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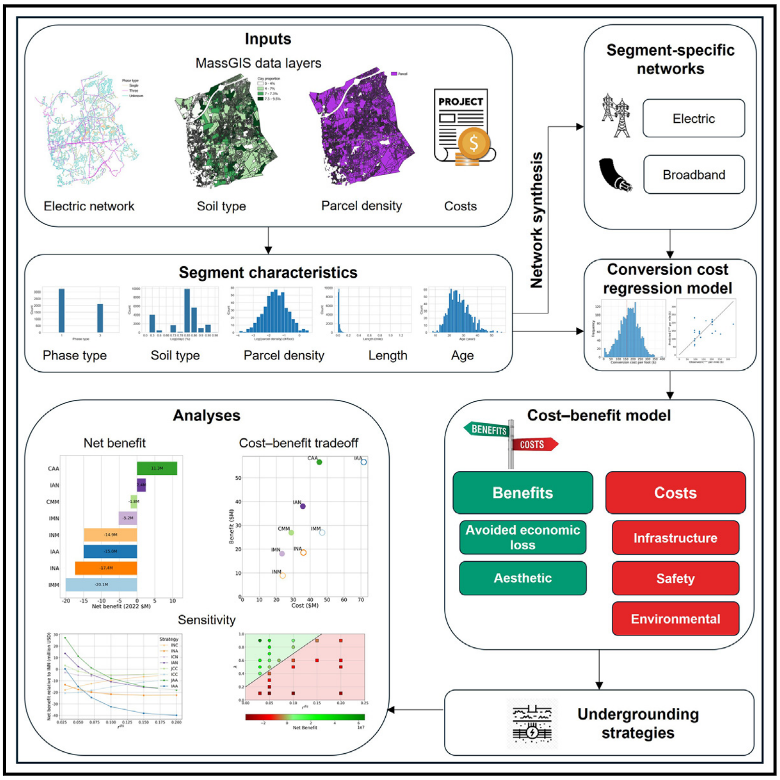
Benefits of aggressively co-undergrounding electric and broadband lines outweigh costs

Graphical abstract



Highlights

- Co-undergrounding electric and broadband lines cuts outages and enhances cost efficiency
- Aggressive co-undergrounding yields the highest net benefit
- Segment-specific cost modeling includes local factors for precise estimates
- The undergrounding cost-benefit framework aids utility planners in diverse regions

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In brief

This paper introduces a novel cost-benefit framework for evaluating undergrounding strategies for electric and broadband networks. Using a case study of Shrewsbury, Massachusetts, in the US, the study reveals that aggressive co-undergrounding strategies yield the highest benefits when undergrounding is warranted. The data-driven segment-specific cost-modeling approach provides precise and actionable insights, empowering utility planners and policy-makers to make informed decisions in less densely populated areas.

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Arabi et al., 2025, Cell Reports Sustainability *2*, 100334
March 28, 2025
https://doi.org/10.1016/j.crsus.2025.100334

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Benefits of aggressively co-undergrounding electric and broadband lines outweigh costs

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https://doi.org/10.1016/j.crsus.2025.100334

SCIENCE FOR SOCIETY The growing need for resilient and reliable infrastructure has made undergrounding electric and broadband lines a robust and effective strategy, especially in the context of climate change and extreme weather events. This study provides a comprehensive, data-driven framework to assess the feasibility and benefits of undergrounding strategies, focusing on co-undergrounding to enhance cost efficiency and resilience. By incorporating local factors such as geotechnical and infrastructural variables, this approach enables robust cost-benefit analysis for utility planners and policy-makers, promoting smarter investments in infrastructure to improve community resilience and connectivity.

SUMMARY

Electric power and broadband have become essential services for modern economies, but utilities face substantial challenges in providing disruption-free access. Recent legislation, including the US Infrastructure Investment and Jobs Act of 2021, has allocated enormous resources toward improving infrastructure systems. Historically, undergrounding has enhanced system reliability but has been cost effective only in densely populated areas. We investigate the conditions under which undergrounding becomes cost effective, particularly when co-deployed with fiber optic lines. We introduce a novel data-driven cost-benefit model and conduct a detailed localized case study in Shrewsbury, Massachusetts. The results indicate that when undergrounding is viable, aggressively co-undergrounding yields the highest net benefit. This finding is robust across various assumptions. Importantly, our model highlights the importance of assumptions regarding undergrounding's effectiveness in reducing outages. Our model is readily deployable to other study areas, providing effective decision-making capabilities even with limited data.

INTRODUCTION

Most power distribution networks in the US rely on legacy infrastructure, with wires strung from utility poles. As of 2012, about 75% of new distribution and transmission lines built in the US were overhead.[1] While these systems generally maintain a high level of reliability, they remain susceptible to weather-related disruptions due to their exposure to external conditions.[2–5] The telecommunications industry has similarly focused on developing wireless technologies and new business models, which have in some cases delayed the deployment of essential fiber optic infrastructure. This has left some regions, particularly those with older overhead broadband infrastructure, more vulnerable to service disruptions and less capable of meeting modern high-speed internet demands.[6]

Given these vulnerabilities, the importance of reliable power and broadband services is becoming more apparent in the context of increasing climate impacts and the need for effective mitigation strategies. Extreme weather events, such as Hurricane Beryl[7] and Hurricane Maria,[8] have highlighted vulnerabilities in the power grid, leading to notable outages in recent years.[9–11] A key strategy for climate change mitigation is electrification,[12,13] which has further highlighted the need for reliable electricity, especially in cold climates where a power outage could be extremely dangerous.[14,15] Broadband is increasingly important with the growth of the internet,[16] and its role in the

Table 1. Policy dimensions and resulting strategies

Strategy–	Co-undergrounding policy–	Aggressiveness policy	
		Electric	Broadband
INN	independent (*I*)	no conversion (*N*)	no conversion (*N*)
INM	–	–	moderate (*M*)
INA	–	–	aggressive (*A*)
IMN	–	moderate (*M*)	no conversion (*N*)
IMM	–	–	moderate (*M*)
IAN	–	aggressive (*A*)	no conversion (*N*)
IAA	–	–	aggressive (*A*)
CMM	co-undergrounded (*C*)	moderate (*M*)	moderate (*M*)
CAA	–	aggressive (*A*)	aggressive (*A*)

power system is expected to expand, particularly as more intermittent renewable energy sources are integrated into the grid. Technologies such as virtual power plants, demand-side management, and smart appliances and buildings are likely to play a key role in managing a net-zero grid, all of which depend on reliable broadband access.[17] As such, efforts to improve the reliability of both power and broadband services are becoming more critical.

The potential benefits of undergrounding in minimizing disruptions caused by weather events are evident.[3,18–20] Yet, there are significant challenges, including high installation costs, complex maintenance requirements,[1] and negative environmental and safety impacts.[21] For instance, high-density cities have been

Table 2. Key parameters

Parameter	Description	Value
λ	effectiveness of undergrounding	0.60[a]
r^{acc}	avoided co-undergrounding conversion cost rate: the additional cost of installing broadband facilities when co-undergrounded with electric	0.15[41]
r^{dis}	discount rate	0.05[42]
$SAI_{B,0}$	average outage duration per customer per year, assumed to be the same for broadband and electricity, in hours	1.38[43]
$VLL_{E,R}$	value of lost electric load for residential customers ($/h)	10.00[b]
$VLL_{B,R}$	value of lost broadband load for residential customers ($/h)	15.00[c]
r^{plf}	property loss factor due to overhead lines	0.05[3]

[a]Evidence for this value varies significantly, with studies indicating a range from as low as 0.05[39] to as high as 0.9.[38]

[b]The cost of an hour-long power interruption per person in Massachusetts is estimated at $4.38.[44] Factoring in additional costs due to outages, such as spoiled food, damaged home appliances, missed remote work hours, and increased use of backup power sources, we assume this value could reach up to $10.00.

[c]The value of lost broadband load for residential customers ($15.00) is assumed higher than electric load ($10.00) due to the increasing reliance on internet services for remote work, education, and communication, leading to greater economic and social impacts from outages.

undergrounding electric and telecommunication infrastructure since the late 18th century.[22] As an example, densely populated areas of New York City have benefited from underground distribution networks since the blizzard of 1888, with 86% of its electric lines now undergrounded to reduce service disruptions.[23] In contrast, less-dense cities, such as Riverside, California, face greater per capita costs of undergrounding, resulting in a patchwork grid of largely overhead wires.[24] Thus, the economic feasibility of such projects remains a topic of ongoing analysis.[2,3]

Recent technical improvements in physical and digital infrastructure, including alternative approaches such as pipe-lining technologies, design standardization, auger boring, fast micro-tunneling, and plowing-in cables, have significantly reduced the cost of underground installation by as much as one-third.[25] Co-undergrounding electric and broadband lines in the same trench can also significantly reduce costs,[26] while providing the benefits of resilient and reliable networks.[27,28] This co-undergrounding approach is essential not only for cost efficiency but also for resilience, as it simultaneously protects these interdependent services and ensures operational continuity during disruptions.

Multi-purpose utility tunnels (MUTs) have been extensively studied as a solution for consolidating utility lines in dense urban areas, where shared tunnels reduce long-term costs and minimize maintenance disruptions.[29–31] These studies emphasize the role of public-private partnerships in cost-sharing,[32] life-cycle-cost analyses that identify economic tipping points for MUT adoption based on utility density and excavation frequency[33] and models for cost-sharing fairness to ensure balanced benefits for participating utility companies.[34] Advanced construction techniques, such as trenchless and micro-tunneling methods, have also been explored for their potential to optimize project efficiency and reduce social disruptions, such as traffic delays and noise.[35–37] However, MUT studies primarily focus on urban environments and do not consider the unique challenges of less-dense areas, where higher per capita costs and dispersed infrastructure make such approaches less feasible. Moreover, these studies do not comprehensively address aspects such as environmental safety, aesthetics, and broader societal impacts, which are essential for evaluating the full implications of co-undergrounding.

Despite advances in undergrounding studies and related construction techniques, there remains a gap in comprehensive analyses of long-term cost-benefit trade-offs across various undergrounding strategies, especially in less-dense areas. A key gap in existing knowledge lies in understanding the specific conditions under which undergrounding becomes cost effective and how these conditions might vary when considering the co-deployment of fiber optic lines for broadband. For instance, while some studies indicate that outages in underground systems are substantially less frequent and shorter in duration compared with overhead systems,[1,3] others show smaller gains.[38,39] This disagreement highlights the need for analysis that transparently incorporates assumptions on how undergrounding impacts the likelihood of outages. Additionally, despite advances in trenchless technology, improved materials, and innovative installation techniques[40] and substantial cost reductions from co-undergrounding fiber optic and electricity

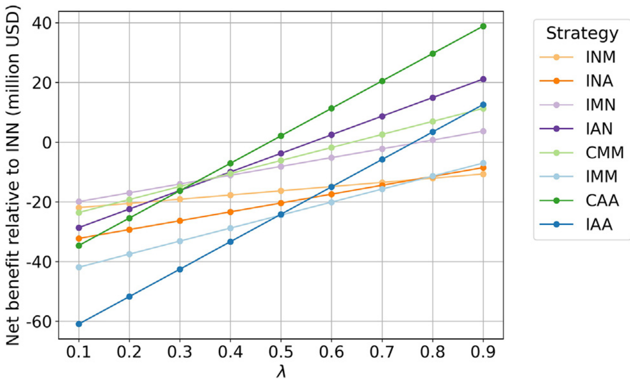

Figure 1. The net benefit of undergrounding strategies as a function of the effectiveness of undergrounding (λ)

lines, no research has yet quantified the costs and benefits of a range of undergrounding strategies. Existing research often overlooks the integration of broadband infrastructure,[1,3] which is crucial not only for supporting a range of smart technologies essential for a low-carbon energy system but also for enhancing cost effectiveness. Moreover, comprehensive data-driven segment-specific cost models that incorporate local variability in environmental and demographic factors are lacking, which is critical because these factors can significantly impact the overall cost and feasibility of undergrounding projects.

To address these critical gaps, we develop a novel data-driven cost-benefit approach for evaluating a range of undergrounding strategies for electric and broadband networks, making several key contributions to advancing the financial feasibility and technical understanding of undergrounding utility lines. First, we develop a segment-specific cost model that incorporates local factors such as soil type and density, offering more precise estimates compared with regional averages. This model is validated through a detailed case study in Shrewsbury, Massachusetts and can be readily applied to other small cities to inform decision-making for similar municipalities. Second, our framework implements multiple policy dimensions, including both independent and co-undergrounding, across nine strategies, providing comprehensive insights for utility planners. We provide a clear understanding of cost effectiveness when considering the co-deployment of electricity and broadband lines, highlighting potential synergies and cost savings. Third, we examine the conditions under which undergrounding is justifiable in rural and semi-rural areas, thus addressing a major gap in the literature on less-dense regions. For example, this analysis parameterizes the effectiveness of undergrounding in terms of how it impacts the frequency and duration of outages. By addressing these gaps, our approach advances the technical and financial understanding of undergrounding, offering actionable insights for utility planners and policy-makers in diverse regions.

Table 3. Model indices and mappings

Symbol	Description	Value
$i \in [1, N^{seg}]$	line segments	–
$k \in \{R, C, I\}$	customer class/sector	{R: residential, C: commercial, I: industrial}
$s_{i,y} \in \{O, U\}$	underground status of line segment i in year y	{O: overhead, U: underground}
$y \in [1, Y]$	year in analysis period	–
$\tau \in \{E, B\}$	line segment type	{E: electric, B: broadband}
$v_{i,y} \in \{0, 1\}$	conversion status of line segment i in year y	{0: not converted; 1: converted}

Objectives and framework

Our comprehensive data-driven framework evaluates the costs and benefits of various undergrounding strategies, integrating geospatial, cost, environmental, and demographic data on utility lines. We evaluated a set of nine undergrounding strategies (Table 1) over a 40-year horizon. Each strategy is defined by the co-undergrounding policy, aggressiveness policy, and the type of line segment (electric, broadband, or both). The co-undergrounding policy levels are *independent* (I), with electric and broadband lines undergrounded in separate trenches, or *co-undergrounded* (C), in which both lines are undergrounded simultaneously in the same trench. The aggressiveness policy has three levels. Under "no conversion" (N), each segment is replaced with one of the same type, overhead or underground. At "moderate" level (M), each overhead segment is replaced with an underground one at the end of its lifespan, while at the "aggressive" level (A), this is done at half lifespan. All the costs are reported relative to the no conversion status quo (*INN*), which includes the cost of replacing the line segments with the same type. Baseline results are based on the estimated values of parameters in Table 2, all of which are examined through sensitivity analysis in Figure 11.

RESULTS

Aggressive co-undergrounding is the most beneficial strategy when undergrounding is justified

Undergrounding is justified when it provides a positive net benefit. The viability of undergrounding depends crucially on the assumption about its effectiveness for reducing outages. We parameterize this using λ, which represents the effectiveness of undergrounding (proportion of outages that are responsive to undergrounding). Our baseline value, $\lambda = 0.6$, implies that full undergrounding would avoid 60% of the status quo outages. We found that the evidence for this value is sparse and widely divergent, with papers indicating that this value may be as low as 0.05[39] or as high as 0.9.[38] Figure 1 shows that when $\lambda < 0.5$, undergrounding is not justified. However, whenever undergrounding is justified, i.e., when $\lambda \geq 0.5$, the optimal strategy is always to aggressively co-underground electricity and broadband networks.

Under our baseline assumptions, only *CAA* and *IAN* result in a positive net benefit, as shown in Figure 2. The detailed breakdown of undergrounding costs, avoided economic losses, and the aesthetic benefits demonstrate that although aggressive strategies have higher initial costs compared with moderate strategies, the higher avoided economic losses from reducing

Table 4. Description of model variables

Symbol	Description
$a_{i,y}$	age of line segment *i* in year *y*
$A_{U,y}$	the area of the locations impacted by undergrounding in year *y*
C^{con}	cost of converting from $s = O$ to $s = U$
C^{cap}	capital expenditure
C^{env}	environmental cost
C^{ftl}	fatal incident cost
C^{lci}	life-cycle infrastructure cost
C^{nft}	non-fatal incident cost
C^{ope}	operating expenditure
C^{saf}	safety cost
ℓ_i	length of line segment *i*
L^{eco}	economic loss

outages in the earlier years result in higher net benefits. We observed that these avoided economic losses are greater for electricity lines because more people depend on electricity for work and daily life compared with broadband and broadband itself depends on electricity.

The trade-off between costs borne by local municipalities or utilities and the widely diffused benefit to consumers is a crucial factor in evaluating undergrounding strategies. As shown in Figure 3, four strategies are Pareto-dominated, meaning that another strategy exists that is both lower cost and higher benefit. The dominated strategies include independent undergrounding of both networks (*IMM* and *IAA*) and broadband-only undergrounding (*INM* and *INA*). We further note that the co-undergrounding strategies (*CMM* and *CAA*) are 39% more cost effective than the independent counterparts (*IMM* and *IAA*).

Aggressive co-undergrounding is robust

To evaluate the robustness of the proposed framework, we conducted a sensitivity analysis of the net benefit with respect to several key parameters (Figure 11). We found that aggressively co-undergrounding (CAA) is remarkably robust—that is, whenever undergrounding is justified, the best strategy is to aggressively co-underground. The value of lost load for electricity and for broadband and the impact of overhead lines on property value have almost no impact on the net benefit relative to *INN*.

Table 5. Data sources

Data source	Application
Bronze book[45]	localized model parameters
MassGIS data layers	segment-specific conversion cost model
Open Street Map (OSM)	segment-specific conversion cost model
Shrewsbury electrical network	network modeling
Town of Shrewsbury[46]	localized model parameters
Zillow transaction and assessment database (ZTRAX)[1]	localized model parameters

The average outage duration per customer per year $(SAI_{B,0})$, avoided co-underground conversion cost rate (r^{acc}), and analysis years (Y) have some impact on the magnitude of the benefits but do not change the optimal strategy. The only parameter besides λ with an impact is the discount rate (r^{dis}) (Figure 4). The discount rate is important because both the costs and the benefits are largely in the future. We found that an increase in the discount rate r^{dis} reduces the net benefit for most strategies, as the future avoided economic losses tend to dominate future costs. Interestingly, two strategies, *IMM* and *INM*, actually increase in value because the immediate cost savings and efficiency gains in the early years outweigh the discounted future costs, making these strategies more attractive under higher discount rates. Under our baseline assumptions, undergrounding is only justified if the discount rate is below 7%. For the conversion cost rate, we employed a segment-level regression model based on undergrounding projects carried out in a similar town from 2007 to 2011, without accounting for inflation (r^{inf}). Sensitivity analysis of the inflation rate for the conversion cost (r^{inf}) showed that any rate exceeding 2% makes all undergrounding strategies unjustifiable.

As λ increases, the net benefit is positive across a wider range of discount rates. Figure 4 illustrates the relationship between the discount rate, the effectiveness of undergrounding (λ), and the net benefit from aggressive co-undergrounding. The solid line represents an estimate of the boundary between a positive and negative net benefit (generated by a support vector machine [SVM] with a linear kernel). Our analysis shows that for $\lambda < 0.2$, undergrounding may not be justifiable due to a negative net benefit, particularly in regions with minimal weather-related outage risks (although more moderate undergrounding strategies may have a positive net benefit). This is also relevant for areas where factors such as terrain or soil conditions increase repair time, potentially leading to extended outage durations. In such cases, the costs of undergrounding outweigh the benefits. Similarly, at discount rates greater than 15%, it is unlikely that any undergrounding strategy will pay off. At a social discount rate of 3%, an effectiveness of just 40% would mean that aggressive co-undergrounding is justified. The sensitivity of the net benefit to selected parameters is shown in detail in Figure 11.

Data-driven approach provides more informative cost estimates compared with the averaging method

In this section, we highlight the importance of our segment-by-segment cost estimation. The histogram in Figure 5 shows the conversion costs for all line segments in the case-study area, using our data-driven model. Our cost estimation approach was developed in two stages. First, we leveraged detailed data derived from several undergrounding projects in Concord, MA, to estimate how segment-specific conversion costs are impacted by parcel density, phase type, and clay content (see methods for details). We then applied the model to estimate costs in our target area, Shrewsbury, MA, based on the characteristics of each segment.

Our model demonstrates that using the average cost from a similar project (in Concord) would have underestimated actual costs by about 11%. Due to the specific characteristics of the segments in Shrewsbury, our model yields an average

Table 6. Global parameters

Symbol	Description	Value
A_T	the total area of the municipality (sq. mi.)	21.7
C^{eas}	conservation easement cost ($/acre)[47]	2,692
C^{inj}	annual injury cost caused by accidents ($)	39,000
λ	undergrounding-dependent outage proportion	0.6
N^{seg}	number of line segments	2,299
N^{uti}	number of employees in utility sector[41]	40
r^{act}	additional co-underground trench cost rate	0.022
r^{acc}	avoided co-underground conversion cost rate[41]	0.85
r^{agc}	annual growth rate of costs	0.02
r^{dis}	discount rate[42]	0.05
r^{ftl}	fatality incidence/per year/worker	0.2
r^{inf}	inflation rate on initial-year conversion costs	0.0
r^{nft}	non-fatality incidence/year/worker	0.0001
$SAI_{\tau,O}$	average outage duration/customer/ year (h)[43]	1.38
r^{oam}	annual operation and maintenance cost as a proportion of replacement cost	0.2
r^{plf}	property loss factor due to overhead lines[3]	0.05
TPV	total property value ($B)[46]	6.87
VSL	value of statistical life ($M)	7.6
w	corridor width of the underground line (feet)[3,45]	15
Y	analysis duration (years)	40

conversion cost of $174 per foot ($918,720 per mile) compared with that in Concord at $157 per foot (indicated by the red dashed line in Figure 5). Moreover, we note that costs for certain segments may reach up to $400 per foot ($2.1 million per mile) depending on technical and geographic specifics. This is notable as it means that aggressive co-undergrounding is robust even under these higher cost estimates.

Our approach mitigates the limitations of simple averaged-cost models, which often overlook local variabilities that can greatly impact undergrounding costs. With a high coefficient of determination ($R^2 = 0.88$), our model provides a reliable estimation of conversion costs across diverse segments. The estimated model coefficients indicate that (1) costs increase in less densely populated areas, (2) single-phase systems are less costly to convert than three-phase systems, and (3) higher clay content increases trenching difficulty, leading to higher costs. These variables are thus crucial in accurately capturing local conditions and refining cost estimates.

Table 7. Parameters specific to overhead (O) and underground (U) status

Symbol–	Description–	Electric		Broadband	
		Over (O)	Under (U)	Over (O)	Under (U)
$C^{rep}_{i,\tau}$	replacement cost of line segment ($/mile)	51,000	154,000	27,720	83,160
$L_{i,s,y}$	lifespan of line segment (years)	40	50	40	50

DISCUSSION

We developed a comprehensive simulation-based cost-benefit analysis framework for undergrounding electric and broadband infrastructure. An important innovation is the use of a segment-specific conversion cost model for transitioning from overhead to underground lines. We provide a holistic evaluation of undergrounding strategies, including co-undergrounding strategies and different levels of aggressiveness. We localized the simulation parameters using data specific to Shrewsbury, MA, to evaluate the effectiveness of undergrounding in this rural area. Increased electrification, the movement toward smart appliances and virtual power plants, and an increased likelihood of extreme weather events mean that there will be a higher value in the future of protecting both power and broadband from outages. While some densely populated urban areas have adopted undergrounding, less-dense municipalities have been slower to adopt this strategy due to the higher per capita costs and logistic challenges. This work shows that, to the extent that undergrounding helps reduce outages, it may be optimal for communities to adopt aggressive co-undergrounding strategies. We found this to be robust to a wide range of assumptions around the costs and benefits of undergrounding. A major challenge, however, is that the costs of these strategies are borne by the local municipality, whereas the benefits are diffuse and somewhat hard to pin down. This means that the optimal solution may not be adopted without clear policy support.

The most important unknown is how effective undergrounding is in reducing outages. This work shows that this is the key driver, with aggressive co-undergrounding being optimal when effectiveness is high and no undergrounding being optimal when it is low. Undergrounding can reduce outages due to several factors, including reduced exposure to weather-related damage, decreased risk of falling trees or branches on lines, and lower vulnerability to vehicle collisions. Moreover, undergrounding in high-risk areas, such as California, can significantly mitigate fire risk and the associated power outages that often occur due to the need for planned power shutoffs to prevent wildfires. However, undergrounding has no impact on outages caused by issues such as equipment failures, problems with upstream transmission lines, or maintenance-related shutdowns. Additionally, in some cases, undergrounding can extend the length of outages due to the longer time required to locate and repair faults in underground systems. Surprisingly, there is no comprehensive and authoritative information on this.

Utility reports from the US states of California, Virginia, and Massachusetts imply that undergrounding critical infrastructure can significantly enhance long-term reliability by reducing outages from extreme weather events.[2,48,49] While these reports emphasize substantial trade-offs between the goal of improved reliability and the high upfront costs involved, they fail to quantify such trade-offs substantively. For instance, the California

Table 8. Sector-specific parameters: residential (*R*), commercial (*C*), and industrial (*I*)

		Electric			Broadband		
Symbol–	Description–	Res. (*R*)	Com. (*C*)	Ind. (*I*)	Res. (*R*)	Com. (*C*)	Ind. (*I*)
$N^{out}_{\tau,k}$	number of affected people/businesses	14,424	838	269	6,449	838	189
$VLL_{\tau,k}$	value of lost load ($/h)	10	205.7	15,048	15	205.7	9,600

Public Utilities Commission (CPUC) evaluated undergrounding alongside other solutions—such as covered conductors and fire-resistant poles.[48] Using a simplistic assumption of 100% effectiveness for undergrounding and lower numbers for alternative strategies, CPUC reported effectiveness-to-cost ratios as high as 1.4 for these alternatives, compared with 0.33 for undergrounding.[48] Yet, the report neither considered co-undergrounding nor evaluated whether the solutions provided an overall positive net benefit. Our framework, however, provides a practical tool for quantifying these trade-offs by providing a localized, data-driven approach crucially parameterized for the effectiveness of undergrounding. This approach enables utility planners and policy-makers to assess the economic feasibility of undergrounding based on local conditions. It also facilitates informed decision-making by balancing the costs borne by local municipalities with the diffuse benefits of improved reliability.

Future work should prioritize understanding the value and limitations of undergrounding in reducing outages across different scenarios and geographic locations. Other important research directions include optimizing undergrounding plans using the cost model by prioritizing segments with lower conversion costs, expanding scenario analysis through Monte Carlo simulations, exploring outage mitigation alternatives and alternative underground routing options such as beneath sidewalks or bicycle paths, and investigating innovative installation techniques such as micro-trenching, among others.

METHODS

We adopt a cost-benefit framework that distinguishes internal and external factors to evaluate undergrounding strategies. Internal costs include capital expenditures, life-cycle costs, and operational expenses borne by utilities or municipalities. External costs

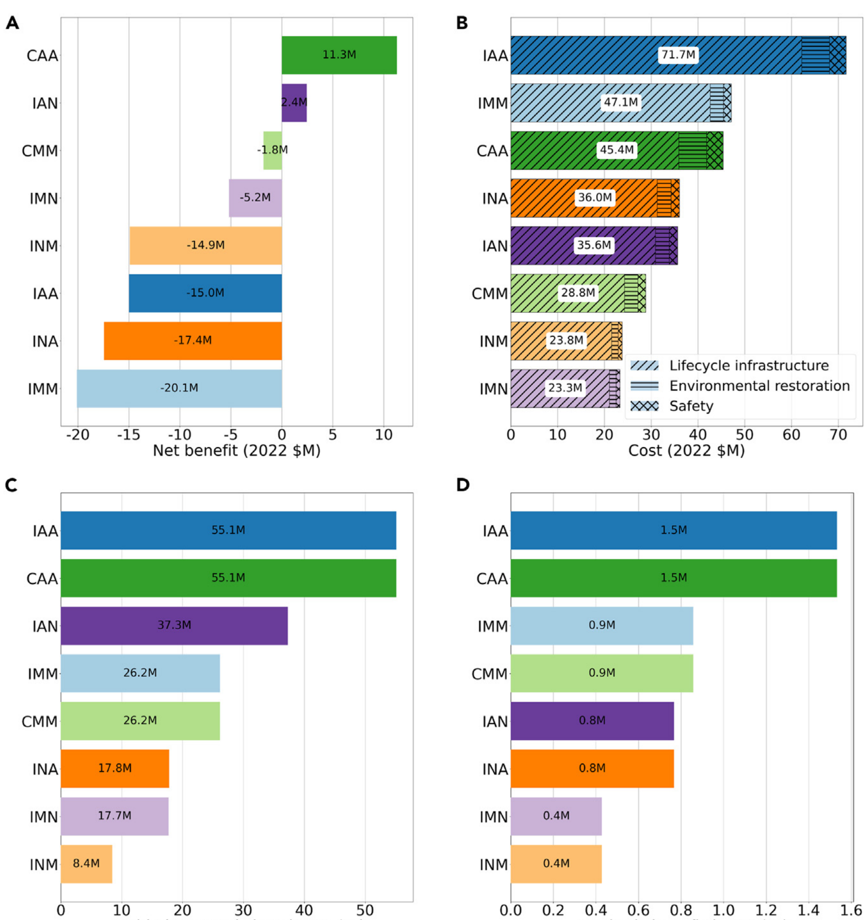

Figure 2. Net benefits, costs, avoided economic losses, and aesthetic benefits for simulated strategies

(A) Net benefits, (B) costs, (C) avoided economic losses, and (D) aesthetic benefits for simulated strategies.

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Figure 3. Benefits versus costs

Dominated strategies are shown using empty circles.

capture broader societal and environmental impacts, such as safety risks and ecological disturbances. Internal benefits focus on avoided economic losses from reduced outages, while external benefits highlight societal advantages such as increased property values and enhanced resilience to extreme weather events. Building on prior work,[3] we develop a mathematical model to quantify the costs and benefits of converting electricity and broadband lines. Model elements are discussed in detail in the following subsections. We derived parameters from empirical data specific to the study area (Shrewsbury, MA), and informed them with prior literature. We note that our socio-environmental costs are lower than in some other studies.[50,51] These studies focused on high-density municipalities in which the socio-environmental costs are large compared with the less-dense areas we investigate. We conducted sensitivity analyses to account for variations in key parameters, ensuring robust and adaptable findings. This framework allows us to evaluate undergrounding strategies holistically, balancing localized specifics with broader insights for similar municipalities. The model indices and variables are listed in Tables 3 and 4, respectively. The framework does not account for any network expansion. Therefore, the total length of the line segments remains unchanged throughout the analysis period (Y).

Costs

The cost model comprises three elements: life-cycle infrastructure, environmental, and safety costs.

Life-cycle infrastructure cost

Life-cycle infrastructure costs include capital expenses (both replacement and conversion) and operational expenditures. The capital expenditure, incurred when replacing or converting a given line segment of type in year is as follows:

$$C^{cap}_{i,\tau,y} = \ell_i \cdot [r^{agc}]^{y-1} \cdot \begin{cases} C^{con}_{i,\tau,y}, & \text{if } a_{i,y} \geq L_{i,s,y}, v_{i,y} = 1 \\ C^{rep}_{s_{i,y}}, & \text{if } a_{i,y} \geq L_{i,s,y}, v_{i,y} = 0 \\ 0, & \text{if } a_{i,y} < L_{i,s,y} \end{cases}, \quad \text{(Equation 1)}$$

where ℓ_i and $a_{i,y}$ are the length and age of the line segment i in year y, respectively. $v_{i,y}$ indicates the conversion status of line segment i in year y, which is defined based on the simulated undergrounding strategy, $L_{i,s,y}$ is the lifespan which is defined based on the underground status s of line segment i, and r^{agc} is the growth rate of the cost. For electric and broadband line segments, the conversion cost $C^{con}_{i,\tau,y}$ is calculated using a segment-specific regression model that considers soil type, parcel density, and phase type. The conversion cost is considered on a per-mile basis. The variable $C^{rep}_{s_{i,y}}$ represents the per-mile replacement cost.

At the system level, the capital expenditure $(C^{cap}_{\tau,y})$ for all line segments of type τ in year y is then computed as the sum:

$$C^{cap}_{\tau,y} = \sum_{i=1}^{N^{seg}} C^{cap}_{i,\tau,y}. \quad \text{(Equation 2)}$$

The operating expenditure $(C^{ope}_{i,\tau,y})$ incurred for operating a given line segment i of type τ during its lifespan in year y is given by

$$C^{ope}_{i,\tau,y} = \ell_i \cdot r^{oam} \cdot C^{rep}_{s_{i,y}} \cdot [r^{agc}]^{y-1}, \quad \text{(Equation 3)}$$

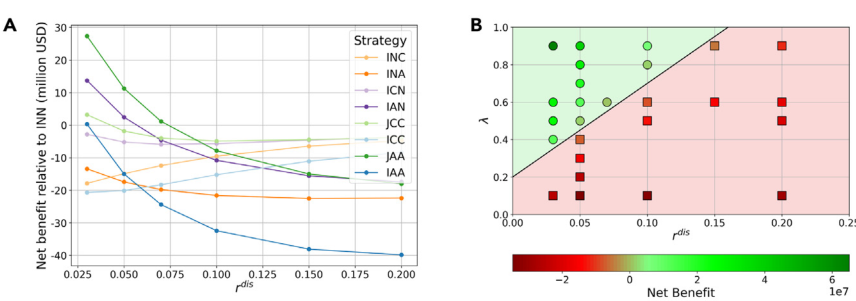

Figure 4. Sensitivity analysis

(A) Sensitivity analysis of the net benefit to the discount rate (r^{dis}) and (B) net benefit of aggressive co-undergrounding as a function of λ and (r^{dis}), with green circles representing positive net benefits and red squares negative and darker markers representing larger magnitudes. The solid line is a support vector machine (SVM) decision boundary separating positive and negative net benefits.

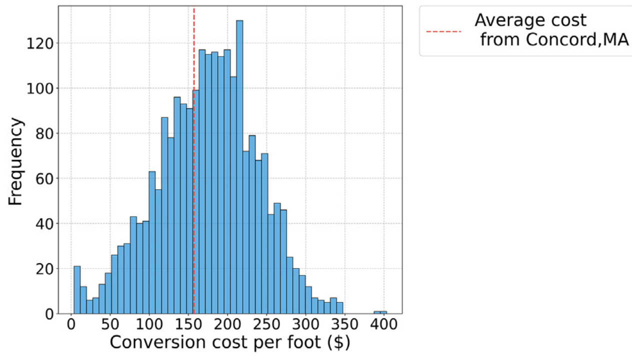

Figure 5. Histogram of per-foot conversion costs across all line segments in the study area, generated using the conversion cost model

The red dashed line represents the average conversion cost per mile from a comparable town, Concord, MA.

where ℓ_i is the length of the line segment, r^{agc} is the growth rate of the cost, r^{oam} is the proportion of replacement cost $(C^{rep}_{s_{i,y}})$ that goes toward annual operation and maintenance costs.

At the system level, for a given year y, $C^{cap}_{\tau,y}$ is calculated by summing of operating expenditures $(C^{ope}_{i,\tau,y})$ for all line segments:

$$C^{ope}_{\tau,y} = \sum_{i=1}^{N^{seg}} C^{ope}_{i,\tau,y}. \quad \text{(Equation 4)}$$

The life-cycle infrastructure cost $(C^{lci}_{\tau,y})$ is then given by

$$C^{lci}_{\tau,y} = C^{cap}_{\tau,y} + C^{ope}_{\tau,y}, \quad \text{(Equation 5)}$$

where $C^{cap}_{\tau,y}$ and $C^{ope}_{\tau,y}$ are the capital and operating expenditures, respectively.

Finally, the total life-cycle infrastructure cost (C^{lci}) is calculated as the summation of the net present value of all life-cycle infrastructure costs $(C^{lci}_{\tau,y})$ for the analysis duration (Y):

$$C^{lci} = \sum_{y \in \{E,B\}} \sum_{y=1}^{Y} NPV\left(C^{lci}_{\tau,y}\right). \quad \text{(Equation 6)}$$

The net present value $NPV(x)$, representing the current value of a future quantity x due in year y is given by

$$NPV(x) = \frac{x}{[1+r^{dis}]^{y}}, \quad \text{(Equation 7)}$$

where r^{dis} is the discount rate.

Table 9. Spearman's correlation coefficient matrix

	$log\ \rho^{prcl}$	ϕ	$log\ p^{clay}$	C^{con}
C^{con}	0.079	− 0.397	0.150	1
$log\ p^{clay}$	− 0.130	− 0.040	1	–
ϕ	− 0.269	1	–	–
$log\ \rho^{prcl}$	1	–	–	–

Environmental cost

Undergrounding can have negative environmental effects, which can result in a significant and long-lasting disturbance in sensitive wetlands, forests, and other ecosystems in electricity lines and broadband connection corridors.[21] In this model, we only consider environmental costs when a line is converted to underground status. Thus, for a given line segment i, this cost $(C^{env}_{i,\tau,y})$ is given by:

$$C^{env}_{i,\tau,y} = \begin{cases} \ell_i \cdot w \cdot C^{eas}, & \text{if} a_{i,y} \geq L_{i,s,y}, v_{i,y} = 1 \\ 0, & \text{otherwise} \end{cases}. \quad \text{(Equation 8)}$$

where ℓ_i is the length of the line segment, $v_{i,y}$ indicates conversion status of line segment i in year y, w is corridor width of underground line, and C^{eas} is conservation easement cost. Conservation easement costs are financial compensations to offset the ecological impact of projects by restricting land development through legally binding agreements, which offer benefits like tax deductions while preserving the land for public or environmental purposes.[52]

At the system level, for a given year y, $C^{env}_{\tau,y}$ is calculated by summing environmental costs for all simulated line segments i, thus

$$C^{env}_{\tau,y} = \sum_{i=1}^{N^{seg}} C^{env}_{i,\tau,y}, \quad \text{(Equation 9)}$$

Finally, the total environmental cost (C^{env}) is calculated as the summation of the net present value of all the environmental costs $(C^{env}_{\tau,y})$ for the analysis duration (Y):

$$C^{env} = \sum_{\tau \in \{E,B\}} \sum_{y=1}^{Y} NPV\left(C^{env}_{\tau,y}\right). \quad \text{(Equation 10)}$$

Safety cost

The installation and maintenance of underground lines pose a significant safety hazard for personnel.[3] Thus, costs associated with non-fatal (C^{nft}_{y}) and fatal (C^{ftl}_{y}) injuries will increase as the share of underground mileage increases each year. We calculated the safety cost at the system level. The annual system-level fatal and non-fatal safety costs in year y are given by

$$C^{nft}_{y} = \gamma_y \cdot r^{nft} \cdot N^{uti} \cdot C^{inj} \quad \text{(Equation 11)}$$

and

$$C^{ftl}_{y} = \gamma_y \cdot r^{ftl} \cdot N^{uti} \cdot VSL, \quad \text{(Equation 12)}$$

where r^{nft} and r^{ftl} are non-fatality and fatality rates, respectively, and N^{uti} is the number of employees working in the electric/broadband utility sector. The parameters C^{inj} and VSL are the annual injury cost caused by accidents and the value of statistical life (VSL), respectively. The value of statistical life is estimated as $7.6 million.[53] The factor γ_y reflects the fraction of underground mileage in year y relative to the base year and is defined as

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Table 10. Segment-specific conversion cost model coefficients and significance

	Coefficient	p Value
$\log \rho^{prcl}$	$-$ 61.4211	0.006
ϕ	$-$ 63.7480	0.040
$\log p^{clay}$	136.8115	0.011

$$\gamma_y = \frac{\sum_{i:s_{i,y}=U} \ell_i}{\sum_{i:s_{i,0}=U} \ell_i}, \qquad \text{(Equation 13)}$$

where ℓ_i is the length of the line segment.

The annual system-level safety cost (C_y^{saf}) is then calculated as the summation of the fatal and non-fatal safety costs:

$$C_y^{saf} = C_y^{nft} + C_y^{ftl}. \qquad \text{(Equation 14)}$$

Finally, the total safety cost (C^{saf}) is calculated as the summation of the net present value of all annual system-level safety costs (C_y^{saf}) for the analysis duration (Y):

$$C^{saf} = \sum_{y=1}^{Y} NPV\left(C_y^{saf}\right). \qquad \text{(Equation 15)}$$

Benefits

Aesthetic benefit

In line with standard environmental economics practices, we quantify aesthetic benefits through property value increases, which reflect the visual improvements from undergrounding. This approach is supported by previous studies, which link aesthetic enhancements to increased property values in residential areas.[3,48] The aesthetic benefit at the system level is formulated as

$$B_{\tau,y}^{aes} = \frac{A_{U,y}}{A_T} \cdot TPV \cdot r^{plf}, \qquad \text{(Equation 16)}$$

where $A_{U,y}$ is the area of the locations impacted by undergrounding in year y, given by

$$A_{u,y} = w \cdot \left[\sum_{i:s_{i,y}=U} \ell_i - \sum_{i:s_{i,y-1}=U} \ell_i \right] \qquad \text{(Equation 17)}$$

and A_T is the total area of the municipality. Thus, the benefits from undergrounding are calculated as the product of the property value of the locations impacted by undergrounding and the property loss factor r^{plf}. The ratio $A_{U,y}/A_T$ is multiplied by the total property value (TPV) of the municipality, to estimate the property

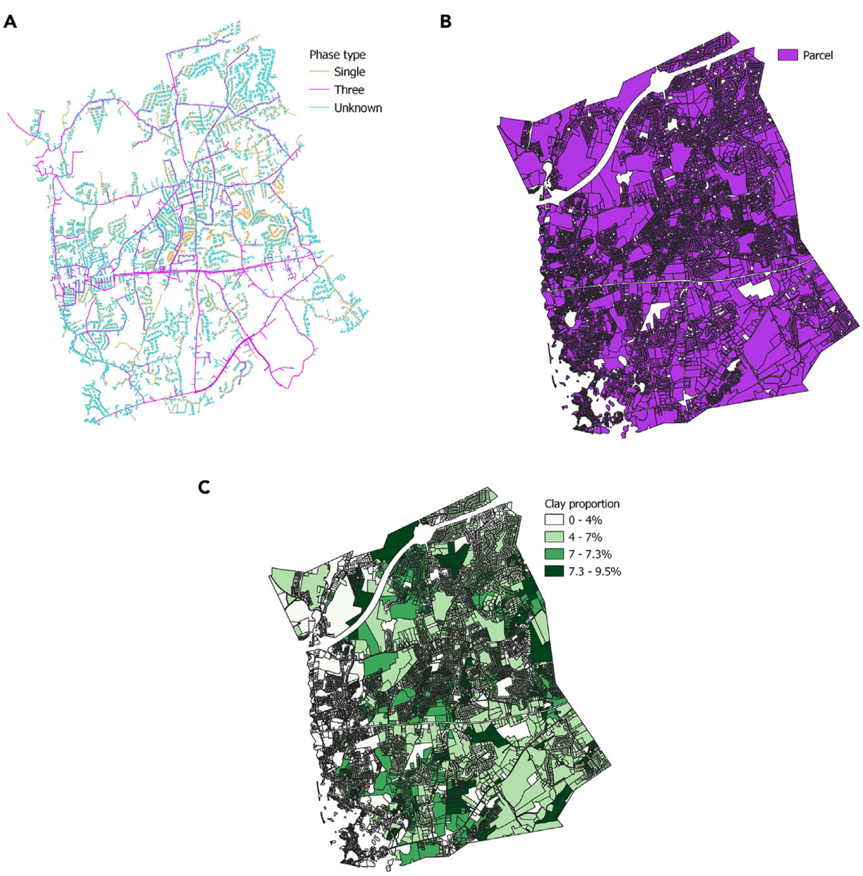

Figure 6. Study area attributes
Study area attributes for the conversion segment-specific cost model including (A) the network's phase design, (B) parcel distribution, and (C) clay proportion.

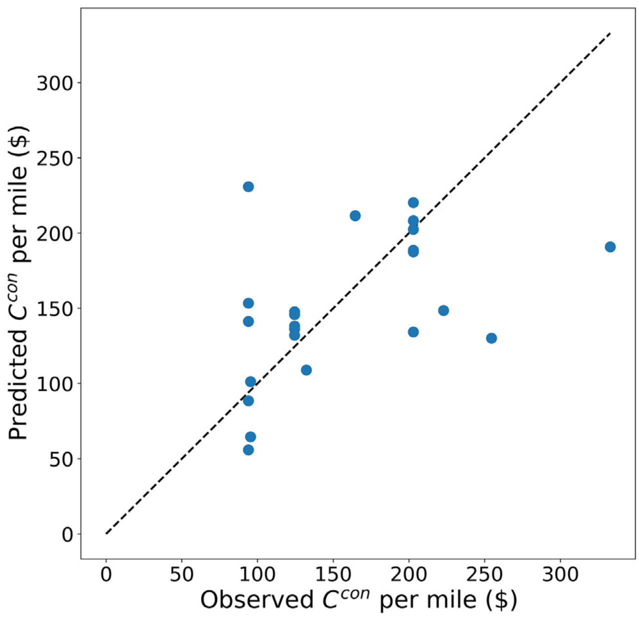

Figure 7. Comparison of predicted (using the developed regression model) and observed conversion costs for a similar town (Concord, MA)

value of the locations affected. We used the *TPV* reported by the town fiscal data, as these values represent a reliable estimate of the property values of the study area. For simplicity, we assumed that all residential properties within the service area (A_T) are equally affected by the aesthetic benefits of undergrounding, reflecting a uniform distribution of benefits across the region.

Finally, the total aesthetic benefit (B^{aes}) is calculated as the summation of the net present value of all aesthetic benefits $(B^{aes}_{\tau,y})$ for the analysis duration (Y):

$$B^{aes} = \sum_{\tau\in\{E,B\}} \sum_{y=1}^{Y} NPV\left(B^{aes}_{\tau,y}\right). \quad \text{(Equation 18)}$$

Avoided economic loss

We evaluate the economic impact of service disruptions by examining the consequences of power and broadband outages. Interruptions to electrical and broadband services can lead to significant disturbances across various sectors. For instance, residential, commercial, and industrial areas may experience information system failures and supply chain issues, which can result in substantial revenue losses, declines in employee productivity, and material shortages. Due to the scarcity of comprehensive data, our assessment of economic losses focuses on the ramifications for customer economies and employee productivity specifically attributed to compromised electric and broadband infrastructure. The expected outage hours for line segment of type τ for a given year y, is given by

$$\overline{SAI}_{\tau,y} = SAI_{\tau,0}\cdot\left[1-\lambda\cdot\sum_{i:s_{i,y}=U}\ell_i\right], \quad \text{(Equation 19)}$$

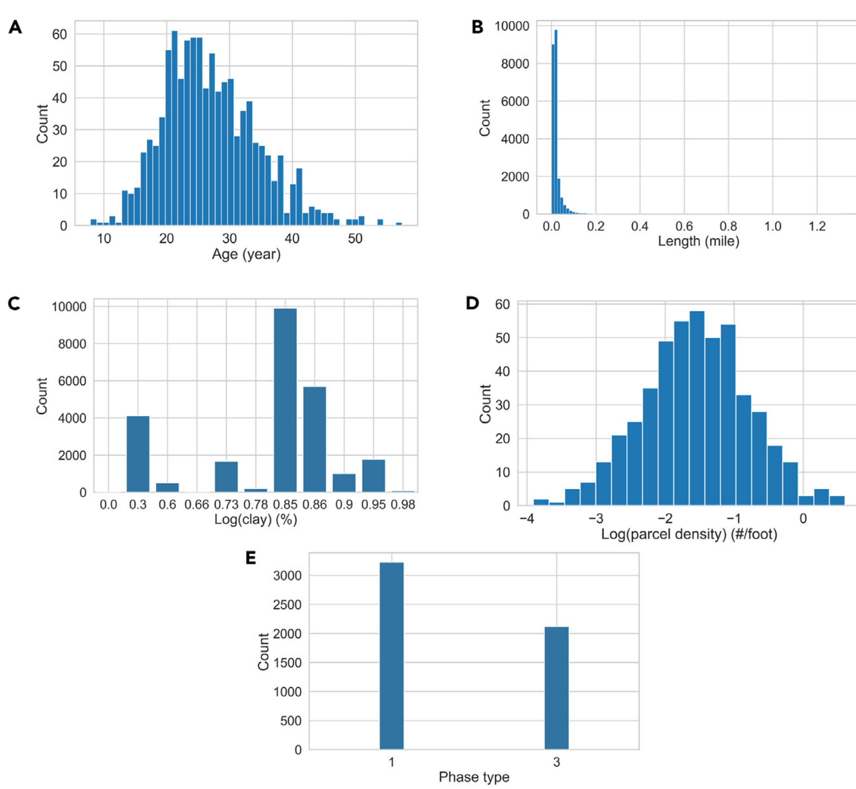

Figure 8. Network attributes for the Shrewsbury study area including age, length, log of clay, log of parcel density, and phase

(A) Age.
(B) Length.
(C) Log of clay.
(D) Log of parcel density.
(E) Phase.

Table 11. Parameter estimates of the fitted distributions

Attribute	Distribution	Parameters
Length (ℓ_i)	gamma	$\hat{k} = 0.711$, $\hat{\theta} = 0.019$
Phase (ϕ_i)	binomial	$\hat{p}_\phi = 0.6$
Age (a_i)	gamma	$\hat{k} = 13.5$, $\hat{\theta} = 2.5$
Clay proportion ($log\ p_i^{clay}$)	multinomial	–
Parcel density ($log\ \rho_i^{prcl}$)	normal	$\hat{\mu} = -1.55$, $\hat{\sigma} = 0.76$

where τ is the line segment type, y is the year in the analysis period, $SAI_{\tau,0}$ is the annual average number of outage hours in the initial year, $\sum_{i:s_{i,y}=U} \ell_i$ is the total mileages of the underground lines in year y, and λ is the proportion of outages that can be mitigated through undergrounding. These equations estimate the expected annual outage hours by incorporating the impact of undergrounding line segments, reflecting the outage reduction as more lines are transitioned underground. Using the estimated expected outage hours, we can then estimate the economic loss ($L_{i,\tau,y}^{eco}$) for a given line segment i of type τ in year y using

$$L_{i,\tau,y}^{eco} = \frac{\ell_i}{\sum_{i'} \ell_{i'}} \cdot SAI_{\tau,y} \cdot \left[\sum_k VLL_{\tau,k} \cdot N_{\tau,k}^{out}\right], \qquad \text{(Equation 20)}$$

where i shows line segments, k is customer class (or sector), ℓ_i is the length of line segment i, $SAI_{\tau,y}$ is the estimated annual average number of outage hours in year y, $VLL_{\tau,k}$ is the value of lost load, and $N_{\tau,k}^{out}$ is the number of affected people/businesses.

At the system level, for a given year y, the economic loss ($L_{\tau,y}^{eco}$) for either electric or broadband is given by

$$L_{\tau,y}^{eco} = \sum_{i=1}^{N^{seg}} L_{i,\tau,y}^{eco}. \qquad \text{(Equation 21)}$$

The total economic loss (L_τ^{eco}) is then calculated as the summation of the net present value of all economic losses $L_{\tau,y}^{eco}$ over the analysis duration (Y):

$$L_\tau^{eco} = \sum_{y=1}^{Y} NPV\left(L_{\tau,y}^{eco}\right). \qquad \text{(Equation 22)}$$

We define L_0^{eco} as the special case of the baseline economic loss in the *INN* strategy. Then, we consider the *avoided* economic loss (B_τ^{eco}) as the economic benefit obtained by subtracting the avoided economic loss in a given strategy (L^{eco}) from that of the baseline strategy ($L_{\tau,0}^{eco}$). Thus,

$$B_\tau^{eco} = L_{\tau,0}^{eco} - L_\tau^{eco}. \qquad \text{(Equation 23)}$$

In the case of *INN*, B^{eco} would therefore be 0.

Finally, the total economic benefit (B^{eco}) is given by the sum of the benefits for both electric and broadband segment types:

$$B^{eco} = \sum_{\tau \in \{E,B\}} B_\tau^{eco}. \qquad \text{(Equation 24)}$$

Experimental design

To empirically assess the trade-offs and potential of co-undergrounding electric and broadband systems, we developed a comprehensive modeling approach. This model simulates various undergrounding strategies and evaluates their costs and benefits. We applied our model to the specific case of Shrewsbury, Massachusetts, using data provided by Shrewsbury Electric and Cable Operations (SELCO).

Data

We collected data and information on undergrounding from various public and commercial sources. First, we obtained geospatial data on SELCO's electric and cable networks. We also obtained outage statistics from SELCO operations in 2020 and characterized the extent of outage data available for other utilities in Massachusetts. We obtained data on the cost of previous undergrounding projects in Concord, MA, and some of the technical parameters of the model, such as corridor width, from the Electric Power Research Institute (EPRI).[45] We received the Zillow transactions and assessor dataset (ZTRAX)[54] on home characteristics and assessments to calculate aesthetic benefits from undergrounding in the form of increased property value. Other required information was acquired through the Shrewsbury electrical network, MassGIS data layers, and Open Street Map (OSM). Figure 6 shows the electric network, Shrewsbury's parcels, and soil data. Table 5 briefly summarizes the data sources and their respective applications.

Localized parameters

We compiled parameters specific to Shrewsbury for the cost and benefit models. Global parameters are given in Table 6, while status- and sector-specific parameters are provided in Tables 7 and 8, respectively. The standard assumption is that underground lines have a shorter lifespan (30 years) than

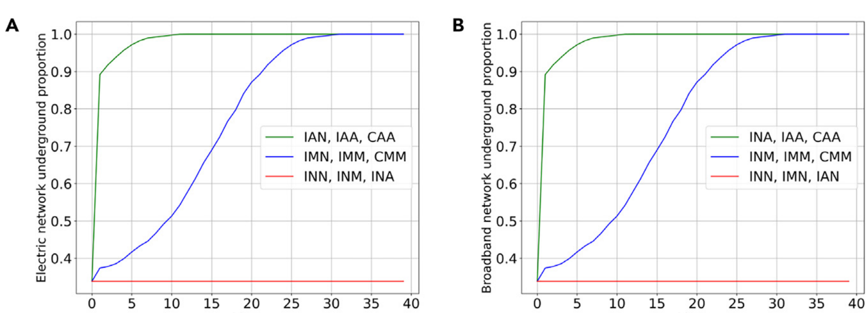

Figure 9. Underground proportion under different strategies
Underground proportion under different strategies for (A) electric and (B) broadband line segments. The electric network benefits more from avoided economic losses due to undergrounding compared with the broadband network.

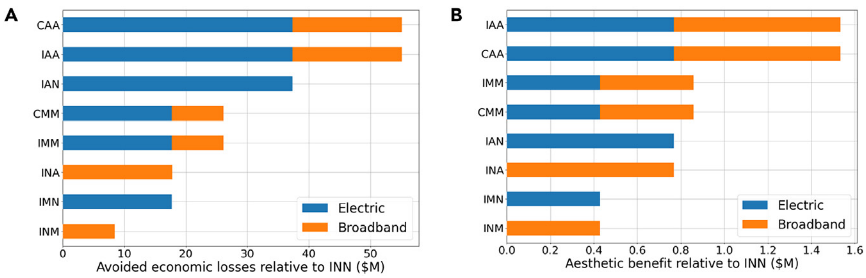

Figure 10. Electric versus broadband

Electric versus broadband (A) avoided economic loss and (B) aesthetic benefit.

overhead lines (40 years).[55] However, based on interviews with experts from Shrewsbury, advancements in underground cable technology suggest that these can now outlast overhead lines. Accordingly, we assumed the expected lifespan of underground line segments to be 50 years. The cost of conservation easements (C^{eas}) is estimated based on the average expenditure on conservation programs in Massachusetts, which amounts to $2,692 per acre.[47] The impact of overhead electric lines on real-estate values is well documented, with reductions in property values typically ranging from 5% to 20%,[3] although some studies suggest a smaller impact of less than 5%.[56,57] We adjusted these figures to reflect the specifics of the Shrewsbury case study, which deals with lower-voltage distribution lines that have a smaller footprint, estimating a property value reduction of 5% due to the presence of these lines.

Segment-specific conversion cost model

The cost of converting line segments varies considerably based on the level of infrastructure, soil type, number of customers served, construction techniques, and vegetation.[1,58,59] Soil type, in particular, is one of the most important factors influencing trenching cost. For instance, the cost of undergrounding utility lines in rocky soil is approximately 33% higher than in sandy soil.[60] Yet, no existing framework adequately considers these heterogeneities. Previous efforts simply used an average per-mile value for conversion cost parameter across all line segments.[3] To address this gap, we developed a multivariate linear regression model that disaggregates conversion costs based on physical network attributes, providing more accurate localized estimates. We obtained cost data from historical estimates of municipal undergrounding projects in a nearby town, Concord, MA, spanning 2007 to 2011. This dataset included 26 observations across five projects, with cost data detailed at the street level. We obtained geographical data from the Massachusetts Bureau of Geographic Information Systems (MassGIS) using property tax parcels and soil survey geographic databases.[61]

Our exploratory data analysis and model selection tests indicated that conversion costs are best explained by an intercept-free multivariate linear regression model using the logarithm of parcel density ($log\ \rho^{prcl}$), a binary indicator for single-phase (ϕ), and the logarithm of the clay proportion in the area ($log\ p^{clay}$). Parcel density is defined as the number of parcels per foot for a given line segment. The pairwise Spearman's correlation coefficients of the model variables are shown in Table 9. It shows that C_{con} and ϕ have the strongest negative correlation ($-$ 0.397), while $log\ p_{rcl}$ and $log\ p_{clay}$ have a positive correlation (0.150). The final regression model is given by Equation 25.

$$C^{con} = -61.4211\left(log\ \rho^{prcl}\right) - 63.7480\phi + 136.8115\left(log\ p^{clay}\right) \qquad \text{(Equation 25)}$$

The estimated coefficients of the final model are shown in Table 10. All coefficients are significant ($p < 0.05$) and the model achieves $R^2 = 0.88$. The negative coefficients for $log\ \rho^{prcl}$ and ϕ^1 indicate that conversion costs increase in less densely populated areas (lower $log\ \rho^{prcl}$) and when a three-phase power supply is required ($\phi = 0$). The negative coefficient of $log\ \rho^{prcl}$ is justified by network effects and the likelihood of less vegetation in denser areas, which reduces clearing costs. The positive coefficient for $log\ p^{clay}$ indicates higher conversion costs in areas with clay-rich soil, due to the increased difficulty of penetrating such soil. We applied this model to estimate conversion costs for both networks within our cost-benefit framework. Figure 7 illustrates the predicted conversion costs using the data-driven segment-specific cost model versus observed values.

Network modeling

To accurately evaluate the different undergrounding strategies for utility lines, we synthesized a simplified network model that reflects key characteristics of the actual infrastructure. This model includes the distributions of essential line segment attributes such as length, phase design, age, log of clay proportion, and log parcel density. Figure 8 displays the distribution of these attributes for Shrewsbury. The best-fitting distributions for the attributes were determined through statistical analysis.

Given the lack of actual age data for the line segments, we assumed a gamma distribution for this variable.[3] The model assumes an average age of 30 years across 22,988 line segments, each with an average length of 0.021 miles. However, to simplify the computational process, we aggregated the lines into 2,299 larger segments, each with an average length of 0.21 miles. This approach balances detail with computational feasibility. All line segments were treated as independent.

The distribution of phase designs within the network was also modeled based on observed data. Specific information was available for 22% of the network, where we observed that 60% of the line segments were overhead. Using this observation, we modeled the phase-design distribution as a binomial

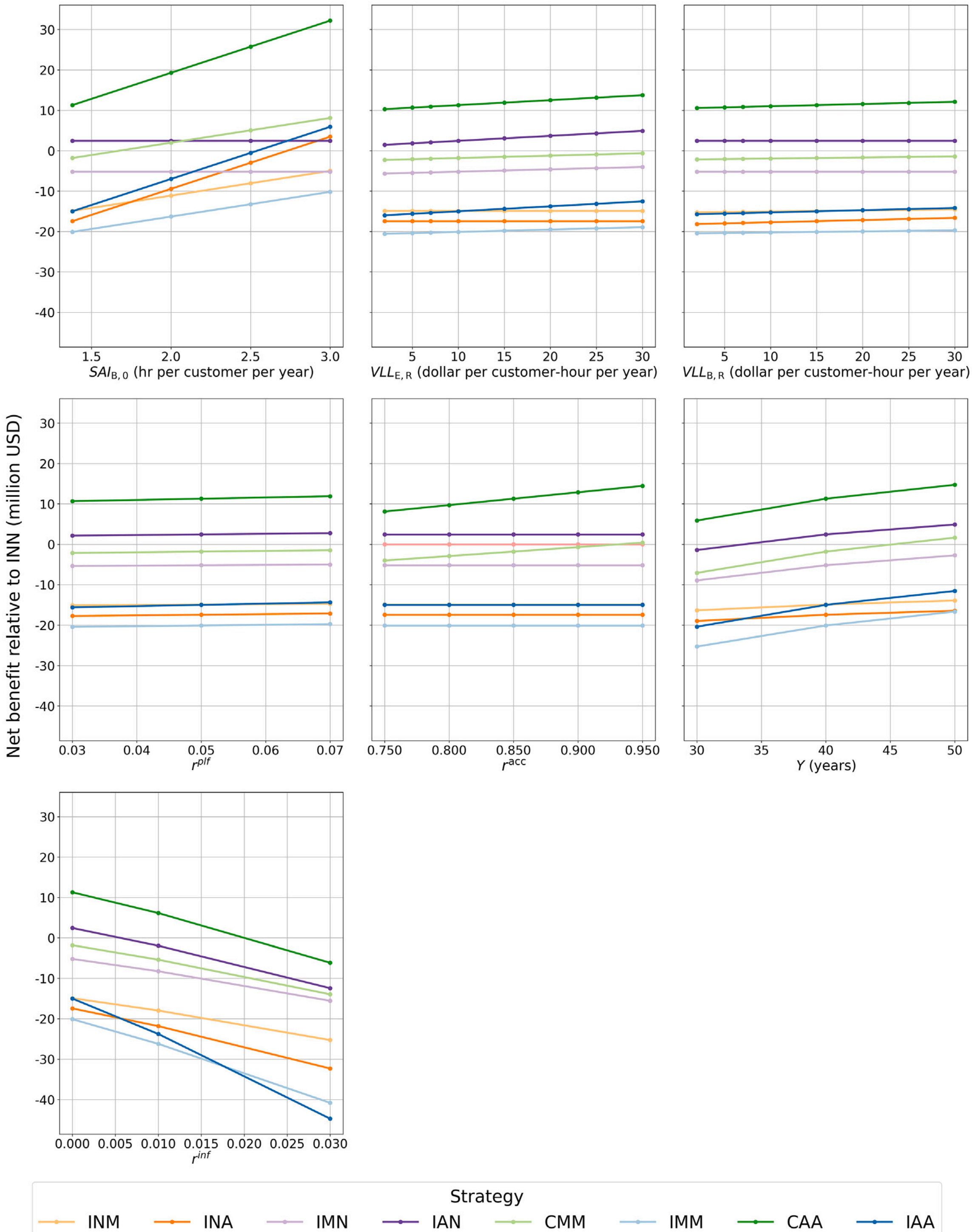

Figure 11. Sensitivity analysis of the net benefit to the critical parameters

Sensitivity analysis of the net benefit to the critical parameters including $SAI_{B,0}$ (average broadband outage duration/customer/year [h]), $VLL_{E,R}$ (value of electric lost load for residential sector [\$/h]), $VLL_{B,R}$ (value of broadband lost load for residential sector [\$/h]), r^{plf} (property loss factor due to overhead lines), r^{acc} (avoided co-underground conversion cost rate), Y (analysis duration [years]), and r^{inf} (inflation rate on initial-year conversion costs).

Table 12. Glossary of abbreviations

Abbreviation	Description
APPA	American Public Power Association
CBA	cost-benefit analysis
Deed	demonstration of energy and efficiency developments
EPRI	Electric Power Research Institute
GIS	geographic information system
MMWEC	Massachusetts Municipal Wholesale Electric Company
NRCS	Natural Resources Conservation Service
OSM	Open Street Map
SELCO	Shrewsbury Electric and Cable Operations
SSURGO	soil survey geographic database
ZTRAX	Zillow transactions and assessor dataset

distribution and applied this proportion uniformly across the entire network due to the lack of detailed data for the remaining 78%.

The length ℓ and $log\ p^{clay}$ follow log normal and multinomial distributions, respectively, with the number of observations totaling 24,972 and 11 possible categories for log clay%. For log density, a normal distribution provided the best fit. Furthermore, phase design, with 60% of line segments configured as single-phase and 40% as three-phase, was best described by a binomial distribution. The parameters of these fitted distributions for all attributes considered in the study are summarized in Table 11. A glossary of terms can be found in Table 12.

Further analyses

Aggressive strategies achieve a fully undergrounded network three times faster than moderate approaches

Undergrounding utility lines can improve system resilience,[62] as the greater the proportion of underground line segments, the lower the likelihood of outages, especially during storms or other extreme weather events. Our simulations show that, with aggressive conversion strategies (strategies *IAN*, *INA*, *IAA* and *CAA*), full undergrounding is attained much earlier within 10 years, compared with 30 years under moderate strategies (*IMN*, *INM*, *IMM*, and *CMM*) (Figure 9). This rapid replacement enhances resilience by providing an earlier and sustained reduction in outage risks.

Figure 10 shows avoided losses and aesthetic benefits for electric and broadband networks. Avoided losses of the broadband network are smaller than those of electric. This is likely because customers affected by broadband outages are fewer than customers affected by power outages. In contrast, for aesthetic losses, both electric and broadband poles have a similar aesthetic impact on the area. Regarding the costs, we cannot easily differentiate between electric and broadband, as under co-undergrounding strategies (*CMM* and *CAA*), we have a uniform cost of installation for both electric and broadband.

Sensitivity analysis

Whenever undergrounding is justified, the aggressive co-undergrounding strategy (CAA) demonstrates robustness. We observed an insignificant change in net benefit magnitude when varying the value of lost load per hour for the electric network ($VLL_{E,R}$), the value of lost load per hour for the broadband network ($VLL_{B,R}$), and the property loss factor due to overhead lines (r^{plf}). There is only a small impact from the average outage duration per customer per year ($SAI_{B,0}$) and the avoided co-underground conversion cost rate (r^{acc}). For all analyzed years (y), the aggressive co-undergrounding strategy (CAA) shows a positive net benefit relative to *INN*. Conversion costs were estimated using a segment-specific regression model based on Concord, MA undergrounding projects (2007–2011) without accounting for inflation, with an average cost of $918,720 per mile (Figure 5). In the sensitivity analysis, we applied 1% and 3% inflation rates (r^{inf}). Any rate above 2% makes all strategies unfavorable, resulting in a negative net benefit compared to Figure 11.

Costs and benefits

Table 13 details the costs and benefits, relative to *INN*, of all the strategies we considered.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Mahsa Arabi (marabi@umass.edu).

Materials availability

Not applicable.

Table 13. Discounted costs, and benefits for simulated strategies

	Cost				Benefit			Net benefit
Strategy–	Infrastructure	Environmental	Safety	Total	Aesthetic	Avoided economic loss	Total	–
CAA	35.9	5.94	3.55	45.4	1.53	55.1	56.6	11.3
IAN	30.1	2.97	1.77	35.6	0.77	37.3	38.1	2.44
CMM	24.3	2.84	1.66	28.8	0.86	26.1	27.0	– 1.81
IMN	21.1	1.42	0.83	23.3	0.43	17.7	18.1	– 5.19
INM	21.6	1.42	0.83	23.8	0.43	8.45	8.88	– 14.9
IAA	62.2	5.94	3.55	71.6	1.53	55.1	56.6	– 15.0
INA	31.3	2.97	1.77	36.0	0.77	17.8	18.6	– 17.4
IMM	42.6	2.84	1.66	47.1	0.86	26.1	27.0	– 20.1

The net benefit for each strategy is computed by subtracting cost from benefit. All values are in million USD.

Data and code availability

All the data and code used to generate the results and figures presented in this paper are publicly available at https://github.com/narslab/project-groundwork.

ACKNOWLEDGMENTS

We acknowledge funding from the Massachusetts Municipal Wholesale Electric Company (MMWE no. 2355) via the American Public Power Association (APPA). This research was also supported by the Elevating Equity Values in the Transition of the Energy System (ELEVATE), which is funded by the National Science Foundation NSF Research Traineeship (NRT) program (award no. 2021693), and partially funded by the US Department of Energy (DE-EE0010143). We also thank Christopher Roy, General Manager of Shrewsbury Electric & Cable Operations (SELCO), for his support and for providing the data used in the analyses.

AUTHOR CONTRIBUTIONS

Conceptualization, J.O., J.T., M.B., and A.G.; methodology, M.A., J.O., A.P., and A.A.; formal analysis, M.A., E.B., and J.O.; writing—original draft, M.A.; writing—review and editing, M.A., E.B., and J.O.; visualization, M.A.; funding acquisition, E.B., A.G., and M.B.; supervision, J.O., J.T., and E.B.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: August 5, 2024
Revised: November 26, 2024
Accepted: January 27, 2025
Published: February 21, 2025

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