

A delivery gap in electricity grid expansion

Damiano Alessi

Institute for Data, Energy, and Sustainability, Vienna University of Economics and Business (WU Vienna)

Behnam Zakeri

Institute for Data, Energy, and Sustainability, Vienna University of Economics and Business (WU Vienna)

<https://orcid.org/0000-0001-9647-2878>

Kavita Surana

kavita.surana@wu.ac.at

Institute for Data, Energy, and Sustainability, Vienna University of Economics and Business (WU Vienna)

<https://orcid.org/0000-0003-2424-7406>

Article

Keywords:

Posted Date: October 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10550866/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

A delivery gap in electricity grid expansion

Damiano Alessi^{1*}, Behnam Zakeri¹ and Kavita Surana^{1,2*}

¹Institute for Data, Energy and Sustainability, Vienna University of Economics and Business, Vienna, Austria .

²Complexity Science Hub, Vienna, Austria .

*Corresponding author(s). E-mail(s): damiano.alessi@wu.ac.at;
kavita.surana@wu.ac.at;

Contributing authors: behnam.zakeri@wu.ac.at;

Abstract

Expanding transmission grids is critical for meeting climate and energy goals worldwide, but the process is slow and prone to delay. Despite a growing consensus that current deployment rates are incompatible with the urgency of the energy transition, empirical evidence quantifying these delays remains scarce. We address this gap with a novel dataset of over 900 European transmission investments over a 16-year timeframe, covering the major cross-border interconnectors and internal grid reinforcements. Commissioning timelines average 14.1 years, exceeding official estimates of 10 years. Administrative and planning phases, including permitting, account for over 70% of this duration. 55% of investments face delays averaging 4.7 years and nearly half of the announced investments are ultimately canceled. We argue this reflects promoters treating development rights as options to build rather than commitments. The result is an inflated investment pipeline that overstates deliverable grid capacity, with direct implications for how transmission plans inform 2040 climate and energy targets.

Historically, infrastructure deployment has served as a benchmark for administrative capacity¹. However, through millennia of progress, the deployment of such projects has remained a lengthy and difficult process. An unexpected parallel emerges when comparing eras: the Aqua Claudia, one of the most important Roman aqueducts, required 14 years to complete (38–52 AD)², a duration similar to the median delivery time of cross-border transmission lines in 21st-century Europe. While technological capabilities have evolved, the structural challenges of infrastructure remain constant. Today, however, this length poses a major obstacle to global climate and economic ambitions^{3–6}. This challenge is particularly critical in Europe, where, as Mario Draghi recently emphasized, rapidly deploying the power grid is fundamental for sustaining industrial competitiveness and meeting decarbonization targets⁷. Despite a growing political consensus that current deployment rates are incompatible with the energy transition’s urgency^{3,8–10}, empirical evidence quantifying this length and delay remains scarce. Using Europe’s standardized multi-decadal planning framework, this paper develops a novel dataset of more than 900 investments across 16 years of planning (2010–2026) to analyze how fast does transmission grid deployment proceed and what are the primary drivers of its delays and failures?

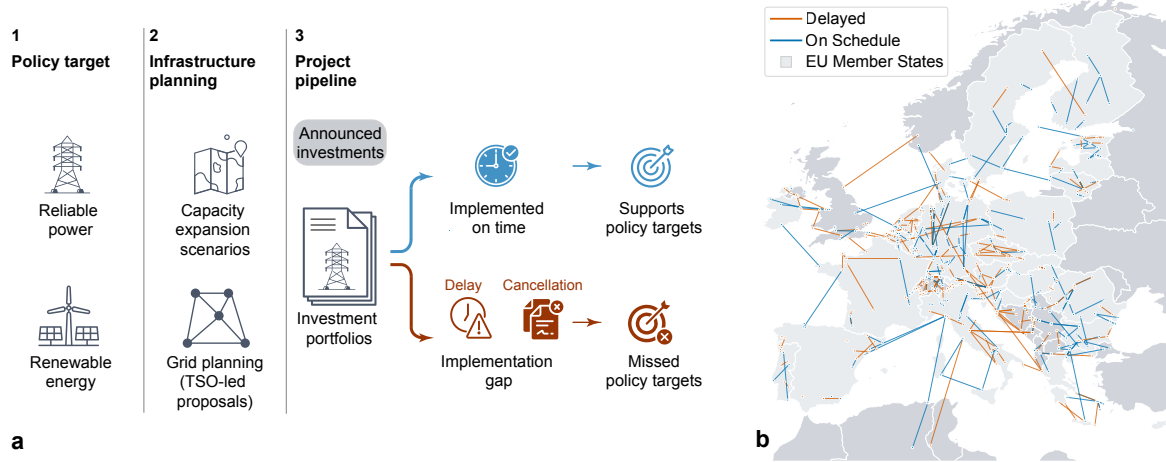


Fig. 1: Implementation status and jurisdictional landscape of the TYNDP investment portfolio ($N = 965$). **a**, Conceptual framework of grid expansion. Top-down policy targets drive institutional network planning, generating an investment pipeline that empirically splits into two outcomes: on-time implementation supporting policy goals (blue), or delays and cancellations leading to delivery gaps (red). **b**, Spatial distribution of investments included in TYNDP cycles (2010–2026). Red lines denote delayed investments; blue lines represent investments on schedule or completed. The map includes only investments with precise geographic coordinates; those with ambiguous or offshore locations are excluded.

Large megaprojects are notoriously slow and prone to failure. As documented in economic literature, they rarely escape Flyvbjerg’s “Iron Law”: “over budget, over time, over and over again”¹¹. Linear infrastructures—such as aqueducts, long-distance railways, and pipelines—face even greater complexity. Because they span vast geographical areas and cross multiple jurisdictions, they trigger fragmented governance structures that create administrative bottlenecks. Like all energy infrastructure, transmission lines must also meet stringent environmental requirements. These procedures often operate sequentially rather than in parallel, frequently accounting for more than half of the total implementation timeline^{9,10,12}. Moreover, as administrative and environmental standards have become increasingly complex, bureaucratic hurdles can now reach a threshold where they actively disincentivize investment, leading projects to be cancelled before construction even begins¹³. Furthermore, power lines suffer heavily from public opposition. Unlike generation facilities, which can offer local economic benefits or tax revenues, high-voltage lines impose concentrated local burdens in exchange for diffuse, system-wide benefits^{14–17}. This resistance often results in formal legal appeals, protracted public consultations, and blocked land acquisitions, which severely exacerbate existing permitting bottlenecks¹⁶. These delays are compounded by surging global demand for grid technologies, stretching lead times and escalating costs.^{3,10,18} Finally, transmission planning is subject to coordination failure; it must adapt to the evolving development of generation plants, where any shift in generation investment may disrupt grid construction schedules^{3,19}.

Despite the importance of building out electric grid infrastructure in the face of compounding bottlenecks, scholars and policymakers have little empirical understanding of transmission deployment. Historically, research has focused on renewable generation technologies, leaving the associated grid infrastructure under-studied. Existing literature on transmission delays predominantly relies on single-project case studies or country-specific qualitative analyses^{20–22}; while valuable, they lack the scale required for generalizability. Consequently, grid planning still depends on forward-looking projections often plagued by optimism bias regarding project timelines¹¹.

This study provides the first large-scale empirical assessment of electricity transmission deployment using a novel multi-decadal, continental dataset. Europe provides the ideal environment for this analysis. The European power system is the largest synchronous grid globally, serving over 500 million customers³. To coordinate this massive infrastructure, the European Network of Transmission System Operators for Electricity (ENTSO-E) employs a centralized methodology through the biennial Ten-Year Network Development Plan (TYNDP), which serves as an official assessment for

several planning and regulatory processes²³. This positions the TYNDP not merely as an engineering roadmap, but as the primary pipeline for capturing political support and public capital⁹. The regulatory framework governing this investment pipeline has evolved substantially since the TYNDP was established in 2009, shifting toward integrated supranational planning, changes we account for in our models (Supplementary Note 1). Within this framework, individual Transmission System Operators (TSOs) act as primary promoters of the project²³. Tasked with the legal mandate to expand the high-voltage grid, they formulate and submit investment proposals, making their strategic behavior and risk management central to the actual deployment of the European network. Here, we treat the European power system as a representative set for grid deployment, harmonizing 16 years of planning records across 43 countries (Figure 1). This allows us to establish the empirical lifecycle of transmission expansion, isolate the institutional and technical factors that govern its pace, and trace the origins of the delays and cancellations that affect the investment pipeline. These patterns point beyond timelines: they suggest that when the location of future generation and demand is uncertain, promoters hold planned capacity as an option rather than a firm commitment. We argue that this dynamic threatens the credibility of Europe’s 2040 targets and leads to direct economic and emissions costs.

Duration and phases of transmission development

Analysts estimate that transmission deployment often exceeds a decade^{3,24,25}, yet incomplete datasets lead to wide approximations rather than realistic empirical quantification. Although raw TYNDP data imply a median 10-year lifecycle, this figure is skewed by two statistical artifacts. Left-truncation, i.e., omission of investments that entered the pipeline at an advanced stage, undercounts early-stage durations. Conversely, right-censoring, i.e., recording ongoing investments under optimistic deadlines, masks late-stage overruns and fails to capture subsequent delays.

To address this gap in understanding of the timescales of transmission development, we first developed a novel dataset of European transmission grid expansion²⁶ (see Methods and Supplementary Note 2) and then disaggregated the investment lifecycle of European grid expansion into five sequential phases: (1) *Consideration*, encompassing needs assessment and feasibility; (2) *Planning*, involving engineering and route evaluation; (3) *Design and Permitting*, requiring environmental and statutory clearances; (4) *Construction*, representing physical implementation, (5) *Commissioned*, representing when an investment-related upgrade or project enters operation (Figure 2a). We also note that investments may be (6) cancelled at various phases before they are commissioned.

The phase-specific disaggregation of the completed investments extends the empirical duration to 13.1 years (Figure 2b). However, because this metric reflects only historical successes, it constitutes a conservative lower bound that fails to account for accumulated delays in the existing project pipeline.

To correct for these truncation and censoring effects, we employed an absorbing Markov chain model to isolate the success path from project cancellations (see Methods). This approach indicates that a transmission investment entering the Consideration phase requires an expected 14.1 (95% CI [13.1, 15.2]) years to reach commissioning, with a cumulative success probability of only 12.2% (Figure 2c). Physical construction requires an expected 3.8 years—accounting for only 27% of the total lifecycle, while the remaining 73% is consumed by administrative and planning requirements. The 14.1 years expectation accounts for a pronounced long tail, which reflects bottlenecks in infrastructure buildout rather than statistical anomalies.

Drivers of transmission project duration

Although investments take 14.1 years on average, deployment timelines vary depending on the specific context. To understand what drives these differences, we used a multi-state Cox model to identify how geography, investment type, and policy changes act as accelerators or bottlenecks throughout the lifecycle (Figure 3)(see Methods and Supplementary Note 3).

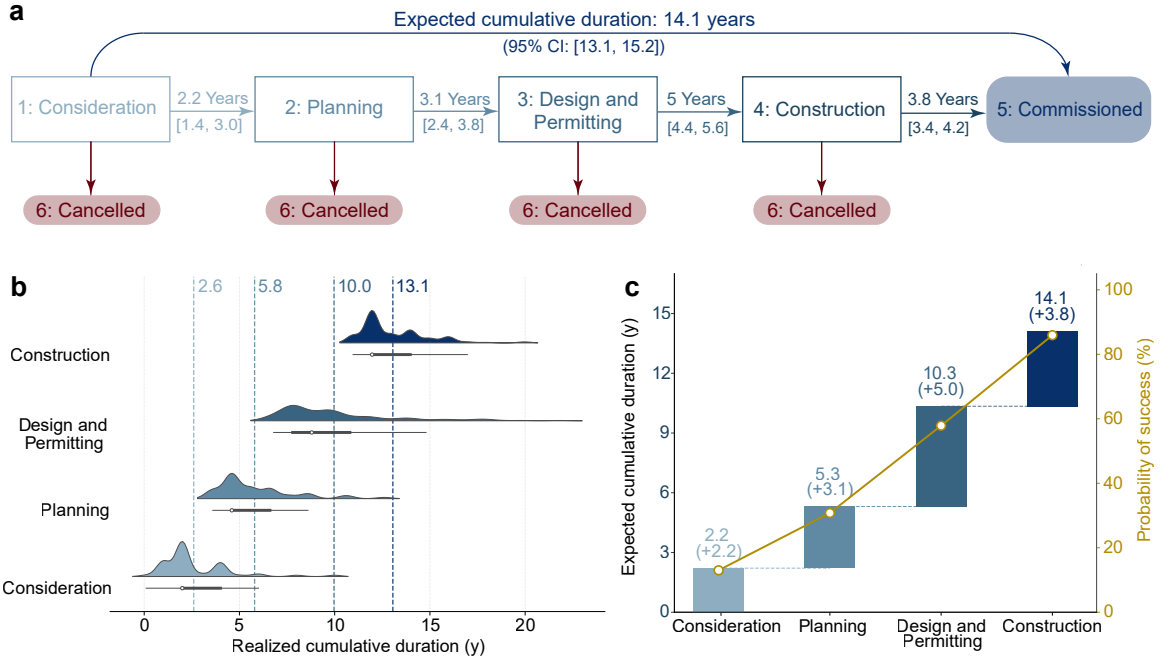


Fig. 2: Implementation timeline, empirical duration variance, and attrition of European transmission investments ($N = 965$). **a**, Schematic representation of the multi-state transition model defining the infrastructure lifecycle. **b**, Raincloud plot illustrating the empirical distribution of transition durations for completed project phases ($N \approx 120$ per phase). The multimodal peaks reflect the biennial cadence of TYNDP reporting cycles (2010–2026). Boxplots denote the median and interquartile range (IQR). **c**, Cumulative expected durations and phase-specific success probabilities derived from the absorbing Markov chain model (based on $n = 1331$ observed phase transitions)..

The jurisdictional and regulatory context strongly influences the speed of development, particularly at the start of a project. Within the European Union (EU), investments advance 159% faster through the Consideration phase than investments involving Extra-EU countries (Table 1). Cross-border status provides a similar early-stage acceleration of 80%, aligning with the centralized coordination provided by the TYNDP framework and Project of Common Interest (PCI) status²⁷. However, while the speed advantage for cross-border investments is temporary, the broader EU effect persists.

Although the literature suggests upgrades are faster than greenfield investments^{25,28}, our results show that this advantage is limited to Design and Permitting. In this phase, upgrades move 95% faster, but they provide no meaningful acceleration during Planning or Construction phases. This indicates that using existing corridors helps with specific permits but does not shorten the entire investment lifecycle.

EU reforms impacting the TYNDP since 2018—specifically the revised EIA directive (2014/52/EU) and Regulation (EU) No 347/2013 (See Supplementary Note 1)—have accelerated deployment, boosting permitting speed by over 400%, likely reflecting the sudden advancement of historically stalled investments. Conversely, the COVID-19 pandemic slowed advancement during the 2022–2024 cycles, with the most acute delays occurring in the Design and Permitting phase, where it reduced transition intensity by 90%.

Table 1: Structural and temporal drivers of project advancement. Results from the multi-state Cox regression estimating the impact of jurisdictional, technical, and policy factors on the transition to successive development phases. The model is stratified by project environment and baseline states. Hazard Ratios (HR) > 1 indicate an acceleration of the phase, while HR < 1 indicate a delay. For example, an HR of 2.59 for EU Member projects in the Consideration phase indicates that they advance through this phase 159% faster than non-EU projects.

	Consideration	Planning	Design and Permitting	Construction
Variable	HR (<i>p-val</i>)	HR (<i>p-val</i>)	HR (<i>p-val</i>)	HR (<i>p-val</i>)
Region: EU Member	2.59*** (<0.001)	0.99 (0.978)	1.96** (0.010)	2.02** (0.003)
Jurisdiction: Cross-border	1.80** (0.010)	1.10 (0.708)	1.24 (0.275)	1.13 (0.508)
Infr. Type: Upgrade	0.65 (0.117)	1.13 (0.650)	1.95* (0.012)	0.99 (0.969)
Covid-19 Impact	0.18*** (<0.001)	0.15*** (<0.001)	0.10*** (<0.001)	0.34*** (<0.001)
New EU reforms	3.45*** (<0.001)	1.91* (0.021)	5.45*** (<0.001)	2.29* (0.010)
Elem: Nodal Infr.	0.71 (0.223)	1.36 (0.265)	1.65. (0.050)	0.80 (0.417)
Tech: DC	0.36*** (<0.001)	1.43 (0.168)	0.94 (0.879)	1.15 (0.640)

$n = 1082$, events=839. Concordance=0.716. Model uses Efron approximation for discrete-time ties. Full regression results, including 95% Confidence Intervals, are provided in Supplementary Table 2. Significance levels: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, . $p < 0.1$

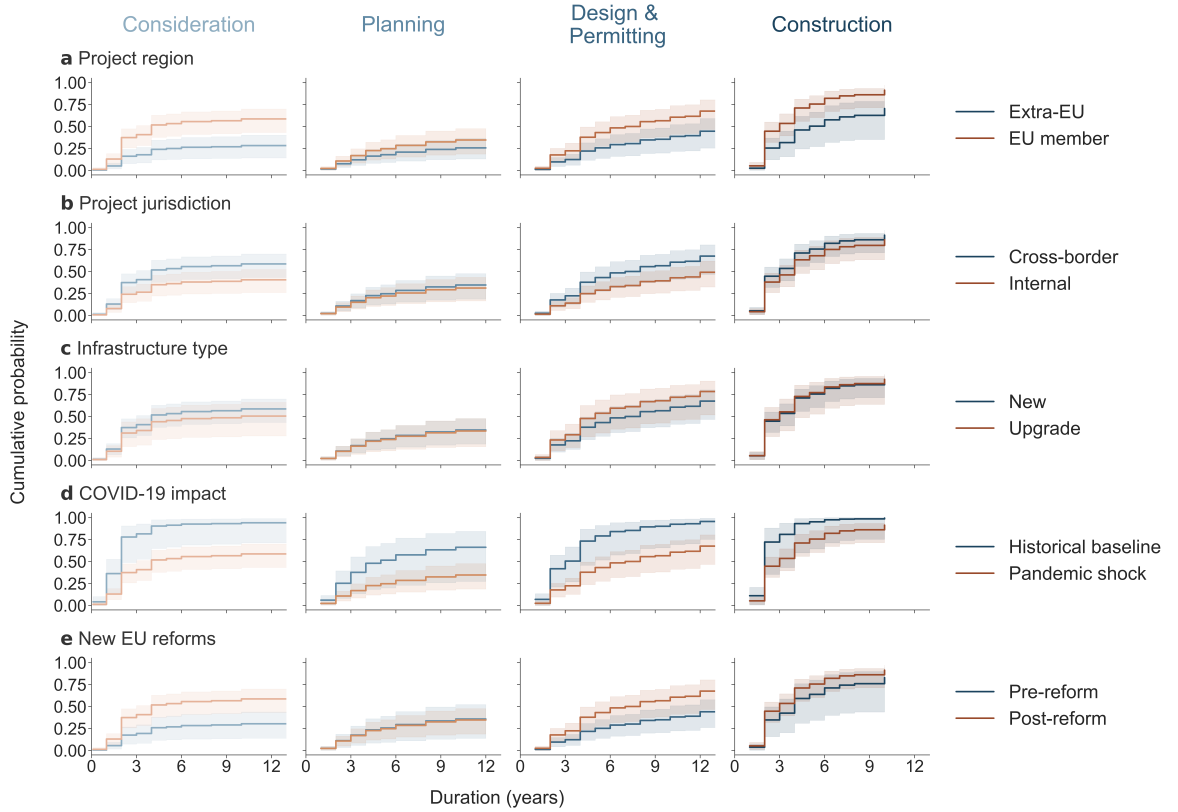


Fig. 3: Cumulative incidence of successful stage transitions in energy infrastructure investments. Estimated Cumulative Incidence Functions (CIF) for successful phase completion across four sequential phases (from Consideration to Construction) (see Methods). Rows represent specific investment-level covariates. Curves denote the absolute probability of successful transition over time, estimated via the Fine-Gray subdistribution hazard method to account for investment cancellation as a competing risk. Shaded areas represent 95% confidence intervals. For visual interpretation, consider the top-left panel (Project Region, Consideration): the EU Member curve remains strictly above the Extra-EU curve, demonstrating that EU investments have a higher probability of successful transition at any given time, which indicates a faster average phase progression. Model statistics: $n = 1082$ transition spells (462 successes, 377 cancellations, 243 censored).

Incidence and drivers of schedule overruns and cancellations

The expansion of the European grid is structurally slow and highly unpredictable. Consistent with the optimism bias typical of megaprojects¹¹, transmission promoters systematically underestimate deployment hurdles. Consequently, original commissioning deadlines are unreliable: of the tracked investments, 55% fail to meet their initial targets, accumulating an average delay of 4.7 years (95% CI, 4.3, 5.0) (see Methods).

Schedule unpredictability manifests as either early-stage rescheduling or late-stage delay (Figure 4). Variance is highest during the initial Consideration phase, where 35% of investments postpone commissioning by an average of 3.9 years (95% CI, 3.4, 4.3), while 8% advance their expected delivery by 3.6 years (95% CI, 2.9, 4.2). Our analysis of promoter justifications shows these early adjustments are primarily driven by strategic and systemic interdependencies (28.4%, specifically generation connection timelines), followed by technical scope and data (22.4%), and siting and land acquisition (5.7%)(Table 2).

As projects enter the Design and Permitting phase, the early variance in scheduling timelines becomes a persistent delay. Schedule overruns peak here, affecting 47% of investments with an average delay of 2.3 years (95% CI, 2.1–2.4). The stated reasons also shift: regulatory and permitting frameworks account for 42.6% of stalled projects, followed by changes in technical scopes and data (18.4%), strategic and systemic interdependencies (12.6%), social oppositions, siting and land acquisition (11.4%), and financial and industrial execution (6%) (Table 2, see Methods and Supplementary Note 4).

Table 2: Reported reasons for schedule deviations. Comparison of the primary drivers for early-stage rescheduling (n = 317) and late-stage delay (n = 484). Thematic categories were derived from promoters’ textual justifications using natural language processing. "Lack of information" denotes missing, empty, or uninformative entries.

Drivers of Rescheduling	Drivers of Delay
Strategic and systemic interdependencies (28.4%)	Regulatory and permitting (42.6%)
Technical scope and data (22.4%)	Technical scope and data (18.4%)
Siting and land acquisition (5.7%)	Strategic and systemic interdependencies (12.6%)
Regulatory (4.4%)	Social opposition, siting and land acquisition (11.4%)
	Financial and industrial exec. (6%)
<i>Lack of information (39.1%)</i>	<i>Lack of information (9.1%)</i>

Cumulatively, these forecasting failures leave 13.5% of the total investment portfolio with schedule deviations exceeding six years. This unpredictability frequently leads to project abandonment. The investment pipeline experiences high attrition: of the 965 tracked investments, nearly half (447) were cancelled or withdrawn, while only 181 reached commissioning and 337 remain in development (see Methods). An investment entering the Consideration phase faces an 87% probability of cancellation. This risk declines as projects mature, dropping to 70% in Planning, 42% in Design and Permitting, and 14% during Construction.

The reasons for cancellation have shifted over time, although inconsistent reporting limits detailed attribution. Early historical records, primarily the 2014 Monitoring Update, indicate that financing issues (27%), generation-side changes (28%), and alternative transmission investments (18%) were the main drivers. In contrast, cancellations since the 2020 planning cycle are increasingly driven by institutional requirements. While financial distress remains a factor, exclusion from the TYNDP between 2020 and 2026 is largely enforced through compliance frameworks (28%), with projects removed for missing deadlines or failing mandatory criteria. Beyond this, projects were removed due to strategic or policy obsolescence (22%), dissolved and reabsorbed into redefined project groupings (14%), and voluntary withdrawals (12%); for a further fifth, no rationale was recorded at all (see Methods and Supplementary Note 5). Ultimately, the data show that project survival now depends more on regulatory and strategic alignment than on pure market viability.

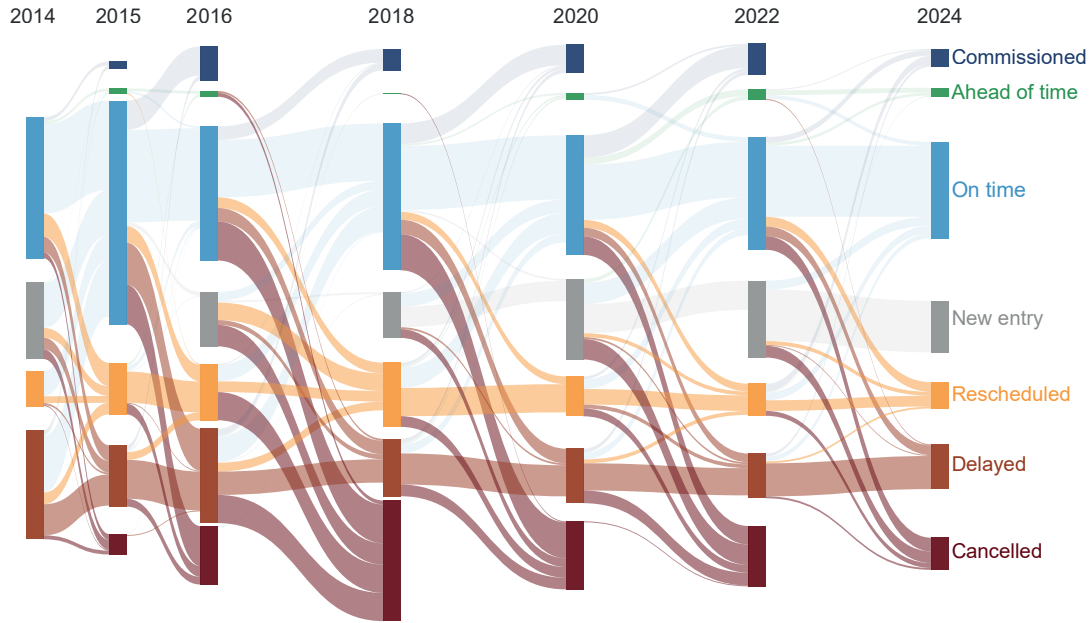


Fig. 4: Longitudinal evolution of grid investment statuses (2014–2024) ($N = 965$). Sankey diagram illustrating the state transitions of infrastructure projects across successive TYNDP reporting cycles. Data are extracted and harmonized from official ENTSO-E TYNDP reports. Flow thickness is proportional to the number of investments. The trajectories reveal a strong path dependency: projects experiencing initial delays rarely recover to an ‘on-time’ schedule, frequently cascading into further delays. Ultimately, a substantial proportion of the tracked portfolio results in cancellation rather than commissioning. The visualized timeframe (2014–2024) excludes earlier cycles (2010–2013) due to the absence of standardized status reporting, as well as the ongoing 2026 cycle. The concentration of cancellations in the 2018 cycle reflects institutional filtering under stricter assessment criteria (Supplementary Note 6)

Discussion

Commissioning a transmission investment takes an expected 14.1 years against a previously assumed baseline of 10 years (41% increase) of which physical construction accounts for only 3.8 years. By providing novel granular data on transmission grid investments that are central to European net-zero climate policy goals and quantifying the timeline of grid buildout at the phase-specific level, we identify specific opportunities and barriers that extend beyond current permitting reform efforts²⁹.

Current policy reforms predominantly target the Permitting stage, which takes roughly five years. The Consideration and Planning phases combined also take about five years yet receive little policy attention. Centralized EU-level coordination mechanisms accelerate deployment, while technical workarounds that aim to reduce physical complexity (e.g., using existing corridors for grid upgrades) do not substantially shorten the overall investment lifecycle. Even where recent European reforms (e.g. Directive 2014/52/EU, Regulation (EU) NO 347/2013) have accelerated permitting, the three-year Planning phase remains a bottleneck with no technical or regulatory solutions yet in place.

The extended timeline for grid infrastructure buildout reflects delays and uncertainty: 55% of investments face an average 4.7-year overrun, and nearly half are ultimately canceled, making official grid expansion plans unreliable. System dependencies, i.e. delays in generation connection timelines that exacerbate transmission delays, contribute to early-stage bottlenecks during Consideration and Planning (28.4% of investments) and Design and Permitting (12.6%). This points to the need for grid planning to adapt to the uncertain location of future generation and demand, complementing efforts

to address regulatory and permitting delays during the Design and Permitting phase, which affects 42.6% of investments.

Grid infrastructure requires large, irreversible investments^{30,31}, that are fundamentally risky^{4,27}. Because renewable generation and large new loads like data centers take 2 to 5 years to build compared to 14 years for a transmission line, grid planners must act first, forcing them to absorb the uncertainty of future supply and demand. Faced with this temporal mismatch and high regulatory uncertainty, promoters de-risk investments by treating the transmission planning pipeline as a portfolio of non-binding options. They secure the right to develop infrastructure without immediately committing major capital, wait for market or regulatory uncertainties to resolve, and let the option expire if conditions deteriorate, resulting in cancellation³². Our data are consistent with this interpretation as the primary driver of project cancellation and removal is the failure to meet TYNDP’s compliance frameworks (28%) rather than physical unfeasibility.

This pattern of option-holding behavior may produce a market failure, as institutional grid planning acts as a market signal. Evidence from Chile demonstrates that announcing transmission expansion leads to anticipatory investments in renewables³³. Similarly, an investment pipeline saturated with uncommitted options signals uncertainty to renewable energy developers who need reliable timelines to avoid stranded assets. This leads to a feedback loop with grid promoters waiting for generation certainty and renewable energy developers waiting for grid certainty¹⁹, raising the cost of the energy transition. Furthermore, an inflated investment pipeline masks the probable failure of grid projects, preventing the market from investing in alternatives like battery storage or relocating large demand.

The failure to build out the electric grid on time could have negative consequences for societal welfare and net-zero climate goals³⁴. If historical failure rates were to persist, between 2030 and 2040, the resulting grid bottlenecks would lead to cumulative welfare loss of €158 billion, renewable energy curtailment of 2,826 TWh (equivalent to the EU’s entire 2025 electricity consumption), and additional greenhouse gas emissions of 488 MtCO₂e, (surpassing Italy’s total emissions in 2024) (see Methods and Supplementary Note 7). Without near-term efforts to reduce risks in grid infrastructures, the delays could lead to a permanent deficit in transmission capacity post-2040 and further increase welfare loss. According to ENTSO-E’s modeling, achieving the optimal 2040 grid topology requires 28 GW of transmission capacity that has not entered the Planning phase in 2026. Because projects are expected to take 14.1 years to reach commissioning, any capacity not already in advanced planning cannot physically meet this 2040 deadline. Compounded by the continued cancellation of existing projects, the post-2040 grid infrastructure gap would impose an annual penalty of roughly €18 billion in lost welfare, curtail 280 TWh of clean energy, and increase emissions by 33 MtCO₂e^{35–37} (see Methods and Supplementary Note 7 for the full sensitivity analysis).

The issues in grid infrastructure deployment that we identify in this paper are reflective of comparable issues in advanced economies worldwide^{3,34}. In the United States (US), large transmission projects crossing state lines (e.g., SunZia, TransWest, and Grain Belt) face multi-jurisdictional barriers and social opposition¹⁷, and have 15- to 20-year development cycles comparable to those observed in Europe (Supplementary Note 8). In contrast, when a transmission project involves a centralized authority (e.g., the Texas CREZ initiative), deployment takes less than 10 years, consistent with the early-stage speed we observe for intra-EU projects. Europe illustrates how regulatory instruments can coordinate in a multi-jurisdictional setting—for example, through a supranational planner, statutory permitting deadlines, national one-stop shops, priority judicial treatment, and dedicated project funding. Therefore, while our results on transmission timelines and delays are generalizable to grid infrastructure buildout in other countries, they also represent a lower bound for transmission delivery under favorable institutional conditions, such as those in Europe.

Although Europe possesses an advanced centralized planning framework, its announced infrastructure pipeline overstates the capacity that will actually be delivered. While the EU Agency for the Cooperation of Energy Regulators (ACER) estimates that half of the identified cross-border capacity needs already lack a planned investment³⁸, our results suggests that nearly half of the currently planned investment pipeline will also not be built. This option-holding behavior persists because it is invisible. Currently, the TYNDP resets its planning baseline every two years, reporting delays relative only to the preceding cycle rather than the promoter’s initial commitment. Furthermore,

phase-specific cancellation probabilities are not systematically tracked, and the reported reasons for both delays and cancellations are frequently vague, inconsistent, or omitted entirely. No institutional record therefore exists against which a promoter’s stated intentions can be evaluated.

To close this information gap and align grid expansion with net-zero realities, we propose a three-tiered regulatory approach in which historical project data make commitments and de-risking enforceable. First, reporting frameworks must anchor every investment to its initially stated expected commissioning date. Regulators should systematically track and publish the historical probability of phase-specific cancellations and delays; the empirical framework presented in this paper can serve as a foundation for this. This tracking will allow the market to accurately price investment pipeline reliability, evaluate promoter efficiency, and value potential alternatives. Second, regulators must demand stricter commitments to maintain investments in official planning reports. While maintaining a flexible approach during the early Consideration phase is necessary to avoid top-down rigidity and to allow exploration of technical solutions, advancing to subsequent phases must trigger increasingly strict, binding commitments. The European Grids Package already filters generation queues through a maturity-based “first-ready, first-served” approach³⁹. Transmission investment pipelines require an equivalent filter. Regulators must enforce precise milestones that require investments to either advance or face exclusion. Coupling these milestones with financial penalties for unjustified delays will clear the investment pipeline of speculative options and allow competitive alternatives to emerge promptly. Third, recognizing the financial risk of first movers, anticipatory investments should be included in network tariffs^{24,40}, thereby accelerating grid expansion. However, this regulatory de-risking must be strictly conditional. With better information on investment-specific risks, policymakers can accurately target policy incentives toward viable projects with realistic timelines, effectively penalizing inefficient ones.

Ultimately, improving the transparency and memory of institutional datasets is a near-zero-cost prerequisite to help the market deploy alternative investments more quickly and can complement other efforts to accelerate physical grid construction. Climate and energy system assessments that use transmission planning as an input should therefore treat the investment pipeline as a measure of the capacity promoters are prepared to build, rather than a forecast of future capacity. The gap between planned and delivered transmission capacity is larger than stated in official capacity expansion scenarios, with direct consequences for how net-zero pathways are modeled and implemented.

Methods

Database development and data collection

We constructed a longitudinal dataset of European transmission investments (2010-2026) using the biennial ENTSO-E Ten-Year Network Development Plan (TYNDP), the 2012 and 2014 Monitoring Updates, and Draft Project Portfolios (2020–2026) (See Supplementary Table 1). The raw Ten-Year Network Development Plan (TYNDP) databases exhibit structural breaks, missing parameters, and inconsistent nomenclature. We harmonized all TYNDP reporting cycles, enabling the continuous tracking of each investment from its first appearance in the network development plan to its eventual completion or discontinuation.

ENTSO-E aggregates upgrades into broad ‘Projects’ containing up to 30 heterogeneous sub-components (e.g., mixing onshore AC upgrades with subsea HVDC cables) at varying maturity stages. To avoid double-counting and masking technology-specific bottlenecks, we used the granular ‘Investment ID’ as our primary unit of analysis, tracking over 900 distinct assets. We mapped over 100 disparate column headers to a unified schema and normalized string entries via regular expressions.

We tracked investments across nine biennial reports, merging the 2014-2026 editions sequentially via the Investment ID. To bridge a reporting structural break, we linked 2010-2013 investments to the 2014 cycle using topological matching of spatial nodes (‘Substation From’ and ‘Substation To’). This approach, however, triggers false positives when parallel but technically distinct investments are developed simultaneously at the exact same nodes. To resolve these nodal duplicates, we hardcoded splits to prevent erroneous cross-cycle merging. For instance, at the Krajnik and Mikulowa substations

in Poland, we explicitly isolated Phase Shifting Transformer (PST) installations from concurrent line upgrades. Similarly, highly aggregated UK conceptual nodes (e.g., 'Under Consideration (GB)') were divided into distinct identifiers based on their technical descriptions (e.g., 'East Coast' vs. 'Wind Farms'). This targeted disaggregation ensures that divergent project timelines occurring at identical geographic coordinates are accurately tracked as independent infrastructure spells.

Standardizing investment progress required mapping textual project statuses into a continuous 6-level ordinal scale, where level 5 represents "Commissioned" and level 6 denotes "Cancelled". However, during the integration of the 2020, 2022, and 2024 TYNDP editions, we identified a critical reporting inconsistency: ENTSO-E occasionally assigned the numerical ID "6" to denote "Completed" projects. To avoid misclassifying successfully commissioned infrastructure as abandoned (which would artificially inflate the overall cancellation rate), we corrected these specific instances, forcing them into level 5 ("Commissioned") prior to the duration and survival analyses.

Expected commissioning dates in the raw databases are frequently reported as text strings, ranges, or non-standard formats (e.g., "2028-2030" or "End of 2025"). To extract a standardized numerical value, we deployed a regular expression (Regex) parser constrained to realistic operational horizons (2000–2060). When promoters reported a temporal range, our algorithm extracted the maximum valid year (the upper bound of the range). This conservative assumption ensures that we benchmark against the latest anticipated delivery date, preventing the artificial overestimation of subsequent project delays. Specific typographical errors identified in the 2024 reporting cycle (e.g., TYNDP IDs 1014 and 1207) were manually verified and hardcoded to their true anticipated delivery years (2029 and 2036, respectively) to prevent outliers from distorting the duration analysis.

The raw institutional databases are frequently missing key technical parameters for early-stage or complex projects (e.g., capacity, voltage, technology type, and line length). To avoid the exclusion of these assets through listwise deletion, we constructed a deterministic imputation dictionary (missing_data.json). Missing variables for major pan-European assets (e.g., the ElecLink interconnector, the ISLES Project, and the Baltic Synchronization) were manually populated and cross-validated against national transmission development plans and official project promoters' repositories. A similar validated correction matrix (correction_map) was applied to correct typographical errors in substation nomenclature and to resolve known geographic misplacements (e.g., standardizing 'Le Mandarins' to 'Mandarins, Coquelles, France', or fixing country mismatches).

The unrefined 'Substation' fields contained syntactic noise, such as voltage metrics (e.g., "400kV"), generic functional descriptors (e.g., "ss", "hub", "station", "offshore"), and numeric identifiers. To isolate pure geographic toponyms, we implemented a Regex normalization pipeline to strip these artifacts. For investments missing explicit country attributes, we deployed a hierarchical imputation algorithm scanning project descriptions to extract valid country-level tokens, standardizing geographic affiliations to the ISO-3 format. Prior to querying the Nominatim geocoding API⁴¹, we implemented a strict exclusion list for investments lacking precise point-source geographic locations. Excluded records encompassed broad regional descriptors (e.g., 'Aragon Region'), non-specific border designations, administrative placeholders, and ambiguous offshore energy hubs. This prevented the geocoder from defaulting to generic country-level centroids, avoiding artificial spatial clustering. For the remaining valid records, we retrieved their geographic coordinates and calculated point-to-point line lengths using the Haversine formula, using these distances to flag and manually correct any geocoding misplacements.

Given the biennial nature of the TYNDP reporting cycle, technical parameters (e.g., capacity, voltage, and technology type) were occasionally reported in early submissions but omitted in subsequent updates for the same active investment. To reconstruct a continuous and complete parameter matrix without introducing external bias, we employed a Last Observation Carried Forward (LOCF) imputation strategy. For any missing technical attribute in year t , the algorithm horizontally scanned the longitudinal panel and carried forward the most recent validated entry from year $t - n$. This chronological forward-filling ensures that the consolidated physical metrics accurately reflect the latest technical consensus provided by the promoters before the asset's execution or cancellation.

To evaluate the impact of governance and spatial constraints in our multi-state survival model, we standardized the fragmented technical typologies into consolidated macro-categories (i.e., 'Cable/-Line' and 'Nodal Infrastructure') and derived specific operational environments (i.e., 'Onshore' versus 'Offshore') based on categorical keyword extraction (e.g., parsing for "Subsea"). We classified cross-border infrastructure based on the location of its connecting nodes. An investment was categorized as an "EU Member" project if and only if all topological connection nodes were located within the jurisdictional boundaries of the 27 European Union Member States. Interconnectors linking an EU Member State to a third country (e.g., Italy-Montenegro or Greece-Turkey) were classified as "Extra-EU." This conservative classification isolates the internal effect of the EU's streamlined regulatory frameworks (e.g., the TEN-E guidelines) from the slower coordination dynamics typical of external borders.

We recoded textual progress descriptions into a 6-level ordinal scale: (1) Under consideration; (2) Planned but not yet permitting; (3) Design and Permitting; (4) Under construction; (5) Commissioned; and (6) Cancelled. Because investments frequently disappear from reports without explicit updates, we applied a deterministic imputation rule based on maturity. Let R_y denote the report published in year y . The status S of an investment i appearing in R_y but missing in R_{y+2} is:

$$S_i = \begin{cases} \text{Commissioned} & \text{if } E_i(y) \leq y + 2 \\ \text{Cancelled} & \text{if } E_i(y) > y + 2 \end{cases}$$

where $E_i(y)$ is the expected commissioning year in R_y . This heuristic assumes investments expected before the next report are commissioned, whereas those vanishing with distant delivery dates are withdrawn from the TYNDP process. This imputation yields 181 commissioned, 447 cancelled, and 337 ongoing investments.

We validated this heuristic against official Draft Project Portfolios (2020–2026), which track non-submitted, non-compliant, and newly commissioned projects. Despite ENTSO-E's aggregation at the *Project* level, manual verification confirmed high consistency with our *Investment*-level imputations. Imputed "Commissioned" and "Cancelled" statuses aligned with officially commissioned, non-submitted, or discontinued flags. Discrepancies primarily arose from our higher granularity: technical re-scoping of a single sub-component is captured as a cancellation in our dataset (reflecting physical asset termination), even if the overarching *Project* remained formally active in ENTSO-E records (Supplementary Note 9).

Duration analysis

Naive averages of realization times are structurally biased by right-censoring, left-truncation, and cancellations. Among 1,316 valid phase transitions (i.e., observed progression of an asset from one phase to a subsequent phase or terminal state), 500 succeeded, 442 cancelled, and 130 exhibited non-linear behaviors (e.g., phase-skipping or re-scoping), while 244 stalled. To correct these biases, we modeled the lifecycle as an absorbing Markov chain, defining active phases (1-4) as transient states, and Commissioned (5) and Cancelled (6) as absorbing states⁴². From empirical transition counts, we constructed the transition probability matrix P , partitioned into transient-to-transient (Q) and transient-to-absorbing (R) submatrices. We calculated the fundamental matrix F :

$$F = (I - Q)^{-1} \quad (1)$$

yielding absorption probabilities $B = FR$. To estimate expected realization times, we calculated the Conditional Mean First Passage Time (MFPT) to the Commissioned state. We computed the conditional transition matrix Q^* :

$$Q_{ij}^* = Q_{ij} \frac{b_j}{b_i} \quad (2)$$

We then derived the conditional fundamental matrix $F^* = (I - Q^*)^{-1}$, where each entry represents the expected number of visits to a specific phase given eventual commissioning. Finally, letting W

be the column vector of empirical mean waiting times spent in each transient state per visit, the conditional expected duration ($MFPT^*$) to commissioning for an investment starting in state i is simply the sum of the expected times spent across all visited states:

$$MFPT^* = F^*W \quad (3)$$

This methodology mitigates survivorship bias and incorporates the time penalties of stalled investments. A funnel-cohort analysis restricted to investments tracked from Consideration, and to a secondary cohort tracked from Planning, yields cumulative durations of 11.8 and 12.7 years respectively; because both cohorts are themselves right-censored and capture only the fastest projects, these figures are lower bounds consistent with the 14.1-year Markov estimate (Supplementary Note 10).

Multi-state transition analysis and Cox proportional hazards

To evaluate the progression and attrition of energy infrastructure investments, we conceptualized the investment development lifecycle as a multi-state process. Our risk set comprises $n = 1,082$ transition spells. Within this framework, we observe a total of 839 terminal events, consisting of 462 successful phase transitions and 377 project cancellations. We employed a clock-reset (semi-Markov) Cox proportional hazards model to estimate transition-specific intensities⁴³. This approach simultaneously models competing risks at each investment phase: successfully advancing to the subsequent phase versus investment cancellation. For an investment entering phase i , the hazard of transitioning to state j (either the next phase or cancellation) at time t is given by:

$$h_{ij}(t|x) = h_{ij,0}(t) \exp(\beta_{ij}^T x)$$

where $h_{ij,0}(t)$ is the baseline hazard function for the transition from i to j , t is the time elapsed since entry into state i (clock-reset formulation), x is the vector of covariates, and β_{ij} is the vector of transition-specific coefficients. The clock-reset formulation ensures that the baseline hazard is reset to zero upon entry into a new phase, effectively isolating the duration spent within each specific developmental phase.

The model was stratified both by the phase of origin and the investment environment (onshore versus offshore). This dual stratification permits the baseline hazards, $h_{ij,0}(t)$, to vary freely across different phases of development while rigorously controlling for structural baseline differences between onshore and offshore infrastructure projects. Crucially, we interacted all covariates with the phase of origin to estimate phase-specific hazard ratios (β_{ij}), capturing how the drivers of deployment speed dynamically evolve between early planning and late-stage construction. To account for unobserved heterogeneity and intra-investment correlation—given that a single investment contributes multiple spells as it transitions through successive phases—we clustered the standard errors at the individual investment level.

We verified the proportional hazards assumption by examining the Schoenfeld residuals⁴⁴. For the primary cause-specific model evaluating successful phase transitions, the global test confirmed full compliance with the proportional hazards assumption ($\chi^2 = 29.42$, $df = 28$, $p = 0.39$), with no individual covariates exhibiting significant non-proportionality. To account for intra-investment correlation, global model significance was evaluated and confirmed using robust score tests ($p < 0.001$). The multi-state models were implemented using the survival package in R.

Our primary specification models phase-specific transition intensities as a function of geographical, technical, and temporal covariates. We account for geographic and jurisdictional scope by distinguishing between EU and extra-EU projects, as well as internal and cross-border assets, thereby capturing the multi-level regulatory coordination governing multinational grids. Technical characteristics include infrastructure type (new build versus upgrade), element category (nodal infrastructure versus line assets), and transmission technology (AC versus DC). In addition, we incorporate time-varying dummy indicators to dynamically capture exogenous temporal shocks at the individual phase level, constructing these metrics from the specific start and end reporting years of each spell. Specifically, New EU reforms captures the regulatory acceleration driven by the revised EIA Directive

(2014/52/EU) and Regulation (EU) No 347/2013, taking a value of 1 for transitions commencing in or after the 2018 reporting cycle. Finally, COVID-19 controls for administrative and supply chain disruptions, taking a value of 1 if an investment’s active phase intersected with the 2022 or 2024 reporting windows, and 0 otherwise.

To visualize the actual probability of investment realization over time, we translated our hazard estimates into True Cumulative Incidence Functions (CIF). Because standard Kaplan-Meier estimates are structurally biased upward in the presence of competing risks, we estimated the CIFs using Fine-Gray subdistribution hazard models, properly weighting the risk sets to account for investments experiencing the competing event (cancellation)⁴⁵. To isolate the marginal impact of individual predictors and generate the visualized curves, we simulated the predicted cumulative incidence while holding all non-target covariates constant at their respective modal values, thereby ensuring a balanced and representative baseline for comparison.

Finally, we excluded physical metrics (capacity, line length, voltage) from the primary model to prevent severe sample selection bias and multicollinearity. These variables are missing for 25–33% of registered investments, specifically during early phases (Missing Not At Random). Including them would trigger the listwise deletion of early-stage investments, artificially skewing the baseline hazard toward mature projects. Furthermore, continuous metrics suffer from structural heterogeneity (e.g., nodal infrastructure such as substations, transformers, and reactive compensation devices has zero line length), and voltage lacks variance across the extra-high voltage grid. To verify robustness, we report a fully specified supplementary model using categorical transformations: the impact of primary geographic and temporal covariates remains consistent (Supplementary Note 3 and Supplementary Table 2-5).

Delay analysis

We tracked expected commissioning dates across all TYNDP reporting cycles. Absolute cumulative delay was calculated as the temporal difference (in years) between the final realized (or latest projected) commissioning date and the initial expected year declared upon investment pipeline entry. Delayed investment rates are calculated by dividing the number of delayed investments by the total number of investments across multiple reports; single-report entries are excluded. To capture internal timeline fluctuations, we computed marginal schedule deviations by subtracting the expected commissioning year at time t from the updated expectation at $t + 1$. Positive values indicate delays; negative values indicate schedule advances. Cross-referencing these marginal deviations with the active administrative status at t isolated phase-specific volatility, distinguishing the bidirectional fluctuations of early-stage *Consideration* from the compounding overruns of the *Design and Permitting* phase.

To test whether physical complexity accounts for the magnitude of overruns, we regressed log-transformed standardized delay on jurisdictional, geographic and technical characteristics, with capacity and line length entered as categorical bins to avoid listwise deletion ($n = 398$ delayed investments). Physical and technical attributes explain only a marginal share of the variation (adjusted $R^2 = 0.074$) (Supplementary Note 11 and Supplementary Table 12).

To identify the causes of schedule deviations (delays and rescheduling), we developed an NLP pipeline combining clustering, Large Language Models (LLMs), and manual validation through the following four steps (Supplementary Note 4). First, for initial clustering, textual justifications were vectorized using TF-IDF and evaluated using the K-means algorithm⁴⁶. K-means on TF-IDF vectors served as an exploratory lexical baseline; as the inertia declined smoothly without a sharp elbow — consistent with the continuous thematic overlap of promoter justifications — it was used only to orient the interpretation, not to fix the final number of categories (Supplementary Fig 1,2). Second, we applied HDBSCAN for semantic clustering to form robust groups, extract their core meanings, and isolate uninformative outliers. The texts were encoded using a SentenceTransformer (all-MiniLM-L6-v2)⁴⁷ and processed with UMAP⁴⁸ and HDBSCAN. Hyperparameters were grid-searched over silhouette score; among the top-ranked configurations, we selected the one yielding the most interpretable thematic granularity (Supplementary Fig 3,4). Third, drawing upon the keywords and meanings extracted from the previous step, an expert taxonomy of schedule deviations was established. We then used the Llama 3.2 model (via the Ollama API, with temperature set

to 0.0 for reproducibility)⁴⁹ to classify all extracted delay and rescheduling justifications (n = 484 delay events, 317 rescheduling events, drawn from the 2014–2024 cycles) (Supplementary Table 6,7). Finally, because automated models can misinterpret long, complex, or syntactically ambiguous promoter statements, we conducted a manual screening. Misclassifications were corrected, missing data flagged, and the granular categories were aggregated into overarching macro-categories (e.g., "Regulatory and Permitting", "Strategic and systemic interdependencies") for evaluation (Supplementary Table 6).

Cancellation analysis

To identify the qualitative root causes of project cancellations, we analyzed the textual justifications for abandoned investments. Because cancelled assets are frequently excluded from official cycles without explicit explanation, we reconstructed these data longitudinally from two primary historical horizons. For the early planning era, data were extracted directly from the 2014 TYNDP report, which explicitly published predefined and clustered reasons for dropped investments. Conversely, for the recent 2020–2026 planning cycles, where no prior classification existed, we extracted the explanation of cancellations from the official "Non-submitted" and "Non-compliant" lists within the TYNDP Draft Project Portfolios (Supplementary Note 5).

From the TYNDP 2020–2026 Non-submitted and Non-compliant portfolios, we identified 51 projects removed from the transmission pipeline. Given the small sample size, we combined a programmatic first pass with manual validation. We first ran a deterministic keyword-matching script that scanned each promoter's stated reason for lexical strings (e.g. "deadline", "criteria", "PCI/PMI", "reclustering", "withdrawn by project promoter", "no longer needed") and assigned it to one of a set of mutually exclusive categories established through an inductive reading of the texts: administrative and compliance failures (missed deadlines, failed eligibility criteria, promoter dissolution), technological or policy obsolescence (loss of strategic rationale, including projects rendered redundant by updated policy assumptions or by post-Brexit changes in the geographic scope of the framework), reclustering (dissolved and reabsorbed into redefined project groupings), permitting and siting roadblocks, voluntary withdrawal, and entries with no stated rationale. Because the keyword pass is sensitive to phrasing (for example, hyphenation or the incidental presence of "PCI" in an unrelated sentence), we manually reviewed every assignment against the original text and corrected misclassifications. The manually validated labels are used throughout; the script is provided as a replicability aid rather than as the final classifier (Supplementary Table 8).

System-wide impact

To quantify the macroeconomic cost of institutional bottlenecks, we integrated our Markov chain outputs with the project-level Cost-Benefit Analysis (CBA) of the ENTSO-E TYNDP 2024⁵⁰. Using the 2030 and 2040 National Trends scenarios, we assessed systemic losses in Socio-Economic Welfare (SEW), curtailed renewable energy, and avoided CO2 emissions. Where the CBA framework provided benefit ranges for these indicators, we systematically utilized the weighted average reported values rather than maximum or minimum extremes (Supplementary Note 7).

Crucially, we avoided a "weakest link" assumption. While transmission projects typically comprise multiple interdependent investments—where a single delayed or cancelled component could theoretically bottleneck the entire infrastructure—we instead mapped average investment-level failure rates and deployment times onto aggregate project CBAs. This approach explicitly prevents overestimation, establishing a strictly conservative lower bound for systemic losses.

We calculated the costs of delays by linearly interpolating CBA benefits across each project's "delay gap" (the temporal difference between our empirically computed commissioning year and the promoter's initial target). For cancellations, we assessed forgone benefits in two phases: cumulative losses up to 2040, followed by a permanent annual penalty post-2040. To reflect the probability of planners deploying alternative infrastructure, we applied a baseline 30% substitution rate (with 10% and 50% sensitivity margins) to the abandoned portfolio (see Supplementary Note 7 and Supplementary Table 9).

Finally, we evaluated the post-2040 28 GW structural gap identified by ENTSO-E. We derived the average macroeconomic benefit per gigawatt from the active 2024 portfolio and scaled it by the 28 GW shortfall. Adjusting this with the same 30% substitution rate, we estimated the ongoing annual deficit imposed by planning inertia.

Author contribution:

K.S. suggested the research question, which D.A. further developed. D.A. conceived and designed the study and developed the methodology with contributions from B.Z and K.S. D.A. collected the data, performed the analysis, and created the figures. D.A. and K.S. interpreted the results. D.A. wrote the paper with review and editing from B.Z. and K.S. K.S. supervised the project.

Declarations

- Funding: The contribution of BZ and KS was supported by the Austrian Federal Ministry for Innovation, Mobility and Infrastructure (BMIMI) under the endowed professorship for "Data-Driven Knowledge Generation: Climate Action"
- Competing interests: The authors declares no competing interests.
- Data availability: The primary data underlying this study are the Ten-Year Network Development Plan (TYNDP) project portfolios and Cost–Benefit Analyses published by ENTSO-E for the 2010–2026 cycles, which are publicly available from the ENTSO-E website (see Table 1 Supplementary Informations). The 2018 portfolio was retrieved from a page that is no longer online; the scraped copy, together with the harmonised longitudinal dataset generated in this work and the manually validated classification files (delays, reschedulings and cancellations), is deposited in the repository listed under Code availability. During peer review these files are provided to reviewers via a private link; on acceptance they will be archived with a permanent DOI. All processing steps needed to reproduce the derived datasets from the original sources are included in the code.
- Code availability: All code required to reproduce the analyses and figures is available at <https://github.com/damianoalessi/transmission-timeline>. The repository contains the data-processing pipeline (Python/Jupyter), the multi-state survival models (R), the reason-classification pipeline, and the figure notebooks, with a README documenting the execution order and a pinned software environment (requirements.txt for Python; R 4.5.2 with survival, cmprsk, dplyr and car). The natural-language classification of delay and rescheduling reasons uses the Llama 3.2 model served locally via Ollama; because large-language-model outputs are not bit-for-bit reproducible across environments, the final manually validated labels are deposited as the definitive record and are the basis for all reported figures.
- Declaration of AI Use: The authors declare that an LLM was used during the preparation of this manuscript to polish the language, refine the structural organization of the text, and assist in writing and troubleshooting code for data processing. The authors take full responsibility for the final content of the manuscript.

Acknowledgements

We thank J. Huenteler, C. Rumpelnik, R.C. Fischer, S. Dierksmeier, R. Way, H.H. Kügler, I.L. Azevedo, A. Nuñez-Jimenez, A. Pampado, the 2026 ETH PhD Academy on Sustainability and Technology and the 2025 ETH Energy Transition Summer School participants for helpful comments and discussions.

References

- [1] M. Mann, The autonomous power of the state: its origins, mechanisms and results. *European Journal of Sociology / Archives Européennes de Sociologie* **25**(2), 185–213 (1984). <https://doi.org/10.1017/S0003975600004239>

- [2] Frontinus, Sextus Julius, *Frontinus. The Stratagems and The Aqueducts of Rome*, Loeb Classical Library Series., vol. L174 (G. P. Putnam's Sons; William Heinemann, New York; London, 1925). URL <http://archive.org/details/frontinus-stratagems-aqueducts-loeb>
- [3] IEA, Electricity Grids and Secure Energy Transitions. Tech. rep., Paris (2023). URL <https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions>. Licence: CC BY 4.0
- [4] P.L. Joskow, Transmission Capacity Expansion Is Needed to Decarbonize the Electricity Sector Efficiently. *Joule* **4**(1), 1–3 (2020). <https://doi.org/10.1016/j.joule.2019.10.011>
- [5] S.J. Davis, N.S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I.L. Azevedo, S.M. Benson, T. Bradley, J. Brouwer, Y.M. Chiang, C.T.M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C.B. Field, B. Hannegan, B.M. Hodge, M.I. Hoffert, E. Ingersoll, P. Jaramillo, K.S. Lackner, K.J. Mach, M. Mastrandrea, J. Ogden, P.F. Peterson, D.L. Sanchez, D. Sperling, J. Stagner, J.E. Trancik, C.J. Yang, K. Caldeira, Net-zero emissions energy systems. *Science* **360**(6396), eaas9793 (2018). <https://doi.org/10.1126/science.aas9793>
- [6] K. Surana, S.M. Jordaan, The climate mitigation opportunity behind global power transmission and distribution. *Nature Climate Change* **9**(9), 660–665 (2019). <https://doi.org/10.1038/s41558-019-0544-3>
- [7] Mario Draghi, The future of European competitiveness. A competitiveness strategy for Europe. Tech. rep., European Commission (2024). <https://doi.org/10.2872/9356120>. URL https://commission.europa.eu/topics/competitiveness/draghi-report_en
- [8] ENTSO-E, European Grids Package: ENTSO-E Recommendations. Tech. rep., ENTSO-E, Brussels (2025). URL <https://www.entsoe.eu/european-grids-package/>
- [9] Hannah Ahamad, Alexandre Lotito, European grids package: Lessons learnt from the implementation of the TEN E framework. Tech. Rep. PE 774.695, European Parliament, Brussels (2025). URL [https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI\(2025\)774695](https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2025)774695)
- [10] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Grids, the missing link - An EU Action Plan for Grids. Tech. Rep. COM(2023) 757 final, Brussels (2023). URL <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52023DC0757>
- [11] B. Flyvbjerg, What you Should Know about Megaprojects and Why: An Overview. *Project Management Journal* **45**(2), 6–19 (2014). <https://doi.org/10.1002/pmj.21409>
- [12] A. Steinbach, Barriers and solutions for expansion of electricity grids—the German experience. *Energy Policy* **63**, 224–229 (2013). <https://doi.org/10.1016/j.enpol.2013.08.073>
- [13] Z. Liscow, Getting Infrastructure Built: The Law and Economics of Permitting. *Journal of Economic Perspectives* **39**(1), 151–180 (2025). <https://doi.org/10.1257/jep.20221347>
- [14] P. Devine-Wright, Explaining “NIMBY” Objections to a Power Line: The Role of Personal, Place Attachment and Project-Related Factors. *Environment and Behavior* **45**(6), 761–781 (2013). <https://doi.org/10.1177/0013916512440435>
- [15] S. Batel, P. Devine-Wright, T. Tangeland, Social acceptance of low carbon energy and associated infrastructures: A critical discussion. *Energy Policy* **58**, 1–5 (2013). <https://doi.org/10.1016/j.enpol.2013.03.018>
- [16] D.J. Hess, R.G. McKane, C. Pietzryk, End of the line: environmental justice, energy justice, and opposition to power lines. *Environmental Politics* **31**(4), 663–683 (2022). <https://doi.org/10.1080/09644016.2021.1952799>
- [17] L.W. Davis, C. Hausman, N.L. Rose, Transmission Impossible? Prospects for Decarbonizing the US Grid. *Journal of Economic Perspectives* **37**(4), 155–180 (2023). <https://doi.org/10.1257/jep>

- 624 37.4.155. URL <https://pubs.aeaweb.org/doi/10.1257/jep.37.4.155>
- 625 [18] IEA, Building the Future Transmission Grid. Tech. rep., Paris (2025). URL <https://www.iea.org/reports/building-the-future-transmission-grid>. Licence: CC BY 4.0
- 626
- 627 [19] Joseph Rand, Nick Manderlink, Steven Zhang, Chris Talley, Will Gorman, Ryan Wiser, Joachim
- 628 Seel, Julie Mulvaney Kemp, Seongeun Jeong, Fritz Kahrl, Queued Up: 2025 Edition Character-
- 629 istics of Power Plants Seeking Transmission Interconnection As of the End of 2024. Tech. rep.,
- 630 Lawrence Berkeley National Laboratory, Berkeley, CA (2025). URL <https://emp.lbl.gov/sites/default/files/2025-12/Queued%20Up%202025%20Edition%20-%2012.15.2025.pdf>
- 631
- 632 [20] A. Ciupuliga, E. Cuppen, The role of dialogue in fostering acceptance of transmission lines:
- 633 the case of a France–Spain interconnection project. *Energy Policy* **60**, 224–233 (2013). <https://doi.org/10.1016/j.enpol.2013.05.028>
- 634
- 635 [21] J.K. Knudsen, L.C. Wold, Aas, J.J. Kielland Haug, S. Batel, P. Devine-Wright, M. Qvenild,
- 636 G.B. Jacobsen, Local perceptions of opportunities for engagement and procedural justice in
- 637 electricity transmission grid projects in Norway and the UK. *Land Use Policy* **48**, 299–308
- 638 (2015). <https://doi.org/10.1016/j.landusepol.2015.04.031>
- 639 [22] M. Cotton, P. Devine-Wright, Putting pylons into place: a UK case study of public perspectives
- 640 on the impacts of high voltage overhead transmission lines. *Journal of Environmental Planning*
- 641 *and Management* **56**(8), 1225–1245 (2013). <https://doi.org/10.1080/09640568.2012.716756>
- 642 [23] European Union. REGULATION (EU) 2022/869 of the European Parliament and of the Council
- 643 of 30 May 2022 on guidelines for trans-European energy infrastructure (2022). URL <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022R0869>
- 644
- 645 [24] European Commission, Commission Notice on a guidance on anticipatory investments for devel-
- 646 oping forward-looking electricity networks. C series, C/2025/3179, 6.6.2025, Official Journal of
- 647 the European Union, Brussels (2025). URL <https://eur-lex.europa.eu/eli/C/2025/3179/oj>
- 648 [25] E. Chojkiewicz, U. Paliwal, N. Abhyankar, C. Baker, R. O’Connell, D. Callaway, A. Phadke,
- 649 Accelerating transmission capacity expansion by using advanced conductors in existing right-
- 650 of-way. *Proceedings of the National Academy of Sciences* **121**(40), e2411207121 (2024). <https://doi.org/10.1073/pnas.2411207121>
- 651
- 652 [26] ENTSO-E, Ten-Year Network Development Plan (TYNDP): Executive summaries and monitor-
- 653 ing reports. Tech. rep., ENTSO-E (2010). URL <https://www.entsoe.eu/tyndp/>
- 654 [27] M.G. Pollitt, The European Single Market in Electricity: An Economic Assessment. *Review*
- 655 *of Industrial Organization* **55**(1), 63–87 (2019). <https://doi.org/10.1007/s11151-019-09682-w>.
- 656 URL <http://link.springer.com/10.1007/s11151-019-09682-w>
- 657 [28] L. Reed, M.G. Morgan, P. Vaishnav, D. Erian Armanios, Converting existing transmission cor-
- 658 ridors to HVDC is an overlooked option for increasing transmission capacity. *Proceedings of*
- 659 *the National Academy of Sciences* **116**(28), 13879–13884 (2019). <https://doi.org/10.1073/pnas.1905656116>
- 660
- 661 [29] European Commission, Communication from the Commission to the European Parliament, the
- 662 Council, the European Economic and Social Committee and the Committee of the Regions:
- 663 ‘European Grids Package’. COM(2025) 1005 final, European Commission, Brussels (2025). URL
- 664 [https://energy.ec.europa.eu/document/download/869c0537-3fcb-4d0a-bd05-e8b0c3696c12_en?](https://energy.ec.europa.eu/document/download/869c0537-3fcb-4d0a-bd05-e8b0c3696c12_en?filename=COM_2025_1005_1_EN_ACT_part1_v6.pdf)
- 665 [filename=COM_2025_1005_1_EN_ACT_part1_v6.pdf](https://energy.ec.europa.eu/document/download/869c0537-3fcb-4d0a-bd05-e8b0c3696c12_en?filename=COM_2025_1005_1_EN_ACT_part1_v6.pdf)
- 666 [30] R.S. Pindyck, Irreversibility, Uncertainty, and Investment. *Journal of Economic Literature* **29**(3),
- 667 1110–1148. (1991). URL <http://www.jstor.org/stable/2727613>
- 668 [31] R. Kellogg, The Effect of Uncertainty on Investment: Evidence from Texas Oil Drilling. *American*
- 669 *Economic Review* **104**(6), 1698–1734 (2014). <https://doi.org/10.1257/aer.104.6.1698>

- [32] R. Pringles, F. Olsina, F. Garcés, Real option valuation of power transmission investments by stochastic simulation. *Energy Economics* **47**, 215–226 (2015). <https://doi.org/10.1016/j.eneco.2014.11.011>
- [33] L.E. Gonzales, K. Ito, M. Reguant, The Investment Effects of Market Integration: Evidence From Renewable Energy Expansion in Chile. *Econometrica* **91**(5), 1659–1693 (2023). <https://doi.org/10.3982/ECTA20769>
- [34] J.M. Kemp, D. Millstein, W. Gorman, S. Jeong, R. Wiser, Electric transmission value and its drivers in United States power markets. *Nature Communications* **16**(1), 8055 (2025). <https://doi.org/10.1038/s41467-025-63143-5>
- [35] ENTSO-E, TYNDP 2026 System Needs Workshop. Tech. rep. (2025). URL https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/events/2025/ENTSOE-Presentation-TYNDP_2026_system_needs_workshop.pdf
- [36] ENTSO-E, Opportunities for a more efficient European power system by 2050. Infrastructure Gaps Report. Tech. Rep. TYNDP 2024 (2025). URL https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2024/foropinion/Infrastructure_Gaps_Report.pdf
- [37] T. Tröndle, J. Lilliestam, S. Marelli, S. Pfenninger, Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe. *Joule* **4**(9), 1929–1948 (2020). <https://doi.org/10.1016/j.joule.2020.07.018>
- [38] ACER, Electricity infrastructure development to support a competitive and sustainable energy system. Market Monitoring Report, European Union Agency for the Cooperation of Energy Regulators (ACER), Ljubljana (2024). URL https://www.acer.europa.eu/monitoring/MMR/electricity_infrastructure_2024
- [39] European Commission, Commission Notice – Guidance on efficient and timely grid connections. C/2025/8473, Official Journal of the European Union, Brussels (2025). URL <https://eur-lex.europa.eu/eli/C/2025/6703/oj/eng>
- [40] G. Strbac, M. Pollitt, C.V. Konstantinidis, I. Konstantelos, R. Moreno, D. Newbery, R. Green, Electricity transmission arrangements in Great Britain: Time for change? *Energy Policy* **73**, 298–311 (2014). <https://doi.org/10.1016/j.enpol.2014.06.014>. URL <https://linkinghub.elsevier.com/retrieve/pii/S0301421514003863>
- [41] OpenStreetMap contributors. OpenStreetMap (2026). URL <https://www.openstreetmap.org>
- [42] J.G. Kemeny, J.L. Snell, *Finite markov chains: with a new appendix "generalization of a fundamental matrix"*, reprint edn. Undergraduate texts in mathematics (Springer, New York, NY Heidelberg Berlin, 1983)
- [43] H. Putter, M. Fiocco, R.B. Geskus, Tutorial in biostatistics: competing risks and multi-state models. *Statistics in Medicine* **26**(11), 2389–2430 (2007). <https://doi.org/10.1002/sim.2712>. URL <https://onlinelibrary.wiley.com/doi/10.1002/sim.2712>
- [44] P.M. Grambsch, T.M. Therneau, Proportional hazards tests and diagnostics based on weighted residuals. *Biometrika* **81**(3), 515–526 (1994). <https://doi.org/10.1093/biomet/81.3.515>. URL <https://academic.oup.com/biomet/article-lookup/doi/10.1093/biomet/81.3.515>
- [45] J.P. Fine, R.J. Gray, A Proportional Hazards Model for the Subdistribution of a Competing Risk. *Journal of the American Statistical Association* **94**(446), 496–509 (1999). <https://doi.org/10.1080/01621459.1999.10474144>. URL <https://www.tandfonline.com/doi/full/10.1080/01621459.1999.10474144>
- [46] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg, J. Vanderplas, A. Passos, D. Cournapeau, M. Brucher, M. Perrot,

- 716 Duchesnay, Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*
717 **12**(85), 2825–2830 (2011). URL <http://jmlr.org/papers/v12/pedregosa11a.html>
- 718 [47] N. Reimers, I. Gurevych, *Sentence-BERT: Sentence Embeddings using Siamese BERT-Networks*,
719 in *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing*
720 *and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*
721 (Association for Computational Linguistics, Hong Kong, China, 2019), pp. 3980–3990. <https://doi.org/10.18653/v1/D19-1410>. URL <https://www.aclweb.org/anthology/D19-1410>
722
- 723 [48] L. McInnes, J. Healy, J. Melville. UMAP: Uniform Manifold Approximation and Projection
724 for Dimension Reduction (2018). <https://doi.org/10.48550/ARXIV.1802.03426>. URL <https://arxiv.org/abs/1802.03426>. Version Number: 3
725
- 726 [49] A. Grattafiori, and others. The Llama 3 Herd of Models (2024). [https://doi.org/10.48550/](https://doi.org/10.48550/ARXIV.2407.21783)
727 [ARXIV.2407.21783](https://doi.org/10.48550/ARXIV.2407.21783). URL <https://arxiv.org/abs/2407.21783>. Version Number: 3
- 728 [50] ENTSO-E. TYNDP 2024 Projects Sheets (2024). URL [https://tyndp2024.entsoe.eu/](https://tyndp2024.entsoe.eu/projects-map/transmission)
729 [projects-map/transmission](https://tyndp2024.entsoe.eu/projects-map/transmission)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SIAdeliverygapinelectricitygridexpansionNatureEnergy.pdf](#)