and consumer load. Their outcomes include SAIDI, energy not supplied and a monetary reliability-cost indicator.

System Configuration and Environmental Effects

Oli et al. [72] compared parallel feeders, underground cables and automatic reclosers in a Nepalese distribution case study. Underground cables reduced SAIFI but increased CAIDI owing to longer fault-location and repair times, while the marked SAIDI and energy-not-supplied improvements reported in the study related to parallel-feeder installation. Gouda [73] also assessed environmental effects on underground cable systems through combining theoretical modeling and experimental validation. Optimized installation methods were shown to be essential for reliability improvement in underground networks. In another work, a thermally informed reliability model was introduced for underground distribution networks by Liu and Kopsidas [74]. Their assessment integrated cable electrothermal behavior and emergency ratings, showing that steady-state and transient thermal representations can produce different reliability evaluations under emergency loading. In a recent study, Huda and Živanović [75] simulated the reliability of urban distribution systems and showed that the reliability of mixed overhead–underground feeder configurations depends on the proportion and location of the two line types as well as their failure and repair characteristics. As another advancement to assess underground cable efficiency under emergency load operations, an integration of Markov models and a dual-sequence Monte Carlo simulation framework was proposed in a study by Zhang et al. [76]. The results showed that emergency-rated operation reduced expected unserved energy in the

simulated scenarios, while incorporating cable-design and aging-risk factors reduced the resulting network-performance gains. In a complementary work to accurately support operational and resilience planning under increasingly severe weather conditions, a hybrid modeling approach that combines simulations with machine learning techniques was developed by Hughes et al. [77] to predict outage probabilities.

Synthesis and Limitations

These studies address different layers of reliability modeling rather than establishing a single hierarchy of accuracy. Exponential models provide a constant-failure-rate baseline, whereas Weibull and proportional-hazards models represent aging and explanatory factors [10,13]. Markov models represent failure and recovery transitions, while Monte Carlo simulation propagates component events to network-level reliability or availability [15,56,58]. Electro-thermal and dual-sequence models add loading, temperature and aging effects [74,76], but feeder configuration and restoration also influence performance [75]. Greater model detail therefore requires stronger failure, repair, thermal and network data, and the underlying assumptions should be checked before applying these models to undergrounding decisions.

3.2.3. Metaheuristic Optimization for Resilience Planning

Metaheuristic optimization algorithms are used to deal with complex planning problems where traditional optimization methods may be computationally complex. These algorithms are particularly suitable for applications in power distribution networks involving interactions among several components and multiple weather risk scenarios.

Marcos et al. [78] developed a single-stage, multi-criteria planning model using a tailored genetic algorithm to jointly select undergrounding sections, remote-controlled switches and distributed energy resources. Investment costs and energy not supplied under simulated extreme-weather scenarios were evaluated to identify non-dominated resilience–cost alternatives. In their case study, remote-controlled switches provided substantial reductions in energy not supplied at moderate investment costs, followed by undergrounding and distributed energy resources.

Limitations and Applicability

The genetic-algorithm model examines resilience–cost investment combinations [78], unlike the stochastic mixed-integer formulation of Taheri et al. [24], which minimizes load curtailment under undergrounding constraints. Its results depend on the assumed extreme-weather scenarios, including the assumption that underground lines are unaffected, and the single-stage formulation does not determine multi-year investment timing. Transferability therefore depends on local hazard exposure, infrastructure characteristics and restoration conditions.

3.2.4. Internet of Things (IoT) and Real-Time Monitoring

In the context of IoT in power systems, computational intelligence techniques are employed to assist in continuous condition monitoring and asset assessment. This is achieved through the integration of sensors and communication technologies, which enable real-time data collection, transmission and diagnostics across the systems' components. These methods are designed to predict and also to prevent failures, thereby optimizing network efficiency in dynamic operating conditions. Their application is particularly beneficial for underground cables whose limited accessibility makes inspection and maintenance more challenging than overhead lines, so the key benefits of real-time monitoring are rapid response and adaptive decision-making.

In a study by Wu et al. [79], with the aim of preventing external damage to urban underground cables, an IoT monitoring system was proposed using vibration sensing, edge computing and intelligent cable markers to provide early warnings of construction-related disturbances. Similarly, Peter et al. [80] proposed an IoT-enabled framework for smart fault monitoring using Microsoft Azure and a hardware prototype to support fault identification and service restoration. The study addressed operational fault management rather than underground-cable replacement optimization. In complementary research, a robotic diagnostic system was introduced by Althaf et al. [81] for the localization of faults in underground cables. The robot uses an injected low-frequency signal and detects changes in the resulting magnetic field to locate cable discontinuities. This approach can help reduce exploratory excavation, although network-wide reliability and cost benefits were not quantified. In another recent study, Ye and Gao [82] reviewed the use of distributed acoustic sensing (DAS) for continuous monitoring of underground power distribution assets. The review identified potential applications for detecting external disturbances and monitoring cable routes and accessories, while emphasizing that warning reliability depends on deployment conditions, sensing configuration and the evaluation of false and missed alarms.

Synthesis and Limitations

Monitoring methods support different operational functions rather than directly optimizing undergrounding investments. IoT sensing provides external-disturbance warnings [79], remote monitoring supports fault isolation and restoration [80] and robotic or acoustic approaches support fault localization and route monitoring [81,82]. Evidence ranges from field trials to prototypes and reviews, while performance depends on sensor placement, environment, communications and warning accuracy. Monitoring benefits should therefore be linked to measurable effects on failure prevention, fault-location time and restoration duration and compared with implementation costs.

3.3. Cross-Method Comparison

Table 1 compares the main methodological families using representative studies. The broader 79-study evidence base informs the preceding literature synthesis and the input- and output-variable classifications in Section 4.

The various methods discussed here focus on different stages of the undergrounding decision process rather than providing interchangeable outcomes. Empirical models are used to identify relevant factors, reliability and hazard simulations assess performance based on stated assumptions, optimization techniques compare feasible alternatives and financial analysis examines their economic consequences. Monitoring methods can supply operational evidence that can then be used to update model inputs. However, predictive accuracy alone does not demonstrate avoided interruption losses, while improved simulated reliability does not establish economic feasibility. For the methods to be linked together, consistent assumptions regarding hazards, failures, restoration and costs are necessary, and these assumptions should be verified against local operating conditions.

Table 1. Qualitative comparison of the reviewed methodological families for undergrounding-related decisions. The comparison reflects the review authors' synthesis of reported study conditions, limitations and findings; it is not an experimentally measured ranking.

Approach and Examples	Applicable Conditions and Required Data	Uncertainty and Computational Considerations	Contribution and Principal Limitation
Statistical and econometric [5,43,48]	Harmonized interruption histories, asset descriptions and weather-related or utility-related variables.	Observed variation and regression assumptions may be affected by inconsistent reporting and omitted variables.	Identifies the associations and baseline factors; however, the utility-level results do not prove the causal benefits of undergrounding specific feeders.
Component life and reliability [9,13,15]	Cable stress, age, temperature, load and failure/repair histories.	Life distributions or Markov states require calibration; state complexity increases with model detail.	Estimates deterioration, failure and availability; does not independently select conversion locations or budgets.
Network planning and optimization [14,24,34,41]	Topology, loads, asset costs, feasible routes or switches and decision constraints.	Depends on chosen scenarios and objective functions; mixed-integer and scenario expansion can increase solution effort.	Selects network or investment alternatives; some cited models concern operational reconfiguration rather than underground construction.
Financial and financial analysis [46,47,50]	Capital and lifecycle costs, the consequences of interruption, the valuation assumptions and discount factors.	The expected benefits are influenced by factors relating to sensitivity or by probabilistic assumptions; valuation and location data can be difficult to obtain.	Tests economic feasibility and benefit distribution; results transfer poorly without local costs and customer valuations.
Hazard and reliability simulation [56–58]	Hazard intensity, component fragility, topology, failure and restoration distributions.	Scenario design and repeated Monte Carlo trials determine computational effort and output uncertainty.	Estimates interruption or resilience distributions; a scenario simulator is not itself an investment optimizer.
Machine learning [38,52,55]	Representative labelled failure, sensor or weather records and validation data.	Predictive scores depend on sample, imbalance, drift and external validation; retraining may be needed.	Enables condition or fault prediction; however, the classification accuracy does not indicate the number of outages avoided or the return on investment.
Metaheuristic search [78]	Explicit candidate decisions, network model, costs and performance objective.	Several fitness assessments; stochastic search generally cannot establish global optimality.	Explores complex hardening portfolios; outcomes depend on assumptions and may not capture multi-year investment timing.
Sensing and digital twins [60,61,79]	Sensors, communications, cable parameters and updated operational records.	Placement, model fidelity, warning errors and data synchronization govern field performance.	Supports warnings, localization or operational models; no direct economic justification for underground conversion follows without measured effects.

4. Results

Variable categorization for reliability modeling

4.1. Input Variables Based on Distribution Line Type

Input and explanatory variables in power distribution network reliability studies are often selected based on the type of distribution line configuration, namely underground, overhead or mixed. Each of these configurations involves specific performance behaviors and reliability challenges. The input and explanatory variables identified in prior literature are summarized in Table 2 and grouped according to the associated distribution line types, namely underground or mixed, to highlight the significant factors relevant to undergrounding strategies. This overview aims to provide insight into how the variables that influence power grid reliability are tailored to specific network architectures and how they can therefore be integrated into the development of more accurate reliability evaluations for specific network characteristics.

Table 2. Input variables in power grid reliability based on distribution line characteristics.

Input Variables in Reliability Modeling	Distribution Line Type Discussed	Applications
	Underground	
Voltage/current signal strength		[59,81]
Capacitive current in the system		[28]
Load current		[74,76]
Current variations in cable phases		[52]
Number of consumers per cable		[34]
Cable length		[10,13,33,34,38,42]
Transmission line location and type		[68]
Working conditions		[8]
Ambient temperature		[9,15,26,54,55,73,74]
Wind speed		[26,30,48,67,77]
Cable age		[38]
Geographic location		[30,38,48]
Underground cable deployment context		[16],
Precipitation level and relative humidity		[9,26,30,55,79]
Vibration frequencies		[9]
Soil characteristics		[40,74,76]
Type of surrounding activity (construction, excavation)		[79]
Rainfall		[48,55]
Maintenance strategy/inspection interval		[18]
Cable wear mechanism		[52,58]
Fault location		[80]
Historical outage characteristics		[18,25,33,44,45,47,72]
Feeder failure history		[72]
Location of DERs and mobile communication units		[35,78]
Stakeholder values		[39]
Cable scouring depth		[52]

Table 2. *Cont.*

Input Variables in Reliability Modeling	Distribution Line Type Discussed	Applications
Automation level in switching and fault isolation		[62,78]
Ice acceleration/ice load level		[29]
Average power flow		[34]
Traffic exposure		[50]
Customer willingness to pay		[45]
Cable laying depth		[40,73]
Number of cable joints		[10]
Electricity consumption profile of customers		[69]
Customer type (residential, industrial, etc.)		[18,69]
Type and criticality of infrastructure		[65]
Network topology (radial, open loop, closed loop)		[18,70]
Flood level		[57]
Location of underground cables and overhead lines		[24,25,66,75,77,79]
Customer outage cost		[8,46]
Cable condition		[17,19,38]
Type of reserve power arrangement		[42]
Component fragility		[20,21,23,29]
Ground motion intensity and earthquake probability		[20,21,23]
Cost of investment per strategy		[23,46]
Resident characteristics (proximity to lines, etc.)		[32]
	Mixed (Underground and Overhead)	
Historical feeder performance		[5,14,17,41,72,75]
Use of auto-reclosures		[72]
Use of remote-controlled switchgear		[80]
Transformer capacity options		[14]
Network voltage levels		[14,60]
Number of retail customers		[43]
Percent of line miles underground		[33,43]
Type of network infrastructure (overhead vs. underground)		[7,31]
Miles of distribution lines per customer		[49]
Percent of service territory that is forested		[43]
Extreme weather events		[4,5,25,29–31,41,51,57]
Animals		[4,6]
Cable rehabilitation strategy (rejuvenation vs. replacement)		[37]
DER (Distributed Energy Resources) configuration and P2P (Peer-to-Peer) energy sharing		[31]
Trees or vegetation		[4–6,22,43]
Theft and vandalism		[4]
Other environmental factors affecting cable insulation		[47,52,77]

Table 2. *Cont.*

Input Variables in Reliability Modeling	Distribution Line Type Discussed	Applications
Storm type (hurricane, winter or summer storm)/severity		[6,7,25,29,44,47,78]
Weather damage index		[49]
Wildfire exposure level		[22,25,65,66]
Human/operator error		[4]
Equipment failures (overhead & underground cables)		[4]
Type of outage (storm-related, planned, contact with overhead/underground lines, wiring/ transformers, lightning)		[6]
Type and severity of anomalies		[17]
Damage status of lines and nodes		[35]
Cable electrical parameters/resistance		[59,60]
Implementation of smart fault monitoring system		[80]
Integration of IoT technology in power distribution		[61,63,80]
Demand or overload		[4,14,15,36,41,54]
Load demand variations		[72]
Population density category		[7,26,27,34,42,43,45,47,67,68,79]
Investment levels (capital expenditures on UG vs. OH)		[7,23,46,72]
Policy environment (state undergrounding initiatives)		[7]
Income per capita		[27,49]
Type of electrical infrastructure		[22]
Customer locations		[14]

4.2. Output Variables Based on Distribution Line Type

An essential aspect of power grid assessment is understanding the relationship between output and response variables and the existing types of distribution lines, thereby ensuring the relevance of modeling approaches. The selection and assessment of reliability outcomes are commonly based on the operational features and reliability concerns of overhead, underground and hybrid power distribution configurations. A summary of the output and response variables is presented in Table 3 and grouped according to the type of power lines discussed in the literature. This classification aims to clarify the variables commonly associated with specific grid designs and to support the development of more targeted reliability assessment frameworks.

The reliability outcomes include the interruption occurrence, duration and level of service continuity, while the resilience outcomes relate to performance and recovery in the face of disruptive events. These different outcomes are shown in Table 3. The way the lines are grouped indicates the configurations that have been considered in a study and does not mean that all the effects reported are due only to underground assets.

Table 3. Output (dependent) variables in power grid reliability based on distribution line characteristics. Variables are classified by line type; aggregate usage frequencies are reported separately in Section 4.4.

Output Variables in Reliability Modeling	Distribution Line Type Discussed	Applications
	Underground	
Underground distribution percent		[27]
Resilience improvement score		[29,51]
Voltage drop across the network		[60,70]
Number of joint failures		[54]
House price		[50]
Interruption cost		[18,69]
Total financial damage per line		[66]
Investment prioritization ranking		[66]
Lifetime total cost (technical + customer cost)		[40]
Total annualized investment cost		[78]
Cost–benefit trade-off rankings		[46,51]
Wildfire financial loss		[67]
Component failure probability		[15]
Cost-effectiveness of strategies		[23,46]
Outage frequency and duration reduction		[31,55]
Occurrence of electrical faults		[17]
Cable failure prediction		[38]
Remaining useful life (RUL)		[9]
Failure rate of underground cables		[18,58,74]
Component availability		[10,15]
Resilience outcomes under disruptive-event scenarios		[31,57]
Outage probability		[30,77]
Fault classification accuracy		[52]
Fault vulnerability score		[40,62]
Extent of wildfire damage to infrastructure		[22]
Diagnostic detection of weak points		[16,57]
Detection accuracy		[38,59,61,63,81]
Risk exposure score of grid components		[65]
Risk level/risk reduction		[29]
Risk prioritization for maintenance zones		[40]
Optimal cable replacement decisions		[34]
Average restoration time		[13,18,21,35,41,58]
Repair rate		[20,75]
Life-cycle environmental impact/greenhouse gas emissions		[37]
Visual aesthetics improvement		[45]

Table 3. *Cont.*

Output Variables in Reliability Modeling	Distribution Line Type Discussed	Applications
	Mixed (Underground and Overhead)	
Number of avoided outages		[17]
Operation and Maintenance (O&M)/Total Utility Cost		[7,14,18,36,41,43–45,47,51,69,75,78]
Number of outages		[33]
Number of customers affected		[30,33]
Customer-hours lost		[33]
Outage hours		[33]
Household energy cost/savings		[31]
Net benefit/benefit-cost ratio		[46]
Fault-location error		[59]
Fault-detection response time		[59]
Load shed/reduction in load shed		[25]
Financial loss due to outage		[29,67,68,72]
Reliability/interruption performance under extreme-weather events		[5]
Costs per mile of construction or conversion		[7]
SAIDI (System Average Interruption Duration Index)		[4–8,13,17,41,43,44,48,49,51,71,72,75,77,80]
SAIFI (System Average Interruption Frequency Index)		[4,6–8,17,35,41,43,44,47–49,51,71,72,75,77,80]
Energy Not Served (ENS)		[13,18,21,23,29,41,42,72,74–76]
CAIDI (Customer Average Interruption Duration Index)		[6,7,13,44,72,75]
Reliability performance		[4,5,9,15,19,20,24,28,37,42,51,58,73,77]
CAIFI (Customer Average Interruption Frequency Index)		[6]
MAIFI (Momentary Average Interruption Frequency Index)		[6]
ASAI (Average Service Availability Index)		[6,13]
Extent of wildfire damage to infrastructure		[22]

4.3. Classification and Prevalence of Input Variables in Underground Cable Reliability Research

In the context of undergrounding strategies, to identify the input and explanatory variables used in the modeling and assessment of power network reliability, a detailed review of the literature was performed. These variables provide a clearer understanding of system operation and the factors that influence grid reliability. For this purpose, Table 4 was created to present a categorized summary of the most frequently used input variables, which are grouped according to their conceptual relevance and frequency of occurrence in the reviewed studies. The objective of this classification is to identify the input-variable categories most frequently represented in reliability modeling and to support variable selection for future methodologies used by utilities, particularly in underground infrastructure planning. For the frequency analysis, the reported values represent recorded uses of variables across the reviewed studies rather than the number of studies, since an individual study may contribute several input and/or output variables.

Table 4. Key input variables in power grid reliability in underground power distribution: categories and usage frequency. Frequencies represent 235 recorded uses of input variables across 79 studies, as individual studies may consider several variables.

Key Input Variables in Reliability Modeling	Category	Usage Frequency
	Grid and network design	42/235
Number of retail customers/Number of consumers per cable		
Percent of line miles underground		
Cable length		
Type of network infrastructure (UG vs. OH)		
Transmission line location and type		
Feeder failure history		
	Environmental factors	67/235
Percent of service territory that is forested		
Extreme weather events/Wind speed/Ambient temperature		
Animals		
Underground cable deployment context		
Precipitation level and relative humidity		
Wildfire exposure level		
	Distribution network planning	68/235
Demand or overload/Population density		
Investment levels (expenditures on UG vs. OH)		
Underground cables/overhead lines location		
Component fragility		
Investment levels and costs		
	Electrical parameters	22/235
Feeder switching system performance Current level Voltage level		
	Reliability related	12/235
Historical outage characteristics		
Cable condition		
Cable age		
	Maintenance and repair	7/235
Repair time		
Line replacement and O&M costs		
Underground installation conditions/failure history		
Infrastructure hardening/maintenance activities		
	Fault management	10/235
Type of outage (storm-related, planned, momentary)		
Human/operator error		
Fault location		
	Communication and cybersecurity	7/235
Integration of IoT in power distribution		
Automation level in switching/fault isolation		

Among the input variables demonstrated in Figure 2, the distribution network planning category is the most frequently addressed input-variable category, accounting for 68/235 (28.9%) of the recorded uses. This is followed closely by the environmental factors category, which represents 67/235 (28.5%), and then grid and network design with 42/235 (17.9%), which reflects the emphasis of the reviewed studies on the topics of grid architecture and climate resilience. The remaining categories, namely electrical parameters 22/235 (9.4%), reliability 12/235 (5.1%) and fault management 10/235 (4.3%), account for smaller shares of recorded variable uses. In contrast, the rest of the categories, including maintenance and repair 7/235 (3.0%) and communication and cybersecurity 7/235 (3.0%), have received less attention in the reviewed models.

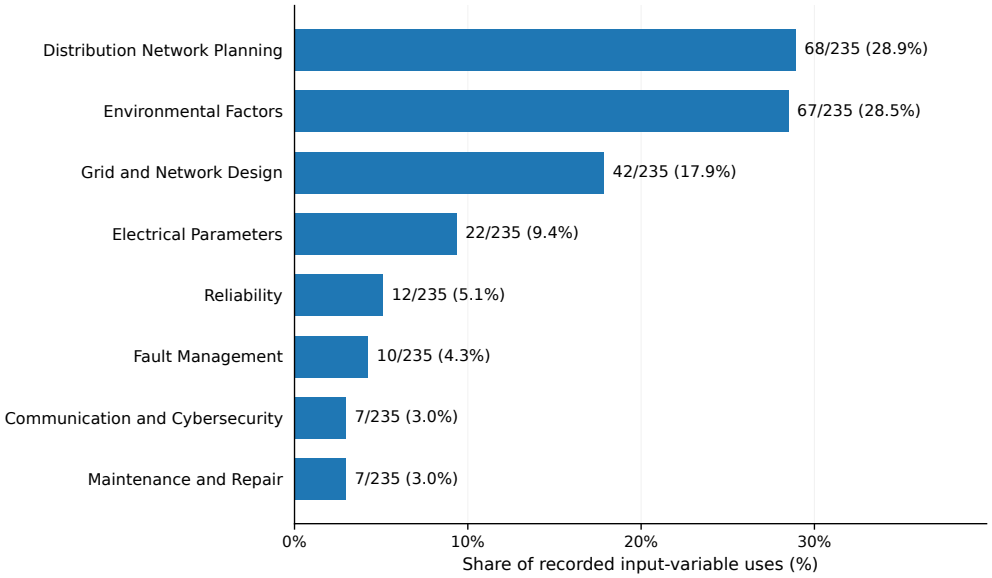


Figure 2. Distribution of recorded input-variable uses in underground power distribution studies.

The three largest categories together make up 177 of the 235 recorded input-variable occurrences (75.3%). This distribution shows the focus of the models under review rather than the relative impact of each factor on network reliability. With regard to decisions about undergrounding, the evaluation of routes, network configuration and environmental exposure should therefore be supplemented by an assessment of repair accessibility, restoration procedures and communication requirements. Such integration is important since reducing failure exposure does not always determine the length or economic effects of the outages that still occur.

4.4. Classification and Prevalence of Output Variables in Underground Cable Reliability Research

To better understand the research emphasis across reliability-focused studies, we compiled and categorized the output variables commonly assessed in the literature, with a particular focus on studies related to underground power cables. These variables represent the key performance outcomes used to evaluate grid behavior across categories such as financial metrics, reliability and asset management. The output variables are summarized by category, and the reported frequencies refer to recorded variable uses across the reviewed studies rather than the numbers of studies.

To help frame methodological choices and highlight the research emphases within the field discussed in Table 5, the distribution of the categories associated with output variables is illustrated in Figure 3, providing a quantitative overview of the most commonly addressed research themes.

Table 5. Key output variables in power grid reliability in underground power distribution: categories and usage frequency. Frequencies represent 169 recorded uses of output variables across 79 studies, as individual studies may consider several variables.

Key Output Variables in Reliability Modeling	Category	Usage Frequency
System Average Interruption Duration Index (SAIDI)	Reliability indices	95/169
System Average Interruption Frequency Index (SAIFI)		
Customer Average Interruption Duration Index (CAIDI)		
Failure rate		
Energy Not Served (ENS)		
	Financial metrics	33/169
Operation and Maintenance (O&M)/Total Utility Cost		
Interruption Cost		
Total system revenue/financial loss due to outages		
Investment prioritization ranking		
	Grid performance and stability	15/169
Number of outages/avoided outages		
Number of customers affected		
Customer-hours lost		
Resilience improvement score		
	Fault detection and asset management	15/169
Fault vulnerability score Risk level/Risk reduction Risk exposure score of grid components		
	Maintenance and network optimization	11/169
Restoration time		
Repair rate		

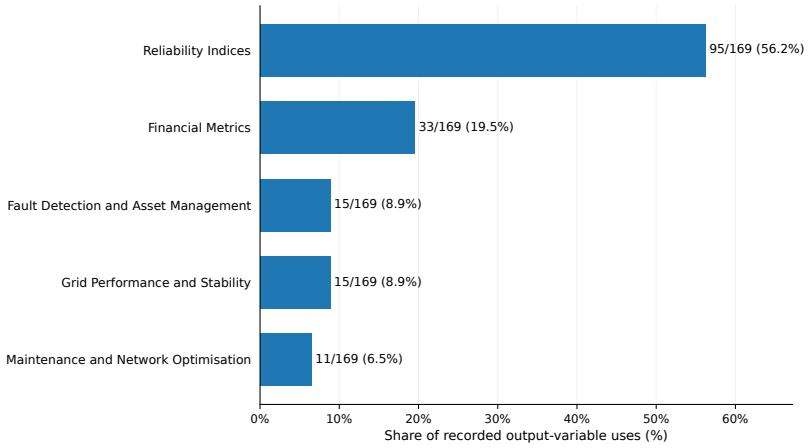


Figure 3. Distribution of recorded output-variable uses in underground power distribution studies.

A significant portion of the recorded output-variable uses, accounting for 95/169 (56.2%), relates to reliability indices, which emphasizes the central role of traditional reliability metrics such as SAIFI, SAIDI, CAIDI and failure rate and energy not served in grid performance assessment related to the context of this study. The second most common output variable category, 33/169 (19.5%), pertains to financial metrics, which reflects the attention given to the economic aspects of reliability enhancement. The other categories of "Grid Performance and Stability" 15/169 (8.9%), "Fault Detection and Asset

Management" 15/169 (8.9%) and "Maintenance & Network Optimization" 11/169 (6.5%) account for smaller portions of the recorded output-variable uses, which suggests that these outcomes are less frequently represented than reliability and financial metrics.

The fact that this distribution indicates that conventional reliability indices and financial results are more often included in the models examined does not prove that the outcomes which are reported less frequently are of lesser importance. In the context of undergrounding planning, interruption frequency and duration should be taken into account together with restoration performance, customer interruption costs and long-term expenditure. Having a wider range of outcomes would enable utilities to compare undergrounding with other measures such as network automation, maintenance and alternative restoration strategies.

4.5. Temporal Evolution of Modeling Approaches for Underground Power Cable Studies in Grid Reliability

To explore the progression of research performed in the context of grid reliability modeling and underground cable placement strategy, the literature is classified and presented in Figure 4 according to the discussed methodological approaches and chronological periods. The reviewed studies are classified into seven broad modeling categories, whose cumulative annual totals are illustrated in Figure 4.

The methodological trend analysis shown in Figure 4 illustrates how modeling approaches have changed over time. Among the seven methods, simulation and statistical analysis are the most frequently represented in the reviewed studies. Statistical analysis is present throughout the observation period, while simulation shows particularly strong growth after 2020. Furthermore, financial analysis and conventional optimization have also been represented over the observation period. In contrast, machine learning techniques have been represented since 2013 and have recently attracted more attention. Their cumulative use equalled that of conventional optimization in 2022, rather than surpassing it. IoT monitoring and metaheuristic optimization remain less frequently represented in the reviewed literature. The results for 2026 correspond to an incomplete publication year and should therefore be interpreted with caution.

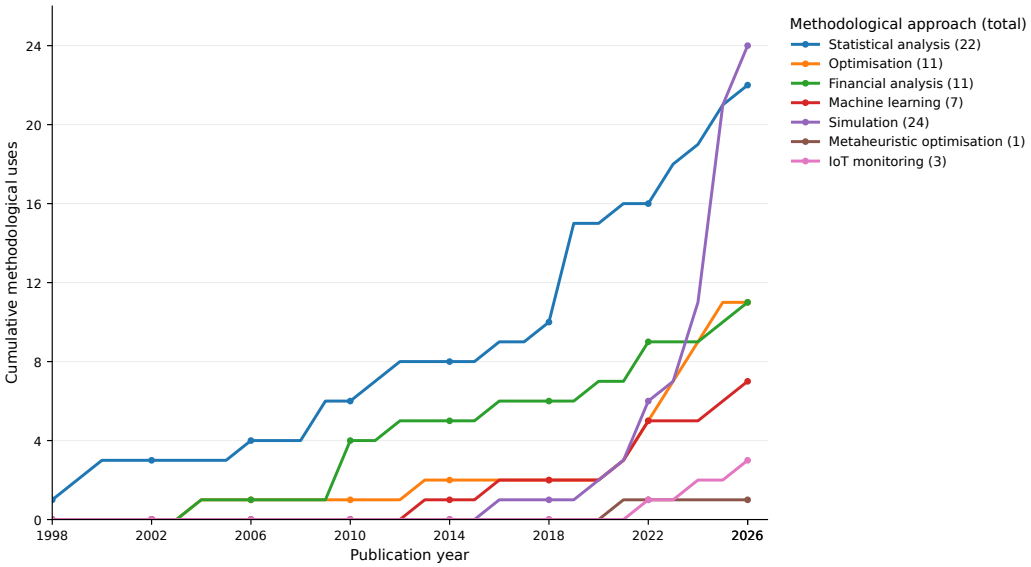


Figure 4. Cumulative number of reviewed studies by methodological approach (1998–2026). The 2026 count represents an incomplete publication year.

Publication frequencies alone do not establish stages of technological maturity. As an analogy from a methodological point of view and not as evidence concerning underground cables, the cyclical TRIZ framework for the development of electric motors separates short-term interventions from longer-term system transformation [83]. While it might provide a means of organising methodological development, it does not confirm the temporal trends seen in the present review.

5. Discussion

The literature search was conducted using Compendex and Google Scholar, but relevant studies indexed in other databases may have been omitted. Compendex was chosen because it provides coverage of engineering journals and conference proceedings, whereas Google Scholar extended the search to include related multidisciplinary research and technical material. Screening, eligibility assessment and data extraction were conducted by a single author without independent duplicate review, which may have affected the consistency of study selection and variable classification. The frequencies with which the variables were used have not been weighted according to the quality of the evidence. Since the sources included differ in respect of study design, validation and applicability, these frequencies show the areas in which research has focused rather than reflecting the strength of the evidence for particular outcomes.

In addition, because the reviewed studies used heterogeneous modeling approaches, the identified variables and methodologies were grouped into broader categories. Accordingly, the reported frequencies should be interpreted as an indication of research emphasis rather than the relative importance of individual variables. Moreover, given the multidimensional nature of grid reliability, regional conditions can be analyzed through the classification of design, environmental, operational and electrical variables, particularly in areas susceptible to ice storms or dense vegetation, such as Québec. Although many studies have illustrated reliability improvements by applying an undergrounding strategy in these environments, its practicability is still limited by economic feasibility and cost-effectiveness considerations that depend on local conditions. These findings point to the need for further research on undergrounding strategies that account for regional variations.

Underground cable placement decisions also involve several levels of planning and management. Firstly, policies and long-term resilience objectives affect infrastructure choices at the strategic level. But, at the planning level, investment priorities and selective undergrounding programs are determined by utilities, while at the operational level, the performance of the implemented strategies is affected by maintenance, fault response, and monitoring activities. Therefore, coordination between these different levels is important to balance reliability improvement, economic feasibility and local conditions. From a broader systems perspective, power distribution networks can be viewed as complex adaptive systems, in which the interactions among network components, different operating conditions, existing environmental hazards and planning decisions alter the reliability of the system. Therefore, undergrounding should not be considered as an isolated reliability strategy in this context, since undergrounding may interact with other strategies such as automation, distributed energy resources, network topology and maintenance practices. Therefore, future modeling approaches and simulations should increasingly consider these interaction effects and how they affect overall system reliability and resilience. Reliability improvement also depends on activities related to maintenance, monitoring and the use of operational data. The increasing application of condition-based maintenance, predictive diagnostics and real-time monitoring reflects a shift from reactive maintenance toward more proactive and data-driven risk management. In the future, these developments may support a greater integration of Digital Twin technologies for reliability assessment

and maintenance planning. Improving data quality and coordination between planning, operation and asset management can therefore support more effective reliability decisions. An example of a similar methodological approach from a different field is the use of an FMEA template in the area of collaborative robotics, which shows the importance of taking into account not only technical variables but also human and psychosocial factors [84]. The reference is included to illustrate the scope of risk-factor identification and should not be interpreted as empirical evidence concerning the reliability of underground cables.

5.1. Illustrative Application: Hydro-Québec Distribution Reliability Model

As an illustrative application of the variables discussed above, the following example draws on the probabilistic Monte Carlo simulator developed by Gaha et al. [56] through research at IREQ (Institut de recherche d'Hydro-Québec). The model considers network configuration, stochastic failure, repair behavior and operational restoration within a single distribution-network assessment. It is included as an illustration of the referenced study, not as an independent finding of this review.

The model covers approximately 2700 lines and 360 substations throughout Québec, supporting electricity delivery to over four million customers. Real data from Hydro-Québec's distribution network were used to characterize the parameters incorporated into the Monte Carlo simulation for assessing network reliability. It is noteworthy that the line types (i.e., underground, overhead and hybrid) are treated differently and are distinguished by the statistical distributions of their failure rates. The failure rates of underground and hybrid lines are modeled using a Weibull distribution, whereas those of overhead lines follow a log-normal distribution. Repair times are modeled using a log-normal distribution. Statistical models were developed to characterize repair duration and outage frequency as functions of network length, line type and location. Key reliability indices, including SAIFI (System Average Interruption Frequency Index) and CAIDI (Customer Average Interruption Duration Index), are then calculated by the simulator. The main input factors, intermediate simulation variables and reliability outputs considered in the Hydro-Québec model are summarized in Table 6.

The example illustrates how model inputs, restoration assumptions and simulated reliability indices are connected. It does not independently establish the economic benefits or optimal locations for underground conversion.

Table 6. Input factors and reliability outputs considered in the Hydro-Québec distribution network reliability model.

Category	Variable/Factor	Role in the Model
Network characteristics	Line type	Overhead, underground or hybrid; used in the statistical characterization of failure behavior
	Line length	Used in statistical characterization of outage frequency
	Geographical location	Used in statistical characterization of outage frequency and repair duration
	Network configuration	Includes load-block arrangement and protection components and can be modified to assess its effect on reliability.

Table 6. *Cont.*

Category	Variable/Factor	Role in the Model
Operational and stochastic factors	Restoration strategy	Determines restoration actions following an outage
	Patrol speed and crew travel time	Used to determine the time required for the restoration crew to reach and locate a fault.
	Switching time	Depends on the type of switching component and whether it is remotely controllable.
	Failure frequency	Assigned to load blocks according to statistical distributions and line characteristics.
	Repair duration	Sampled according to a log-normal distribution
Reliability outputs	SAIFI	System Average Interruption Frequency Index
	CAIDI	Customer Average Interruption Duration Index

5.2. Future Research Directions

From the analysis of the various approaches, three research priorities arise. First, the generalizability of undergrounding models should be studied across different feeders, regions and environmental conditions rather than relying only on individual case studies [56,75]. Second, future planning should integrate undergrounding with network automation, distributed energy resources and maintenance when dealing with multiple hazards and over a range of investment periods [24,25,78]. Future research should also look into whether undergrounding reduces the total risk to the system or instead shifts vulnerability across different hazards and restoration processes [25,72]. When prioritizing segments, attention should be given simultaneously to the level of local hazard exposure, the consequences of an outage, the length of time taken for restoration and the investment cost, rather than viewing the underground conversion as a single, uniform reliability-improvement strategy [24,46,78,85]. Moreover, taking into account the interdependencies with communication and other supporting infrastructure would also help to improve the representation of restoration after extreme conditions [35,78]. A contradiction-oriented design approach [86] may provide a conceptual means of examining the tensions between reliability improvement, investment costs and restoration requirements, although its application to undergrounding remains untested. Third, hazard and aging models should be updated using operational monitoring and restoration data, while predicted reliability improvements should be linked to customer interruption costs and long-term expenditure [76,79]. Reporting uncertainty, computational requirements and validation conditions would also enhance the practical transferability of these methods.

Further research could also involve extending underground-cable planning by combining digital twin technologies with GIS-based network representations, using explainable artificial intelligence to provide more transparent decision support and incorporating probabilistic reliability models that explicitly take uncertainty into account. When underground networks become more and more dependent on sensing, communication and automated control systems, climate-adaptation planning and cyber-physical resilience should also be taken into consideration. At the same time, AI-assisted asset management could help integrate data from condition monitoring, failures, maintenance and environmental sources in order to improve the prioritization of interventions and long-term investment planning.

6. Conclusions

This study presents a systematic review of reliability-oriented power distribution network planning, focusing on undergrounding strategies, the principal modeling approaches used in the literature and the input and output variables considered for improving reliability and resilience. It extracts the key variables in previous studies, summarizes their frequency of use and provides a comprehensive assessment of the methodologies employed across previous studies. Through a structured analysis of covariates and modeling approaches used for evaluating grid performance and informing planning decisions, a wide range of techniques were identified, from econometric models and simulation tools to advanced machine learning algorithms. In addition, a content analysis of the reviewed literature enabled a comprehensive categorization of covariates. Based on the 79 examined studies, the input and output variables considered in the literature were extracted to develop a clearer understanding of the factors most frequently considered in power distribution reliability research.

The comparison of the reviewed approaches also shows that no single methodology is able to take account of changing hazards, the aging of assets, restoration processes, the timing of investments and the economic implications. Future undergrounding frameworks must therefore enhance the transferability of their models between feeders and regions, coordinate reliability and resilience objectives with economic limitations and more clearly report the uncertainty involved and the conditions under which the models have been validated. Such developments would aid in turning the identified factors and modeling methods into more adaptable undergrounding decisions. From a practical planning perspective, the choice of modeling approach should depend on the decision objective. Statistical and reliability models are suitable for identifying influential failure and performance factors, while simulation approaches are particularly useful for evaluating reliability and resilience under uncertain operating and hazard conditions. Optimization methods are more appropriate when selecting or prioritising feasible interventions, whereas financial and econometric approaches are needed when underground-cable investments must be assessed against costs and expected benefits. For maintenance-oriented decisions, condition-monitoring, predictive and data-driven approaches can support asset prioritization and intervention planning.

From a sustainability perspective, the findings of this review point towards a more balanced approach to underground-cable planning by bringing together the technical objectives of reliability and resilience with economic, environmental and long-term asset-management considerations. Improved reliability can support more continuous electricity service and hence reduce interruption-related impacts on customers and communities, while the assessment of life-cycle costs, maintenance requirements and environmental conditions can support more efficient use of infrastructure resources. The review has identified the key factors and modeling approaches that are most relevant to undergrounding decisions and thus provides a basis for the development of planning strategies which consider not just the performance of the system but also long-term economic feasibility, climate adaptation and sustainable infrastructure management.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su182110765/s1, Table S1: Summary of the characteristics of the 79 studies included in the systematic review, including publication year, study focus and modeling approach, line/network context, main input factors and output measures; Supplementary Material S2: Completed PRISMA 2020 checklist.

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