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EDITORIAL

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Energy Metaverse: a virtual living lab of the energy ecosystem

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Introduction

As it has become evident that climate change is an imminent threat to human well-being and the health of the planet, the transformation of the energy ecosystem towards more sustainable energy sources has become a top priority.

However, the energy ecosystem is a very complex and highly interconnected system, comprising stakeholders, technologies, infrastructure, regulations, and policies. This complexity necessitates an innovative approach to the exploration and implementation of new technologies, regulatory frameworks, and business models.

The Energy Metaverse offers such an innovative approach by providing a digital ecosystem space that provides a virtual living lab of the energy ecosystem. The Energy Metaverse aims to create a digital replica of the ecosystem of the physical energy system. By connecting all counterparts of the physical energy ecosystem through data and information exchange protocols, the Energy Metaverse allows stakeholders to experiment, evaluate, and optimize new technologies, regulatory framework conditions, and business models before introducing them into the physical energy ecosystem.

In this editorial paper, we will define the Energy Metaverse, discuss its characteristics and importance, and examine the technologies and approaches needed to create it. The paper will also explore the stakeholders who will benefit from using the Energy Metaverse and how it can support the green transition of energy systems. By providing a comprehensive overview of the Energy Metaverse, we hope to promote further research and accelerate the adoption of this innovative concept in the energy ecosystem.

What is the Metaverse?

The term "Metaverse" has gained mainstream attention recently, especially after Mark Zuckerberg's keynote speech at Facebook Connect 2021. However, the concept of a Metaverse is not new and was first introduced by science fiction author Neal Stephenson in his 1992 novel Snow Crash. The Metaverse is a virtual reality space that connects people in the physical world with their digital counterparts in a virtual world, where they can interact with each other, and the environment generated by a computer.

Second Life, an online computer game launched in 2003 by Philip Rosedale, is an early example of a metaverse that gained widespread popularity. The name "Second Life" reflects the promise of an alternative reality beyond the physical world. In Second Life, players can connect with other residents, socialize, participate in group activities, and create and trade digital property in a virtual world known as "the grid." Second Life is still available today, offering many of the features promised by newer metaverses such as Mark Zuckerberg's Meta. Other examples of metaverses can also be found in popular culture, including science fiction movies like The Matrix from 1999 and Avatar from 2009, as well as video games like The Sims series, which was first released in 2000, and the more recent Fortnite from 2017.

The term "metaverse" has been formally defined by the Oxford dictionary as a virtual reality space in which users can interact with an environment generated by a computer and with other users. While this definition captures the basic characteristics of the metaverse, it is important to note that the concept has evolved over time and may continue to do so as technology advances and new use cases emerge.

To facilitate user interaction with both the environment and other users in the metaverse, the digital representations are linked to their physical counterparts via a range of input devices and display technologies. These input devices range from conventional mouse and keyboard to more sophisticated devices such as motion capture skeletons, force feedback suits, and gloves. The display technologies employed likewise encompass a range of options, from traditional monitors to Virtual Reality headsets.

What is the Energy Metaverse?

While many science fiction and existing metaverses are designed to simulate social aspects of life from an individual's point of view, little attention has been given to technical- or ecosystem-oriented metaverses, such as the Energy Metaverse.

The Energy Metaverse is a digital ecosystem that interconnects digital twins of energy-related society aspects and uses data and information exchange protocols to link all counterparts of the physical energy ecosystem. This allows stakeholders to study the effects of changing the ecosystem's configuration and to experiment, evaluate, and optimize new technologies, regulatory framework conditions, and business models before introducing them into the physical energy ecosystem.

Using data and information from smart energy meters, environment sensors, and information databases, the Energy Metaverse captures the behaviors of stakeholders, infrastructure artifacts, environmental factors, and energy flows reflecting the impact of business models, regulations, and policies. The emergent results of the interactions among the stakeholders in the energy ecosystem are displayed to the users of the Energy Metaverse through display technologies such as monitor displays and Virtual Reality headsets.

While the Energy Metaverse shares many conceptual similarities with existing social-oriented metaverses, it fundamentally differs in its purpose and use. Existing social-oriented metaverses focus on creating a user-centric experience that addresses the needs and desires of individuals. In contrast, the Energy Metaverse focuses on analyzing the behaviors emerging from the collective tangible and intangible interactions between stakeholders, infrastructure, environment, business models, regulations, and policies in the energy ecosystem. Furthermore, while users in social-oriented metaverses are represented by avatars interacting with each other in a virtual reality world, users in the

Energy Metaverse interact with a digital replica of the energy ecosystem in the physical world.

Why the Energy Metaverse is important?

By capturing the physical energy ecosystem in a digital replicate, the Energy Metaverse provides a virtual living lab of the energy ecosystem. Access to a virtual living lab of the energy ecosystem allows stakeholders to experiment with and evaluate new technologies, regulatory framework conditions, and business models before these are introduced in the physical energy ecosystem.

Experimentation with and evaluation of new technologies, business models and regulatory framework conditions not only can reduce uncertainty and risks but also facilitate policymaking that effectively supports the green transition of energy systems. The green transition of energy systems plays an essential role in the fight against climate change by reducing CO2 emissions from conventional power plants through the large-scale adoption of renewable energy technologies like wind and solar power.

For instance, the European Union's framework program European Green Deal strives to make Europe the first climate-neutral continent by 2050. Large-scale adoption during a long period usually relates to large investments, significant changes, and impacts on many aspects of society. Hence, the virtual living lab provided by the Energy Metaverse offers an opportunity to investigate, test, evaluate, optimize, plan, and even control energy ecosystem elements with an environment-friendly, cost-efficient, user-friendly, risk-avoided approach.

The Energy Metaverse can help to reduce the time, resources, and risks associated with the development and implementation of new technologies, regulatory frameworks, and business models in the energy ecosystem. Through the virtual living lab, stakeholders can test and optimize new energy technologies, business models, and regulations before implementing them in the physical world.

In this way, the Energy Metaverse can play an important role in supporting the green transition of energy systems, as it can help stakeholders to make informed decisions that are both environmentally and financially sustainable. The Energy Metaverse provides a new, innovative, and promising way to create a sustainable future, and it has the potential to transform the way the energy ecosystem is managed and operated.

Who will use it?

To identify the stakeholders who will benefit from using the Energy Metaverse, ecosystem thinking can be employed to obtain a comprehensive view of the energy system. Ecosystem thinking facilitates the identification of stakeholders involved in supply chains, value chains, lobbying groups, policymaking institutions, legislation authorities, and regulatory pathways, among others. A systematic approach that utilizes ecosystem thinking to analyze ecosystems is introduced in Ma et al. (2021); Ma 2022; Ma 2019). This methodology can be applied to the analysis of the energy ecosystem to identify relevant stakeholders, such as national ministries and agencies, regulatory bodies, local authorities, system operators, technology suppliers, energy market operators, energy producers, energy traders, energy retailers, and energy consumers. The general responsibility of each stakeholder in the energy ecosystem is listed in Table 1.

Table 1 General responsibilities of stakeholders in the energy ecosystem

Stakeholder	General responsibility
National ministries of energy	Are responsible for national energy policy and international cooperation on energy issues
National energy agencies	Are responsible for tasks linked to energy production, supply, and consumption, as well as efforts to reduce carbon emissions
Regulatory bodies	Are responsible for legally regulating aspects of the energy sector, independent of other non-government agencies. This responsibility may be distributed among several public organizations
Local authorities	Are responsible for local planning and zone regulations
System operators	Are responsible for operating the transmission and distribution grids
Technology suppliers	Supplies the equipment necessary for operating the energy sector
Energy market operators	Are responsible for operating the trading on the energy markets
Energy producers	Are responsible for the production of energy from primary and secondary sources
Energy traders	Are responsible for buying and selling shares of energy stocks and commodities exchanges to offer companies ways to hedge electricity price-related risks
Energy retailers	Are responsible for buying electricity and gas in wholesale markets, packaging it with transportation services, and selling it to end customers
Energy consumers	Are responsible for the end-use of energy

Each stakeholder group in the energy ecosystem has specific interests and requirements that are determined by their roles and responsibilities within the ecosystem. Based on these roles and responsibilities, stakeholders in the energy ecosystem can use the Energy Metaverse for various purposes, such as planning, designing, testing, and evaluation tasks. Different user interfaces, such as graphical user interfaces (UIs) and application programming interfaces (APIs), will be required to provide different perspectives on the energy ecosystem for various stakeholders. Relevant use cases for each stakeholder are listed in Table 2.

Despite the diversity of stakeholder groups, predicting the consequences of making changes to the ecosystem's configuration is the common element of all use cases. However, predicting the cascading effects of such changes in inherently complex systems is a non-trivial task. What appears to be a simple alteration in one part of the ecosystem may have significant repercussions in other areas. Therefore, predicting the future effects of changes necessitates a comprehensive simulation of stakeholder behaviors, interactions, infrastructure artifacts, environmental factors, and energy flows that reflect the impact of business models, regulations, and policies.

To accurately reflect the physical energy ecosystem's actual state, the Energy Metaverse simulation must be linked to the physical energy ecosystem through a sensing and actuating infrastructure that enables the Energy Metaverse to sense and interact with its physical world counterparts. This infrastructure would typically include smart meters, Internet of Things (IoT) sensors, and Supervisory Control and Data Acquisition (SCADA) systems.

How do we create it?

Contrary to traditional social-oriented metaverses that only connect people, the Energy Metaverse also connects tangible assets like energy meters and environmental sensors and intangible assets like policies, regulations, and business models using data

Table 2 Individual stakeholder's use cases for the energy ecosystem

Stakeholder	Use cases
National ministries of energy	Can investigate the dynamics between policies, regulatory framework conditions, and technology adoption
National energy agencies	Can investigate the consequences of proposing different tariff models and CO2 taxes
Regulatory bodies	Can verify the consequences of proposed regulatory changes before they take effect
Local authorities	Can experiment with alternatives before deciding on the final zoning and land use planning
System operators	Can investigate different solutions for optimizing the use of existing grid infrastructure and thereby reducing the need for future investments
Technology suppliers	Can test their existing and future technologies in a virtual ecosystem before going forward with market introduction
Energy market operators	Can experiment with different market designs for supporting the integration of intermittent renewable energy resources
Energy producers	Can investigate the consequences of investing in alternative technologies for replacing or increasing production capacity under different regulatory framework conditions and market demands
Energy traders	Can evaluate trading strategies based on different scenarios for the market's resiliency towards fluctuations in energy prices
Energy retailers	Can experiment with different designs of business models for delivering energy services
Energy consumers	Can evaluate new technologies for improving energy efficiency and increasing flexible energy use before implementing them

and information exchange protocols. It becomes evident that the technologies needed to realize the Energy Metaverse are different from those for traditional social-oriented metaverses.

Since the energy metaverse connects stakeholders, tangible and intangible assets in the physical energy ecosystem with their digital counterparts, data and information flows between the physical and the digital energy ecosystem that constitutes the Energy metaverse.

The Energy Metaverse's technological need can be met by Digital Twin technology, as Digital Twin technology is built around a bidirectional connection between the physical and digital worlds. However, in most prior works, Digital Twins represent a single physical artifact like an aerospace vehicle (Glaessgen and Stargel 2010). In the case of the Energy Metaverse, the Digital Twin needs to represent the complexity of all entities and process flows that make up the ecosystem of the energy systems.

This system-wide perspective implies that the single-unit prediction models used in prior works must be replaced with system-wide prediction models that can capture the intrinsic complexity of emergent behaviors in the energy ecosystem.

One well-known candidate method for capturing emergent behaviors in complex systems is agent-based modeling and simulation. It has been used for several studies involving different stakeholder interests in the energy ecosystem, e.g., (Failed 2019; Christensen et al. 2020; Howard et al. 2021; Fatras et al. 2022). By replacing the single-unit prediction models in prior Digital Twin designs with system-wide prediction models based on agent-based modeling and simulation and combined with other simulation methods (e.g., discrete event simulation, system dynamics) and AI (Artificial Intelligence) models, it becomes possible to support the type of use cases listed in Table 2.

Therefore, to realize the Energy Metaverse, it will be necessary to integrate multi-modeling and simulation methods to predict the emergent behaviors associated with changes in the configuration of the energy ecosystems, in addition to Digital Twin technology. This is because the complexity of the ecosystem of energy systems necessitates a comprehensive modeling and simulation approach that can capture the interactions among stakeholders, tangible and intangible assets, policies, regulations, and business models.

By integrating Digital Twin technology with multi-modeling and simulation methods, the Energy Metaverse can offer a virtual living lab for stakeholders to experiment, evaluate, optimize, plan, and control energy ecosystem elements in a cost-efficient, environmentally friendly, and risk-avoided manner. This will enable stakeholders to assess the impact of new technologies, regulatory framework conditions, and business models before their introduction into the physical energy ecosystem, facilitating policymaking that supports the green transition of energy systems.

What comes next?

Building on the concepts and ideas presented in this editorial paper, as well as the characteristics of the Energy Metaverse that have been described, we propose the following definition: The Energy Metaverse is an exact digital replica of the physical energy system's ecosystem, enabling stakeholders to explore the effects of changes to the ecosystem configuration.

This definition facilitates the use cases presented in Table 2, allowing stakeholders to investigate potential risks associated with the adoption of new technologies, regulations, policies, and business models before implementing them in the physical world.

The Energy Metaverse will serve as a vital platform for stakeholders, supporting their efforts to realize a green transition in the energy ecosystem. By providing a virtual living lab, the Energy Metaverse allows for the exploration of "what-if" scenarios that would be too costly or impractical to investigate in the physical world. Through this, the Energy Metaverse enables stakeholders to mitigate potential adoption chain, co-innovation, and execution risks, thereby reducing uncertainty and supporting effective policymaking. Overall, the Energy Metaverse holds significant potential to drive progress towards a sustainable future.

Abbreviations

API	Application programming interface
UI	User interface
IoT	Internet of Things
SCADA	Supervisory Control and Data Acquisition

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