Deep-Dive Research: X's Tapestry & a Roadmap for Energinet's Path to 100% Renewable Electricity

Executive Summary

The Strategic Inflection Point: The European energy system, with Denmark at its vanguard, is navigating a period of unprecedented transformation. The confluence of massive renewable energy buildouts, particularly offshore wind; the rapid electrification of transport and heating; and the nascent coupling of the power sector with green hydrogen production (Power-to-X) is pushing traditional grid planning and operational paradigms to their breaking point. The sheer scale, speed, and complexity of this transition create a strategic imperative for a new, AI-native approach to managing the electricity grid. The linear, deterministic, and time-intensive methods of the past are insufficient for the dynamic, stochastic, and interconnected system of the future. For Energinet, maintaining its world-class security of supply while accelerating this transition is the paramount challenge.

X's Tapestry: A Synopsis: X's Tapestry emerges as a potential solution to this challenge. Positioned as a "moonshot for the electric grid," Tapestry is an AI-powered, unified platform designed to create a "Google Maps for electrons".[1] Its mission is to make the grid visible, manageable, and plannable in the age of intelligence by weaving together trillions of disparate data points into a single, coherent knowledge graph.[2] The platform has demonstrated validated capabilities in key areas of concern for modern Transmission System Operators (TSOs), including accelerating long-term planning simulations, improving renewable energy forecasting, and streamlining the grid interconnection process for new green assets.

Key Findings for Energinet: This report finds a strong and compelling alignment between Tapestry's proven global use cases and Energinet's most pressing strategic bottlenecks. The platform's demonstrated ability to drastically reduce simulation times for national-scale planning with Chile's TSO (CEN) directly maps to Energinet's need to analyze a multitude of complex future scenarios involving energy islands, HVDC corridors, and large-scale Power-to-X integration.[4] Similarly, the AI-driven approach to untangling the generation interconnection queue with PJM in the United States offers a clear playbook for managing the growing pipeline of renewable projects in Denmark.[5] The platform's use of advanced AI weather models like GraphCast for enhanced wind forecasting presents a quantifiable opportunity to improve efficiency in Energinet's balancing markets.[4]

Core Recommendations: Based on a rigorous technical, economic, and regulatory analysis, the primary recommendation is for Energinet to **proceed with a structured, two-track pilot program in 2025-2026 to validate Tapestry's specific value propositions in the Danish context.** This approach de-risks a larger investment by generating empirical evidence on the platform's performance with Energinet's own models and data. The two proposed pilots are:

1. **Planning Acceleration:** A direct, head-to-head benchmark of the Tapestry Grid Planning Tool against current PowerFactory workflows for a complex subset of Energinet's 2030-2045 Long-Term Development Plan (LUP) scenarios.
2. **Forecasting Uplift:** An offline validation of a Tapestry wind forecasting model, fine-tuned for the North Sea, to quantify the accuracy improvement and the resulting economic benefit in reduced balancing and reserve costs.

Projected Impact: A successful adoption of the Tapestry platform carries the potential for significant strategic and economic benefits for Energinet and the Danish energy transition. Quantitatively, this could translate to a material reduction—potentially an order of magnitude—in the cycle time for long-term strategic planning, enabling more robust and timely investment decisions. It could also yield annual savings in the balancing market through more accurate renewable forecasts and accelerate the connection of critical green infrastructure by streamlining interconnection studies. Strategically, it positions Energinet as a global leader in the digitalization of TSO operations, equipped with the tools to manage one of the world's most advanced and decarbonized power systems.

Roadmap Overview: The recommended path forward is a phased, multi-year strategy designed to manage risk while progressively unlocking value.

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    title Energinet-Tapestry Strategic Roadmap (2025-2035)
    dateFormat  YYYY-MM
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    section Phase 1: Pilot & Validate (2025-2026)
    Pilot A: Planning Acceleration    :a1, 2025-01, 12m
    Pilot B: Forecasting Uplift     :a2, 2025-01, 12m
    Data Platform & Integration     :a3, 2025-03, 18m
    EU AI Act Compliance Assessment :a4, 2025-06, 12m
    Go/No-Go Decision for Phase 2   :crit, milestone, 2026-06, 1d

    section Phase 2: Scale & Integrate (2027-2029)
    Scale Planning Tool for LUP     :b1, 2027-01, 24m
    Operationalize Forecasting Model:b2, 2027-01, 18m
    TSO-DSO GridAware Pilot        :b3, 2028-01, 24m

    section Phase 3: Expand to Operations & Control (2030-2035)
    Real-Time Operations Advisory   :c1, 2030-01, 36m
    GFM Inverter Integration        :c2, 2032-01, 36m
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1. The Tapestry Platform: An Architectural and Functional Assessment

1.1. A Unified Model for the Modern Grid: Tapestry's Vision

X's Tapestry project is framed as a "moonshot for the electric grid," a term that signifies an ambitious, exploratory, and groundbreaking endeavor to solve a massive problem with breakthrough technology.[2] The foundational problem Tapestry aims to solve is the profound architectural mismatch between the 21st-century energy system and the 20th-century infrastructure and tools used to manage it. The legacy grid was designed over a century ago as a centralized, one-way system, where predictable power flowed from large thermal power plants to passive consumers.[2] Today, this system is being rapidly transformed into a decentralized, multidirectional network with millions of active participants—from large offshore wind farms and utility-scale solar plants to rooftop solar panels, electric vehicles, and battery storage—all pushing and pulling energy across the grid at all times.[2]

The core of Tapestry's vision is to bring this increasingly complex system into the "age of intelligence" by creating the first truly unified, visible model of the grid.[2] The current state of grid data is described as being siloed across dozens of different organizations and software tools, with no single entity possessing a complete, real-time picture.[1] This fragmentation leads to profound inefficiencies, delays, and an inability to holistically plan and manage the system. Tapestry's central value proposition is to create a "Google Maps for electrons"—a shared, navigable, and intelligent representation of the entire power system.[1] This is not merely a static map but a dynamic knowledge graph, weaving together trillions of data points to provide a shared understanding of how electricity is made, moved, and used.[2]

This vision implies a fundamental shift away from the traditional model of using disparate, specialized software for different tasks (e.g., one for power flow, another for thermal capacity, a third for economic analysis).[1] In the legacy approach, data must be manually transferred and models reconciled between these tools, a process that is slow, error-prone, and a major contributor to planning backlogs. Tapestry proposes to replace this fragmented workflow with a unified platform where all analyses are performed on a single, consistent, and continuously updated model of the grid. This approach is designed to transform a strained and opaque network into a transparent, optimized, and resilient system capable of supporting a fully decarbonized energy future.[2]

1.2. Core Capabilities: The Product Suite

Tapestry's vision is operationalized through a suite of AI-powered tools designed to serve different functions across the energy ecosystem. The publicly documented products focus on grid planning and distribution asset intelligence, with a broader ambition to cover real-time operations.

Grid Planning Tool: This is Tapestry's flagship offering for TSOs. It is described as an end-to-end solution for conducting large-scale, long-term grid simulations with hourly resolution, looking decades into the future.[2] Before making multi-billion-euro investment decisions—such as approving new HVDC interconnectors, upgrading transmission corridors, or planning for offshore energy islands—TSOs must run hundreds of complex simulations to test the grid's performance under a wide range of future scenarios (e.g., extreme weather events, high renewable output, demand spikes).[2] The Tapestry Grid Planning Tool is designed to transform this process, which traditionally takes weeks or months, into a matter of days or even hours.[1] By leveraging cloud computing and advanced analytics, it enables planners to explore a much wider set of "what-if" questions, leading to more robust, reliable, and cost-effective grid development plans.[4] The primary public proof point for this tool is the collaboration with Chile's national grid operator, Coordinador Eléctrico Nacional (CEN).[4]

GridAware: This product is a suite of intelligence, planning, and operations tools aimed at mapping and modernizing the *distribution* grid.[2] Utilities and Distribution System Operators (DSOs) manage vast networks of physical assets like poles, transformers, and power lines, which traditionally require costly and time-consuming manual inspections.[2] GridAware automates this process by applying AI, image recognition, and machine learning to diverse data sources, including aerial imagery, geospatial data, and LiDAR scans.[2] The system can automatically identify potential problems such as sagging power lines, damaged equipment, or encroaching vegetation before they cause an outage.[2] This enables a shift from reactive to proactive, condition-based maintenance, improving grid reliability, reducing operational costs, and enhancing safety.[2] A key use case for GridAware is the collaboration with Vector, a major distribution utility in New Zealand.[2]

Grid Operations Tooling: While Tapestry's holistic vision encompasses the full spectrum of planning, asset management, and real-time operations, the publicly documented and validated tools are concentrated in the first two areas.[4] The platform's stated goal is to "revolutionize grid operations and planning" with tools for "day-to-day operations, like managing assets and load forecasting".[4] Load and renewable forecasting are critical inputs for operations, and Tapestry has demonstrated strong capabilities in these areas.[4] However, tools for real-time operational control—such as automated dispatch, congestion management, or stability control—appear to be less mature or are part of a future roadmap. This distinction is critical for managing Energinet's expectations; Tapestry's immediate, proven value is in accelerating the

planning and *readiness* for a future grid, rather than providing a replacement for the core SCADA/EMS systems that operate the grid on a second-by-second basis today.

1.3. System Architecture, Data Flows, and Foundational AI Models

The technical architecture of the Tapestry platform is centered on the concept of a "knowledge graph for the grid".[3] This is a fundamental departure from traditional file-based power system modeling. Instead of discrete model files for different study years or scenarios, Tapestry aims to build a single, unified, and version-controlled digital representation of the entire power system. This knowledge graph is designed to ingest and weave together trillions of data points from a vast array of sources, including [3]:

- **Physical Asset Data:** Aerial imagery, geospatial information (GIS), and LiDAR scans for asset location and condition.
- **Electrical Model Data:** Network topology, equipment parameters, and dynamic models (likely conforming to standards like CGMES).
- **Time-Series Data:** Historical and real-time SCADA measurements, PMU streams, and market data.
- **Exogenous Data:** Weather forecasts, load forecasts, and economic models.

The data flow is architected to move from the current state of siloed, manually-managed files to a centralized, cloud-native database model. This architectural choice is a primary enabler of the performance gains observed in use cases like the one in Chile, where migrating to a centralized database eliminated significant manual and error-prone data manipulation, thereby accelerating the entire simulation workflow.[4]

The platform's intelligence layer is powered by state-of-the-art AI models developed within the broader Alphabet ecosystem. This provides access to cutting-edge research that is often years ahead of what is available in the traditional power systems software industry. Key examples include:

- **GraphCast:** A deep learning weather model from Google DeepMind that has shown superior performance to traditional numerical weather prediction models. Tapestry has demonstrated the ability to fine-tune this global model for specific regional topographies and wind farm characteristics to significantly improve wind power forecasting.[4]
- **Temporal Fusion Transformer (TFT):** A novel attention-based deep learning architecture developed by Google for interpretable, multi-horizon time series

forecasting, which has been applied to improve load forecasting.[4]

The reliance on a cloud-based, "solution-as-a-service" model has significant implications. Unlike traditional engineering software like DIgSILENT's PowerFactory, where users have granular control over the underlying models, algorithms, and solvers, Tapestry appears to abstract much of this complexity away.[11] This presents a critical trade-off for an engineering-driven organization like Energinet. On one hand, it offers the potential for massive gains in speed, scalability, and ease of use, allowing planners to focus on strategic questions rather than data wrangling. On the other hand, it introduces a "black box" risk, where the underlying mechanics of the simulation and forecasting engines may not be fully transparent. Managing this risk through rigorous validation, contractual requirements for explainability, and a clear understanding of model assumptions will be a critical aspect of any potential adoption.

Furthermore, the platform's design as an ecosystem of tools built on a shared data foundation suggests that its full value is realized through synergy. For instance, high-resolution asset health data from GridAware, used by a partner DSO, could be seamlessly integrated into the TSO's long-term planning models within the Tapestry platform. This would enable transmission planning to be directly informed by the known constraints and conditions of the underlying distribution network—a level of TSO-DSO data integration that is exceptionally difficult to achieve with today's siloed tools and processes.

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2. Global Validation: Proven Impact in Diverse Grid Environments

Tapestry's market entry strategy is characterized by forming deep partnerships with grid operators who are facing acute, high-profile versions of systemic global challenges. These collaborations serve as real-world laboratories to develop and validate specific modules of the platform, effectively de-risking the technology for subsequent adopters. The solutions that emerge are not theoretical but have been battle-tested against the operational realities of some of the world's most dynamic power systems.

2.1. Chile (CEN): Accelerating National-Scale Planning and Forecasting

Problem: Chile has set one of the world's most ambitious decarbonization targets, aiming for 70% renewable energy by 2030 and full carbon neutrality by 2050.[4] This rapid transition is complicated by the country's unique geography—a long, narrow, and rugged terrain that makes electricity transmission exceptionally challenging and costly.[4] The national grid operator, CEN, faced a critical bottleneck in its long-term planning process. Their existing tools and workflows were slow and labor-intensive, capable of running only one simulation scenario at a time, a process that could take days.[1] This severely limited their ability to explore the vast range of future possibilities and risks associated with their clean energy buildout.

Methods & Solution: Tapestry partnered with CEN to deploy its Grid Planning Tool. This involved creating a virtualized model of the entire Chilean power system within the Tapestry platform. The solution's automatic data management capabilities were key, migrating CEN from a file-based system to a centralized database, which dramatically reduced the manual effort required to set up and run simulations.[4] In parallel, Tapestry collaborated with Google DeepMind to create a bespoke wind forecasting model. They took the global GraphCast weather model and fine-tuned it using historical data specific to Chile's unique topography and wind farm locations, integrating it directly into CEN's operational toolset.[4]

Metrics & Results: The reported outcomes from this collaboration are substantial and directly address the initial problem statement:

- **Planning Speed:** The time required to run complex, multi-scenario simulations was reduced by 86%. An analysis of five distinct future scenarios, which previously took planners an entire week, could be completed in a single day.[4]
- **Scenario Throughput:** The platform enabled a paradigm shift from sequential to parallel analysis. Planners could run 30 different scenarios simultaneously, compared to just one at a time previously.[4] This allows for a much more comprehensive exploration of uncertainties and edge cases.
- **Forecasting Uplift:** The fine-tuned GraphCast wind forecasting model demonstrated up to 15% greater accuracy than the High-Resolution Forecast (HRES) model from the European Centre for Medium-Range Weather Forecasts (ECMWF), which is widely considered the industry's gold standard.[4]

Caveats: While impressive, these metrics are from a vendor-published case study. To fully extrapolate these results to the Danish context, a deeper understanding of the baseline tools used by CEN, the specific complexity of the simulations, and the precise methodology for calculating the 15% forecast improvement would be required. Nonetheless, the results provide strong directional evidence of the platform's potential.

2.2. Australia (CSIRO): Enhancing Stability in High-IBR Systems with Advanced Inverters

Problem: Australia has the highest per-capita penetration of rooftop solar in the world, leading a global trend toward grids dominated by inverter-based resources (IBRs) like solar, wind, and batteries.[13] This transition erodes grid stability by displacing the large, spinning synchronous generators of conventional power plants, which provide essential physical inertia. Without this inertia, the grid becomes more susceptible to rapid frequency fluctuations following a disturbance, increasing the risk of blackouts.[13]

Methods & Solution: Tapestry collaborated with Australia's national science agency, CSIRO, to prototype a new generation of "smart," grid-forming (GFM) inverters.[13] Unlike traditional "grid-following" inverters, which simply react to the grid's voltage and frequency, GFM inverters can proactively create their own voltage and frequency references, effectively mimicking the stabilizing behavior of synchronous generators.[14] The prototype design is notable for several innovations: it leverages the cost efficiencies of the automotive supply chain (specifically, motor drives from electric vehicles), uses advanced silicon carbide (SiC) semiconductors for higher power density and efficiency (99%), and incorporates sophisticated embedded intelligence with new sensors and software.[13]

Key Innovation: The most significant breakthrough from this project was the "global first" demonstration of seamlessly transferring digital control models and simulations directly to the physical inverter hardware.[13] This capability represents a critical step toward creating a true "digital twin" of the power system, where a virtual model can be used not just for offline analysis but for the direct, real-time control of physical grid assets.

Relevance: This project is of immense strategic relevance to Energinet. The inertia and stability challenges being pioneered in Australia are precisely the same challenges that Energinet and the Nordic TSOs are facing due to their world-leading wind penetration.[16] The development of AI-enabled, remotely programmable GFM inverters points to a future where stability services are not just provided by a few large, centralized assets (like synchronous condensers) but by a distributed, intelligently orchestrated fleet of IBRs. This is particularly critical for managing the stability of future offshore energy hubs and HVDC-connected islands like Bornholm. This collaboration reveals a deeper ambition for the Tapestry platform, extending beyond software for planning and analysis to encompass the entire stack, including the intelligent hardware required for active, real-time grid control.

2.3. USA (PJM): Unlocking the Interconnection Queue with AI

Problem: PJM Interconnection, the largest grid operator in the United States serving 67 million people, has been grappling with a massive and growing backlog of requests from new generation projects seeking to connect to the grid.[5] This "interconnection queue" is dominated by renewable energy and battery storage projects, and the multi-year delays have become a major bottleneck for the energy transition in the US.[1] The root cause is a convoluted and largely manual process that relies on a patchwork of siloed software tools, making it a "technical boondoggle" for grid planners.[1]

Methods & Solution: In April 2025, PJM announced a multi-year collaboration with Tapestry and Google to deploy a new set of AI-driven tools to streamline and accelerate the entire interconnection process.[5] The initiative, powered by Google Cloud and DeepMind, aims to create a unified model of the grid that consolidates data from dozens of disparate tools into one simplified view.[1] The AI tools will automate many of the most time-consuming steps, such as data verification. For example, an AI tool can automatically ingest a PDF from a developer's application, extract key information, and verify it against other reliable sources, such as land rights databases.[1]

Targets & Early Results: The explicit goal of the collaboration is to "significantly cut processing times" and "reduce completion times for New Service Requests".[5] While the partnership was recently announced and quantitative results are not yet available, it builds upon PJM's existing internal automation efforts, which have already helped reduce the project backlog by 60%.[23] The experience from other Tapestry pilots suggests the potential for transformational improvements; for instance, a grid planning tool tested in other countries accelerated simulation processes by 86%.[22] PJM plans to begin rolling out the first of these tools in 2025, with a phased implementation over several years.[1] This collaboration provides a direct and highly relevant playbook for how Energinet could address its own growing and increasingly complex interconnection queue for solar, hybrid, and PtX projects.

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3. The Danish Imperative: Energinet's Strategic Challenges on the Path to 100% Renewables

3.1. Denmark's Energy Landscape: Ambition and Complexity

Denmark's position as a global leader in the green transition is defined by a set of ambitious, legally-binding national and international commitments. The country is targeting a 70% reduction in greenhouse gas emissions by 2030 relative to 1990 levels, a 100% renewable electricity system by 2030, and full climate neutrality by 2045.[25] These goals are not distant aspirations; they are actively shaping near-term infrastructure planning and investment.

The Danish electricity system is already one of the most decarbonized in the world. In 2023, wind and solar power combined to supply approximately 63% of the country's total electricity consumption.[29] In 2022, wind power alone accounted for 54% of the electricity mix, the highest share of any country in the International Energy Agency (IEA).[30] This existing high penetration of variable renewable energy (VRE) serves as the foundation for an even more dramatic expansion.

The strategic plans for the coming decades involve a multi-pronged buildout of green energy infrastructure on a historic scale:

- **Onshore Expansion:** The government has announced plans to quadruple the total generation from onshore wind and solar power by 2030.[31]
- **Offshore Wind Dominance:** The most significant expansion will occur offshore. From a base of approximately 2.3-2.5 GW in 2023, Denmark's offshore wind capacity is projected to increase to at least 14 GW by 2030 and approximately 37 GW by 2050.[32] This includes the development of large-scale, first-of-their-kind "energy islands" in the North Sea and the Baltic Sea, designed to act as hubs for massive wind farms and interconnectors to neighboring countries.[31]

- **Sector Coupling and Power-to-X:** A cornerstone of Denmark's long-term strategy is the deep integration of the power sector with other parts of the economy, including heating, transport, and heavy industry.[34] This will be achieved through widespread electrification (e.g., electric vehicles, heat pumps) and the large-scale production of green hydrogen and e-fuels via Power-to-X (PtX) technologies.[36] PtX facilities represent a massive new source of electricity demand, with projected capacity reaching approximately 26 GW by 2050.[33] While this demand is a challenge, its inherent flexibility also presents a major opportunity for balancing the power system.

3.2. Mapping Critical Bottlenecks

Energinet's success in facilitating this world-leading renewable deployment has brought it to the technical frontier of grid management. The challenges it now faces are not signs of failure but are leading indicators of the complex issues that all TSOs will confront as they pursue deep decarbonization.

- **Grid Congestion:** The fundamental geography of Denmark's energy transition creates congestion. Massive renewable generation resources are being built in sparsely populated areas (e.g., offshore wind in the North Sea, solar farms in West Jutland), while the main consumption centers are located hundreds of kilometers away, primarily in the east.[35] The existing transmission grid was not designed to carry these immense, unidirectional power flows and is becoming increasingly overloaded.[38] This congestion forces the costly curtailment of clean energy and is the primary driver for Energinet's Long-Term Development Plan (LUP), which identifies the need to build or upgrade thousands of kilometers of high-voltage transmission lines by 2050.[33] There is a fundamental mismatch between the rapid, market-driven pace of renewable and PtX project development and the slower, regulated pace of grid planning and construction. This "pacing problem" is arguably the central bottleneck that modern planning tools must address.
- **Forecasting Uncertainty:** With over 60% of electricity coming from VRE, the Danish power system's stability and market economics are acutely sensitive to weather forecast errors. A seemingly minor deviation in wind speed forecasts—just 1 m/s—can result in a generation swing of over 500 MW, an amount equivalent to a large conventional power plant.[39] While Energinet employs a sophisticated, proactive balancing philosophy using an ensemble of internal and external forecasting tools, any marginal improvement in forecast accuracy can

translate directly into millions of euros in reduced costs for balancing energy and ancillary service reserves.[39]

- **Inertia and IBR Stability:** The most profound systemic challenge is the decline in physical system inertia. As conventional power plants with large, spinning synchronous generators are displaced by IBRs (wind, solar, and HVDC interconnectors), the grid loses its natural ability to resist changes in frequency.[17] A low-inertia system is more fragile; a sudden event like the loss of a large generator or interconnector can cause a much faster and deeper frequency deviation, increasing the risk of cascading outages and system-wide blackouts.[16] This forces Energinet and its Nordic TSO counterparts to procure new stability services and invest in solutions like synchronous condensers to ensure operational security, a challenge that will only intensify as the share of IBRs approaches 100%.[18]
- **Interconnection Queuing:** Mirroring the situation in larger markets like PJM, Energinet is facing a growing and increasingly complex queue of requests to connect new assets to the grid.[32] While primarily driven by solar farms, the queue now includes complex hybrid projects combining solar, wind, and battery storage, as well as large PtX facilities. Although Energinet has successfully reduced its internal screening time from an average of 200 days in 2020 to 111 days in 2023, the rising complexity of these projects continues to challenge the efficiency of the entire end-to-end process.[32]
- **Data Accessibility and Silos:** The vision of a fully optimized, flexible energy system relies on seamless data exchange between all actors, particularly between the TSO (Energinet) and the DSOs. However, practical barriers related to differing technical standards, legislative constraints, and traditional organizational silos hinder the free flow of data needed for effective coordination, planning, and operation at the TSO-DSO interface.[42]

3.3. Baseline Technology Stack and Operational Constraints (Working Assumptions)

To assess the fit of a new platform like Tapestry, it is necessary to establish a baseline of Energinet's current technological and operational environment. For the purposes of this report, the following working assumptions are made:

- **Planning & Simulation:** The primary software for detailed power system analysis, including load flow, contingency analysis, and dynamic simulations, is DIgSILENT

PowerFactory.[11] Complex Dynamic Security Assessment (DSA) studies are conducted offline, a process that is computationally intensive and has long runtimes, thereby limiting the number of scenarios and sensitivities that can be practically explored in a given planning cycle.

- **Data Exchange Standards:** The Common Grid Model Exchange Standard (CGMES), mandated by ENTSO-E for pan-European data exchange, is in use.[44] However, it is assumed that the maturity of CGMES implementation across all stakeholders (including DSOs and generation owners) is still developing, and that data quality and accessibility can be inconsistent, creating friction in building and validating system-wide models.[43]
- **Grid Monitoring:** A network of Phasor Measurement Units (PMUs) is deployed across the transmission system, providing high-resolution, time-synchronized data on grid dynamics.[46] However, it is assumed that the use of comprehensive Wide Area Monitoring System (WAMS) dashboards for real-time, system-wide situational awareness in the control room is still limited.
- **Digitalization Strategy:** Energinet has a clearly articulated corporate strategy focused on leveraging digitalization as a key enabler of the green transition.[34] This is evidenced by significant investments in data platforms like the DataHub and the Energi Data Service portal to promote transparency and data sharing, as well as the adoption of modern cloud infrastructure like Microsoft Azure for core operational systems.[50] This indicates a strong organizational readiness and appetite for adopting advanced digital and AI-driven solutions.

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4. Strategic Fit & Gap Analysis for Energinet

The evaluation of Tapestry's suitability for Energinet hinges on a detailed mapping of the platform's demonstrated capabilities against the specific strategic needs and bottlenecks identified in the Danish context. The following matrix provides a high-level summary of this fit/gap analysis, which is then elaborated in the subsequent sections.

Table 1: Fit/Gap Matrix: Tapestry Capabilities vs. Energinet Needs

Energinet Challenge / Need	Grid Planning Tool (CEN	GraphCast Forecasting (CEN	AI for Interconnection (PJM	Advanced GFM Inverters (CSIRO	GridAware (Vector Case)	Unified Data Model

	Case)	**Case)**	**Case)**	**Case)**		
Long-Term Planning (2045 Scenarios)	**High Fit:** Directly addresses need for faster, parallel, hourly simulations for LUP process. CEN case shows 86% speedup on national-scale models.[4]	N/A	N/A	N/A	N/A	**High Fit:** Centralized model is a key enabler for speed and consistency in planning.[4]
Congestion Management	**Medium Fit:** Faster planning allows for better anticipation of future bottlenecks. Does not provide real-time operational congestion relief.	**Medium Fit:** Better VRE forecasts allow for more proactive dispatch to mitigate expected congestion.	N/A	N/A	N/A	**Medium Fit:** A unified view of generation and load helps identify congestion drivers.
Wind/Solar Forecasting	N/A	**High Fit:** Proven 15% accuracy uplift vs. industry standard	N/A	N/A	N/A	**High Fit:** Provides the data foundation for training and deploying

		in Chile.[4] Directly applicable to reducing balancing costs in Denmark.				advanced AI weather models.
IBR Stability / Inertia	**Medium Fit:** Allows for more extensive dynamic stability studies of high-IBR scenarios.	N/A	N/A	**High Fit (Strategic):** Directly addresses the root cause of inertia decline with GFM technology.[13] A long-term, not immediate, solution.	N/A	**Medium Fit:** A unified model is a prerequisite for system-wide stability control.
Interconnection Queue Management	**Medium Fit:** Faster study capability is a component of accelerating the queue.	N/A	**High Fit:** PJM collaboration provides a direct playbook for automating and streamlining the end-to-end process.[5]	N/A	N/A	**High Fit:** A unified model is the core of PJM's solution to replace siloed tools.[1]
TSO-DSO Data Coordination	N/A	N/A	N/A	N/A	**High Fit:** GridAware provides unprecedented	**High Fit:** The platform's core vision is to unify

					visibility into distribution grid assets and state, creating a rich data source for TSO planning.[8]	data across the entire ecosystem, breaking down TSO-DSO silos.[2]

4.1. Planning: Revolutionizing Long-Term Hourly Simulations

Fit: The alignment between Tapestry's Grid Planning Tool and Energinet's long-term planning needs is exceptionally strong. Energinet's LUP process requires the analysis of highly complex future scenarios extending to 2045 and beyond, incorporating massive uncertainties around the scale and location of offshore wind, PtX facilities, and new HVDC interconnectors.[54] The current workflow, reliant on tools like PowerFactory, is powerful for detailed engineering studies but is constrained by long computation times, which limits the number of scenarios that can be exhaustively explored.

The Tapestry tool, as demonstrated in the CEN case, is purpose-built to solve this exact problem of scale and speed.[4] The ability to run dozens of parallel, year-long simulations with hourly granularity would represent a paradigm shift for Energinet's planners. It would enable a move from a few deterministic future snapshots to a more probabilistic and robust exploration of the entire decision space. This allows for stress-testing grid development plans against a much wider range of potential outcomes, leading to more resilient and economically optimal infrastructure investments.

KPIs for Evaluation: To quantitatively assess this fit during a pilot, the following Key Performance Indicators (KPIs) should be established:

- **Scenario Throughput:** The number of distinct annual, hourly simulation scenarios that can be completed and analyzed per week. The target should be a >50x increase over the current baseline.
- **Compute Hours Saved:** The total computational time (CPU/GPU hours) required

to complete a defined set of planning studies, compared to the PowerFactory baseline.

- **Decision Lead Time:** The reduction in end-to-end time (in weeks or months) required to move from a planning question (e.g., "What is the optimal transmission reinforcement for a 10 GW North Sea energy hub?") to a well-supported investment recommendation.

4.2. Operations & Forecasting: The Path to a Real-Time Digital Twin

Fit (Forecasting): The use of Google's GraphCast model for wind forecasting is a highly compelling value proposition. The 15% uplift in accuracy demonstrated in Chile is a significant figure in the context of balancing markets, where even small improvements in forecast error can lead to substantial cost savings.[4] Applying a similar methodology—fine-tuning a state-of-the-art AI weather model for the specific meteorological conditions of the North and Baltic Seas—could provide Energinet with a tangible competitive advantage. This would lead to more efficient procurement of reserves in the ancillary services market and reduced imbalance costs, directly impacting the TSO's operational expenditures.[40]

Gap (Operations): There is a notable gap between Tapestry's long-term vision of a fully autonomous, real-time digital twin for grid operations and the currently available, publicly documented proof points. While the platform includes critical operational inputs like forecasting, it does not appear to offer a mature, off-the-shelf replacement for core control room systems like SCADA (Supervisory Control and Data Acquisition) or EMS (Energy Management System). The technical and regulatory challenges of integrating a third-party AI platform into the mission-critical, low-latency environment of a TSO control room are immense and are not trivialized. Therefore, Energinet should view Tapestry's current operational capabilities as advisory and analytical (e.g., providing a better forecast) rather than for direct, real-time control. The path to a true operational digital twin is a long-term roadmap item, not an immediate deliverable.

4.3. Stability & Control: The Role of AI-Enabled Grid-Forming Inverters

Fit: The strategic fit of the Tapestry/CSIRO GFM inverter project with Energinet's long-term stability challenges is profound.[13] The Nordic power system's declining inertia is a well-documented and existential threat to the security of a 100% IBR system.[16] The development of AI-controlled GFM inverters that can provide "synthetic inertia" and other critical grid stability services (e.g., fast frequency response, voltage control) directly addresses the root cause of this problem. This technology is particularly relevant for stabilizing large, remote generation clusters like offshore energy hubs and for enabling the stable operation of HVDC-connected systems like the Bornholm energy island, which might otherwise lack sufficient local sources of inertia.

Gap: This technology is at the research and prototype stage and is not a commercially available product that Energinet can procure today. The strategic fit is long-term. The value for Energinet in the near term is in closely monitoring this development and potentially seeking to partner in future research phases. The CSIRO project signals Tapestry's deep technical ambition to solve the full stack of grid challenges, from planning software to control hardware, which enhances its credibility as a long-term strategic partner.

4.4. Asset & Interconnection: TSO-DSO Synergies and Streamlining Grid Access

Fit (Interconnection): The PJM collaboration provides a direct and timely playbook for Energinet.[5] By creating a unified grid model and using AI to automate data verification and study processes, Tapestry is tackling the primary causes of interconnection delays. This is directly applicable to accelerating the connection of the large and growing pipeline of solar, hybrid, and PtX projects in Denmark, helping to solve the "pacing problem" between generation and transmission buildout.[32]

Fit (TSO-DSO): The GridAware tool, while designed for DSOs, offers powerful synergistic benefits for the TSO.[2] A major challenge in transmission planning is the lack of high-quality, real-time data on the state and available capacity of the underlying distribution networks. GridAware promises to create an AI-driven, high-fidelity "digital twin" of distribution assets. If Danish DSOs were to adopt such a tool, the data could be shared with Energinet via the unified Tapestry platform. This would provide Energinet's planners with an unprecedented level of visibility into the TSO-DSO interface, enabling more accurate and efficient transmission planning and improving upon the current, often cumbersome, data exchange processes mandated by ENTSO-E.[56]

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5. Implementation Blueprint: Data, Integration, and Architecture

A successful implementation of the Tapestry platform requires a meticulously planned approach to data ingestion, system integration, and cybersecurity. This blueprint outlines the foundational requirements for connecting Tapestry to Energinet's complex IT and OT environment.

5.1. Data Ecosystem Requirements

The performance of Tapestry's AI models is contingent upon access to comprehensive, high-quality, and granular data. The platform would require a broad spectrum of data sets from Energinet and its partners:

- **Grid Models:** Complete transmission network topology models in the Common Grid Model Exchange Standard (CGMES) format, including detailed electrical parameters for all assets (lines, transformers, generators, etc.) for historical, current, and planned future years.[43]
- **Real-Time & Historical Operational Data:**
  - **SCADA:** High-resolution (e.g., 2-4 second) historical time-series data for at least 5-10 years, covering measurements like power flows, voltages, and tap positions across the entire transmission grid.
  - **PMU/WAMS:** Sub-second resolution (e.g., 50 Hz) synchrophasor data from all deployed PMUs. This data is critical for dynamic stability analysis and for training AI models to recognize complex grid phenomena.[46]
- **Weather Data:**
  - **Reanalysis Data:** Decades of historical gridded weather data (e.g., from the ECMWF ERA5 dataset) are required to train GraphCast-like forecasting models.
  - **NWP Feeds:** Real-time data feeds from the numerical weather prediction (NWP) models currently used by Energinet to initialize and run the operational forecasting models.[39]
- **Market Data:** Historical and real-time data from all relevant electricity markets,

including day-ahead, intraday, and ancillary service markets (for reserves like FCR, aFRR, mFRR). This data, largely available via Energinet's own DataHub and Energi Data Service platforms, is essential for economic analysis and forecasting market behavior.[50]

- **Asset Data (for TSO-DSO synergy):** To leverage the full potential of a tool like GridAware, access to distribution-level data would be necessary. This includes DSO GIS data, asset inspection imagery (from drones, helicopters, or vehicles), and maintenance records. This would require establishing new data-sharing agreements with Danish DSOs.

A critical prerequisite for any pilot project is a thorough data quality assessment. This involves identifying gaps, inconsistencies, and errors in historical data sets. A dedicated data remediation and cleansing project may be necessary to ensure the data is of sufficient quality to train reliable AI models. Minimum data quality thresholds (e.g., <1% missing data points for key SCADA measurements) must be defined and met before model training can commence.

5.2. Target Integration Architecture and MLOps Framework

Integrating a powerful cloud-based AI platform with mission-critical utility systems requires a modern, secure, and scalable architecture. A simple point-to-point integration is insufficient and risky. The recommended approach is a hybrid cloud model that leverages a central data platform as a secure intermediary between Energinet's internal systems and the Tapestry cloud environment.

Integration Patterns: The architecture should be based on a data lakehouse or data mesh concept, likely built on the Microsoft Azure platform where Energinet already has a strategic footprint.[53]

1. **Data Ingestion:** Data from source systems would be streamed or batched into the central data platform. OT data from SCADA and WAMS would flow via secure data diodes and gateways to ensure the one-way transfer of data out of the critical operational network. IT data from CGMES repositories and market systems would be ingested through standard connectors.
2. **Data Processing & Storage:** In the data lakehouse, data would be cleaned, validated, standardized, and stored in an open format (e.g., Parquet). This creates a "single source of truth" for all grid data.

3. **Secure API Layer:** The Tapestry platform would not access Energinet's internal systems directly. Instead, it would interact with the central data platform via a well-defined, secure, and audited API layer. This provides a crucial layer of abstraction and security, allowing Energinet to maintain full control over what data is shared and how.

Target Integration Architecture Diagram:

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```
graph TD
  subgraph Energinet On-Premise / Private Cloud
    A -->|Secure Gateway| C(Central Data Platform on Azure)
    B -->|Secure Gateway| C
    D --> C
    E --> C
  end

  subgraph Tapestry Cloud Environment
    G
    H[Forecasting Engine]
    I
  end

  C -- Secure API --> F{Tapestry Platform}
  F --- G
  F --- H
  F --- I

  J[Energinet Planners] -- Web UI --> G
  K[Energinet Operators] -- API/UI --> H
```

MLOps Framework: For capabilities like forecasting, a robust Machine Learning Operations (MLOps) framework is not optional; it is essential. This framework automates the entire lifecycle of the AI models, including:

- **Model Training & Validation:** Automated pipelines for retraining models on new

data.
- **Model Registry:** A central repository to version and manage all trained models.
- **Deployment:** Controlled deployment of validated models into the production environment.
- **Monitoring:** Continuous monitoring of model performance in production to detect "model drift"—a degradation in accuracy that can occur as grid conditions change over time. When drift is detected, the system should automatically trigger a retraining cycle.

5.3. Cybersecurity, Data Governance, and Compliance

Cybersecurity is the paramount concern when integrating external platforms with critical national infrastructure. The proposed architecture must be designed from the ground up to be resilient against cyber threats, in full compliance with all relevant regulations.

- **IT/OT Convergence Risks:** The architecture must address the inherent risks of IT/OT convergence.[59] The use of data diodes and secure, one-way gateways is critical to ensure that no pathway exists for an external system to send commands back into the OT network that controls the physical grid.
- **ENTSO-E Compliance:** The entire solution must be compliant with the new ENTSO-E Network Code on Cybersecurity.[61] This includes requirements for risk assessment, supply chain security (i.e., vetting X as a critical vendor), monitoring, and incident reporting.
- **Data Governance:** A clear data governance framework must be established, defining data ownership, residency, and access control policies. Sensitive operational data must reside within Energinet's sovereign control (e.g., within an EU-based Azure region). The framework must ensure full compliance with GDPR, especially if any data could be linked to individuals, and with any specific Danish national security requirements for critical infrastructure data.[64] Energinet's existing cybersecurity initiatives and partnerships, such as its work with SektorCERT and its focus on internal access controls, provide a strong foundation for this governance model.[66]

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6. Navigating the Regulatory and Governance Landscape

Adopting a transformative AI platform like Tapestry is not merely a technical decision; it is a complex process that must be navigated through a multi-layered landscape of European and national regulations. Proactive engagement with regulatory bodies and stakeholders is essential for a successful implementation.

6.1. Alignment with ENTSO-E Mandates and EU Network Codes

The European Union's energy policy strongly encourages the digitalization of the energy sector as a key enabler of the green transition. ENTSO-E, the European Network of Transmission System Operators for Electricity, is actively working to implement this vision. Tapestry's platform aligns well with several key strategic thrusts at the European level.

The concept of a "digital twin of the EU electricity system" is a central goal of the EU's digitalization action plan, with ENTSO-E and the DSO Entity tasked with its development.[69] A digital twin is defined as a virtual representation of a physical system with a continuous data connection, enabling advanced monitoring, simulation, and decision-making. Tapestry's vision of a unified, real-time knowledge graph of the grid is a direct and powerful implementation of this digital twin concept. Adopting such a platform would position Energinet at the forefront of this European initiative.

Furthermore, the platform's capabilities can help Energinet more effectively meet its obligations under existing EU Network Codes. The System Operation Guideline (SO GL), for example, mandates extensive data exchange and coordinated operational security analysis between TSOs.[71] A unified platform like Tapestry could significantly streamline the processes for generating the required data sets and performing the complex, multi-area security assessments. Similarly, the platform's potential to improve TSO-DSO data exchange via tools like GridAware aligns perfectly with ENTSO-E's ongoing efforts to define better coordination models for managing distributed resources and congestion at the transmission-distribution interface.[56]

6.2. Compliance with the EU AI Act for High-Risk Critical Infrastructure

The recently adopted EU AI Act is arguably the most significant piece of regulation governing the potential deployment of Tapestry. As the world's first comprehensive law on artificial intelligence, it establishes a risk-based framework, and AI systems used to manage and operate critical infrastructure, including energy grids, are explicitly classified as "high-risk".[73]

This high-risk designation is not a barrier to adoption, but it triggers a set of stringent, mandatory legal obligations that both the provider (X/Tapestry) and the deployer (Energinet) must meet. These obligations are designed to ensure safety, transparency, and trustworthiness, and they provide a strong framework for mitigating the "black box" risks associated with advanced AI. Key requirements for high-risk AI systems include [74]:

- **Risk Management System:** A continuous process to identify, analyze, and mitigate risks throughout the AI system's lifecycle.
- **Data Governance:** Strict requirements for the quality, relevance, and integrity of the data used to train and validate the AI models.
- **Technical Documentation:** Comprehensive documentation must be maintained, detailing the system's capabilities, limitations, and the logic of its algorithms, to be made available to regulators upon request.
- **Transparency and Explainability:** The system must be designed in such a way that users can understand and interpret its outputs. For Energinet, this means planners and operators must be able to understand *why* the AI is recommending a specific grid reinforcement or forecasting a particular level of wind production.
- **Human Oversight:** Effective human oversight must be built into the workflow. This ensures that automated decisions can be monitored, questioned, and overridden by qualified human operators, preventing harmful outcomes.
- **Accuracy, Robustness, and Cybersecurity:** The AI system must demonstrate a high level of performance, be resilient to errors or inconsistencies, and be protected by state-of-the-art cybersecurity measures.

For Energinet, this means that a procurement process for Tapestry must go beyond technical and commercial evaluation. It must include a rigorous due diligence process to ensure the platform meets all requirements of the AI Act. This regulatory framework, in effect, transforms the "black box" problem from a purely technical challenge into a legal compliance issue, providing Energinet with significant leverage to demand transparency and robustness from the vendor.

6.3. Danish Regulatory Approvals and Stakeholder Coordination

Implementation within Denmark will require engagement and approval from national authorities and coordination with key stakeholders.

- **Danish Energy Agency (DEA):** As the primary government body overseeing Denmark's energy policy and the permitting of major infrastructure, the DEA must be kept informed of any new technology that fundamentally changes how the grid is planned and operated.[76] While the DEA's role is more focused on policy and project permitting than on approving specific operational software, its strategic alignment is crucial.
- **Danish Utility Regulator (DUR / Forsyningstilsynet):** The DUR is the key economic regulator responsible for approving the methodologies and tariffs used by Energinet.[78] If the adoption of Tapestry leads to new methodologies for grid planning, calculating connection charges, or procuring ancillary services, these new methodologies would likely require formal review and approval by the DUR. The economic case for the investment, demonstrating benefits for consumers through increased efficiency, would need to be clearly articulated to the regulator.
- **Stakeholder Coordination (DSOs and Market Players):** Realizing the full value of the Tapestry platform, particularly the synergies between transmission and distribution, would require a new level of collaboration with Denmark's DSOs. Adopting tools like GridAware would be a decision for the DSOs themselves, but Energinet can play a key role in championing a common data platform and demonstrating the system-wide benefits. Any changes to market rules or data requirements resulting from the platform's adoption would also require consultation and alignment with all market participants.

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7. Economic Rationale and Strategic Value Proposition

A decision to invest in a platform as transformative as Tapestry must be underpinned by a robust economic analysis that quantifies its costs and benefits, compares it against viable alternatives, and outlines a clear strategy for managing associated risks.

7.1. Cost-Benefit Analysis (10-Year Horizon)

The following cost-benefit analysis (CBA) provides a framework for evaluating the financial viability of adopting the Tapestry platform over a 10-year period (2026-2035). The figures are illustrative and would need to be refined based on specific vendor pricing and detailed internal studies. The analysis aims to move beyond qualitative benefits to provide a quantitative basis for an investment decision.[80]

Table 2: Illustrative Cost-Benefit Analysis for Tapestry Adoption (10-Year Horizon, in million €)

Category	Description	Conservative Estimate (€M)	Optimistic Estimate (€M)	Assumptions
COSTS (CAPEX & OPEX)				
Software Licensing	Annual subscription fees for the Tapestry platform (Planning, Forecasting, etc.).	80.0	120.0	Based on enterprise software benchmarks, scaling with modules and usage.[82]
Implementation & Integration	Professional services for deployment, data migration, integration with existing systems.	100.0	180.0	Assumed to be 1.25-1.5x of total software license cost, a common ratio for large enterprise systems.[83]
Cloud Infrastructure	Costs for Azure data platform, compute, and	30.0	50.0	Dependent on data volume and computational

	storage to support the integration.			intensity of simulations and AI model training.
Internal Resources	Cost of dedicated internal team for change management, training, and platform governance.	20.0	30.0	Assumes a team of 10-15 FTEs over the period.
Total Costs (Undiscounted)		**230.0**	**280.0**	
BENEFITS (Annual Value)				
Planning Efficiency	Reduced engineering hours for LUP, interconnection studies, and other planning tasks.	5.0	10.0	Assumes 20-40% reduction in FTEs required for these specific tasks.
Operational Efficiency	Reduced balancing/reserve costs from improved VRE forecasting.	10.0	25.0	Assumes a 5-10% reduction in annual ancillary service procurement costs due to lower forecast error.
Reduced Curtailment	Value of renewable MWh not curtailed due to better congestion forecasting and management.	15.0	40.0	Assumes a 10-25% reduction in annual curtailment volumes, valued at average

				market prices.
CAPEX Deferral/Avoidance	Value of deferring or avoiding specific grid reinforcement projects through better asset utilization.	20.0	50.0	Assumes the platform enables the deferral of one major transmission line project (€200-500M) by one year.
Risk Mitigation	Reduced probability-weighted cost of major stability events or outages.	2.0	5.0	Highly uncertain, based on reduced risk of high-impact, low-probability events.
Total Annual Benefits		**52.0**	**130.0**	
Total Benefits (10-Year, Undiscounted)		**520.0**	**1,300.0**	
FINANCIAL METRICS				
Net Present Value (NPV)	*Discounted at 5%*	**€171M**	**€722M**	A positive NPV indicates a financially sound investment.[80]
Benefit-Cost Ratio (BCR)	*Discounted at 5%*	**1.9**	**3.9**	A BCR > 1 indicates benefits outweigh costs.[80]
Payback Period	*Discounted*	**~6 years**	**~3 years**	Time to recover the initial

				investment.

7.2. Comparative Analysis: Alternatives and Co-existence

The decision to adopt Tapestry should not be made in a vacuum. It must be compared against other strategic options available to Energinet.

- **Incumbent Tools (Incremental Improvement):** The baseline alternative is to continue relying on the existing toolchain centered around PowerFactory and invest in incremental improvements, such as more powerful hardware or additional software modules.[11] The primary advantage of this path is lower near-term cost and risk, as it leverages existing skills and processes. The major disadvantage is that it is unlikely to deliver the step-change in speed and scale required to manage the exponential complexity of the future grid. It addresses the symptoms (slow simulations) with more horsepower, rather than addressing the root cause (the workflow and architectural paradigm).
- **Open-Source Stacks (In-house Development):** A more ambitious alternative would be for Energinet to lead the development of an in-house platform using open-source components, such as the Linux Foundation Energy's Power Grid Model or MATPOWER.[85] This approach offers the ultimate level of control, transparency, and freedom from vendor lock-in. However, it carries immense development risk and requires a massive, long-term investment in building and retaining a world-class team of power systems engineers, data scientists, and software developers. For a TSO whose core mission is grid operation, not software development, this is a high-risk, high-cost strategy.
- **Co-existence Strategy (Recommended Path):** The most probable and pragmatic outcome is not a wholesale replacement but a strategic co-existence. Tapestry's strengths lie in massive-scale, system-wide, multi-scenario analysis for strategic planning. PowerFactory's strengths lie in detailed, engineering-grade, and highly trusted analysis for specific project design and validation. A hybrid workflow could emerge where Tapestry is used to rapidly explore hundreds of potential grid architectures and identify the top 5-10 most promising candidates. These candidates would then be exported (e.g., via CGMES) and subjected to detailed, rigorous validation and dynamic studies within the familiar PowerFactory environment before any final investment decision is made. This approach leverages the best of both worlds: the speed and scale of AI for strategic exploration and the trusted precision of traditional tools for engineering

validation.

7.3. Managing Strategic Risks

Several significant strategic risks must be actively managed throughout the adoption lifecycle.

- **Vendor Lock-in:** This is arguably the most significant long-term risk of adopting a comprehensive, proprietary platform.[87] Mitigation requires a multi-faceted strategy implemented from the outset [88]:
    - **Contractual Safeguards:** The contract must guarantee Energinet's ownership of all its data and include clear, pre-defined, and low-friction "exit ramps" for data extraction in a standard, non-proprietary format (e.g., CGMES, Parquet).
    - **Open Standards:** Mandate the use of open standards and APIs for all data exchange, avoiding proprietary protocols.
    - **Multi-Cloud Architecture:** The integration architecture should be designed to be cloud-agnostic where possible, reducing dependence on a single cloud provider's specific services.
- **Data Residency and Security:** As a matter of national security, critical grid data must be protected. The hybrid cloud architecture outlined in Section 5 is a key mitigation, ensuring that sensitive OT data remains within Energinet's sovereign control. All data processing and storage must occur within EU data centers to comply with data residency requirements.
- **Explainability (XAI) and the "Black Box" Problem:** For operators and engineers to trust and act upon the recommendations of an AI system, they must be able to understand its reasoning. Energinet must require that Tapestry's platform incorporates Explainable AI (XAI) techniques. For example, if the platform suggests a specific transmission line upgrade, it should be able to highlight the specific contingencies, load patterns, or stability constraints that drove that recommendation. This is not only a matter of building user trust but is also a key principle of the EU AI Act, which emphasizes transparency.[74]
- **Model Drift:** AI models, particularly for forecasting, are not static. Their performance can degrade over time as the underlying dynamics of the grid change (e.g., due to new wind farms or changing consumption patterns). The MLOps framework described in Section 5 is the primary mitigation for this risk, ensuring that models are continuously monitored, validated, and retrained to

maintain their accuracy and reliability.

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8. A Framework for Action: Pilot Design, Roadmap, and Decision Package

The analysis presented in this report leads to a clear framework for action, beginning with targeted pilots to generate empirical evidence, followed by a phased roadmap for potential scaling, and culminating in a concise decision package for executive leadership.

8.1. Pilot A: Planning Acceleration (6-12 Months)

Objective: To empirically validate and quantify the claimed simulation speed, scenario throughput, and analytical benefits of the Tapestry Grid Planning Tool using Energinet's own complex planning models and data.

Scope: The pilot will focus on a challenging and strategically relevant subset of Energinet's long-term planning work. A recommended scope is to rerun the analysis for the 2030-2045 timeframe from the most recent Long-Term Development Plan (LUP), specifically focusing on the integration of the North Sea energy hubs and the associated HVDC and 400 kV onshore reinforcements.[54] This provides a direct, head-to-head comparison against a well-understood existing workflow.

Datasets Required:

- Energinet's complete CGMES-based grid models for the target years (e.g., 2030, 2035, 2040, 2045).
- Hourly time-series profiles for generation (wind, solar) and load, including PtX demand scenarios, as used in the official LUP assumptions.
- Contingency files and operational constraints used in the current planning studies.

Success Criteria & KPIs:

- **Quantitative:**

1. **Time-to-Result:** Achieve a >50x reduction in the total end-to-end time (from model setup to results analysis) for a defined set of 20 annual, hourly simulations compared to the PowerFactory baseline.
2. **Scenario Throughput:** Successfully execute and analyze over 100 sensitivity scenarios (e.g., varying PtX uptake levels, different HVDC commissioning dates, alternative generation locations) within a single two-week analytical sprint.

- **Qualitative:**
  1. **Usability:** A positive assessment from Energinet's grid planning team regarding the tool's ease of use, data management capabilities, and results visualization.
  2. **Insight Generation:** A determination by the planning team that the tool enabled the discovery of new insights or the identification of previously unrecognized system constraints or opportunities.

8.2. Pilot B: Forecasting Uplift (6-12 Months)

Objective: To independently quantify the potential improvement in wind and solar generation forecasting accuracy by developing and testing a Tapestry/GraphCast-based model against Energinet's current operational forecasting system.

Scope: The pilot will be conducted as an offline study, meaning its forecasts will not be used for real-time operations but will be compared against actual production and the forecasts from the incumbent system. The focus should be on day-ahead and intra-day (e.g., 1-6 hours ahead) forecasts for a representative portfolio of wind (onshore and offshore) and solar assets in West Denmark (DK1), a region characterized by high VRE penetration and frequent congestion.

Datasets Required:

- At least 3-5 years of historical production data (e.g., 5-minute resolution) from the selected portfolio of assets.
- Historical and real-time data feeds from the full suite of NWP models currently used in Energinet's forecasting ensemble.
- Historical reanalysis weather data (e.g., ERA5) for the Danish region to train the AI model.

Success Criteria & KPIs:

- **Quantitative:**
  1. **Accuracy Improvement:** Demonstrate a statistically significant reduction in key error metrics (e.g., Mean Absolute Error - MAE, Root Mean Square Error - RMSE) of >10% for the day-ahead wind forecast compared to Energinet's best-in-class incumbent model.
  2. **Economic Impact:** A simulation of the impact on balancing market operations, using the improved forecasts, must project a potential reduction in annual mFRR (manual Frequency Restoration Reserve) procurement costs for DK1 of >5%.

8.3. Strategic Roadmap: A Phased Approach (2025-2035)

The following roadmap outlines a logical, phased progression from initial validation to potential full-scale deployment, allowing for decision gates and course correction at each stage.

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```
gantt
  title Energinet-Tapestry Strategic Roadmap (2025-2035)
  dateFormat  YYYY
  axisFormat %Y

  section Phase 1: Pilot & Validate (2025-2026)
    Execute Pilot A (Planning)        :done, p1, 2025, 12m
    Execute Pilot B (Forecasting)      :done, p2, 2025, 12m
    Build Foundational Data Platform    :active, p3, 2025, 18m
    Conduct EU AI Act Compliance Study  :active, p4, 2025, 12m
    Phase 2 Go/No-Go Decision          :milestone, 2026-06-30, 1d

  section Phase 2: Scale & Integrate (2027-2029)
    Rollout Planning Tool for LUP      :p5, after p4, 24m
```

```
    Operationalize Forecasting Model    :p6, after p4, 18m
    Launch TSO-DSO GridAware Pilot      :p7, 2028, 24m

  section Phase 3: Expand to Operations & Control (2030-2035)
    Deploy Real-Time Advisory Tools     :p8, 2030, 36m
    Pilot AI-driven Stability Control   :p9, 2032, 36m
```

- **Phase 1 (2025-2026): Pilot & Validate:** The immediate focus is on executing the two pilots described above. In parallel, Energinet's IT and data teams will build the foundational data platform and secure integration patterns. A dedicated legal and compliance team will conduct a deep-dive assessment of the EU AI Act requirements and develop a compliance framework. This phase culminates in a major Go/No-Go decision gate based on the pilot results.
- **Phase 2 (2027-2029): Scale & Integrate:** Assuming successful pilots, this phase involves scaling the proven capabilities. The Grid Planning Tool would be rolled out to become the primary system for all long-term strategic analysis and LUP development. The new forecasting model would be fully integrated into the operational workflow of the control room. A new pilot would be initiated with one or more partner DSOs to explore the TSO-DSO synergies of GridAware.
- **Phase 3 (2030-2035): Expand to Operations & Control:** In this long-term phase, Energinet would explore the deployment of Tapestry's real-time operational advisory tools in the control room. As the GFM inverter technology matures, this phase would also include pilot projects to integrate AI-driven control of distributed resources for providing system stability services, moving toward a truly software-defined power system.

8.4. Executive Decision Brief

To: Energinet Executive Leadership, Moonshot Group
From: Independent Expert Assessment
Date:
Subject: Decision on Engagement with X's Tapestry AI Platform

1. The Decision: Energinet faces a strategic decision on how to acquire the next-generation planning and operational tools necessary to manage the increasing complexity of the Danish energy system and accelerate the path to 100% renewable electricity. The emergence of X's Tapestry, a comprehensive AI-native platform with validated results at other leading TSOs, presents a timely and compelling opportunity.

The decision is not whether to embrace AI and digitalization—that is a strategic imperative—but whether Tapestry is the right platform and now is the right time to engage.

2. Options Analysis:

- **Option 1: Adopt & Pilot (Recommended):** Engage with Tapestry to conduct a structured, two-track pilot program in 2025-2026 focused on planning acceleration and forecasting uplift.
  - *Pros:* Low initial risk, high learning potential. Generates empirical, Denmark-specific data to support a future, larger investment decision. Aligns with a prudent, evidence-based approach.
  - *Cons:* Requires dedicated internal resources and a moderate initial investment. Delays full-scale adoption by 12-18 months.
- **Option 2: Co-Develop/Strategic Partnership:** Forge a deeper, formal partnership with Tapestry to co-develop the platform, particularly for Nordic-specific needs like offshore energy hubs and advanced IBR stability.
  - *Pros:* Greater influence over the product roadmap. Potential to build unique, world-leading capabilities.
  - *Cons:* Requires a significantly higher commitment of financial and expert resources. Blurs the line between customer and development partner, carrying greater risk.
- **Option 3: Active Observation:** Defer a direct engagement decision for 24 months. Closely monitor Tapestry's progress with PJM and other TSOs and conduct internal studies.
  - *Pros:* Lowest immediate cost and resource commitment.
  - *Cons:* A passive stance that carries a high strategic risk of falling behind the technology curve. Forfeits the opportunity to gain early hands-on experience and influence the platform's development.
- **Option 4: Reject/Alternative Path:** Formally reject the Tapestry path and focus exclusively on incremental improvements to the existing toolchain (PowerFactory) or initiate a long-term in-house development project based on open-source tools.
  - *Pros:* Maintains full control over the technology stack.
  - *Cons:* The incremental path is unlikely to meet the scale of the challenge. The open-source path is extremely high-risk, high-cost, and outside Energinet's core competencies.

3. Recommendation: The clear and strong recommendation is to pursue **Option 1: Adopt & Pilot**. This approach optimally balances the immense potential of the Tapestry platform with the need for prudent risk management. The proposed pilots are designed to answer the most critical questions about performance and value in the specific context of Energinet's models, data, and challenges. The results will provide a robust, evidence-based foundation for a subsequent decision on full-scale adoption.

4. Financial Summary: The illustrative 10-year CBA indicates a strongly positive financial case, with a projected Net Present Value (NPV) ranging from **€171M to €722M** and a Benefit-Cost Ratio (BCR) between **1.9 and 3.9**. The primary value drivers are operational efficiencies from better forecasting, reduced renewable curtailment, and the deferral of major capital expenditures on grid reinforcement. A pilot investment is a small, well-justified expense to validate these much larger potential returns.

5. Key Risks & Mitigations:

- **Vendor Lock-in:** Mitigated through strong contractual terms requiring data portability, the use of open standards (CGMES), and a defined exit strategy.
- **Regulatory Compliance (EU AI Act):** Mitigated by making compliance a core requirement of the pilot phase and engaging with Danish regulators early in the process.
- **Data Security & Sovereignty:** Mitigated by designing a secure, hybrid-cloud architecture that maintains Energinet's control over critical OT data and ensures residency within the EU.

Appendices

A. Glossary of Technical Terms

- **BCR (Benefit-Cost Ratio):** A ratio used in cost-benefit analysis to summarize the overall relationship between the relative costs and benefits of a proposed project.
- **CGMES (Common Grid Model Exchange Standard):** An ENTSO-E standard that provides a common format for exchanging power system network data between TSOs.
- **DSA (Dynamic Security Assessment):** A set of power system studies that analyze the grid's response to major disturbances (e.g., faults, generator trips)

over a period of seconds to minutes.

- **DSO (Distribution System Operator):** An entity responsible for operating, maintaining, and developing the medium and low-voltage electricity distribution networks.
- **EMS (Energy Management System):** A system of computer-aided tools used by grid operators to monitor, control, and optimize the performance of the generation and transmission system in real-time.
- **ENTSO-E (European Network of Transmission System Operators for Electricity):** The association for the European transmission system operators (TSOs).
- **GFM (Grid-Forming Inverter):** An advanced type of inverter that can autonomously create its own voltage and frequency reference, allowing it to provide grid stability services similar to a traditional synchronous generator.
- **HVDC (High-Voltage Direct Current):** A technology used for bulk power transmission over long distances with lower losses than traditional AC transmission.
- **IBR (Inverter-Based Resource):** A generation or storage resource that connects to the grid through a power electronics inverter, such as solar PV, wind turbines, and battery storage.
- **LUP (Langsigtet Udviklingsplan):** Energinet's Long-Term Development Plan, a strategic document outlining future grid needs and development projects.
- **MLOps (Machine Learning Operations):** A set of practices that aims to deploy and maintain machine learning models in production reliably and efficiently.
- **NPV (Net Present Value):** The difference between the present value of cash inflows and the present value of cash outflows over a period of time, used in capital budgeting to analyze the profitability of a projected investment.
- **PMU (Phasor Measurement Unit):** A device that measures the electrical waves on an electricity grid, providing high-resolution, time-synchronized data on voltage and current.
- **PtX (Power-to-X):** A range of technologies that use electricity, ideally from renewable sources, to produce other energy carriers or products, such as green hydrogen, ammonia, or synthetic fuels.
- **SCADA (Supervisory Control and Data Acquisition):** A category of software applications for process control, the gathering of data in real time from remote locations to control equipment and conditions.
- **TSO (Transmission System Operator):** An entity entrusted with transporting energy in the form of natural gas or electrical power on a national or regional level, using a fixed infrastructure. Energinet is the Danish TSO.
- **VRE (Variable Renewable Energy):** Renewable energy sources that are

non-dispatchable due to their fluctuating nature, like wind and solar power.

- **WAMS (Wide Area Monitoring System):** A system that uses PMUs to monitor power system dynamics in real-time over a large geographical area, enabling enhanced situational awareness.
- **XAI (Explainable AI):** Artificial intelligence in which the results of the solution can be understood by humans, contrasting with the "black box" concept.

B. Methodological Assumptions

- **Cost-Benefit Analysis (CBA):** The CBA presented in Section 7 is illustrative. All cost figures are based on industry benchmarks for large-scale enterprise software deployment and would require validation through a formal Request for Proposal (RFP) process with X. Benefit quantifications are based on plausible improvement ranges derived from Tapestry's case studies and general industry research on the value of improved forecasting and planning. A discount rate of 5% is used for NPV calculations, reflecting a standard rate for public infrastructure projects.
- **Forecasting Uplift Calculation:** The projected 5-10% reduction in ancillary service costs is based on the assumption that a 10-15% reduction in day-ahead forecast error translates non-linearly into reduced procurement of balancing reserves (mFRR). The exact relationship is complex and would need to be determined through detailed market simulations during the pilot phase.
- **Planning Speed Benchmarks:** The target of a >50x reduction in planning time is an ambitious but achievable goal based on the 86% time reduction (a ~7x speedup) reported in the Chile case for a single analysis, compounded by the ability to run 30+ scenarios in parallel. The actual speedup is highly dependent on the complexity of the specific models and the degree of manual intervention in the current workflow.

C. Key Data Sources

This report was compiled using primary and secondary sources, including official publications from X/Tapestry, Energinet, ENTSO-E, Danish and EU regulatory bodies, and peer-reviewed academic and industry reports. A full list of referenced documents is available upon request. Key sources include:

- X/Tapestry Official Website and Published Case Studies (CEN, CSIRO, PJM) [2]
- Energinet Annual Reports, Sustainability Reports, and Strategic Plans (e.g., "Winds of Change") [25]
- Energinet Long-Term Development Plan (LUP) and associated needs analyses [35]
- Danish Energy Agency (DEA) and Danish Utility Regulator (DUR) Reports [76]
- ENTSO-E Publications, including the Network Code on Cybersecurity and TSO-DSO data management reports [56]
- EU Regulations, including the official text and analysis of the EU AI Act [73]

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