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Building a Digital Twin for European Energy Infrastructure

The role of open source.

AS GRIDS ARE INCREASINGLY DIGITIZING, the concept of a digital twin (DT) is becoming more and more relevant in the electricity sector. However, there is a lack of standardization of the definition and the characteristics of DTs. Many tools are defined as DTs even if they serve completely different purposes and are based on significantly different technologies. And some use cases and system-level studies require assembling and interfacing several DTs, which need to be properly designed and documented to be used in this context. This article aims at providing recommendations in this regard through the application of open approaches and the example of the large-scale European TwinEU project, which is among the first to tackle such issues at scale.

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Introduction

With the goal taking a coherent approach to the topic, in the context of this article, we refer to a DT as a model of an electrical system of components that, thanks to appropriate data exchange, is capable of evolving over time to be a reliable representation of the corresponding system of components. Apart from their application at the component-versus-system level, DTs are also driven by the specific use case that they support. Some basic use cases include

- a digital replica of a grid component for preemptive maintenance
- a static model of a grid for the purpose of grid planning
- a dynamic model for grid stability and contingency analysis.

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Another noteworthy application is the study of off-grid components and systems when they are connected to the grid, for example, in the case of microgrids.

For system-level applications, it is critical to consider a standard solution for grid description. In this respect, the Common Information Model (CIM) standard has emerged as a widely adopted solution. The adoption of common standards is facilitating data exchanges among operators and the creation of advanced use cases based on the interaction among different grid operators, such as in the case of flexibility analysis between distribution system operators (DSOs) and transmission system operators (TSOs). On the other hand, current CIM descriptions do not include a complete description of the component to support a dynamic analysis. Evolution in this regard is already happening, but a clear standard has still to emerge.

Two different approaches exist for innovating together on DTs: the closed approach and the open approach. This article demonstrates and illustrates how an open approach accelerates DT developments. It is self-evident that speed is a crucial factor in the realm of digital products and services. The reinjection of an evolution of code or preexisting data is part of an incremental construction, which guarantees interoperability of the coproduced modules. The fact that we are working together to build a standard DT model ensures that validation will be widely shared, in a piecemeal approach, freeing us from the habit of consortia. We do not want to depend on a limited closed solution.

Benefits of the Open Approach

For the open approach, we can leverage open source (OS), open data, open innovation, and other open practices (knowledge and so on), which have proved very powerful for vendors, utilities, academics, and other stakeholders to achieve the maximum potential for success and move toward a distant but coherent target where stranded costs are minimized. Benefits include cost reduction, a medium-to-high technology readiness level, time to market, vendor lock-in mitigation, and increasing customization, transparency, sovereignty, scalability, interoperability, collaboration [simplifying traditional intellectual property (IP) issues], and flexibility to instantiate the most interesting use cases of DTs.

Zooming in, OS, or OS software (OSS), is a more precise term in digital discussions, and free/libre OSS encompasses the concept more fully, granting freedoms to use, study, modify, and (re)distribute software with or without copyleft, which dictates redistribution terms. OSS is a paradigm that aligns remarkably well with the objectives of interoperability. Whether as proprietary or OSS, DTs will not reach their full potential unless they are inherently designed for interoperability. That is one of the main conclusions of the National Interoperability Framework Observatory (https://joinup.ec.europa.eu/collection/nifo-national-interoperability-framework-observatory) work at the European Commission level, which published, in October 2023, an in-depth report and guidance document on interoperability challenges for local DTs and data spaces.

Adopting an OSS approach not only mitigates IP disputes but also fosters a deep commitment to transparency. DTs are, at their core, models. The functioning of these models is a critical and ongoing question, especially evident in today's artificial intelligence landscape. Whether it is enhancing transparency or reducing the effort required to engage with an OSS community, comprehensive documentation is vital. It enables a clear understanding of how the code operates and facilitates modifications.

An open approach to developing DTs also enhances scalability. Consider representing the DT of a complete wind turbine, including its control/command system. While this may serve your immediate needs, consider the broader implications. What if you need to scale from your DT to 100 wind turbines? At such a scale, a detailed description is not always necessary. For instance, if only mechanical parameters are crucial, an OS DT allows for easy upscaling or downscaling.

The validation of DTs' numerical models could further benefit from an open data approach. One can readily envision a scenario where open datasets provide robust frameworks for validation. Moreover, an extensive array of tools, techniques, and methodologies is paramount to facilitate collaboration across diverse interfaces, encompassing both human-to-machine and machine-to-machine interactions. Indeed, this can be supported by open standards and formats. Yet, it is even more intriguing to instantiate a pivotal data model within the DTs. Such pivot formats enable the mapping of detailed fields from standardized data formats to different perspectives of the DT. For instance, a real-time wind turbine operator and a technician preparing for corrective maintenance intervention would both have a reliable view of the wind turbine. Proposing to augment highly detailed standardized formats (based on standards) with this pivot data model would also be realized in an open approach (data and algorithms).

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OSS communities often gravitate toward software forges like GitHub, GitLab, and Bitbucket, pivotal for collaborative software development. These platforms offer a dynamic cooperative development environment with just a click. They provide a comprehensive suite of features that streamline and enhance the software development lifecycle, including version control systems, web hosting, continuous integration/continuous deployment pipelines, and versatile project management tools.

To illustrate the open approach, let us discuss the TwinEU project. Supported by the European Commission, this project aims to create a DT of the European electricity infrastructure, showcasing the potential and applicability of OS methodologies in large-scale complex systems.

The TwinEU Project

Early in 2024, a large-scale European project on DTs for power systems was kicked off: TwinEU. It assembles a large consortium of experienced partners from industry and academia that aims at developing the foundations for a European power system DT ecosystem. And all of this will be OS.

Project Description

TwinEU is a project funded by the European Commission within the Horizon Europe program. The goal of the project is to create the foundation for a European-level DT of the electricity infrastructure. In this regard, the vision is to develop the technology that will support a DT covering every country in Europe, encompassing all the voltage levels. This DT should be the result of a long list of grid operators working at the transmission and distribution levels.

The project is executed by a large consortium of more than 70 partners across Europe, involving all the key stakeholders for the development but also the application. In this sense, a DT makes sense as a mechanism of interaction among stakeholders, not only among grid operators but also between grid operators and other actors in the energy system. In a nutshell, the DT should facilitate an exchange of data that will enable new business cases.

While preserving privacy and data sovereignty, an appropriate data exchange, based on recent technologies developed in the field of data spaces, can open new possibilities that are supposed to speed up the energy transition. A simple example may actually help. Let us suppose a wind farm operator would like to start a new project with the deployment of a new installation. The business decision on the location does not depend only on the technical possibilities in terms of the wind field but also on the complexity of the process in terms of grid connection. The possibility to assess different points of a network from the point of view of available capacity would be a great support for more educated business decisions facilitating faster development of new projects.

A different but equally relevant example is given by a security assessment performed by grid operators. The emerging complexity of the modern grid stemming from the presence of distributed generation is making the job of transmission operators more complex. While in a classical setting, the whole set of key information was related to assets directly connected to the transmission network, in the new scenario, the dynamic interaction with the distribution grid plays a key role. While this process is already under development under the pressure of national regulation (e.g., Redispatch 2.0 in Germany), moving in the direction of dynamic analysis will require new types of data interactions between transmission and distribution.

TwinEU will provide an open framework of development to support all these types of use cases. The focus will be on the interoperability of the data exchange and the creation of an architecture able to support the data interaction in a flexible way.

TwinEU Foundations and Technology

A DT of this complexity cannot be interpreted as the creation of a single very large model but, on the contrary, as the interaction of a set of twins managed by different grid operators involved in the experiment. We should, then, refer to this solution as a *federated DT*.

This process of federation is very similar to the data aggregation process in that data spaces are able to provide support and that, in effect, the background technology of TwinEU has been developed in the framework of similar efforts in the area of data spaces. In particular, a key element for the data exchange process, and then federation, is the OneNet Connector, developed in a project of the same name and based on the standards defined by the International Data Spaces Association.

Data connectors are a key innovation in the field of data sharing that combine the exchange of data with a metadata process to create trust and support data sovereignty.

In a nutshell, a data provider participates in a data space, while providing the data can also add the rules defining who can use the data and for what the data can be used.

The OneNet Connector provides profiles for about 30 different cases of data exchange in the energy sector, offering an easy customization for the application in a variety of real cases. The connector will soon be released as OS, offering the possibility to extend the set of use cases supported, with the aim to create a standard method for data sharing that could be adopted from all the possible stakeholders in the energy sector, from the customers up to the transmission operator.

> ***Adopting an OSS approach not only mitigates IP disputes but also fosters a deep commitment to transparency.***

In the framework of the DT effort, it is relevant to consider the possibility to extend the connector to support not only data but also models. Currently, the connector is mostly designed to support data according to the CIM standard, in particular, according to the Common Grid Model Exchange Specification extension developed by the European Network of Transmission System Operators. In TwinEU, standard representation of models (including the mechanisms of data protection and sovereignty) will offer new ways of interaction among stakeholders, as in the examples reported above.

The project is not aiming to create a standard solution that each grid operator should adopt but standard methodologies of data exchanges that will support the federation.

TwinEU starts from already available experiences in terms of national DTs and wants to create conditions for a proper interaction of these components.

At the same time, new use cases will bring new tools that will be developed within the project as OS components to be shared with the other operators to speed up adoption.

In effect, the majority of the new tools that will be developed in this project will be released as OS to facilitate cooperation among different stakeholders. The variety of demonstrations included in the project will drive the development of a large set of use cases, which will enrich the OS components available for further development.

Simulation as Data Federation

To better illustrate the concept, let us start considering a very simple scenario, i.e., the connection of two actors in the TwinEU ecosystem. The situation is depicted in Figure 1. In this case, one instance of the OneNet Connector is activated. Adding more players would require the activation of more instances of the connector, but it would not change the concept.

In the current assumption, two models and corresponding simulation engines are interacting via the connector. Thanks to the data space architectures managing identities and thrust, the two actors will establish the connection, with clear rules on the type of data exchange.

The connector operation will be regulated by the data sovereignty principles that will regulate the data exchange between these two players. In this respect different scenarios can be possible:

- The two actors agree on fully sharing their models according to a standard, such as the CIM.
- The two actors agree on sharing interconnection data but no information about the systems or other points in the systems.
- The two actors agree on the sharing of a specific set of data.

The type of data exchange could also be influenced by the type of engines connected to the models:

- The two actors use the same engines, so they can adopt data exchange fully supporting the integration of the two models.
- The two actors use completely different engines, which share a cosimulation interface.
- The data exchange is used only to initialize some boundary conditions in the other model.

As can be understood by analyzing the different options, the same mechanism supports different levels of integration and sharing of the models. In a fully open sharing approach in which both actors are also using the same engine, a full integration of the modeling exercise is achieved. In other cases, the cosimulation is limited, but it is, in any case, determining an enhancing of the quality of the internal representation thanks to data exchange. The key principle is the preservation of the data sovereignty principle, allowing every actor to decide the level of integration and data exchange without compromising the potential of model enhancement.

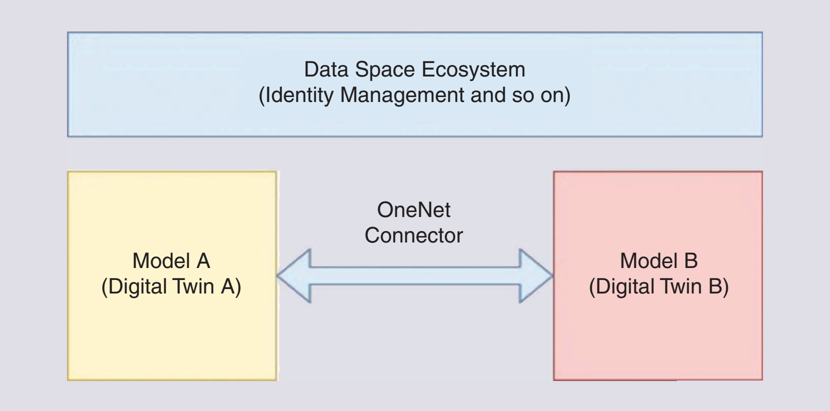

Figure 1. The data space federation.

This flexibility is also key to create innovative business cases in which external actors can be involved in the DT. Grid operators, for example, may provide limited but meaningful information to external actors that are evaluating significant investment dependent on the availability of appropriate grid infrastructure.

> ***Designing a DT of the European power system is a true moonshot project whose "landing moment" is still ahead of us.***

Selected National Demonstrators

Dutch Demonstrator on Cyberphysical Security

This demonstrator addresses an important but unfortunately pretty complex aspect of DTs of future power systems: cyberphysical dynamics and their cybersecurity. Future power systems can be seen as a vast combination of various digital elements, such as the Internet of Things, IT, or operational technology, and physical elements, such as power generation, power grids, or loads. This discrete/continuous mix is hard to describe and also hard to assess when it comes to control behavior. Existing analytical mathematical methods (swing equations and stability limits) are not applicable, so numerical methods are usually applied with such cyberphysical systems.

The goal is to find ways to replicate such future power systems in the DT and to use the DT for cybersecurity purposes: risk assessment, impact estimation, and attack response. It is important that on top of the challenges of establishing new types of numerical models and developing new types of mathematical/numerical methods to contribute to cybersecurity, it is the human factor that plays a decisive role: operators in the control room need to be trained to work with these new methods in order to realize that attacks are prepared or already executed, to know how to respond, and to determine how to recover as quickly as possible.

The TwinEU consortium operates a "Control Room of the Future" at its TU Delft location (Figure 2), where human operators can be exposed to a twin-powered setting of power system attacks. Aspects such as communication network latencies or failures, cyberphysical cascades, or supervisory control and data acquisition supply chain attacks can be exercised via so-called red team/blue team games in a safe environment. Both TSO and DSO settings, and a combination of the two, can be studied.

An example of such an exercise is a grid with increased renewable generation, such as wind and solar, where the power inverters have an intended or accidental malfunction. They contribute to dynamic instability, and things escalate: the protection system disconnects feeders due to frequency and voltage oscillations, the grid becomes unstable, and a cascading outage happens. Such a scenario will be used to design new protection schemes, new damping controls, automatic and manual islanding policies, and recovery plans. The key is seamless cooperation of security experts and power grid operations experts in order to design and operate the system in a resilient way.

German Demonstrator on DSO–TSO Interaction

The German grid is under pressure to accommodate unprecedented growth in renewable sources installation: an additional capacity of 210 GW is supposed to be added before 2030. The majority of the sources (according to some estimates, about 90%) will be connected to the distribution grid. This process results, first of all, in incredible growth in the number of connection requests that an operator is called to manage. Assessment of this impact must be conducted, while at the same time, the consumption pattern of the customers is dramatically changing because of new loads, such as electric vehicles or heat pumps.

At the same time, as reported above, this changing scenario necessitates closer interaction between distribution and transmission. In this demo, Westnetz, a DSO member of the E.ON group, will explore this interaction with Amprion, one of the four German TSOs.

Figure 2. TwinEU's "Control Room of the Future," where the human in the loop of cyberphysical resiliency can be studied.

In this case, both operators already have their own solution for a DT, but they plan to extend the functionalities through the demo activity in relation to grid monitoring, grid planning, and end-to-end flexibility management, with focus on congestion management.

> ***Modeling for DTs in power systems is still a relatively young field, where a lot of research is still happening.***

Particularly for this last aspect, the interaction with the TSO is critical, with the scope to use the DT to identify valuable and trustworthy information about available (micro)flexibilities in the power system. These flexibilities are currently located mostly at the distribution level, where the data connection will play a key role.

The demonstrator will include a variety of flexibility providers, including residential and commercial suppliers, distributed renewable sources, batteries, and electric vehicle charging stations, all already installed through various previous activities, including at E.ON labs.

One instance of the platform will be linked in Fraunhofer FIT's control room environment via standard interfaces to real-time-capable power flow calculations and dynamic simulations using the SOGNO platform, an OSS product developed at RWTH Aachen University and further developed within the Linux Foundation Energy framework.

OS in TwinEU

OS is a key element of the strategy of the TwinEU project.

This aspect has implications in two distinct dimensions. Primarily, the core components of the federation, notably the data connector, should be universally accessible to all stakeholders, ensuring both ease of adoption and equitable usage. It is not reasonable to imagine that the key instrument for data exchange in the whole European energy system could be a proprietary solution. For the same reason, new components that will be developed within the project to be part of the federation process will be released as OS. The goal is fair and equal participation of all the stakeholders within the energy system. The OneNet Connector has not yet officially been released as OS, but plans are on the way.

In this respect, the Linux Foundation Energy framework plays a key role as the right instrument to manage this licensing process, with the possibility to create a community that will support and maintain the components in the future. It is, for example, reasonable to imagine that regulation changes will call for new adaptation of the connector and then the need of new releases.

It is also critical to have an open community to guarantee that in the future, there will be open access to the technology to avoid any possibility of market lock-in for such critical components of the energy system.

Another element is given by the modeling aspects of the DT. Modeling for DTs in power systems is still a relatively young field, where a lot of research is still happening. It is critical to create the conditions to make the simulation tools evolve over time.

This situation calls for a slightly different type of community, i.e., for a research-oriented community adopting OS solutions. This is exactly the task of the Collaborative Research for Energy System Modeling (CRESYM) association (https://cresym.eu), which is also a partner of the TwinEU project, with the goal to create a sustainability plan for research results. One of the most critical aspects in the research field is exactly the possibility to create the conditions for long-term support of research results. Many brilliant research ideas risk death at the end of a funding cycle; creating communities of research is a way to provide a future for research ideas and facilitate the transition to real products.

In this respect, the CRESYM communities and the Linux Foundation Energy framework can be seen as a perfect pipeline of synergies. Research originally developed in academic environments grows in communities managed by CRESYM to become a mature project that can transition to the Linux Foundation. TwinEU is pioneering this development cycle, bringing together these two types of communities and exploring how to better exploit research results in the long term.

This process, however, is not in conflict with commercial exploitation. Companies will be able to use and integrate these results in commercial products while benefitting from the work of the communities. In this sense, a fully OS approach can be seen as an accelerator for the innovation process in which precompetitive components are shared to optimize development time while also reducing development costs.

The TwinEU project aims high. Designing a DT of the European power system is a true moonshot project whose "landing moment" is still ahead of us. Still, the path there is already full of valuable output. Discussing a truly international DT with regard to principles, philosophy, data formats, data ownership, model lifecycle, and many more aspects is an exciting process. These things are not trivial even if the twin is a local or national one that is owned and operated by one stakeholder. Coming to useful decisions among a consortium with more than 70 international partners from the energy sector will lift the design to a new level, a level that makes it prepared and robust for an uncertain future.

Key Takeaways for Present and Future DT Initiatives

The TwinEU project is illustrative of the key role of the open approach and OS in the development of DTs. We strongly recommend that the approach and standard methodologies be followed by every DT project, especially for off-grid applications.

This starts by embracing the open approach and OSS practices in designing individual components of DTs for interoperability. IP issues should be addressed from the very beginning through adequate licensing. Comprehensive documentation is essential for DT projects, especially since applications are use case specific. The assumptions and limits of individual models should be as explicit and precise as possible in order to allow discussions on how to assemble them properly with regard to the target use cases. This will also help tackle issues related to scalability and the level of detail needed. Using OS tools will foster collaboration among different interfaces and accelerate the development and interfacing of DTs.

The federated DT framework adopted by the TwinEU project should also be followed whenever possible, as it complements the OS approach with best practices from data space initiatives. Using data connectors is a key enabler for data and model sharing processes. The OneNet Connector, based on the standards defined by the International Data Spaces Association, will soon be released as OS, which will expand its already large set of available profiles and supported use cases. In addition, DT initiatives should define and follow standard methodologies of data exchanges that will support the federation in this context. As the TwinEU project tackles this challenge, most of its tools will also be released as OS, which will provide a starting point for other initiatives. The key elements of the federation, the data connector first of all, must be accessible to all the stakeholders for easy and fair adoption.

Hosting projects under the umbrella of OS foundations like the Linux Foundation will ensure that the developed DTs are openly accessible in a neutral environment and that a community can continue maintaining, adapting, and improving, with the relevant governance. This long-term clarity is essential for critical components of the energy system and to allow all stakeholders to contribute in this shared innovation effort. This process does not interfere with commercial exploitation.

Through the open approach, key requirements, such as cybersecurity, confidentiality, fraud prevention, and data integrity, can also be ensured, with transparent and well-tested inspection and audit techniques. However, this works only if properly addressed and if there is a robust community behind the projects. Here again, OS foundations bring experience and best practices in managing large-scale OS initiatives.

The open approach can also create strong synergies with research communities, leveraging academic communities and collaborative projects supported by public funds. This is key since there is still a lot of research on modeling DTs in power systems. At the other end of the spectrum, standardization and OS can work very well together for digital applications and, especially, DTs.

Following these guidelines is especially relevant for DTs of components or systems that may function both off-grid or connected to the bulk power system, such as microgrids. Indeed, such DTs may be developed primarily to address issues when disconnected from the grid, and without a framework to properly connect these DTs with grid DTs, it will be difficult to study the interconnection or interaction with the bulk power system. Phenomena may not be properly captured, or there may not be an ability to study them in large networks when relevant. The open and federated DT approaches have the potential to alleviate those issues and should be considered as early as possible to ensure interoperability by design.

For both bulk power systems and off-grid applications, DTs will make sense only if there is a flow of data, and the only way to do this is through cooperation. Cooperation and openness are not a luxury, they are a must.

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For Further Reading

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