ChatGPT

GridFM: Open-Source Foundation Model Framework for Power Grids

Introduction

GridFM is an open-source initiative under the Linux Foundation's LF Energy umbrella aimed at developing **foundation models** for electric power grids [1]. Foundation models (FMs) refer to very large AI models trained on vast datasets and adaptable to many tasks – they have revolutionized domains like natural language and weather modeling [2]. GridFM extends this philosophy to power systems, envisioning a **universal AI model of the grid** that can be fine-tuned for diverse applications. By leveraging cutting-edge AI (graph neural networks, transformers, etc.) and **collaborative open development**, GridFM seeks to address the growing complexity of modern grids while accelerating innovation through shared efforts [3] [4]. This report delves into the technologies and design of GridFM, its value proposition for Transmission System Operators (TSOs) – with a focus on Energinet (Denmark's TSO) – and its role in digital grid integration. We also compare GridFM to other digital grid platforms (open-source and commercial) and discuss strategic or regulatory advantages for TSOs in adopting such open solutions.

Technologies and Philosophy Behind GridFM

Foundation Model Concept: GridFM is built on the concept of *foundation models* – extremely powerful AI models trained via self-supervised learning on massive datasets to capture rich representations of a domain [5]. In GridFM's case, the domain is the electrical grid. The philosophy is that a single large model pre-trained on diverse grid data and network topologies can later be fine-tuned to many downstream tasks in grid operations, planning, and control [6]. This approach mirrors successes in NLP (e.g. GPT models) and climate modeling, suggesting that complex physical systems like power grids can benefit from similar AI breakthroughs [7]. A key expected benefit is **significant computational speed-up** – GridFMs could approximate or emulate physics-based simulations (like power flow or contingency analysis) much faster than traditional solvers [8], enabling near-real-time analysis of scenarios that today are computationally intensive.

Open Collaboration and Neutral Governance: The project's philosophy is inherently open and collaborative. Originated by Hydro-Québec (a Canadian utility) and IBM, GridFM was contributed to LF Energy to ensure **neutral governance** and a community-driven roadmap [9]. In the LF Energy model, no single company controls the project – instead, stakeholders jointly invest and collaborate on the common codebase under open licensing [10]. This open ethos aligns with a broader industry trend: TSOs and utilities see open source as a way to reduce software costs, improve quality, and accelerate development through shared effort [11]. Energinet, for instance, has embraced open-source development (e.g. contributing its Green Energy Hub platform) as a means to **avoid vendor lock-in while pooling innovation** with peers [12] [13]. GridFM's open framework invites participation from academia, AI specialists, and grid operators globally, creating a **technology platform for collective innovation** in AI for grids [14].

Key Technologies: Technically, GridFM leverages state-of-the-art AI and data engineering tailored to power systems. At its core, GridFM models use **graph neural networks (GNNs)** to represent grid topology and physics [15]. Power grids are naturally graph-structured (nodes for buses, edges for transmission lines), and GNNs excel at learning representations of such networks via message-passing between connected nodes [16]. Recent research indicates that attention-based graph models (Graph Attention Networks, Graph Transformers) perform best for grid tasks like power flow and optimal power flow (OPF) solutions [17]. GridFM builds on these advances by adopting **attention mechanisms** and even exploring *hierarchical* GNN architectures – for example, one that can capture both transmission and distribution grids in a unified model [18].

Another pillar is the handling of **multi-modal data**. GridFM is designed to ingest and learn from at least four data modalities: **tabular data** (e.g. asset attributes), **time-series** (loads, generation, measurements over time), **graph-structured data** (grid connectivity and network parameters), and **geospatial data** (location of assets, weather maps, etc.) [19]. This is critical, as managing a modern electric grid requires understanding temporal patterns (like demand curves), spatial/weather effects, and network constraints together. The model will likely employ a combination of encoders for each modality and a fusion mechanism (potentially a unified token space or a mixture-of-experts) to learn a cohesive representation [20] [21]. In fact, the team envisions two possible designs: (1) a single colossal multi-modal model, or (2) multiple specialized foundation models integrated via a Mixture-of-Experts framework [20]. Both approaches aim to handle the grid's complexity by breaking it into learnable components while retaining a unified overall model.

Self-Supervised Learning & Data Strategy: GridFM's training will rely heavily on self-supervised learning from vast quantities of grid data. The initial phase of the project focuses on generating a **large corpus of solved AC power flow cases** under many conditions [22]. This includes varying grid topologies, component parameters, load/generation levels, and even contingencies (n-1, n-k outages). To achieve this, the GridFM team created an open data generation toolkit ("gridfm-datakit") that can produce hundreds of thousands of power flow scenarios at scale. This toolkit leverages existing open network models (e.g. the **PGLib-OPF** library of grid test cases) and randomizes load profiles, network parameters, and outages to create a comprehensive training dataset [23] [24]. Compared to prior power flow datasets, GridFM's data pipeline uniquely supports large networks (>1000 buses), multiple simultaneous outages (n-k), and uses real-world load profile statistics, all with scalable cloud-based generation [25].

Using these data, GridFM will train a model to perform a kind of **mask-and-reconstruct task** for power flow solutions [26]. In practice, this could mean hiding (masking) certain values in a solved power flow case (e.g. flows on some lines or voltages at some buses) and training the model to predict those from the remaining context [27]. This self-supervised objective forces the model to learn the physical relationships in power flow data without explicit supervision. It's analogous to how language models mask words and learn to fill them in, thereby learning language structure. By **GridFM-v0**, the team expects to have a foundation model capable of reconstructing power flow results and related variables with high accuracy [28]. Subsequent fine-tuning can then adapt this foundation to specific tasks like OPF, contingency analysis, etc., with far less data and effort than training separate models from scratch [28] [29].

Overall, the technology stack of GridFM blends advanced AI (deep learning on graphs and sequences) with deep power system domain knowledge. The project's philosophy stresses openness – not only open source code, but also open **data sharing (within privacy limits)** and open collaboration across organizations. IBM Research, for example, convened a working group including universities (Imperial College London, ETH Zurich), national labs (Argonne), and multiple grid operators (e.g. Hydro-Québec, SSEN in the UK, and a Swiss TSO) to shape the GridFM concept [30]. By pooling expertise from AI and power engineering, and by building in the open, GridFM aims to create a **common AI foundation** that the entire industry can leverage, rather than each utility developing AI models in isolation.

Value Generation for TSOs – Focus on Energinet

For Transmission System Operators like **Energinet**, GridFM promises to unlock significant value by improving grid management, planning, and operational efficiency. TSOs face mounting challenges: rapidly increasing renewable penetration, new demand patterns (e.g. EV charging, data centers), and the need to maintain reliability amid more volatile conditions. Energinet, for instance, is tasked with moving Denmark from ~50% renewable electricity to 100% by 2030 – a mission that introduces immense variability and uncertainty in grid operations [31]. Traditional tools and approaches are being stretched to their limits; as renewables grow, simply building more infrastructure or relying on slow simulations is neither economical nor adequate to prevent issues like brownouts [32]. Below we outline how GridFM can generate value for TSOs, with examples relevant to Energinet's context:

- **Faster Grid Simulations and Contingency Analysis:** TSOs must continuously assess "N-1" contingencies (and beyond) to ensure the grid can withstand outages. Today this involves running thousands of power flow computations, which is time-consuming. A GridFM model, once pre-trained, can serve as a *fast "surrogate" for power flow solvers*, instantly predicting flow outcomes or voltage profiles under different scenarios [7]. This enables near real-time contingency screening and what-if analyses. For Energinet, which operates a highly meshed transmission network with many cross-border links, the ability to rapidly predict the effect of a line or generator outage under various load/generation patterns is invaluable. It can lead to improved operational decisions (like re-dispatching generation or adjusting HVDC flows pre-emptively) that maintain security of supply. By **speeding up complex computations by orders of magnitude**, GridFM helps TSOs cope with the increasing complexity and uncertainty of the energy transition [33] [34].

- **Optimized Grid Planning and Investment:** Foundation models can be fine-tuned for planning applications such as **optimal power flow (OPF)** and capacity expansion. A fine-tuned GridFM could quickly estimate optimal network reinforcements or congestion patterns under future scenarios, guiding TSOs where to invest in new lines or upgrades. This is crucial for Energinet's long-term planning to integrate massive offshore wind farms and new interconnectors. IBM and partners specifically note that GridFMs could support tasks like **grid expansion planning and network reconfiguration decisions**, which traditionally require intensive computation [35] [36]. With GridFM's AI "expertise", planners can evaluate more scenarios (e.g. different generation mixes, demand growth patterns, climate conditions) in less time, leading to better-informed and potentially cost-saving investment strategies. In short, GridFM can help **generate value by finding smarter, data-driven solutions**, potentially reducing over-engineering and focusing investments where they yield the most benefit for system reliability.

- **Enhanced Renewable Integration & Forecasting:** As renewables dominate, forecasting and managing their variability becomes critical. GridFM's architecture includes time-series and geospatial data, meaning it can incorporate weather forecasts, load forecasts, and even text data (like maintenance schedules or outage reports) to anticipate grid conditions [29] [37]. Downstream tasks envisioned for GridFM include **renewable generation forecasting, load forecasting, and even outage prediction** [29]. While TSOs like Energinet already use forecasting tools, a foundation model could improve accuracy by learning subtle patterns across multiple data sources (e.g. how specific wind farm outputs correlate with larger weather systems and network constraints). A more **accurate forecast** directly translates to value: it means fewer surprise imbalances, less reserve procurement, and more efficient utilization of resources. Moreover, GridFM could assist in **real-time renewables dispatch or curtailment decisions** by predicting grid stability limits given forecasted conditions, thereby maximizing renewable usage while safeguarding the grid.

- **Operational Decision Support and Automation:** GridFM can serve as an AI assistant to grid operators. For example, it could be fine-tuned to detect anomalous conditions or impending stability issues (like voltage collapse or oscillations) faster than rule-based systems. It might analyze SCADA streams and PMU (phasor measurement unit) data to flag patterns humans might miss, providing **early warning for emergencies**. Another application is **dynamic stability assessment** – current tools for transient or voltage stability are slow and scenario-specific, but a trained foundation model might rapidly evaluate stability margins for many contingencies. Energinet's control room, which already deals with large data streams from simulations and live measurements, currently leaves much data "untapped" [38]. GridFM could uncover insights from this data deluge to improve grid management [39]. For instance, it could suggest redispatch actions to alleviate a constraint before it binds, or identify the optimal configuration of grid assets (tap changers, FACTS devices, etc.) to maintain stable voltages. By elevating the intelligence in control centers, GridFM helps TSOs **run the grid closer to its limits safely**, extracting more capacity from existing assets and avoiding unnecessary preventive curtailments or costly standby reserves. Ultimately, for the public, this means a grid with fewer outages and more affordable electricity thanks to efficiency gains [40].

- **Fine-Tuning with Local Data (Privacy Preserved):** One of GridFM's value propositions is that TSOs can fine-tune the shared base model with their own operational data securely. The base GridFM is trained on broad datasets (including synthetic and public data), and then, say, Energinet could adjust it using its private historical grid data *behind its firewall* [41]. This results in a specialized model that understands Denmark's grid idiosyncrasies (specific equipment behavior, unique load patterns, etc.) without Energinet having to expose its sensitive data to outsiders. The process is **scalable and economical** because Energinet leverages the heavy-lifting already done in pre-training [42]. This ability to localize the model means TSOs get bespoke insights and accuracy, while still benefiting from the collective improvements to the core GridFM. It's a way to share innovation while **protecting data sovereignty** – a balance increasingly demanded by both utilities and regulators [43].

In Energinet's case, adopting GridFM could postpone or reduce the need for expensive grid expansions by enabling smarter operations. If AI can squeeze more performance out of the existing network (through better prediction and control), the TSO can handle higher renewable penetration with less overbuilding. Additionally, Energinet would benefit from the **community aspect**: improvements made by others (IBM's algorithms, Hydro-Québec's validation, academic research findings) feed into GridFM and thus become available to Energinet. This shared innovation model means value generation is continuous and cost is distributed. Energinet has publicly stated that open-source development "reduces the cost of software while increasing quality and pace of development," a trend they see growing among TSOs [11]. By participating in GridFM, Energinet aligns with this strategy – contributing to and drawing from a common pool to **solve mutual challenges** like decarbonization and grid resilience.

Technical Architecture, Modularity, and Integration

Architecture Overview: GridFM's architecture can be visualized as a layered stack (as conceptualized in the project's materials [44]). At the bottom is the **data layer**: vast collections of grid scenarios (power flows, time-series of demand/generation, grid component data, etc.) from both historical records and synthetic generation. Above that lies the **pre-training layer** where self-supervised learning occurs – this is where the model learns general representations of grid behavior (for example, learning the implicit physics of power flow through masked reconstruction tasks). The top layers consist of **fine-tuning modules** for specific applications (like specialized heads for contingency analysis, OPF, forecasting, etc.), and an **API/interaction layer** that allows grid software to interface with the model (for querying predictions or embedding it in simulations). This modular design means GridFM is not a monolithic black box, but rather a foundation with plug-in modules for various use cases.

Modularity and Fine-Tuning: A core design principle is modularity – the idea that various components or subsystems of the grid can be handled somewhat independently within the model. For instance, the project discusses possibly using a **mixture-of-experts (MoE)** approach [20] : one could imagine separate expert models for different voltage levels (transmission vs distribution) or regions, which then collaborate within an overarching model. This modular approach could reflect the physical hierarchy of power systems, yet still allow a unified model view. It also aids scalability; if one part of the grid (say distribution networks) needs a different architecture or more parameters to model accurately, it can be an expert of its own, rather than forcing one huge uniform model. Modularity is also evident in how the model handles modalities: there are distinct preprocessing/tokenization strategies for time-series, graph structure, and geospatial data, each producing "tokens" or embeddings that then feed a common model core [45] [46] . This way, improvements or updates to how one data type is encoded (e.g. a better way to encode weather maps or temporal patterns) can be made without overhauling the entire model. The use of modern ML frameworks (PyTorch, TensorFlow, etc.) along with experiment tracking (the GridFM GitHub mentions MLflow for tracking runs [47]) suggests the architecture is built to be extensible and reproducible for contributors.

In terms of software architecture, GridFM will likely be packaged as a library or service that integrates into a TSO's IT/OT environment. The **GridFM GraphKit** (an apparent toolkit mentioned in the GitHub search result [48]) indicates there will be CLI and programmatic interfaces to train, fine-tune, and use GridFM models. We can expect containerization for deployment (e.g. Docker images) and possibly microservice architecture when serving the model (to scale inference in production). This aligns with how other modern grid analytics are delivered – for example, commercial platforms are using microservices and APIs to embed AI-driven analytics into control room tools [49] . GridFM being open source means TSOs could deploy it on-premises or in their cloud, ensuring compliance with any security or latency requirements.

Digital Grid Integration Capabilities: GridFM is being designed to **integrate with existing digital grid systems**, not replace them outright. For example, consider state estimation or power flow software that TSOs run every few minutes – GridFM could be integrated as a fast "helper" that provides an initial guess or a validation of results. Because it learns from standard power system data (adhering to common formats and models), it can interface with tools like EMS (Energy Management System) software, simulation tools, or data platforms. Notably, the training data pipeline itself uses interoperable sources: it can ingest networks from **PGLib or Pandapower** formats and load profiles from open datasets [50] [51] , which means the model naturally speaks in terms of common grid data structures (buses, lines, generators, etc.). This makes integration easier – for instance, a PSS®E or CIM model of a grid could be converted to a format that GridFM understands for fine-tuning or inference.

Furthermore, GridFM is not being built in isolation but alongside other open tools. The **UN's 2025 report on digital transformation** highlighted GridFM as one piece of a larger open ecosystem enabling "seamless communication between diverse grid assets and systems" [52] . This implies that GridFM could work in concert with platforms like **PowSyBl** (an open library for power system modeling/simulation) [53] and others. For example, a TSO might use PowSyBl's CGMES data import capability to load a grid model, run a number of contingencies through GridFM for quick evaluation, and only if GridFM flags a risky scenario does the TSO then use a slower traditional simulator for detailed analysis. Similarly, integration with **OpenSTEF** (an open short-term forecasting tool) is conceivable – forecasted load from OpenSTEF [54] could feed into GridFM to predict resulting power flows or bottlenecks. In essence, GridFM can act as an **intelligent layer atop digital twins** or data hubs, enhancing them with predictive AI capabilities.

Handling of Interoperability and Standards: Since TSOs operate critical infrastructure, any new system must fit into a stringent framework of interoperability and security standards. GridFM's open nature inherently favors interoperability – it is being developed as a public project with open APIs, making it easier to connect with various vendors' systems. Open-source approaches "foster interoperability by design, lowering integration costs and avoiding vendor lock-in" [55]. We see evidence of this in the project's alignment with emerging standards: for example, the EU's concept of **Energy Data Spaces** (part of the European Commission's digital strategy and the AI Act) emphasizes common data models and trust in data sharing [56]. GridFM's model of sharing a pre-trained AI model rather than raw data is complementary to this – utilities can contribute to a common model without exposing proprietary grid data, which addresses **data sovereignty and privacy concerns** while still reaping collective benefits [43]. In a way, the GridFM approach could become a *de facto* standard for AI-based grid model exchange: rather than each TSO exchanging sensitive system data, they might exchange model weights or insights derived from a common GridFM, under agreed data governance.

From an orchestration standpoint, once integrated, GridFM can enhance **smart grid orchestration** by acting as the brain that processes inputs from many parts of the grid and coordinates an optimal response. For example, consider orchestrating a **distributed energy resource (DER) fleet** during a grid event: A GridFM fine-tuned for real-time operations could evaluate where a voltage support or load shedding is most effective and advise the TSO's control system, which in turn sends signals via protocols (like the ones supported by LF Energy's **GXF platform** for field devices [57] or via standards like OpenADR). By ensuring GridFM outputs are accessible and interpretable (potentially accompanied by confidence metrics or explanations), it can slot into control room dashboards or automation schemes as a reliable decision aid.

In summary, GridFM's architecture is *both* cutting-edge in AI design and pragmatic in system integration. It is modular and multi-modal at the AI level, allowing it to learn the many facets of grid behavior. At the same time, it is built to plug into the digital grid ecosystem through open standards and data models. The project's long-term vision even includes possibly combining multiple GridFMs or incorporating additional data types (like textual alarm logs or maintenance records) to broaden its capabilities [58]. This extensibility ensures that as the grid evolves (e.g. more IoT sensors, more granular data), GridFM's architecture can evolve too, protecting the investment TSOs make in adopting this platform.

Interoperability and Open Data Exchange in Smart Grid Orchestration

GridFM's open-source and design choices make it a key enabler of **interoperability** and open data exchange – both crucial for orchestrating increasingly distributed and digitalized power systems. The **interoperability** aspect is addressed at multiple levels:

- **Common Data Representations:** Because GridFM is being developed in the open, it is likely to adopt or influence common data schemas for grid AI. Projects like this tend to coalesce around open data formats (CIM, CGMES, or domain-specific schemas for training data). Indeed, the involvement of international partners and the reference to datasets like PyPSA-Eur (an open model of the European grid) [59] suggest that GridFM will handle data in standardized ways. This means a model fine-tuned on one TSO's data can be understood or further trained by another, provided data is mapped to the common format. For smart grid orchestration – which involves coordinating diverse assets (EV chargers, solar inverters, batteries, etc.) often managed by different parties – having a **shared language of data** is foundational. GridFM could act as a translation layer, where disparate data inputs (market data, weather data, sensor measurements) are embedded into a unified representation that different systems can pull insights from.

- **APIs and Open Interfaces:** As an LF Energy project, GridFM will publish open APIs or libraries. This makes integration with other systems (market platforms, SCADA/EMS systems, DER management systems) straightforward in technical terms. A DSO or microgrid operator could query the GridFM model via an API for guidance on local control actions, while the TSO uses the same model for high-level system analysis. Such a setup inherently **enables data exchange**: the model can absorb data from various sources (market prices, grid states, weather forecasts) and produce outputs that are fed back to different stakeholders. For example, a flexibility market platform could use GridFM's outputs on where grid constraints will occur to better target DER dispatch in a way that benefits the TSO (a form of **market-grid interoperability**). Open interfaces also reduce duplication – rather than every vendor embedding their own AI, they could interface with a TSO-hosted GridFM service, ensuring all actors rely on a **single source of "grid intelligence" truth**.

- **Interoperability by Open Source Design:** The UNECE's July 2025 report explicitly emphasizes that open-source projects (like those in LF Energy) "foster interoperability by design" and avoid siloed solutions [52]. GridFM's role here is notable – by being open, any utility or vendor can inspect how it works, contribute improvements, and adapt it to local needs without starting from scratch. This collaborative environment leads to **convergence on best practices**. It stands in contrast to proprietary AI solutions which might use different data models or optimization criteria, making cross-organization collaboration harder. For TSOs, interoperability is not just a technical nicety but a necessity: they operate grids that are interconnected across borders and interdependent with distribution networks and markets. An open foundation model used by many parties could become a unifying framework. For instance, multiple European TSOs could co-develop a GridFM that captures European grid characteristics, which then each TSO fine-tunes. The models remain compatible, and knowledge (say about handling high inverter-based resources) flows across the community. In effect, GridFM can be seen as **part of the digital commons for the grid**, aligning participants on interoperable solutions.

Smart Grid Orchestration: Orchestrating a smart grid means coordinating generation, loads, and network resources dynamically and often automatically. GridFM contributes here by providing the **predictive and analytical brain** that can process inputs from across the smart grid and suggest optimal coordination actions. Because it is multi-modal, it can take in open data such as distributed sensor readings, DER statuses, or even social media/weather alerts (for storm impacts) and incorporate those into its understanding of grid state. This holistic situational awareness is crucial for orchestration. For example, if a storm is incoming, a GridFM-based tool could predict likely outages or demand spikes and orchestrate pre-emptive actions: batteries charging up, re-routing power flows, positioning repair crews (if combined with asset health data). Traditional siloed tools might handle one aspect (e.g. a storm outage model separate from a load model), but GridFM can interconnect these facets.

Moreover, by being open, GridFM allows **many actors to participate in orchestration**. A DSO could use a version of GridFM to manage its part of the grid, and because it's the same fundamental model as the TSO uses (only fine-tuned to different scope), the TSO and DSO models "speak the same language". This greatly eases TSO-DSO coordination, which is a known challenge in modern grids. In a scenario with active **grid edge management** (microgrids, virtual power plants), those edge systems could even run lightweight instances of GridFM or query the central GridFM to align their actions with the overall system needs. This kind of hierarchical but harmonized control is a vision of smart grid orchestration that open technology enables. It's noteworthy that LF Energy also hosts projects like **Hyphae (microgrid orchestration)** and **GXF (Grid eXchange Fabric)**, which are more about the control infrastructure [57] [60]. GridFM complements these by filling in the intelligence layer. For instance, GXF ensures devices can communicate and be controlled, while GridFM could analyze data from those devices and decide *what* control actions yield the best outcome system-wide.

Another aspect is **open data exchange** itself. GridFM could encourage TSOs and others to share certain data (like anonymized scenario data or model weights) openly, because they see direct benefit in improving the foundation model. This move towards openness is echoed by regulators and policymakers. The UN report calls for "stronger policy alignment around open standards and data governance" and even **financial incentives** to reward interoperable, open solutions [61]. A TSO adopting GridFM is aligning with this direction, potentially benefiting from future incentives or at least positive regulatory treatment for using transparent, collaborative tools. We might also see regulators more comfortable with AI that is open and peer-reviewed (like GridFM) versus black-box vendor solutions. Open data exchange also means **transparent innovation** – academics can use the open GridFM framework to try new algorithms on public data and publish results. If successful, those innovations feed back into the tool that the TSOs use. This virtuous cycle is rarely possible with closed software.

In summary, GridFM stands to be a linchpin for interoperability in the digital grid era. By providing an open, common AI model of the grid, it allows various players (TSOs, DSOs, aggregators, solution vendors) to plug into and contribute to a shared intelligent system. This reduces duplication, ensures consistency across the board, and lowers integration costs when new grid components or participants come online [52]. It aligns well with the **"plug-and-play" future** of power systems, where devices and algorithms interoperate seamlessly through open standards. For smart grid orchestration – essentially the real-time balancing of a complex, distributed energy ecosystem – GridFM offers the foresight and coordination logic needed to orchestrate resources effectively at scale. And crucially, it does so in a way that **no single vendor or utility controls**, which encourages trust and broad adoption in a domain as critical as electricity.

Comparison with Other Digital Grid Initiatives and Platforms

The landscape of digital grid platforms includes both open-source initiatives and commercial solutions. GridFM's approach as an open, AI-centric framework distinguishes it in several ways. Below is a comparison of GridFM with other relevant initiatives:

Open-Source Grid Projects (LF Energy and Others):
- **OpenSTEF (Short-Term Energy Forecasting):** OpenSTEF is an LF Energy project focused on ML-based load forecasting, providing explainable, self-correcting forecasts for operational planning [54]. It addresses a narrow domain (demand forecasting), whereas GridFM aims to cover a broad range of tasks with one foundation. GridFM could actually ingest OpenSTEF's output as one of its inputs. While both are open source, OpenSTEF is a specialized tool, and **GridFM's value is in unifying multiple such tasks** (forecasting, contingency analysis, optimization) under one model. For a TSO, OpenSTEF might be used for one function (forecasting load), but GridFM could leverage that plus network physics to directly predict grid constraints from those forecasts – a higher-level functionality.

- **PowSyBl (Power System Blocks):** PowSyBl is a modular open library for power system modeling and simulation, contributed by RTE (French TSO) [62] [63]. It provides the "building blocks" to build applications like power flow solvers, contingency analysis, etc. In contrast, GridFM provides a pre-trained AI model which can approximate some of those simulations. PowSyBl (and similar tools like PSS®E or DIgSILENT's PowerFactory, which are commercial) are more traditional and require the user to run explicit calculations. GridFM could be seen as a next-generation complement: for example, a developer could use PowSyBl to run a precise power flow for a base case and use GridFM to instantly estimate outcomes for thousands of variant cases, merging the strengths of both approaches. Importantly, PowSyBl and GridFM are **interoperable in principle** – one could feed PowSyBl's network model data into GridFM as noted, since PowSyBl uses standard formats (e.g. CGMES) and GridFM is being built to handle such data.

- **Green Energy Hub (OpenGEH):** This is an open-source platform contributed by Energinet for handling energy market data and settlement processes [64] [65]. While not directly an AI or grid simulation tool, it exemplifies TSOs moving to open, modular IT architectures (OpenGEH uses microservices and domain-driven design for data management [66]). The philosophy is similar – open platforms that multiple parties can build on. GridFM differs in focus (grid physics and AI vs market data handling), but one can envision synergy. For example, outcomes from GridFM (like predicted congestion or flexibility needs) could feed into market platforms like OpenGEH to trigger certain market actions (like activating demand response). In comparing them, the key point is **scope**: OpenGEH manages data transactions in the energy market, whereas GridFM is about analytical modeling of the grid's physical state. Both, however, share strategic benefits of open source: lower cost, community improvements, and avoidance of reinventing the wheel in each organization [11].

- **Other LF Energy projects:** The UNECE report highlighted projects like **GXF (Grid eXchange Fabric)** for device communication and **SOGNO** for automated grid services [57]. These projects handle real-time control and automation at grid edge or distribution level. GridFM is complementary as a high-level intelligence. A notable mention is **OpenSynth (Synthetic Data)** [67] – an initiative to create and share synthetic energy data for AI. This directly supports GridFM's needs, since training a foundation model requires tons of data (and real data can be limited or confidential). **Interplay**: A TSO could use OpenSynth to augment their dataset, train GridFM, and use GXF/SOGNO to implement the control actions that GridFM suggests – a full stack of open solutions from sensing to decision to control.

In summary, **compared to other open-source grid tools, GridFM is unique in its use of AI at scale** and its ambition to be a general-purpose model for many tasks. Other projects tend to target specific functions (communication, forecasting, simulation) or specific domains (transmission vs distribution). GridFM's holistic AI approach and foundation model strategy set it apart, while its open-source nature ensures it can integrate with or complement those other tools rather than compete with them.

Commercial Platforms:
- **GE GridOS:** GE Vernova's **GridOS** is branded as the first comprehensive grid orchestration software portfolio [49]. It includes a data fabric, network modeling, and AI-driven analytics across planning and operations [68] [49]. GridOS uses a microservices-based architecture for scalability and integrates AI/ML in functions like forecasting, virtual operators, and disturbance prediction [69] [49]. In many ways, the goals of GridOS's AI components overlap with GridFM's: both aim to handle renewable variability, increase grid resilience via predictive insights, and help operators with decision support [70] [71]. The difference is **ownership and openness**. GridOS is a proprietary solution – although it touts open APIs, the core algorithms and models are GE's IP. By contrast, GridFM is openly governed and community-built. A utility adopting GridOS might get a turnkey solution (with vendor support and integration into GE's ecosystem of grid software), whereas adopting GridFM means joining a community and possibly investing in internal integration work. However, the utility retains full control and can customize or extend the model as needed. Another difference is that GridOS emphasizes having a "grid-specific data foundation" and merging OT/IT data silos [49] [72]. GridFM likewise needs a solid data foundation, but it's agnostic to vendor – it could sit on top of any well-curated data lake or platform a TSO has. **No vendor lock-in** is a major advantage of GridFM over commercial offerings. TSOs, as natural monopolies

with regulatory oversight, often prefer solutions that won't tie their fate to one vendor's roadmap or licensing. In fact, ENTSO-E (the European network of TSOs) has explicitly recognized "the benefits of open source and shared development" to achieve cost-effective and secure digital innovation for TSOs [73].

- **Other Commercial AI Grid Tools:** Besides GE, players like Siemens, Hitachi Energy, Oracle, and newer AI startups all have products for grid analytics. Siemens' Spectrum Power and Hitachi's ADMS, for example, are incorporating AI for outage management or DER optimization, but these are embedded in proprietary control room software. There are also analytics platforms (e.g. AutoGrid, recently acquired by Schneider Electric, focuses on DER and demand response optimization) that use AI to shift loads or generation. Compared to these, GridFM is *not* a full application out-of-the-box – it's more of a platform or engine that can power applications. The **learning curve and development effort** might be higher for GridFM (one needs data scientists/engineers to implement it for a specific environment), whereas a vendor tool might be plug-and-play for a given use (with the caveat of less flexibility). However, the **community and transparency** around GridFM can lead to greater trust and continuous improvement. For instance, any issues or biases in the model can be openly studied and corrected by the community, whereas a proprietary model's inner workings might be opaque. Regulators might favor open algorithms in critical decision-making for transparency reasons in the future.

- **Foundation Models in Tech vs GridFM:** It's also worth noting that GridFM's concept draws inspiration from big tech's foundation models (like OpenAI's GPT or Google's large models). Big tech companies have started exploring energy applications (Google DeepMind worked with UK's National Grid on wind forecasts, for example), but there isn't yet a known commercial "foundation model for grid" product from them. If they do enter, their approach might be cloud-based AI services that utilities subscribe to. GridFM being open source and energy-community-driven could be more aligned with utility needs (data residency, domain specificity, etc.) than a one-size model from big tech. It also ensures **knowledge stays within the public domain** rather than locked in a corporate research lab.

In a comparative table form:

Platform/ Project	Type	Scope & Focus	Open Source?	Notes for TSOs
GridFM (LF Energy)	AI Foundation Model	Broad power grid AI model (power flow, ops, planning)	Yes (LF Energy)	Collaborative development by utilities & tech; AI-driven speed-ups for many tasks; no vendor lock-in [10] [9].
OpenSTEF (Alliander)	ML Forecasting Tool	Short-term load/ renewable forecasting (explainable)	Yes (LF Energy)	Focused on forecasting only; can feed into GridFM or other tools [54].
PowSyBl (RTE)	Simulation Framework	Library for grid modeling & simulations (CGMES, etc.)	Yes (LF Energy)	Provides physics-based analysis tools; could be used alongside GridFM for hybrid approaches [63].

Platform/ Project	Type	Scope & Focus	Open Source?	Notes for TSOs
Green Energy Hub (GEH) (Energinet)	Data Platform	Energy market data handling, settlement workflow	Yes (LF Energy)	Not grid-physics, but shows Energinet's success with open source to reduce costs and enable new business models [64] [11] .
GXF (Grid eXchange Fabric) (Alliander)	IoT/Device Platform	Communication with field devices (smart meters, etc.)	Yes (LF Energy)	Handles control/sensing layer; pairs with analytics like GridFM for full smart grid solutions [57] .
GE GridOS (GE Vernova)	Commercial Suite	Integrated grid software (data fabric + apps + AI)	No (Proprietary)	Comprehensive and supported; microservices and data fabric for AI integration [49] , but closed-source and tied to GE's ecosystem.
Siemens/ Hitachi ADMS	Commercial ADMS/EMS	Advanced DMS/ EMS with some AI modules (outage mgmt, etc.)	No	Often modular, vendor-specific solutions targeted at control centers; use-case specific AI vs foundation model.
AutoGrid/ Derms Platforms	Commercial DER Optimizer	AI for demand response, DER coordination	No	SaaS platforms focusing on flexible load/generation; complementary to TSOs for demand-side mgmt, but not covering core TSO studies (contingencies, PF) as GridFM would.

Table: GridFM in context of other grid initiatives. (LF Energy projects from **open** ecosystem vs representative **commercial** platforms)

As shown, GridFM's distinctive value is in being an **open, general-purpose AI model for grid analytics**, unlike others that are either narrower in scope or closed proprietary systems. For a TSO like Energinet, this means GridFM can be adopted to cover many analytic needs at once, evolves with community contributions, and avoids the pitfalls of being locked to a vendor's roadmap. The trade-off is that it's a new project (currently in LF Energy's "Sandbox" stage [74]) and will require active participation to mature. In contrast, commercial solutions might be more immediately polished but could constrain flexibility and entail licensing costs. Strategically, many TSOs may opt for a **hybrid approach**: utilize open source like GridFM for core analytical capabilities and innovation, while interfacing with commercial software where needed for enterprise support or UI. The good news is that open interoperability makes this possible – e.g., a TSO could run GridFM to produce analysis and feed it into their existing control system software, effectively blending open-source AI with their current operations. This approach is reinforced by industry recommendations that future solutions combine open source with proprietary elements in a **hybrid model to maximize benefits** [75] .

Strategic and Regulatory Benefits of Adopting GridFM for TSOs

Beyond technical capabilities, adopting GridFM carries several strategic and regulatory advantages for TSOs:

- **Cost Efficiency and Collaborative Development:** By participating in an open-source project, a TSO can **share development costs** with other contributors, reducing the financial burden on any single entity. Energinet's own experience with open source (OpenGEH) demonstrated that shared development can deliver high-quality software faster and cheaper than one-off custom projects [11]. GridFM extends this principle to advanced AI: TSOs jointly invest in building a powerful tool that all can use, instead of each paying vendors or researchers independently for similar capabilities. This is especially important as the challenges (climate change impacts, renewable integration) are common across utilities. Pooling expertise allows tackling "moonshot" projects like foundation models that any single TSO might struggle to justify alone [6]. In effect, GridFM provides a **neutral collaboration arena** for the electricity industry's AI needs, with Linux Foundation's governance ensuring fairness and open access [10]. Over time, TSOs can contribute code or data to steer the project in directions that meet their needs, something not possible with off-the-shelf proprietary software.

- **Reduced Vendor Lock-in, Increased Agility:** Open-source adoption means a TSO is not tied to a single vendor's solution. This **increases strategic flexibility**. They can customize the software, hire different service providers for support, or even fork the code if necessary. For regulators and stakeholders, this is positive as it fosters a competitive marketplace for services around the tool, rather than a monopoly supplier. It also means if new regulations or market rules emerge, TSOs can adapt the open software quickly without waiting for a vendor's next release cycle. The **agility** to update or extend functionality is crucial in the fast-evolving energy landscape. ENTSO-E's leadership has noted that open source development can "develop agility in future digital developments" for TSOs [73] – meaning TSOs can respond faster to change because they collectively maintain the tools. Furthermore, open source encourages the adoption of **open standards**, making integration with other systems easier and future-proof. Regulators generally favor standardization and interoperability, as it leads to more resilient and transparent systems. Using GridFM, which is aligned with open data standards and best practices, can help TSOs comply with data sharing mandates or coordination requirements (for instance, European regulations pushing for digital coordination between TSOs and DSOs).

- **Transparency and Trust (AI Governance):** As AI models begin to influence operational decisions, regulators and the public will demand transparency and explainability. A foundation model like GridFM, developed openly, allows scrutiny of its architecture and assumptions by the entire community. Bugs or biases can be identified and corrected in a transparent manner. This is aligned with emerging AI regulations such as the EU AI Act, which places requirements on high-risk AI systems (the power grid would likely qualify) for testing, certification, and transparency [56]. By using an open model, a TSO can more easily demonstrate compliance – the model's performance and limitations are documented in peer-reviewed papers [76] and open benchmarks, and its code is available for audit. Contrast this with a closed AI solution: the TSO might struggle to explain to a regulator how it arrives at certain decisions. The **open development process also builds trust** among TSOs themselves – if, say, five TSOs co-develop an AI model, each is more confident in using it because they know peers have validated it. This collective validation could become a powerful argument to regulators that a given approach is safe and effective. Indeed, in areas like cybersecurity or system stability, having many eyes on the code (Linus's Law: "given enough eyeballs, all bugs are shallow") increases confidence that the tool is robust.

- **Innovation and Talent Attraction:** Strategically, being at the forefront of open-source AI for grids can bolster a TSO's innovation image and help attract talent. Data scientists and power engineers passionate about AI might prefer to work on cutting-edge open projects like GridFM where they can publish and collaborate globally, rather than on proprietary in-house tools. Energinet and others could leverage this to build internal expertise. It also strategically positions TSOs in partnerships with tech firms and academia. For instance, IBM, universities, and national labs are already around the table for GridFM [30] – a TSO that's involved gets direct access to this knowledge network. This can spawn side projects, pilot studies, or custom solutions faster. Moreover, if a TSO contributes data or use cases to GridFM, they might steer research focus to solve their hardest problems. For example, if Energinet faces a challenge with offshore wind variability, feeding that scenario to the GridFM community could spur specific model improvements. The result is an **R&D multiplier effect**: the TSO's strategic problems gain visibility and resources far beyond their own R&D budget.

- **Regulatory Alignment and Public Benefit:** Governments and regulators increasingly emphasize digitalization and open data in the energy sector as a public good. The UNECE report explicitly calls out that publicly funded or critical solutions should prioritize open-source components for maximum public benefit [77] [78]. A regulator might see a TSO's adoption of GridFM as aligning with these policy goals, potentially easing approvals or support for related investments. For example, if a TSO needs to invest in computational infrastructure to run AI models, citing that it's for an open-source tool used industry-wide might make it more palatable than funding a proprietary software license. There's also an emerging notion of **digital regulatory compliance**: TSOs could be required to share certain data or models. If TSOs use a common open model, sharing and comparing results (say adequacy assessments or risk metrics) becomes straightforward, aiding regulatory oversight across different operators. Additionally, the open approach can facilitate **cross-border grid studies**. European TSOs, under ENTSO-E, often must produce Europe-wide adequacy or stability analyses. Using a shared model (GridFM) that can incorporate each region's data (via fine-tuning) but still operate as a whole could streamline such studies, making it easier to comply with EU regulations on coordinated grid planning and operations.

- **Security and Sovereignty:** While one might worry that open source could pose security risks, for critical infrastructure it can actually enhance security. The code being open means it can be vetted for vulnerabilities by the community and adapted to meet local cybersecurity policies. TSOs often have strict requirements (e.g., software must be hosted on-prem or within certain jurisdictions). With GridFM, they can deploy the software wherever they need, with full control – a form of digital sovereignty. In contrast, some commercial AI solutions might be cloud-only or not disclose what data is leaving the system. Being open also means if geopolitical issues or trade restrictions arise, TSOs are less exposed; no company can suddenly withdraw support or dramatically raise costs. Hydro-Québec's involvement indicates interest in keeping such strategic technology under shared control rather than any one company [9]. All these factors align with the strategic interest of TSOs to maintain control over their core tools and not be beholden to others for critical capabilities.

In conclusion, adopting GridFM offers TSOs like Energinet a forward-looking path that aligns technology with strategy and regulatory trends. It provides a cutting-edge capability (AI foundation models) while embodying the principles of openness, collaboration, and interoperability that the energy sector is increasingly expected to follow [52] [61]. The benefits span improved operations and innovation internally, to external advantages like regulatory goodwill and industry leadership. There will be challenges – such as ensuring the model's outputs are understood by operators, or that sufficient data is available to train it well – but those can be mitigated through the collective effort and knowledge sharing that are part of GridFM's DNA. For Energinet, which has a mandate for 100% renewables and has shown commitment to open solutions, GridFM could be a strategic tool to drive the digital, decarbonized future of the Danish grid.

Executive Summary

GridFM is an ambitious open-source project under the Linux Foundation (LF Energy) aiming to create **foundation AI models for power grids**. Built on advanced technologies like graph neural networks and multi-modal transformers, GridFM is essentially a *large pre-trained AI model of the electric grid* that can be fine-tuned for many applications. The project's philosophy emphasizes openness and collaboration: initiated by IBM and Hydro-Québec and now hosted in a neutral LF Energy setting, it invites global utilities, researchers, and vendors to co-develop a common platform. This open approach brings numerous **benefits for Transmission System Operators (TSOs)**:

- **Technological Edge:** GridFM leverages state-of-the-art AI to handle the complexity of modern grids. By training on hundreds of thousands of simulated grid scenarios (e.g. solved power flow cases), it learns the physics and patterns of grid behavior. The resulting model can perform tasks like contingency analysis, optimal power flow, or load forecasting **much faster** than traditional tools [8] [7]. For TSOs, this means faster decision support – operators can get instant predictions of grid state changes or optimal control actions, enhancing real-time operation and planning efficiency.

- **Value for TSOs (Energinet focus):** GridFM helps TSOs manage the energy transition. In Energinet's context (aiming for 100% renewable integration by 2030), it offers a way to harness the deluge of data (from simulations, sensors, weather, etc.) to improve grid reliability and optimize infrastructure use [79]. It can predict and mitigate issues from renewable fluctuations, reducing the risk of blackouts and the need for costly over-building. A key feature is the ability to fine-tune the generic model with a TSO's own data behind its firewall, yielding **tailored insights without exposing proprietary data** [41]. In short, GridFM acts as an AI engine that can reduce congestion, improve forecasting, and support operators in keeping the lights on, all while enabling TSOs to do more with existing assets.

- **Architecture & Integration:** The GridFM architecture is modular and designed for integration into digital grid ecosystems. It combines multiple data types – grid topology, time series measurements, geospatial weather data – into a single model of the grid's state [19]. It can be deployed via open APIs or microservices, meaning it can plug into control room software, planning tools, or market platforms as needed. Because it's open-source, it adheres to open standards and interfaces by default, facilitating interoperability. GridFM can thus serve as a **unifying analytical layer** across previously siloed systems (operations, IT, market systems), improving situational awareness and smart grid orchestration capabilities.

- **Interoperability & Orchestration:** Adopting GridFM inherently promotes interoperability. The United Nations Economic Commission for Europe highlights such open projects as key to **lowering integration costs and avoiding vendor lock-in through common standards** [52]. GridFM enables different stakeholders (TSOs, DSOs, market operators) to work from a common model, which is crucial as power systems become more interconnected and decentralized. In practical terms, this could streamline TSO-DSO coordination (both using the same AI model for their networks) and enable more effective orchestrating of distributed energy resources, since the foundation model can capture wide-area grid impacts. It supports open data exchange by allowing knowledge (model improvements, learned grid behavior) to be shared without necessarily exchanging raw sensitive data – an approach aligned with emerging "data space" concepts in Europe [56]. Overall, GridFM is an enabler of **smart grid orchestration**, where decisions and data can flow freely between systems to optimize the whole electricity value chain.

- **Comparison to Other Platforms:** Compared to other digital grid initiatives, GridFM stands out for its scope and openness. It is broader in ambition than single-purpose open tools (like OpenSTEF for forecasting or PowSyBl for simulation) and avoids the proprietary lock-in of commercial suites (like GE's GridOS). Commercial platforms often provide integrated data management and AI under one vendor's umbrella [49], whereas GridFM offers a vendor-neutral solution where utilities control the technology. While commercial solutions might be immediately deployable, GridFM's community-driven model ensures that **innovation is continuous and shared**. TSOs can influence its direction and trust that no competitor has a secret advantage – any improvements are contributed back to the common project. This "collaborative competition" can accelerate progress in grid AI faster than closed development.

- **Strategic & Regulatory Upside:** Strategically, embracing GridFM aligns with a future where energy software is open, interoperable, and agile. TSOs gain flexibility (no dependency on a single vendor), and can cultivate in-house expertise on a cutting-edge technology. Regulators and international bodies are encouraging open solutions to enhance transparency and security in critical infrastructure [61]. Using an open AI model like GridFM can make regulatory compliance easier – for instance, explaining AI-driven decisions to regulators or proving the robustness of tools through peer review. It also positions TSOs as innovators committed to the public interest, leveraging collaborative innovation to drive the energy transition. In a regulated industry, cost-efficiency and demonstrable public benefit are crucial; GridFM potentially offers both, by spreading development costs and producing solutions (like better grid reliability and integration of renewables) that benefit society at large.

In summary, **GridFM represents a paradigm shift** in how TSOs can use digital technology. It brings the power of "foundation models" – which have transformed fields like language AI – to the electric grid domain, offering the prospect of smarter, faster, and more integrated grid management. For Energinet and its peers, GridFM is not just a new software tool, but a strategic platform that can evolve with their needs, foster industry collaboration, and ensure that the digital foundations of our future energy systems are as open and sustainable as the physical infrastructure they manage. **Adopting GridFM could help TSOs drive value (operational efficiency, cost savings, innovation) while also aligning with regulatory trends towards openness and interoperability**, ultimately supporting the accelerated yet secure transition to clean energy [77] [73]. The journey is just beginning – GridFM-v0 is expected by late 2025 – but the foundation laid today could become a cornerstone of tomorrow's smart, decarbonized grid. [7] [52]

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