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REVIEW

Opportunities and Challenges of Including Landscape Benefits in Transmission Planning

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Abstract

Purpose of Review Transmission planning has historically been driven by reliability, economics, and land avoidance-based policy – meaning planners exclude vast geographical areas from the planning process. However, a growing body of evidence suggests that there are a multitude of landscape-based benefits associated with electric transmission. The purpose of this work is to help planners, policy makers, and researchers better understand how landscape benefits might be included in transmission planning. The fundamental question this work seeks to answer is "what are the opportunities and challenges associated with including landscape benefits in transmission planning?".

Recent Findings Recent research shows that transmission rights-of-way have the potential to provide a broad range of benefits beyond those commonly recognized today such as reliability and economics. These additional benefits include habitat and pollinator support, recreation, wildfire risk reduction, stormwater and heat mitigation, and local economic opportunities. Recent policy changes, such as the Federal Energy Regulatory Committee's Order 1920 that requires transmission planners to maximize the benefit of transmission projects, provide an opening to integrating non-traditional benefit accounting in formal transmission planning processes.

Summary This work identifies a broad range of potential landscape benefits in existing academic and industry literature. Furthermore, it initiates the process of developing conceptual frameworks for determining 1) how difficult specific landscape benefits are to measure with existing tools, data, and techniques, 2) what techniques are most appropriate for measuring landscape benefits, and 3) how landscape benefits might be combined with traditional metrics in industry-grade transmission planning tools.

Keywords Ecosystem services · Landscape · Transmission benefit quantification · Transmission planning · Transmission policy

Introduction

Throughout the history of electric power grids, reliability has served as a cornerstone of transmission planning efforts. The need for consistent, uninterrupted electric power delivery is necessary for a society that has become increasingly dependent on energy intensive technologies and industries. As power grids have become more sophisticated over time, so too have their planning and operations. Modern transmission planning practices account for a variety of factors, including reliability, detailed cost analysis, and policy integration, as well as avoiding landscapes deemed inappropriate for development, such as critical habitats for protected species or designated wilderness areas. However, there is growing interest in revisiting traditional avoidance-based transmission siting assumptions. This is because the land within transmission rights-of way (ROWs), as well as other similar linear infrastructure such as roads, pipelines, and railways, is capable of providing known, demonstrated benefits related to ecosystem services (ES) and local economic benefits.

ES refers to the benefits that people receive from nature and healthy ecosystems. There are four categories of ES: supporting, regulating, provisioning, and cultural services as defined by the Millenium Ecosystem Assessment [1]. Supporting services are those necessary to maintain fundamental ecosystem processes (e.g., habitat provisioning, nutrient cycling, and photosynthesis) while regulating services refer to benefits

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received through the moderation or control of ecosystem processes (e.g., climate regulation, flood control, and pollination). Provisioning services refer to goods that may be harvested from the environment (e.g., food, water, timber, and fuel) while cultural services refer to the non-material benefits people receive from ecosystems (e.g., recreation, and aesthetic value).

Since utilities have large landholdings, especially within their transmission ROWs, there is significant potential for them to advance multifunctional transmission corridors. There have already been efforts to integrate other activities, such as multi-use trails and/or ecological restoration and conservation into transmission corridors [2]. However, these activities typically occur after a transmission corridor is well established and may entail specific vegetation management approaches, collaborative partnerships with local municipalities or non-governmental organizations (NGOs), and/or formal land use agreements. Recognizing the challenges that new transmission projects face, demonstrating the value of existing multifunctional transmission corridors that provide beneficial ES can help to improve public perceptions and social acceptance of transmission corridors. More positive sentiments towards new transmission builds can help to reduce opposition, which can help to streamline the permitting process.

The purpose of this paper is to serve as a resource for those involved in transmission planning by detailing how landscapes might be accounted for in existing transmission planning processes, introducing the concept of landscape-based benefits in transmission ROWs, and characterizing opportunities and challenges of integrating landscape-based benefits into existing transmission planning processes. Furthermore, it contributes to the area of landscape-informed transmission planning by developing and demonstrating benefit quantification challenge level, a framework for estimating the relative complexity of assigning benefits to different landscape-based features related to transmission planning. The rest of this paper is structured as follows: Sect. "Historical Transmission Planning" provides background on historical transmission drivers and regulators up to present day, Sect. "Transmission Planning Today" discusses important developments in present day transmission planning, Sect. "Future Transmission Planning" details future transmission considerations regarding transmission planning, Sect. "Opportunities and Challenges" analyzes the opportunities and challenges associated with transmission planning that integrates landscape-based benefits, and Sect. "Conclusions" concludes the paper.

Historical Transmission Planning

Reliability has historically been and is expected to remain the key driver of transmission development. However, other factors such as economics, policy, and new generation and load interconnection requests have played significant roles which may grow as transmission planning becomes increasingly sophisticated. In terms of reliability, the Transmission System Planning Performance Requirements (currently revision TPL-001–005 at the time of this writing [3]), which are regularly updated by the North American Electric Reliability Corporation (NERC), drive much of reliability-based planning in the United States. The TPL-001–005 defines the reliability-based studies every planning coordinator and transmission planner in the U.S. must perform annually. Specifically, the TPL defines steady-state and transient simulations that must meet specific performance metrics such as voltage and frequency thresholds upon exposure to contingencies defined in the TPL. If a planning coordinator or transmission planner identifies contingencies that do not adhere to the system performance requirements defined in the TPL, they must develop plans to correct the performance requirements. One potential solution is the construction of new transmission.

Economics also play an important role in the justification and development of new transmission. To help justify the construction of a new transmission line, the financial benefits (i.e., the expected reduction in operational costs resulting from new transmission) are compared to the capital cost of building the new transmission. The benefit divided by the capital cost of the line results in a benefit-to-cost ratio (BCR). To calculate the potential benefit, or reduction in cost, two studies are generally needed: a baseline study that does not include the proposed transmission and a change study that includes the new transmission. Though many different benefits can be studied through a variety of tools [4], measuring production cost savings is one of the most common evaluations, as production cost analysis provides the expected operational cost of an electric power grid over the course of an entire year. Though a minimum BCR greater than 1 demonstrates value of the new transmission, transmission planners frequently target a BCR of 1.25 or more to give their estimate a margin of safety, as realized benefits may not exactly align with predictions.

In the absence of clear reliability or financial benefit, policy or state mandates can drive new transmission investment. Recent state policy efforts have included reductions in power plant emissions or mandates that energy from certain resource types make up a percentage of a state's generation. Renewable Portfolio Standards (RPS) are an example of such a target. California has one of the more aggressive RPS policies in the United States. SB100 in California mandates that the state must achieve 60% renewable energy production by 2030 and 100% renewable energy by 2045 [5]. To ensure that California reaches its RPS goals, the California Independent System Operation (CAISO) evaluates transmission that enables California to meet its mandated RPS

goals in its transmission planning processes [6]. Aside from policy mandates, transmission investment is also driven by standard interconnection requests to accommodate new generation and load on the system [7].

While NERC regulates the bulk electric power system through reliability standards such as the TPL, it is the Federal Energy Regulatory Commission (FERC) that empowers NERC to do so [8]. FERC has additional responsibilities that impact transmission, including regulating interstate wholesale electricity sales between suppliers and utilities and transmission rates as well as ensuring power suppliers have non-discriminatory access to interstate transmission [9].Transmission siting is primarily the responsibility of state regulatory bodies such as public utility commissions. FERC typically does not get involved in the actual siting of transmission lines except in very limited circumstances.

An Environmental Impact Statement (EIS), required under the National Environmental Policy Act (NEPA), is used to help support decision making and plays a major role in capturing the relationship between new transmission and its expected effect on the land on which it resides. The EIS is a comprehensive evaluation of significant environmental effects of a proposed project, both positive and negative that also analyze alternatives and mitigation measures. The EIS does not focus on grid studies or evaluate new transmission based on grid reliability, economics, and policy. Undoubtably transmission can and does negatively impact the land in which it resides, but it is an oversight to not consider full breadth of the potential benefits that new transmission may have outside of reliable energy production. Furthermore, because transmission planning and siting frequently consider multiple options to meet a grid related need, the route with the greatest benefit to impact or BCR can only be selected if all potential benefits are fully analyzed, including benefits outside of energy security and reliability.

Transmission Planning Today

Updates to transmission planning procedures and regulations are infrequent in the U.S. However, when they occur, they can have significant impact. FERC's recent Order 1920 [10–12], promises to be one of those changes. Notable aspects of FERC Order 1920 include:

- requiring each transmission planning region to engage in long-term planning through a set of three plausible and diverse scenarios with outlook of at least 20 years.
- quantifying seven benefit types for all transmission projects identified in the planning process. However, the precise implementation of the benefit quantification is left up to the planner as is whether they want to quantify additional benefits beyond these standards. Furthermore, transmission planning must seek to maximize benefits. The standard benefit types defined are:

  1. Deferred cost of replacing aging infrastructure
  2. Reduced loss of load probability or reduced planning reserve margin
  3. Production cost savings
  4. Reduced transmission energy losses
  5. Reduced congestion from transmission outages
  6. Reduction of costs associated with extreme weather events
  7. Capacity cost benefits from reduced peak energy losses

- developing both a state and default cost allocation such that if the state cannot agree on how to pay for transmission the default cost allocation method is used.

A key aspect of FERC Order 1920 relevant to landscape-based transmission development is the allowance for additional benefit metrics beyond the defined standard types. This allows an opening for transmission-related landscape benefits to be explicitly included in benefit quantification. The fact that transmission plans must maximize benefits, including landscape-based benefits, could prove to be a deciding factor in cases where they are considered. However, given that FERC cost allocation regulations require costs to be allocated proportionally to those receiving benefits, if landscape-based benefits are considered, it will also be important to ensure that measurement techniques have high appeal and buy-in from stakeholders.

This begs the question to what extent are transmission ROWs already being leveraged to benefit society outside of their energy benefits associated with electric power grids? Presently, several organizations and companies appear to be taking leadership in efforts extending the value and benefit of ROWs beyond energy transmission. It is not uncommon for utilities to leverage existing transmission ROWs to the benefit of trail construction for outdoor enthusiasts. One example of this is the 36-mile Albany-Hudson Electric Trail in New York which was developed within a utility corridor on privately owned land. National Grid, the utility, entered into a license agreement with the Hudson River Valley Greenway (HRVG), which granted HRVG the right to design and develop the trail. National Grid provided easements and managed vegetation such that recreational trails in the ROW could be developed [13]. Multi-use trails in transmission ROW are not uncommon, and similar examples are detailed in [14].

Another benefit actively being pursued in existing ROWs by several utilities is the enhancement of ES. For example, the Bonneville Power Administration practices integrated

vegetation management (IVM) to foster native plant species that include low-growing herbaceous flower plants and shrubs and BPA has done extensive work on improving pollinator habitats in its service territory (Bonneville Power Administration, 2023). Further supporting the idea of ROW benefiting insects, [15] finds that transmission corridors support greater diversity of bee populations than typical forested areas. The impact of this finding goes far beyond sustaining bee populations as the authors point out that 75% of flowering plants are pollinated by animals, with a majority of those being pollinated by bees. Finally, [16] finds that simply maintaining a ROW in a successional state results in high diversity of flower visiting insects.

As it relates to vegetation management, and land management more generally, utilities may contribute to the resilience of a landscape [17]. Transmission corridors can act as firebreaks, especially when the land is completely cleared of vegetation, typically through a process such as mastication [18]. The creation of a natural firebreak, or a gap within a forest without combustible material can slow or stop the spread of wildfires. This may even mimic the resilience benefits of undergrounding transmission lines. These natural firebreaks could be considered in the transmission planning process, especially if considering strategic locations that have high wildfire risk or areas requiring more consideration, such as communities and infrastructure. Transmission corridors can also provide accessible pathways for firefighting crews and equipment during wildfire outbreaks or as evacuation or emergency operations routes. Effective long-term vegetation management of the corridor can help to reduce wildfire risk, thereby enhancing grid reliability and reducing potential power outages resulting from fires near transmission lines. An example of a transmission corridor where site mastication was implemented and where IVM is practiced in the Pine Hill Preserve in El Dorado County, California, which reduced wildfire risk through the removal of invasive plant species and the promotion of native rare fire-adaptive plants.

Transmission projects have also been directly responsible for economic benefits in the communities that share the land upon which they are sited. For example, California's ISO's (CAISO) transmission planning process identified several generation projects that required interconnection and transmission development for California to meet its policy objectives. However, these projects would require ROW on the Morongo Indian Reservation. To support the project, the Morongo Band of Mission Indians helped finance the line and currently receives revenue from its operation [19]. Additional examples of transmission-related local economic benefits are given in [20] while [21] describes wealth building models for communities. Table 1 provides an extensive list of transmission-related benefits that utilities commonly consider, though not all are necessarily considered in the transmission planning process.

But how can these benefits be accounted for earlier in the transmission planning process? Given that FERC Order 1920 requires transmission planners to maximize the benefits of transmission projects and leaves the door open for non-traditional benefit accounting, how can non-traditional benefits be integrated into formal transmission planning processes? Are some landscape-based benefits more impactful than others? Furthermore, what is the full breadth of non-traditional benefits that should be included in new transmission development?

Future Transmission Planning

While it is not unusual for utilities to recognize the landscape-based benefits discussed in the previous section, there are various studies that have identified benefits that extend those already explored or identify new benefits altogether. Additionally, several studies have integrated landscape considerations and benefits directly into transmission planning studies in ways that are far less common for utilities. The purpose of this section is to illustrate the full breadth

Table 1 Enumeration of potential transmission benefits

Benefits commonly recognized by utilities and included in transmission planning	Benefits commonly recognized by utilities but not included in transmission planning	Benefits not commonly recognized by utilities but could be integrated into transmission planning
• Reliability; [3]	• [ES-Cultural] Trail Recreation; [13, 14]	• [ES-Supporting] Improved habitat connectivity [22–24]
• Economics; [25]	• [ES-Provisioning] Local wealth building and trust; [19, 20, 26]	• [ES-Supporting] Vegetation management techniques to maximize ES [27, 28]
• FERC Order 1920; [12]	• [ES—Supporting] Habitat support for native species and pollinators, applications to successional state habitats [15, 16, 29];	• [ES-Cultural] Benefits beyond recreation (aesthetics, health, tourism, safety) [30, 31];
• Public Policy; (RPS, Emissions, etc.); [5, 6]	• [ES-Regulating] Wildfire resilience [17, 18]	• [ES-Regulating] Regulating benefits [32–34]

of potential benefits beyond those that are generally recognized (see Table 1).

Vegetation management largely influences ecological outcomes within ROWs, and several studies have focused on benefits of IVM. While these studies have focused primarily on early successional habitat and benefits to pollinators and native plants resulting from effective IVM, there has been less consideration for how these management actions and ensuing environmental outcomes would be considered in a planning context. To evaluate potential ecological benefits in a transmission planning context requires an understanding of how to best enhance ES in ROWs. [27] evaluates different vegetation management practices in both urban and rural settings using the Delhpi method, which relies on expert opinion. They find that pruning (as opposed to clear-cutting) is expected to have little to no impact on the ES provide by trees. [28] also evaluates urban ROWs but focuses on ROW maintenance scenarios ranging from frequently mowed ROWs to ROWs maintained as native prairies. The authors conclude that less frequently mowed ROWs enhance suburban wildlife biodiversity by supporting alternative habitat types for many species.

Transmission ROWs, and linear infrastructure ROWs more generally, provide valuable habitat for wildlife and pollinators. A variety of works have also focused on wildlife benefits of transmission ROWs or linear infrastructure ROWs in general. Transmission towers can serve as hunting perches for birds of prey or as nesting locations [23]. Additionally, linear infrastructure is considered in the context of easing annual migrations, suggesting transmission corridors may facilitate migrating birds. In [22], powerline corridors are found to increase the richness and abundance of butterflies in the surrounding habitats. The corridors are described as "source habitats" for butterflies which serve to connect surrounding habitats. However, [22] also notes that not all species may be positively affected by powerline corridors. The work of [35] supports this negative view of transmission corridors which describes them as contributing to habitat fragmentation in the Shandong province in China. Despite finding increased habitat fragmentation, [35] develops a procedure for measuring this impact which could be useful for transmission planners comparing several competing transmission siting options.

Currently utilities account for the impact of transmission on people in terms of economics and jobs. Some of this is included in the EIS, especially around impacts to visual resources, cultural resources, and socioeconomics. Frequently, they take into account ROW impacts in terms of aesthetics via public forums that allow locals to voice their concerns about impacted lands. These effects [30], however, evaluate human benefits through a different lens. [30] asked people what they think about mowed vs prairie ROWS and found that people tend to believe that it is important for ROWS to provide habitat. Furthermore, the authors found that people more positively perceived the biodiversity of such ROWs than the actual measured biodiversity. These conclusions suggest that the general public might support efforts to increase biodiversity in ROWs. A second way one might consider the direct human benefits of transmission corridors is through recreational benefits that extend beyond the enjoyment of trails made available through utility ROW sharing agreements. In [31], trail benefits are described in terms of health, tourism, safe alternative modes of transportation, and economic activity centers. Additionally, [24] describes the benefits of habitat connectivity (such as transportation commute times) to those living in urban areas, though not in the context of transmission.

Under certain siting and design conditions, such as sufficiently wide ROW with permeable soil and appropriate low-growing vegetation cover, transmission corridors can provide valuable regulating ES. Corridors that are well integrated with vegetation and proper design can intercept and infiltrate stormwater and contribute to pollutant removal for water purification [33], preventing soil erosion [32], and help cool down local microclimate through shading and evapotranspiration [34]. There may be broader considerations when planning around regulating ES since the land surrounding the corridor may need to be accounted for.

There are numerous benefits to co-locating linear infrastructure (e.g., roads, utility corridors, pipelines, and railways) as it reduces the overall environmental footprint and extent of habitat fragmentation and is an efficient and cost-effective land use strategy [36, 37]. Since highways or utility corridors have already been permitted and constructed, it is less disruptive to the environment than developing transmission on undeveloped land. However, there are often restrictions or prohibitions on co-locating transmission on interstate highways. Aside from the practical advantages of co-locating infrastructure, there are additional landscape-scale benefits that are enhanced where infrastructure is sited together, particularly where there is the potential to stack parallel ROW. This allows for an expansion of linear corridors and a possible increase in the surface area of the ROW. When IVM is implemented, the additional land included in the ROW can help to improve surface permeability. With the increased surface permeability, ROWs, especially those associated with highways and co-located transmission could reduce the extent of environmental pollutants associated with runoff.

Benefits may be further considered across geographies, where some benefits may be more relevant for urban settings, while others are more suitable for rural settings. While transmission infrastructure is less common in densely populated urban areas, it is often sited within metropolitan areas

to connect to a distribution center. While much of this effort is focused on transmission corridors, there are also opportunities to think about benefits within distribution corridors. There may be potential downsides to co-location in certain regions, for example in agricultural areas, where farms abut the road or highway.

As previously discussed, landscape siting considerations are often more prominently studied after transmission needs are identified. [1], however, moves landscape and siting considerations to play a more prominent role in transmission planning which may serve as one example for how to incorporate the previously discussed benefits into transmission planning. It does this by first developing candidate lines for the whole system through a landscape-based impact score which incorporates a variety of environmental and social factors. A business as usual (BAU) least cost capacity expansion plan (CEP) is then used to identify transmission and generation investment while capturing the cumulative impact score of the investment portfolio. Finally, a constraint is added to the CEP by the planner to force reductions in systemwide impact score from the BAU, which results in adjusted transmission and generation investment portfolio and costs. By progressively decreasing the maximum allowed impact score of the capacity expansion plan the planner is able to evaluate the tradeoffs in cost and landscape-based planning in the earliest investigation of transmission planning.

Opportunities and Challenges

While the previous sections of this paper characterize the breadth of potential benefits for consideration in transmission planning, the purpose of this section is to investigate the opportunities and challenges associated with integrating these benefits into the transmission planning process. A number of approaches can be used to quantify ES benefits using non-monetary and monetary metrics. To achieve this, we begin with an investigation into how to quantify ES and benefits associated with the lands occupied by transmission infrastructure.

Landscape Benefit Valuation Approaches

Evaluating landscape benefits often begins by leveraging established approaches for quantifying ES. These methods have been widely advanced in environmental planning and science, offering a robust foundation for understanding the magnitude and diversity of benefits that landscapes can provide. ES assessments typically have similar characteristics: classification of ES into four categories (provisioning, regulating, cultural, and supporting), identification of where benefits are generated and who receives them, and description of how those benefits flow through space and time.

ES quantification and valuation are related but distinct components of this broader ES assessment framework. ES quantification measures the amount, location, and flow of services while valuation interprets how those services benefit people. Valuation can be monetary to capture material benefits (i.e., economic valuation) or non-monetary to capture non-material benefits that are challenging to quantify, such as those addressed through socio-cultural valuation. The appropriate economic valuation method depends on the pathway through which ES affect people or economic activity [38]. Production-function approaches are applicable where ecological conditions or services can be linked to measurable changes in marketed output or production costs, such as increased crop production supported by pollination or reduced costs associated with erosion control. For protective services, expected-damage or avoided-damage approaches estimate value based on reductions in the likelihood or severity of economic losses [38]. Other methods are suited to different benefit pathways: Factor-income methods estimate changes in income supported by ecosystem services; travel-cost methods infer recreation value from the costs incurred to visit a site, and hedonic-price methods estimate environmental values reflected in the prices of related market goods, such as property values. Stated-preference methods use surveys or choice experiments to estimate willingness to pay and may capture both use and non-use values [38, 39]. Replacement-cost methods estimate the cost of providing an equivalent service through an alternative, human-built system rather than directly measuring ES benefits. Such estimates should be interpreted cautiously because the replacement costs may exceed the social benefits provided by the service [38, 39]. No single method is appropriate for every ES, so estimating ES benefits may require multiple complementary methods [38, 39]. Although these methods differ in how they estimate value, their application requires credible estimates of the magnitude and spatial distribution of service provision, as well as identification of the beneficiaries affected.

At the transmission corridor scale, geospatial analysis and GIS workflows can provide this spatial basis by translating distributed landscape conditions into comparable ES indicators and, where relevant, linking service flows to potential beneficiaries. In practice, this means incorporating multiple geospatial data layers, such as land cover, land use, land management, terrain, population, and infrastructure, together with planning constraints (e.g., setbacks, exclusion, and access limitations), so that metrics can be computed consistently and compared across space. Datasets and approaches for quantifying ES are often used in regional applications, and the coarser spatial resolution of

the data limits the applicability to the long, narrow geometry of transmission ROWs. Thus, developing corridor-scale indicators from disparate datasets of varying spatial resolution can present a challenge to planners seeking to quantify benefits. In addition, potential metrics or indicators on landscape benefits differ widely in units, resolutions, and methods. The dynamic nature of ecological and environmental processes makes it challenging to generalize and standardize corridor-wide benefit evaluation.

Building on this GIS-based foundation, ES assessment platforms vary in the ecological or social processes they represent, their data and parameter requirements, their underlying modeling assumptions, and the types of outputs they generate. InVEST is a modular tool that uses land Land Use/Land Cover (LULC) data as the primary spatial input to map and value ES, and it emphasizes ecological and biophysical processes, depending heavily on land cover data and coefficient tables [40]. ARIES uses probabilistic, AI-driven reasoning suited to broad landscape and catchment systems. However, its outputs are not readily accessible to most users without complementary services [41]. SolVES is designed to map cultural services rather than biophysical processes [42, 43]. These platforms address complementary dimensions of ES assessment rather than serving as interchangeable alternatives.

For transmission ROWs, GIS-based screening can support initial assessment, while benefit-specific tools or process models may be needed for more detailed quantification. Within this workflow, InVEST is a plausible platform for first-pass biophysical assessment, given its raster-based modular coverage of carbon storage, pollination benefits, erosion control, and flood mitigation. For corridors where recreation, scenic quality, or other place-based cultural services and benefits are an explicit part of the vision, SolVES could be used. InVEST can be used to characterize baseline ES, provide GIS-ready base line for first-pass ES evaluation, but it has important limitations in transmission ROW contexts [40]. Key limitations include coarse Land-Use-Land-Cover (LULC) inputs that collapse within-ROW heterogeneity into one or two generalized pixels, and largely static representations that do not capture management-driven dynamics (e.g., integrated vegetation and land management) and vegetation succession. As a result, InVEST outputs can be appropriate for regional corridor-wide comparisons and hotspot screening, rather than within-corridor comparisons. To move from regional screening to within-corridor contexts, InVEST would need to be paired with higher-resolution, ROW-specific land cover mapping (including custom classes) and validation data. These limitations point to a broader workflow issue: translating spatial layers into credible benefit indicators often requires benefit-specific models and additional parameterization beyond GIS screening.

Where screening indicates the need for more detailed analysis, different regulating ES often require unique modeling approaches (e.g., microclimate thermal models, stormwater hydrological models), however, the underlying evaluation logic is broadly consistent across benefits [34, 44]. In most cases, the workflow largely follows two steps: First, a 2D or 3D digital representation of an interest or site and surroundings should be built to integrate the spatial context (e.g., ROW width, topography, and surface cover). Next, spatial and material parameters are translated into the model as input data for benefits-specific analysis software. These inputs commonly include land-cover or surface material types, soil permeability or infiltration capacity, and properties of surface energy balance such as albedo, roughness, emissivity, and heat retention, along with vegetation attributes (leaf area index, leaf size) that influence evapotranspiration, based on local climate data.

To quantify local wealth building benefits, we focus on one of the most commonly available wealth sharing arrangements in transmission planning: land easements. In many cases transmission companies pay an up-front fee for the right to build, operate, and maintain transmission lines for a specified period on land they do not own. Depending on who owns the land, these fees may go to individual landowners within a community or to the community itself. A financial tool commonly used to find the present value of infrastructure projects is net present value (NPV) analysis [45]. A project's NPV is computed by taking the difference between the sum of a project's discounted future revenues and the sum of its future discounted costs.

Transmission capital costs are well understood [46], as are revenues which are heavily regulated and are generally based on a guaranteed fixed return on equity (ROE). ROE tends to be around 10% [47] for transmission utilities, which means that for each dollar of project cost, a transmission company can extract 10 cents of profit from their rate base). Given the regulated nature of transmission costs and reimbursement, the actual value of the transmission could be significantly higher than what a transmission company is compensated for (e.g., a line or package of lines where the benefit to cost ratio significantly exceeds 1.25 [25]). When analyzing transmission benefits in terms of local economic benefits it may be useful to divide these benefits into two components. The first component is the actual financial compensation communities and landowners are paid for their land easements (this would show up under a transmission owner's discounted costs). The second component would be any benefit a line provides in excess of a transmission company's approved ROE (as those benefits are shared by all consumers).

More complex scenarios exist such as outright community ownership or shared ownership with a utility [19].

However, the overhead costs and skills required for a community to do this may not make sense in all scenarios, especially if investment in energy infrastructure ownership provides lower returns for the community than alternative investment options. To determine the benefits of transmission ownership, communities need to do the same kind of NPV analysis that they would do for easements. Using NPV analysis, communities could determine whether the additional revenue of ownership outweighs the additional costs associated with responsibilities of ownership.

Opportunity/GAP Analysis

Table 2 synthesizes the spatial indicators for corridor-scale landscape benefit evaluation and summarizes the difficulty of including each benefit indicator in early-stage transmission planning. For each benefit category, Table 2 shows the benefit classification, the dominant analytic approaches, and key factors that should be estimated to translate mapped conditions into each benefit. Table 2 also identifies several key data inputs commonly used to support these evaluations, making it a practical framework for assessing the availability of spatial data and where additional within-ROW detail or targeted modeling is likely required. Finally, Table 2 assigns each benefit a benefit quantification challenge level (BQCL). The BQCL is measured on a scale from low to high with several intermediate rankings (Low, Low-Moderate, Moderate, Moderate-High, High). BQCL is determined qualitatively by analyzing each benefit category across three factors which are also given a challenge rating on the same scale as the BQCL. These factors are defined below.

- **Indicator clarity**: Whether the benefits can be expressed using well-defined spatial metrics, units, extents, and proper spatial resolution.
- **Indicator-benefit links:** How directly available indicators represent the benefits, and how many assumptions or intermediate models are needed to translate "map variables" into meaningful benefit signals.
- **Within-ROW data requirements and availability**: Whether credible estimation requires sub-ROW (e.g., fine grained vegetation mosaics). These component ratings are then synthesized into the final relative challenge level.

Generally, a BQCL is assigned Low to Low-Moderate challenge level when suitable datasets are available, and the indicators can be derived using GIS workflows with clearly defined metrics and thresholds. On the other hand, a BQCL is assigned a Moderate-High to High challenge level when key datasets are missing or are inconsistent, when processed-based modeling (or other complex analysis) is required, or when the indicators rely on assumptions and therefore require additional validation. Justification of the BQCLs in Table 2 are given below.

- **Trail recreation (Low-Moderate):** Planning-relevant screening indicators (e.g., grade/slope, continuous alignment, and connectivity to existing networks and access nodes) are relatively standardized and translate directly into corridor siting decisions, although credible screening often still requires within-ROW constraints (e.g., usable width/clearance and avoidance of wire zones).
- **Ecological connectivity support (Moderate):** Widely used GIS/corridor modeling approaches exist (e.g., resistance surface and least-cost or circuit-based connectivity evaluation). However, results remain sensitive to modeling choices and assumptions about movement and barriers. This may require corridor-specific refinement when ROW intersects protected areas or riparian networks.
- **Native species/early successional habitat support (Moderate-High)**: While candidate indicators are available, the indicators-benefit link is indirect because habitat quality depends on management regimes (e.g., IVM applied areas and its cycles), successional trajectories, and within-ROW heterogeneity. As a result, credible estimation often requires sub-ROW data and ROW-specific land-cover classes, increasing the data-processing burden, and elevating the within-ROW data requirement challenge.
- **Pollinator support (Moderate-High)**: Although mapped proxies for forage and nesting resources can support corridor screening, translating these proxies into benefit-relevant indicators typically requires assumptions about seasonality (bloom phenology), movement/foraging ranges, and stressors (pesticide exposure, traffic effects nearby). Consequently, the indicator-benefit link remains uncertain without additional ecological parameterization and targeted validation, especially when pollinator outcomes are sensitive to fine-scale resource distribution and management.
- **Regulating services support (High):** Many outcomes (e.g., stormwater runoff reduction, erosion control, and heat-related benefits) typically require process-based or targeted modeling with strong sensitivity to parameterization, scale, and assumptions, and often depend on higher-resolution spatial modeling than applying standard regional datasets.
- **Wildfire resilience (Moderate):** Established wildfire hazard, fuel, and exposure datasets can support corridor screening. However, corridor-scale indicators that quantify wildlife-resilient design or treatment effectiveness remain comparatively limited, because the actual risk reduction benefits depend on real-world feasibility and sustained maintenance. Furthermore, both risk and maintenance requirements vary with local fuel patterns and access constraints along the corridor.

Table 2 Analysis of select key modeling factors associated with select transmission benefits

Characteristics	Trails Recreation	Ecological Connectivity Support	Native species and early successional habitat support	Pollinator support	Regulating services Support	Wildfire resilience	Shared community & local wealth building
Classification	ES—Cultural	ES—Supporting	ES—Supporting	ES—Supporting	ES—Regulating	ES—Regulating	ES—Cultural
Analytic Approach	GIS; FRAGSTATS	GIS	GIS	GIS	GIS; Targeted modeling	GIS	SoLVES; InVEST
High-level Screening Considerations and Decision support	Screen for buildable grades and continuous alignment of trails; prioritize segments with gentle slopes and strong connections to existing trail networks and access nodes	Prioritize segments that bridge habitat blocks and avoid major barriers; higher potential where the corridor can reinforce existing riparian/protected-area networks and can reduce fragmentation; prioritize high-value habitat	Prioritize segments where early-successional habitat is feasible to establish and sustain through IVM; emphasize patch size/continuity over narrow edge-only strips	Focus on highest potential where flowering resources and nesting substrates can be sustained within pollinator foraging ranges, with pesticide/traffic stress and strong adjacency to semi-natural cover or farmlands	Use GIS to identify hotspots of risk (e.g., heat, flooding, erosion), then apply targeted modeling tools to quantify their effects and compare scenarios with different design alternatives	Prioritize segments with high burn probability and Wildfire Urban Interface exposure where treatments are feasible; apply wildfire-resilient IVM to reduce fuels and maintain defensible, low-fuel vegetation structure	Prioritize accessible segments near dense population areas and existing destinations; screen for high recreation demand or perceived social value and identify partnership-ready nodes for programming
Specific factors to estimate Potential Benefit (See Table 3 for description)	Trail installation feasibility based on geomorphological conditions (obtained from DEM and LiDAR)	Use resistance/cost surfaces, least-cost path modeling, circuit theory modeling to evaluate fragmentation (patch size, edge density, and/or road density) and proximity to protected areas and riparian networks	Extent of early-successional habitat, Patch configuration metrics (size, edge density, edge-to-core ratio); Vegetation structure-based screening (canopy cover, height);	Forage potential, nesting potential, connectivity evaluation, risk stressors:	Heat mitigation, stormwater runoff reduction potential, erosion/water quality risk reduction, regulatory overlaid	wildfire hazard exposure, fuels and fuel continuity, topographic slope and aspects, WUI proximity and assets-at-risk, accessibility for maintenance	Perceived social value index, hotspots; stakeholder groups comparison, high-value or high-conflict zones, recreation demand/Visitation, intensity, accessibility & population (travel-time buffers), net present value
Indicator clarity challenge level	Low	Moderate	Moderate	Moderate	High	Moderate	High
Indicator-benefits link challenge level	Low	Moderate	High	High	Moderate	Moderate	High
Within-ROW data requirements & availability challenge level	High	Moderate	High	Moderate	High	Moderate	Moderate
Benefit Quantification Challenge Level (BQCL)	Low-Moderate	Moderate	Moderate-High	Moderate-High	High	Moderate	High

Table 2 (continued)

Characteristics	Trails Recreation	Ecological Connectivity Support	Native species and early successional habitat support	Pollinator support	Regulating services Support	Wildfire resilience	Shared community & local wealth building
Data	Geomorphological landform data such as slope, aspect, analyzed by Digital Elevation Model and Digital Surface Model (Multi-Agency); National Historic Trails (National Park Service); National Scenic Trails (National Park Service); Scenic Byways (Department of Transportation); Federal Land ownership (Surface Management Agency) (BLM);	Land Use Land Cover (LULC) data (NLCD, LANDFIRE); Habitat data such as Critical Habitat and Important Bird Areas (USFWS, NOAA); Wilderness Areas (Wilderness Connect); Transportation infrastructure data such as Road Traffic Density, Roads with average annual daily Vehicle traffic, Railroads, Roadless Areas (Forest Service, State Departments of Transportation, Bureau of Transportation Statistics); Critical Habitat Assessment Tool (CHAT) Results (The Nature Conservancy); Site Wind Right—Wildlife Areas (The Nature Conservancy); National Conservation Areas (BLM); National Landscape Conservation System (BLM); Wilderness Study Areas (BLM); Protected Areas Database 4.1 (Geological Survey, et al.,);	Land Use Land Cover (LULC) data (NLCD, LANDFIRE); Habitat data such as Critical Habitat and Important Bird Areas (USFWS, NOAA, USFWS); Wilderness Areas (Wilderness Connect); Critical Habitat Assessment Tool (CHAT) Results (The Nature Conservancy); Site Wind Right—Wildlife Areas (The Nature Conservancy); Protected Areas Database 4.1 (Geological Survey, et al.,); Federal Land ownership (Surface Management Agency)(BLM);	Land Use Land Cover (LULC) data (NLCD, LANDFIRE); Habitat data such as Critical Habitat and Important Bird Areas (USFWS, NOAA, USFWS); Wilderness Areas (Wilderness Connect); Critical Habitat Assessment Tool (CHAT) Results (The Nature Conservancy); Site Wind Right—Wildlife Areas (The Nature Conservancy); Protected Areas Database 4.1 (Geological Survey, et al.,); Federal Land ownership (Surface Management Agency) (BLM);	Land Use Land Cover (LULC) data (NLCD, LANDFIRE); Surface Imperviousness (NLCD); Tree canopy (NLCD); Geomorphological landform data such as Slope, aspect, analyzed by Digital Elevation Model and Digital Surface Model (Multi-Agency) Flood Hazard Zones (Federal Emergency Management Agency); Cooling Degree Days (Multi Agency); Consecutive Days with No Precipitation (Multi Agency); Summer Heat Index (Multi Agency); National Risk Index (Federal Emergency Management Agency); Federal Land ownership (Surface Management Agency) (BLM)	Land Use Land Cover (LULC) data (NLCD, LANDFIRE); Tree canopy (NLCD); Burn severity/history (MTBS); Fire Weather Index—Wildfire (Multi-Agency); Interagency Fire Perimeter History (National Interagency Fire Center); Keetch-Byram Drought Index (Argonne National Laboratory); National Risk Index (Federal Emergency Management Agency); Federal Land ownership (Surface Management Agency) (BLM);	CENSUS Tract for population (EPA); Public Transit Stop Density (National Neighborhood Data Archive); Urban Area (Census Bureau); Land Value (Boston University); Federal Land ownership (Surface Management Agency) (BLM); Roads and transit location data for travel network; Recreational data for Recreation notes (parks, trailheads); National Historic Landmark Points (National Park Service); National Historic Landmark Area (National Park Service);
References	[48]	[49–52]	[53–56]	[57–60]	[61–65]	[66–71]	[43, 72, 73]

- **Shared community & utility revenue (High):** The benefits definition and measurement are inherently contingent on governance arrangement and local contexts, and relevant available spatial proxies (e.g., population, access, visitation intensity, perceived social value) do not directly quantify revenues-sharing outcomes. As a result, indicator clarity and the indicator-benefit link are both comparatively weak without additional socioeconomic modeling, stakeholders- or perception-based validation.

By explicitly rating the expected challenge level of measuring different landscape benefits (even if only qualitatively), we attempt to make clear why some benefit indicators can credibly support corridor-wide evaluation today, while others may need additional datasets, and evaluation techniques before then can be readily integrated into transmission planning. In other words, BQCL is not just a technical note, but may serve as a planning tool that helps prevent over-claiming and sets realistic expectations about what can be concluded from early-stage analysis. While Table 2 lists key parameters and author assessments of BQCL, specific techniques that might be used for evaluating each category of landscape benefit are summarized in Table 6 of Appendix 1.

Role of GIS Tools in Corridor Screening

Integrating landscape benefits into transmission corridors requires a corridor-scale screening logic that is broadly consistent across the benefit types. This process typically begins by defining each benefit as a set of GIS-based criteria, expressed as corridor conditions and their thresholds that presume likely feasibility of benefits such as supporting recreational access and neighborhood connectivity, supporting habitat and pollination, or reducing wildfire risk. Once these criteria are defined, GIS-based screening translates them into measurable indicators using available data layers and widely accessible proxies (e.g., land cover, slope, soils, hazard exposure, proximity to relevant land covers or destinations, and land ownership context). In this process, a range of GIS analytic tools are used to translate criteria into measurable indicators, and ultimately to assess the feasibility of each benefit at corridor scale.

The main drivers of credibility and uncertainty differ by benefit types. Some benefits are primarily biophysical or depend on scenario modeling (e.g., heat mitigation and stormwater runoff reduction, wildfire risk, land use, and land management), while others are more configuration dependent (e.g., habitat connectivity, pollinator support presumed by adjacent land cover and vegetation within ROW, or financial based on land easements or business partnership). As a result, GIS applications support more than corridor-wide scoring; they also help pinpoint where specific benefits are most plausibly actionable within the corridor. For example, screening can highlight gently and diversely sloped segments suitable for dynamic trails or other recreational spaces or locations where opening ROW access could link nearby neighborhoods that are currently poorly connected for walking and biking. In the end, this benefit-by-benefit framing would clearly identify which benefits are tractable using corridor-scale evaluation with currently available data and where additional corridor-specific mapping or stakeholder input is necessary in the middle of transmission planning process.

Integration of Landscape Benefits into Transmission Planning

After addressing the challenge of measuring the benefits associated with different landscape-based features, the next challenge is how to integrate these benefits within current or new transmission planning processes. Arguably the least disruptive method to integrate landscape-based benefits into existing transmission planning procedures would be to use actuarial methods to convert landscape-based benefits into dollars. These in turn could be used in existing benefit cost analysis procedures such as those described in [25]. However, the process of converting landscape benefits into dollars may be challenging as well as highly subjective.

As a result, it may be easier to consider landscape-based benefits in their native units (e.g., miles of recreational trails, increased pollinator populations) in addition to more traditional reliability, financial, and policy-based benefits. Frequently, in situations where researchers are faced with an optimization problem with potentially competing objectives (maximizing landscape benefits while minimizing cost) a tool set commonly referred to as multi-criteria decision analysis (MCDA) is used [74]. Coincidently, many of the most well-established tools already used for traditional economic transmission planning (such as production costing and capacity expansion planning) already use a sub-field of MCDA called linear programming. However, their competing objectives are generally only ever expressed as costs.

Augmenting traditional planning tool capability to accommodate the inclusion of non-traditional benefits presents a compelling opportunity. For example, in [25] a package of new transmission lines is explored across the MISO footprint largely using production costing techniques. If planners could also compute the landscape-based benefits of these lines separately, they could then develop a Pareto Frontier consisting of traditional economic benefits and non-traditional landscape benefits. In the context of Fig. 1, a point belonging to the Pareto Frontier (and therefore worth considering as an optimal transmission planning solution) is one where no other point has more benefits than it in both dimensions displayed.

Alternatively for techniques like capacity expansion planning, where line investments are determined endogenously, traditional

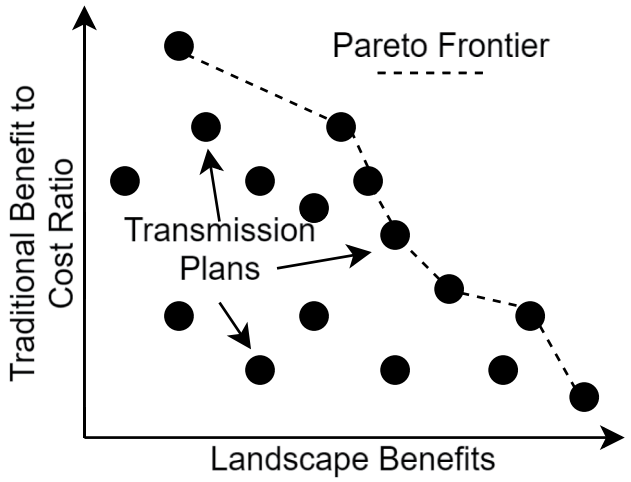


Fig. 1 Illustration of Pareto Frontier for transmission line investment evaluated using both traditional benefit to cost ratio and landscape benefits

economic and non-traditional landscape-based benefits could be optimized simultaneously within the CEP's linear programming algorithm through competing objective function terms.

Landscape Policy in Transmission Planning

Expanding transmission planning activities to accommodate landscape attributes is a technical challenge but also a policy design challenge. While transmission planning is generally executed based on engineering and finance considerations, these design parameters and modeling objectives are influenced by everything from available comprehensive data, industry standards, grid expansion drivers, assignable costs and risks from supply chain to permitting, and an operational balance between simplicity and stakeholder-driven objectives with complex optimization functions. For each of these technical attributes of transmission planning, policy plays a role.

Federal Policy on Transmission Planning and Development

Federal policies for energy systems operate with very broad strokes: national equipment manufacturing standards, tax credits, large-scale grid reliability oversight, market operation, administrative process guidelines. Recent notable federal policy initiatives (Table 3) illustrate the range but the non-specificity of federal transmission policy.

State Governance for Transmission Planning and Development

Transmission planning bodies such as grid operators and multi-utility coordinating entities are the interpreters of federal policy and increasingly, state policy. State policies

Table 3 Active signature federal policies on transmission development

Entity	Reference	Policy Space Where Landscape Interactions Surface
US DOE	Speed to Power [75]	Federal initiative to deploy infrastructure at speed and scale; anticipates significant increase in development and authorization activities from states and industry
FERC	Order 1920 [10]	Identifies new energy and system benefits from transmission development and operation, opens to allowance for additional benefits and metrics (that might include landscape) beyond the defined seven standard types and related goals
White House	Executive Order—Strengthening the Reliability and Security of the United States Electrical Grid (April 8, 2025) [76]	Directs risk-based evaluation of grid performance and emphasizes future investment or otherwise retention of transitioning grid assets in order to ensure reliable and secure electric system performance
Congress	Federal Energy Regulatory Commission (FERC) "backstop" transmission authorization [77]	Authorizes federal action to site electric transmission facilities under certain criteria, such as the facility's location within a designated priority area, benefits to consumers, and whether the proposed facility leverages existing infrastructure and corridors

deal with critical themes in transmission development such as specific land use, economic and public interests, and tradeoffs between public services and spatial management goals. Furthermore, they have a wide range of common mechanisms to deploy these policies such as legislation, administrative rule, energy strategy, working groups, studies, governance and agency design, and in other state mission space strategies.

The most common state policies affecting transmission planning development (Table 4) are not energy policies, they are protection policies—land protections and regulatory pressures that push development to *avoid* specific areas or interactions. These policies are centered around what not to do. The focus on avoidance along with a regulatory process form a de facto armature of state policy.

States are the primary entity to authorize new transmission development, but this authority varies by line proponent and scale of development. In the West, federal Power Marketing Administrations – Bonneville Power Administration and Western Area Power Administration – operate a very large transmission network and build new transmission facilities with regularity. As transmission development proponents, they conduct their own environmental review activities and seek local permits as necessary. When states

Table 4 Common state roles for transmission permitting

State Function	Role in Transmission—Landscape Nexus
Public Utility Commission (PUC)	• Issues Certificate of Public Convenience and Necessity (CPCN) or central transmission siting authorization for facilities within its jurisdiction
	• Determines need and purpose for electricity transmission – why the transmission line or network build is important for electric service
	• With State Energy Office, interacts with larger standards bodies, such as national and interconnection reliability standards
Land Use and Land Management	• Authorizes use of state lands (independent permit)
	• Sets statewide land use governance structures and regulations for local land use agencies to follow, including county conditional use permits for smaller-scale (length, voltage) transmission facilities
	• Manages tradeoffs between statewide land use goals for protection and for development
State Energy Office (SEO)	• Analyzes statewide energy futures, broader public interest, and the role of transmission and transmission alternatives
	• Evaluates and incentivizes innovation and technology – works outside the line-specific context
	• With Public Utility Commission (PUC), supports statewide data development on existing systems and facilities
	• With PUC, monitors interdependencies with neighboring states, regions, and grid-scale units (e.g. ISO/RTOs, interconnections)
	• Implements related state energy policies (e.g. portfolio standards, tax credits), typically promotion of energy development
	• May administer siting process or provide technical support to siting authorization
Transportation	• Issues and implements state utility accommodation policies, which govern eligibility and process for siting powerlines within transportation right of way (ROW)
Natural Resources	• Issues authorizations for effects on fish and wildfire, air and water quality, and for consistency with state natural resource policies
	• Evaluates resource-based effects under state environmental review policies, including state NEPA-like review processes commonly called "SEPA"

do authorize private transmission development, from either investor-owned utilities or merchant developers, jurisdiction from state to state varies widely, is highly heterogenous with no regional clustering. Many states also limit their jurisdictional facilities by scale, either voltage level, length, number of crossings of county lines, and even environmental triggers (Fig. 2). For a detailed review, please visit this reference on state authorities [78].

Emerging State Policies for Landscape Benefits in Transmission Development

This section outlines the emerging category of state policies that drive development positively and create places to site transmission. In the past, states have gone as far as creating "opportunity" zones of land for development, intended to incentivize developers through accelerated permitting processes (e.g. Texas CREZ).

Other states have clear prioritization and incentives for development in transmission, through transportation policy or land use management. One mature example is the state of Wisconsin's policy to utilize transportation corridors for transmission development. Established in 2003, the program today involves dedicated Department of Transportation staff, a program manual, and a successful suite of practices for developers to follow. Other states use simpler mechanics of prioritization, such as a demonstration of investigation of alternatives before a specific corridor is proposed.

Utilizing existing corridors is referenced as a policy priority in FERC transmission backstop authority referenced above in Table 4. Evaluating existing utility corridors is already in practice by some transmission planners [25], showing how transmission planning can accommodate landscape goals of reduced footprints, faster permitting, and improving existing infrastructure.

In 2025 several state legislatures considered bills with explicit language to prioritize existing corridors and transportation right of way including rail [78]. Colorado successfully passed a law in 2025 with a Site Prioritization Order provision, specifying this order of preferred development: "Existing utility corridors, including advanced transmission technology upgrades; State highway rights-of-way; New utility corridors." See Table 5 below.

A common feature of proposed Site Prioritization Order provisions is to create a clear public interest in first using existing utility corridors for transmission development. The public benefit remains one of avoiding new corridor effects, but it also can be beneficial to developers. These corridors should already meet safety and reliability design standards, and they are already "on the map" for capacity expansion and grid modeling evaluation, interconnection, and other substantiating analysis. (Still, structural engineering, easement and land use authorizations, and resource sharing agreements between corridor managers will need to be updated.) From a governance and process policy perspective, states such as Pennsylvania and North Carolina are creating fast-track process approvals for line authorizations in existing corridors, as an incentive to developers [87].

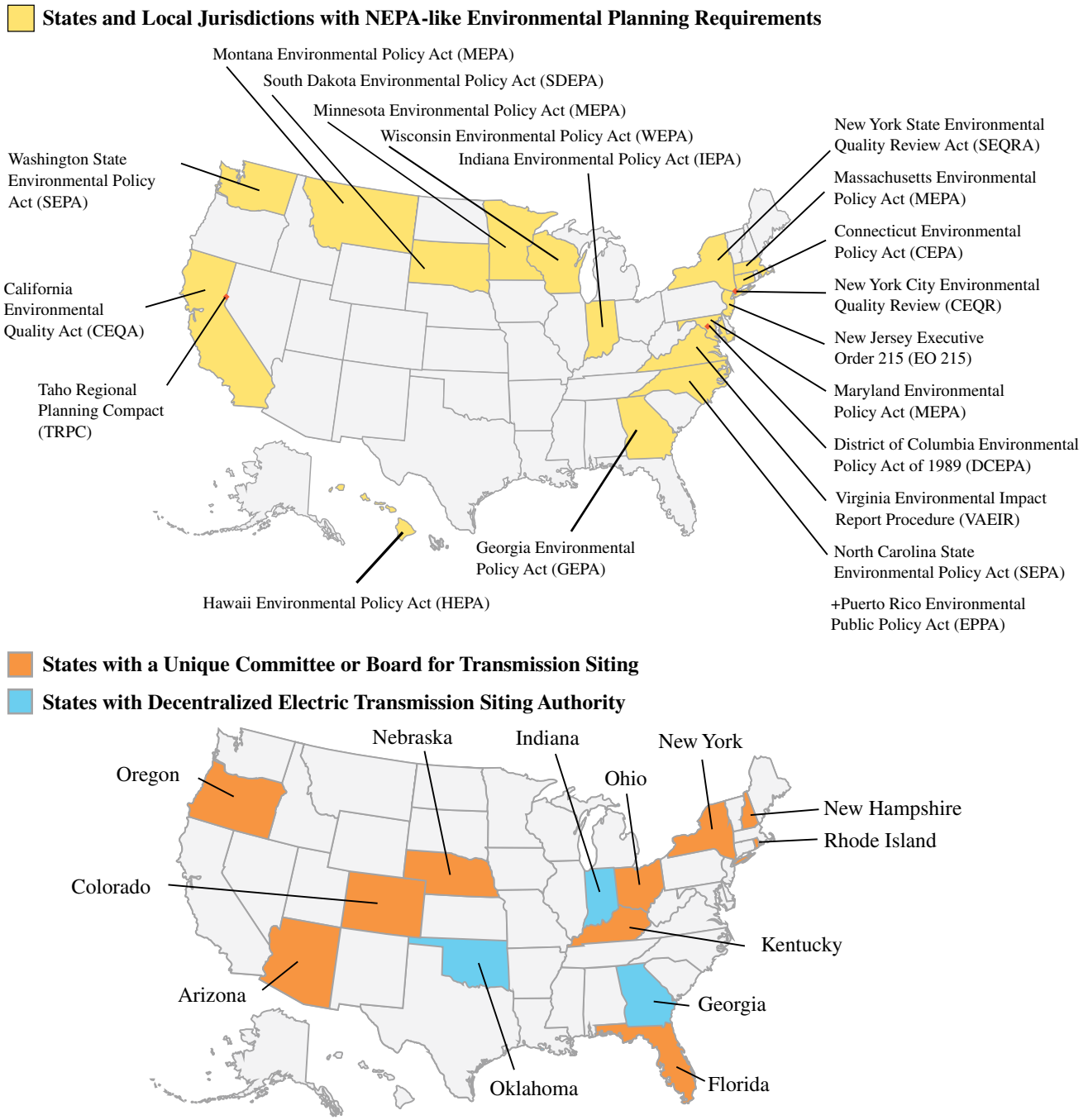


Fig. 2 Differentiating attributes in state siting authority [78]. "U.S. State basemaps, adapted from [79], under CC-BY-4.0 license"

A second pathway to fulfilling this policy is to coordinate transportation corridors with transmission development. To follow this direction in state energy policy, state transportation policies called Utility Accommodation Policies or UAPs are shifting to allow for powerline development in transportation rights of way, enhancing the value of corridor and public space [88]. State UAPs dominantly disallow development of transmission facilities within the right of way [78], but this policy appears to be a relic of a standard action decades ago. Today, states are re-examining and adjusting these policies to fit with land use and energy investment strategies [89].

Classical state policies avoid interactions with protected resources, and transmission planning has reflected these pressures through cost adders and re-routing. As state

Table 5 Example state policy frameworks for transmission development that promote landscape and public spatial benefits

States with Statutory Promotion for Use of Highway ROW for Transmission	
Delaware	Promotes use of transportation ROW for renewable energy projects over 30 MW and connected to PJM transmission grid (2024) [80]
Florida	Transportation department shall accommodate 69 kV or higher lines for baseload power (2021) [81]
Minnesota	Permits longitudinal transmission and requires consideration of ROW during the transmission permit application process (2024) [82]
Wisconsin	Comprehensive energy policy promoting use of transportation ROW (2003) [83]
Maine, New Hampshire	Energy policy promoting transmission siting on specific named interstates and routes (Maine 2010, New Hampshire 2016) [84, 85]
Colorado	Bill (H.B. 25–1292) has passed in 2025—It enables transmission development within state highway ROWs [86]

policies evolve to drive transmission development toward existing corridors, transmission planning can mirror this direction by inspecting its own data resources, creating realistic scenarios that co-locate transfer capacity needs with existing rights of way, and bring forward transmission development packages that can effectively navigate positive state policy and process advantages.

Conclusions

Traditionally, transmission planning in the electric power industry has primarily been driven by reliability, economic, and public policy considerations. However, planners are starting to question if traditional benefit analysis is too narrowly defined. Specifically, there is a growing interest in understanding what landscape features contribute to the overall benefits of new transmission. Recent landmark regulation, such as FERC Order 1920, appear to be compatible with expanding the definition of transmission benefits since it allows for additional benefit metrics beyond the seven explicitly defined standard types.

Thus, there is an urgent need for planners, policy makers, and researchers to better understand how landscape benefits might be included in transmission planning. The purpose of this work is to help initiate this conversation by identifying pertinent landscape benefits applicable to transmission development. Additionally, this work evaluates the opportunities and challenges associated with including landscape benefits in transmission planning, such as how difficult landscape benefits are to measure using existing tools, data, and techniques, what techniques are most appropriate for measuring landscape benefits, and how landscape benefits might be combined with more traditional metrics in industry grade transmission planning tools.

Key References

- MISO, "2024 MISO Transmission Expansion Plan," Midcontinent Independent System Operator, Inc., 2024. Accessed: Dec. 12, 2025. [Online]. Available: https://cdn.misoenergy.org/MTEP24720395.zip

  This reference demonstrates state of the art in how interregional transmission is performed by Midwest Independent System Operator (MISO) using Benefit Cost Analysis. Key portions of the report relevant to this work include Figure 2.137 on page 142 which enumerates benefits captured by different factors as well as total benefits and total costs of the associated transmission package under study. This is then followed by a high-level description of how each of those benefits is computed (pages 142–162).

- M. Garfinkel, S. Hosler, M. Roberts, J. Vogt, C. Whelan, and E. Minor, "Balancing the management of powerline right-of-way corridors for humans and nature," J. Environ. Manage., vol. 330, p. 117175, Mar. 2023. https://doi.org/10.1016/j.jenvman.2022.117175.

  This reference strengthens our argument that the future of transmission planning should move beyond an engineering focused view of ROWs and instead treat them as multifunctional landscape systems with ecological and community value. It is particularly useful because it provides empirical support for the compatibility of wildlife habitat and human activity within transmission ROWs.

- J. Yin, Q. Wei, D. Shao, Z. Luo, and L. Ji, "The impacts of power transmission and transformation projects on ecological corridors and landscape connectivity: a case study of Shandong province, China," *Sci. Rep.*, vol. 15, no. 1, p. 6709, Feb. 2025. https://doi.org/10.1038/s41598-025-91474-2.

  This reference was useful for our manuscript because it strengthens the argument that future transmission planning should consider corridor-scale

ecological connectivity, not just site-level environmental effects. By using morphological spatial pattern analysis and least-cost path analysis, the paper offers a spatial framework for identifying ecological sources, resistance, corridors, and key nodes that can inform routing and mitigation more systematically.

- E. Arango, M. Nogal, H. S. Sousa, J. C. Matos, and M. G. Stewart, "GIS-based methodology for prioritization of preparedness interventions on road transport under wildfire events," *Int. J. Disaster Risk Reduct.*, vol. 99, p. 104126, Dec. 2023. https://doi.org/10.1016/j.ijdrr.2023.104126.

  This reference was useful because it helped us think through how future benefits and intervention priorities can be translated into a spatially explicit planning structure through GIS. It offers a helpful framework for organizing, mapping, and comparing multiple conditions in ways that support future decision-making.

- D. L. Wagner, K. J. Metzler, and H. Frye, "Importance of transmission line corridors for conservation of native bees and other wildlife," *Biol. Conserv.*, vol. 235, pp. 147–156, Jul. 2019. https://doi.org/10.1016/j.biocon.2019.03.042.

  This reference was useful because it gives strong empirical support for the claim that transmission corridors can function as active infrastructure that support biodiversity, not just residual utility spaces. In this manuscript, it helps substantiate the argument that well-managed corridors can generate real conservation value including pollinators and rare species, under ordinary maintenance regimes.

- Å. Berg, K.-O. Bergman, J. Wissman, M. Żmihorski, and E. Öckinger, "Power-line corridors as source habitat for butterflies in forest landscapes," *Biol. Conserv.*, vol. 201, pp. 320–326, Sep. 2016. https://doi.org/10.1016/j.biocon.2016.07.034.

  This reference was useful because it suggests that corridor benefits may extend beyond the corridor footprint itself, with spillover effects into surrounding habitats. That helped argue that future corridor planning should consider not only on-site habitat value, but also broader landscape-scale benefit and connectivity.

- M. D'Amico, I. Catry, R. C. Martins, F. Ascensão, R. Barrientos, and F. Moreira, "Bird on the wire: Landscape planning considering costs and benefits for bird populations coexisting with power lines," *Ambio*, vol. 47, no. 6, pp. 650–656, Oct. 2018. https://doi.org/10.1007/s13280-018-1025-z.

  This reference was useful because it supports landscape-scale strategic routing as part of future transmission planning, and it suggests that following already existing linear infrastructure may help reduce additional ecological conflict. This was also helpful for thinking about road or infrastructure proximity not as an automatic benefit, but as a possible spatial criterion within a broader routing strategy.

- J. Dupras, C. Patry, R. Tittler, A. Gonzalez, M. Alam, and C. Messier, "Management of vegetation under electric distribution lines will affect the supply of multiple ecosystem services," *Land Use Policy*, vol. 51, pp. 66–75, Feb. 2016. https://doi.org/10.1016/j.landusepol.2015.11.005.

  This reference was useful because it frames corridor vegetation management as a question of multiple ecosystem services outcomes, rather than simple vegetation clearance. It helps this manuscript argue that future transmission planning should evaluate management options in terms of tradeoffs and ecosystem services, not only operational safety.

- B. C. Sherrouse, J. M. Clement, and D. J. Semmens, "A GIS application for assessing, mapping, and quantifying the social values of ecosystem services," *Appl. Geogr.*, vol. 31, no. 2, pp. 748–760, Apr. 2011. https://doi.org/10.1016/j.apgeog.2010.08.002.

  This reference helped us think through how social and cultural values can be translated into spatially explicit GIS framework, rather than being treated as vague qualitative considerations. It was especially useful for the part of our draft that pushes toward future planning tools that can map and compare community corridor benefits across space.

- D. I. King, R. B. Chandler, J. M. Collins, W. R. Petersen, and T. E. Lautzenheiser, "Effects of width, edge and habitat on the abundance and nesting success of scrub–shrub birds in powerline corridors," *Biol. Conserv.*, vol. 142, no. 11, pp. 2672–2680, Nov. 2009. https://doi.org/10.1016/j.biocon.2009.06.016.

  This reference was useful because it shows that the conservation value of powerline corridors depends not just on their existence, but on specific design conditions such as width and edge effects. It helps support a more concrete future-planning argument: corridor benefits are shaped by spatial configuration and management design and planning, not simply by labeling ROWs as habitat.

- M. M. Gardiner, C. B. Riley, R. Bommarco, and E. Öckinger, "Rights-of-way: a potential conservation resource," *Front. Ecol. Environ.*, vol. 16, no. 3, pp. 149–158, Apr. 2018. https://doi.org/10.1002/fee.1778.

  This reference was especially useful for the broader framing of this manuscript because it positions rights-of-ways (ROWs) as widespread linear habitats with real conservation potential, while also warning against overclaiming their value without population-level evidence. It helped keep our argument balanced: ROWs may be important multifunctional spaces, but their benefits have to be evaluated beyond simple species presence.

Appendix 1

Table 6 Detailed description for key modeling factors associated with select transmission benefits

Benefit Types	Category and Indicators and modeling approaches	Descriptions
Recreation Trails	**Recreation Trails** Trail-suitable slope (slope 0–10%)	Evaluate trail installation feasibility based on geomorphological conditions (obtained from DEM and LiDAR) for accessible and gentle grades [48]
Ecological Connectivity Support	Raster Cell-level habitat resistance surface from land cover, roads, slope, and barriers (unitless)	Represent the landscape as a grid in which each cell is given a "resistance" score based on land cover, roads, slope, and barriers (low values mean movement is easy, high values mean it is difficulty or unlikely). This resistance surface is the foundational map that later connectivity tools [49, 51, 52]
	Least-cost distance/corridor suitability index (unitless)	Uses the resistance surface like a "toll map" to trace the route between habitat patches that has the lowest accumulated cost, similar to how a navigation app finds the fastest drive. The resulting least-cost paths highlight one or a few optimal corridors that are most efficient for movement and therefore high-priority for protection or restoration [51]
	Current–density-based connectivity index (or score-based connectivity index) (unitless)	Builds on the same resistance surface but treats animal movement like electrical current that can flow along many possible routes, not just a single optimal path. The model shows where this "current" concentrates (high current density), revealing critical corridors and pinch points where connectivity is most vulnerable as well as areas with redundant pathways [50]
	Fragmentation metrics (patch size (ha), edge density (m/ha), road density (km/km^2), proximity to protected/riparian areas (km)	Quantify habitat fragmentation using patch size, edge density, road density, and combines this with distance to protected areas and riparian networks to identify where habitats are most isolated or exposed to edge effects [51]
Native species and early successional habitat support	Extent of native species or early successional habitat (% corridor area; ha)	Define early-successional habitat (e.g., herbaceous/shrub/young forest structure) and compute the area/percent of ROW meeting that condition (corridor-wide or by segment). This could become a base layer for later patch/edge metrics [28, 90]
	Patch configuration of native species or early successional plant species for IVM (mean patch size (ha), edge density (m/ha), Edge-to-Core Ratio (%)	Convert the native species or early successional layer into patches and compute patch size + edge density. This would distinguish "long thin strips" vs. "wider nodes/blocks", around corridors, and would help target where early-successional habitat is large enough to matter for focal wildlife species (birds, small mammals) rather than being purely edge [53, 55, 56]
	Native species and early successional habitat scoring—suitability proxy (0–1 or 0–100; unitless)	Assign land-cover/vegetation classes a habitat-quality weight (e.g., native meadow/shrub = higher score, but turf/impervious/invasive species presence = lower score). Then compute an average quality score per segment. (IVM maintenance/treatment frequency can be incorporated into the total score) [53, 54, 90]

Table 6 (continued)

Benefit Types	Category and Indicators and modeling approaches	Descriptions
Pollinator support	Forage potential estimation by land cover (grassland/ herbaceous/shrub cover, edge habitat) (Low/Medium/High)	Estimate floral potential by mapping land-cover types that provide nectar and pollen resources (e.g., grassland, herbaceous and shrub cover, and edge habitats) and summarizing their extent and configuration within relevant bees' foraging distances (e.g., 0.5–1 mile) [59]
	Nesting potential estimation (soil drainage/texture for ground nesters; woody structure) (unitless)	Estimate nesting potential by combining soil characteristics/drainage and bare-ground availability for ground nesting bees with woody structure (woody stems and dead wood) [57, 60]
	Landscape context & connectivity evaluation (percentage (%) of continuous natural within multi-scale buffers 0.5 mile, 1 mile; bee flying range) to estimate forage potential	Quantify the percentage and continuity of semi-natural habitat within multi-scale buffers around the corridor (e.g., 0.5-1mile) to represent landscape-scale resource availability and connectivity across typical bee foraging ranges [59]
	Screening pollinator risk stressors	Screens for key stressors to pollinators such as intensive pesticide used area, high road or traffic density, and loss of semi-natural land cover, to identify areas where risk is elevated despite good nesting conditions [58]
Regulating services support	Heat mitigation (‘C/‘F) (CFD-based microclimate modeling: Rhino-grasshopper: Ladybug, Butterfly), Envi-Met)	Represent a site as a 3D model and run CFD-based microclimate simulations using local climate data (e.g., temperature, humidity, wind speed, solar irradiance) and spatial context (vegetation, surface materials, structures) to quantify heat-mitigation (evapotranspiration rate, albedo, emissivity, Leaf Area Index and etc. are the sample vegetation inputs for the analysis) [63, 64]
	Stormwater runoff potential reduction (SWMM, PCSWW, HEC-RAS)	Represent the site as a 2D drainage model and uses SWMM, PCSWMM, or HEC-RAS to simulate runoff generation, routing, infiltration, and storage, estimating the potential for stormwater volume and peak-flow reduction under various design alternatives [61, 65]
	Erosion/water quality risk reduction	Assesses erosion and water-quality risk by combining slope, soil erodibility, land cover, and flow accumulation to identify locations where concentrated runoff or disturbed soils are likely to mobilize sediment and pollutants [62]
Wildfire resilience	Wildfire hazard exposure (unitless, 0–1)	Maps wildfire hazard exposure for the corridor and adjacent assets using modeled burn probability and fire intensity, highlighting segments where transmission infrastructure and nearby communities might face the greatest potential impacts [69]
	Fuels and fuel continuity (g/ha)	Assess surface and canopy fuel types, loads, and horizontal/vertical continuity (e.g., using LANDFIRE fuel models) to identify where fuel conditions could support high-intensity of fast-spreading fires and where treatments would most effectively break continuity [67]
	Topographic evaluation through slope (%) and aspects	Evaluate slope, aspect, and related topographic factors that can influence fire spread, intensity, and access for suppression, helping to distinguish inherently high-hazard terrain from locations where fuels or design changes can significantly reduce risk [70]
	WUI proximity and assets-at-risk	Maps proximity to wildland-urban interface communities and other critical assets (e.g., substations, roads, school) to flag corridor segments where ignitions or line failure would pose the greatest risk to people and property [66, 71]
	Accessibility for maintenance	Assess road and trail access, by considering slope and surface condition to determine how easily people can reach out structures for routine inspections, vegetation management, and emergency response [68]
Shared community & local wealth building	Perceived social value mapping (SolVES)	Use SolVES to map perceived social values (e.g., recreation, aesthetics, learning, stewardship) from PPGIS survey points, and capture valued hotspots Identify high-value or high-conflict zones to guide where programming/partnerships are socially feasible [43]
	Recreation demand and visitation (InVEST)	Apply InVEST recreation and accessibility model to estimate relative recreation demand and visitation intensity, combining predicted use with travel-time and population data to approximate potential user per day and associated local economic benefits ($/year or $/season) [72, 73]
	Net Present Value (NPV)	Various tools have discounted cash flows modeled within

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Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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