POLITECNICO DI TORINO
Repository ISTITUZIONALE

COMET: Co-simulation of Multi-Energy Systems for Energy Transition

Original
COMET: Co-simulation of Multi-Energy Systems for Energy Transition / Barbierato, Luca; Schiera, Daniele Salvatore; Scoccia, Rossano; Margara, Alessandro; Bottaccioli, Lorenzo; Patti, Edoardo. - (2022), pp. 1343-1348. ((Intervento presentato al convegno 46th IEEE Annual Computers, Software, and Applications Conference (COMPSAC 2022) tenutosi a Virtual Conference (due to Covid-19) nel 27 June 2022 - 01 July 2022 [10.1109/COMPSAC54236.2022.00212].

Availability:
This version is available at: 11583/2970694 since: 2022-08-20T16:32:12Z

Publisher:
IEEE

Published
DOI:10.1109/COMPSAC54236.2022.00212

Terms of use:
openAccess

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
IEEE postprint/Author's Accepted Manuscript

©2022 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

29 November 2022

COMET: Co-simulation of Multi-Energy Systems for Energy Transition

Luca Barbierato*, Daniele Salvatore Schiera*, Rossano Scoccia‡, Alessandro Margara‡, Lorenzo Bottaccioli* and Edoardo Patti*
*Politecnico di Torino, Turin, Italy. Email: name.surname@polito.it
‡Politecnico di Milano, Milan, Italy. Email: name.surname@polimi.it

***Abstract*—The ongoing energy transition to reduce carbon emissions presents some of the most formidable challenges the energy sector has ever experienced, requiring a paradigm change that involves diverse players and heterogeneous concerns, including regulations, economic drivers, societal, and environmental aspects. Central to this transition is the adoption of integrated multi-energy systems (MES) to efficiently produce, distribute, store, and convert energy among different vectors. A deep understanding of MES is fundamental to harness the potential for energy savings and foster energy transition towards a low carbon future. Unfortunately, the inherent complexity of MES makes them extremely difficult to analyze, understand, design and optimize. This work proposes a digital twin co-simulation platform that provides a structured basis to design, develop and validate novel solutions and technologies for multi-energy system. The platform will enable the definition of a virtual representation of the real-world (digital twin) as a composition of models (co-simulation) that analyze the environment from multiple viewpoints and at different spatio-temporal scales.**

***Index Terms*—Co-simulation, Digital Twins, Multi-Energy-Systems**

I. Introduction

The global energy sector is undergoing an unprecedented transformation to reduce carbon emissions [1]. The so-called Energy Transition presents some of the most formidable challenges the energy sector has ever experienced, requiring a paradigm change that involves diverse players and heterogeneous concerns, including regulations, economic drivers, societal, and environmental aspects. Central to this transition is the adoption of integrated Multi-Energy Systems (MES) to efficiently produce, distribute, store, and convert energy among different vectors [2]. MES allow the exploitation of renewable energy resources and smart energy infrastructures, with a twofold objective: globally optimize the resulting integrated energy system and each single process [3]. A deep understanding of MES is fundamental to harness the potential for energy savings and foster energy transition towards a low carbon future [4], [5]. Unfortunately, the inherent complexity of MES makes them extremely difficult to analyse, understand, design and optimise. So, tools that capture the multi-faceted nature of MES are needed [6], [7].

We believe that a digital twin, i.e., a digital representation of MES, can help existing and new players of energy markets (e.g., distribution system operators and energy aggregators) to test innovative technologies, control policies, or business models [8] in a realistic virtual environment, making their analysis faster and more efficient. This is particularly relevant today, as energy transition strategies are ongoing, and testing innovative solutions before they are applied to the real-world may foster and accelerate sustainable urbanisation into Energy Communities, energy-efficient and energy-flexible urban areas with surplus renewable energy production and net zero greenhouse gas emissions.

In fact, digital twin applications have been successfully adopted in many and diverse fields, including smart grid [9]–[11], aerospace [12], mobility [13] and naval engineering [14]. However, existing applications target small to medium-scale scenarios and do not cover scenarios with heterogeneous subsystems that work at different spatio-temporal scales and interact in complex ways, as in the case of MES. In fact, MES requires a multi-disciplinary approach to be studied and analyzed comprehensively. Commonly, experts from different disciplines use standalone modeling and simulation techniques to design MES [8]. In these complex interactions, a standalone simulation approach fails to capture the complexity of the overall system.

Co-simulation is a technique that splits a complex system into a System-of-Systems (SoS) structure and deploys each of the subsystems into a specific solver or simulation software, managing synchronized time evolution and data exchange across them. Moreover, co-simulation enables scalability through the distribution of individual simulations across different computing nodes. Different co-simulation solutions have been proposed in literature. Mosaik [15]–[17] and HELICS [18]–[20] are two open-source co-simulation frameworks that provide reliable performance, high usability, and flexibility. They can be integrated with several power grid simulators (e.g., pandapower, DRTS) and any other simulators (e.g., Modelica, Simulink, EnergyPlus). Both Mosaik and HELICS orchestrate co-simulation across different models, software and simulators, allowing data exchange and time-steps synchronization. In a nutshell, we see co-simulation as a promising technology to handle the complexity of MES and build a digital twin that precisely captures their multi-faceted nature.

In this paper, we present ongoing work in the design of a Digital Twin co-simulation platform called COMET (CO-simulation of Multi-Energy system for energy Transition). COMET will addresses these needs providing a structured basis to design, develop and validate novel solutions and technologies for MES. Combining digital twin and co-simulation techniques together is a rising approach used by the research community in many contexts, such as Cyber Physical Energy Systems [21]. COMET will benefit from this approach and will implement co-simulation as an enabling technique to integrate the vertical and horizontal system design of different energy vectors. The platform will integrate models of physical and social phenomena, accurately reproducing MES and the environment in which they operate. The COMET platform will enable the integration and simulation of innovative MES components within an existing energy scenario with a plug-and-play approach. COMET will support the different stakeholders in the energy market to take short and long-term decisions (from operational to planning). It will simulate phenomena that evolve at different spatio-temporal scales (from households to districts and cities, from microseconds to years). It will simplify the definition of complex scenarios exploiting domain-specific semantic information about individual models and their interactions, enabling a plug-and-play composition of models.

The rest of the paper is structured as follows: Section II presents the motivation behind this research and the objectives of the COMET platform; Section III presents the architecture of the COMET platform; Section IV highlights the advancement of COMET with respect to previous solutions, and Section V states concluding remarks.

II. Motivation and Objectives

The COMET platform aims to promote and accelerate the energy transition process by developing a simple and efficient platform to simulate and analyze complex multi-energy systems (MES). From a system engineering perspective [22], MES are categorized as complex systems, which include a multitude of components heavily interconnected with each other in a dynamic way.

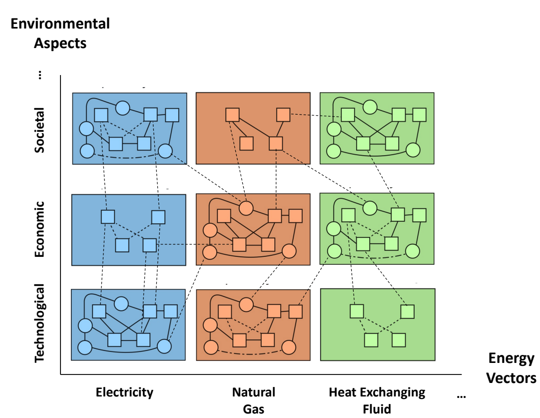

Fig. 1. Dependencies between components in MES

Analyzing, understanding, and predicting the behavior of MES involves capturing the deep dependencies between components along two dimensions (see Figure 1): (i) Each individual energy system interacts with the environment in which it is deployed in a multifaceted way, with concerns that derive from highly heterogeneous aspects of the environment, including technological, regulations, economic and societal (vertical axis in Figure 1). Each of these aspects requires deep domain-specific knowledge to be properly modeled and analyzed; (ii) Multiple energy systems continuously interact with each other (horizontal axis in Figure 1). For instance, changes in the production, accumulation, or distribution of energy coming from one energy vector directly affect the load of other vectors.

A rapid assessment of the feasibility and the benefits of novel solutions in the design of MES is key to foster energy transition. However, systematic analysis of alternative scenarios on a formal basis is impossible when dealing with the complexity of MES design. Also, hardware testing in laboratory or fields trial are expensive and inflexible tools to assess MES scenarios. Instead, we see software simulation as the most promising approach to enable scalable, flexible, and cost-effective analysis of MES.

Moving from these premises, as shown in Figure 2, COMET will develop a digital twin co-simulation platform for MES. The platform will integrate virtual representations (i.e. digital twins) that model the real-world entities building a MES. It will simulate the global behaviour of MES by evaluating the complex dependencies between individual entities (i.e. co-simulation of models). The research community can constantly update the different models and build new scenarios to be co-simulated. Whilst the different stakeholders playing in the energy marketplace can evaluate the co-simulations outcomes according to the MES application (i.e., the use case in Figure 2) they want to assess.

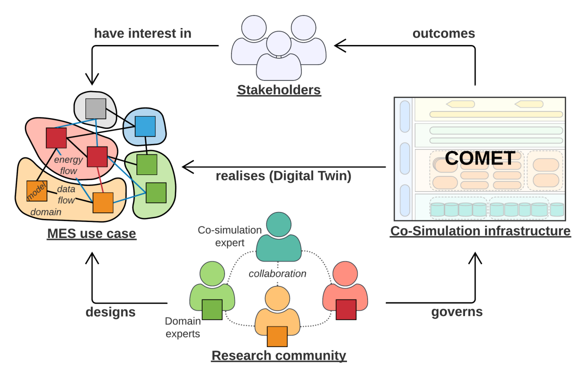

Fig. 2. General overview of the entities linked to the COMET platform.

In designing and developing the platform, the COMET platform will pursue the following objectives:
i) Usability. The COMET platform should be usable by diverse players in the energy market with heterogeneous backgrounds and expertise. To achieve this goal, the platform will expose a simple yet powerful interface to define complex scenarios as a composition of models. It will exploit semantic knowledge of the energy domain encoded in a machine-readable format to validate the correctness of the composition, alert the user in case of inconsistencies or errors in the composition, and suggest corrections.

ii) Interoperability and composability. Accurate and efficient models that simulate individual aspects of MES exist, including models of buildings, Smart Grid, user behavior, etc. The platform should re-use and seamlessly integrate these models. To achieve this goal, we will build on established interfaces adopted by state-of-the-art modelling tools, such as the FMI (Functional Mockup Interface) standard. This will guarantee access to a wide library of models in literature that have been extensively evaluated.

iii) Extensibility. The platform should enable the integration of new models with low effort. The use of standard interfaces will enable not only re-using existing models but also integrating new models when needed in a plug-and-play fashion, for instance to simulate new hardware components, infrastructures, or environmental conditions.

iv) Resolution independence. The platform should enable the analysis of physical phenomena that work at different spatio-temporal scales. To achieve this goal, the platform will adopt a simulation orchestrator that will govern the evolution of individual models at different resolutions and adjust their inter-communication.

v) Performance and scalability. The platform should enable rapid analysis of complex scenarios, allowing extensive simulation campaigns to assess new technologies in a wide range of configurations. To achieve this goal, the platform will adopt distributed computing infrastructures and will deploy the components that participate in a co-simulation on different physical nodes. The platform will scale from small to large scenarios by exploiting only the computational and memory resources needed for the simulation at hand.

vi) Intellectual property. Different parties (e.g., different players in the energy market) should be able to cooperate without disclosing information they are not willing to share (e.g., to avoid violations of intellectual property rights). To achieve this goal, the platform will enable deployment on premise or on public infrastructure as well as hybrid models. Specifically, the platform may run in a federated way, where individual parties host their model without disclosing its details and runtime behaviour with other parties. The orchestrator dispatches messages between models that participate to the simulation as black box components.

vii) Support for dedicated hardware. Simulations may need dedicated hardware to run complex models. Testing new hardware solutions may also call for hardware-in-the-loop simulations, where real hardware components interact with virtual models. By treating models as black boxes that only need to expose standard communication interfaces, the COMET platform will support these hybrid solutions.

The objective of COMET platform is to support the different actors that gravitate around MES in short-term and long-term decision making and planning. Among many application scenarios for COMET, we report in the following the most relevant ones:

1) Digital Twin for integrating planning and operation of multi-energy system. A multi-scale approach to assess different energy scenarios on medium- and long-term capacity expansion of distributed and renewable energy resources, with comparison with the current status. Possible applications are: evaluation of grid bottlenecks and balancing problems caused by the high penetration of distributed and renewable energy resources; choice of the best retrofitting technology to minimize energy consumption and green house emission in the building sector; control and management of energy networks; proposal of new energy-efficient and cost-effective solutions and improvements; maximization of self-consumption in energy communities thanks to a digital twin of the users behaviors and the generation systems.

2) Digital Twin of a building/district/city and exploit model predictive control strategies. The development of model predictive control exploiting e.g., reinforcement learning algorithms requires the ability to test various strategies, including potentially wrong ones, which is clearly not doable in a real building or district. Hence, a safe digital twin test-bed is required to learn the building behavior and the related internal comfort. With such a test-bed an energy manager or an energy aggregator can test and develop the best controller of the HVAC systems in a virtualized representation to unlock the potential of control logic tuned on short-term horizon (days). District heating and cooling operators may optimize energy consumption of their networks by controlling the schedule of the heating and cooling cycles of the connected buildings.

3) Digital Twin with hardware in the loop. The use of hardware in the loop simulations can provide an effective test-bed laboratory to support stakeholders to design, develop, and test new solutions and technologies for MES. COMET will provide a scalable, flexible and cost-effective platform to test and rapidly assess the feasibility and the benefits of state-of-art solutions in the design of MES. In the same way, the test-bed will enable a technical impact on developing new technologies linked to the energy industry that requires testing the proof of concepts or prototypes in a digital twin environment effectively. Moreover, this innovative laboratory will impact cost and time reduction for research, development and deployment phases of the technologies, thus accelerating both the technologies and the Technology Readiness Level of the innovative projects.

4) Digital Twin to study the interaction of buildings and smart grids. Evaluate the energy flexibility provided by the building sector and interact with Distribution System Operators and Transmission System Operators for a higher share of renewable energy sources into the electricy grids. For example, it could be used by Energy Communities manager to maximize the self-consumption thanks to a Digital Twin of the users but also of the generation systems.

III. The COMET Platform

To meet the challenging objectives discussed in Section II, we are developing COMET with the layered architecture presented in Figure 3. It consists of four horizontal layers, namely (i) ***data sources layer***; (ii) ***simulators layer***; (iii) ***co-simulation layer***; (iv) ***user interface layer***; and one vertical ***COMET integration layer*** that includes the concepts, logic,

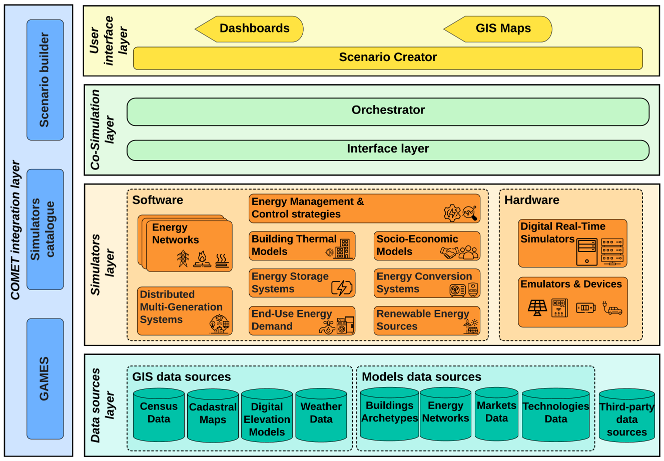

Fig. 3. Layered architecture of the COMET platform.

and functionalities that govern the interaction of the other layers.

The ***data sources layer*** includes the sources of information necessary to describe a MES and offers a uniform interface for data access, query, and retrieval for the other layers. The layer will include: *i)* GIS (Geographical Information Systems) data sources, which provide geographical references for the components of the environment used to model MES (e.g., density of inhabitants or weather information); *ii)* Models data sources, which offer core building blocks that define the models used in platform, such as archetypes of buildings, distribution networks (e.g., district heating, power grid, gas grid), market data, and technological aspects of the individual energy systems to be co-simulated. Moreover, COMET will allow developers to design custom adapters to support additional third-party data sources, such as smart metering infrastructures to retrieve data coming from real-world devices.

The ***simulators layer*** includes the software and hardware components (simulators) that define the behaviour of the various sub-systems of a MES. The platform will integrate software simulators that reproduce the temporal evolution of some of the entities in a MES. Examples include software simulators for energy networks and infrastructures, distributed multi-generation systems, building thermal demand, energy conversion systems, renewable energy production, energy storage systems, end-use sectors and energy demand, and energy management and control strategies. On the hardware side, the platform will integrate digital real-time simulators, as well as emulators and devices for performing hardware-in-the-loop co-simulation. We will integrate an initial catalogue of simulators that we will use to validate our approach and to enable other researchers experimenting with it. The platform will enable integrating additional simulators with minimal effort by relying on open standards and by defining a simple methodology to build adapters for new simulators.

The ***co-simulation layer*** glues together individual simulators to capture the global behaviour of MES. It consists of an interface layer and an orchestrator. The interface layer implements the logic that translates the data produced and consumed by different simulators, enabling interoperability at a syntactical and semantic level. We will support open standards such as FMI, which is widely adopted in simulators of energy systems. The orchestrator is the runtime component that governs the communication and synchronisation of the various simulations building a MES scenario. Specifically, the orchestrator uses the interfaces with individual simulators to manage their workflows and their mutual exchange of data. It considers the different spatio-temporal scales at which simulators work as well as different execution paradigms (e.g., event-based or time-based simulators). It schedules the individual tasks that compose the global simulation to maximise performance (that is, to reduce the time needed for a given simulation) while optimising the use of resources available (that is, maximise the use of resources when needed and release unused resources when possible).

The ***user interface layer*** includes the modules to define complex MES scenarios and visualise the results of a simulation. As usability is a primary goal of the platform, we will exploit domain knowledge about the scenario being modelled to guide and support as much as possible the user in the definition of a MES scenario: for instance, we will suggest suitable connections of sub-systems and highlight erroneous patterns of composition, thus reducing the time to produce a MES scenario and minimising the possibility of errors. We will build upon state-of-the art data visualisation tools (e.g., for time-series, GIS maps, dashboards) to help the users analyse the results of simulations at different spatio-temporal scales.

The ***COMET integration layer*** glues together all the other layers by offering a common framework. It includes a general-purpose architectural model for MES (GAMES), a simulators catalogue, and a scenario builder. GAMES is an architectural modelling framework that captures the complexity of MES along different dimensions and enable integration of knowledge from different domains, including ICT, financial, business, and regulatory [8]. GAMES extends the widely adopted Smart Grid Architectural Model (SGAM) [23] to capture multiple energy vectors. Briefly, GAMES expands SGAM by adding one layer for each energy vector (e.g., heat exchanging fluids and gas). GAMES governs the complexity of MES scenarios through a modular methodology, where the various aspects of a MES scenario can be seen as black boxes and integrated together to form a holistic view. The platform will adopt the GAMES architecture as the theoretical underpinning for the co-simulation platform, enabling a coherent view of a MES as a composition of subsystems, each of them bringing specific domains of knowledge. The simulators catalogue contains meta-information about the simulators that concretely realise the individual building blocks of the overall GAMES architecture. Specifically, the catalogue includes configuration setup of the simulators, such as the topology to inter-connect multiple model instances, their time-steps, initial conditions, required input, provided output, and data flow between model instances. The scenario builder exploits architectural knowledge (GAMES) and simulator-specific knowledge (simulators catalogue) to concretely define the scenario to be simulated and the co-simulation strategies.

IV. Related Advancement

When completed, the COMET platform will advance the state of the art in simulating and analyzing complex MES scenarios along multiple dimensions. At a high level, current solutions mainly fall into two extremes: (i) co-simulation frameworks (such as Helics or Mosaik) enable the integration of multiple simulators (co-simulation) but lack domain-specific knowledge about MES, and (ii) domain-specific energy digital twins focus on custom and narrow scenarios, solve specific problems, and lack the generality, simplicity, and reusability of a modular framework such as COMET.

Next, we compare COMET with these two broad classes of solutions and we show how we plan to advance research and innovation. Table I summarizes the key elements of our comparison. Finally, we report about recent research projects that are related with the goals of COMET.

The ***user interface layer*** will advance the state of the art by seamlessly integrating deep domain knowledge about the energy sector with the generality of a modular architecture. In this respect, co-simulation frameworks offer a modular architecture, but do not capture the specific needs of MES scenarios. Conversely, current digital twins for the energy sector provide custom solutions that do not follow a standardized conceptual architecture for MES but rather propose ad-hoc models for the specific scenario at hand. Instead, the COMET integration layer will bring a unifying conceptual underpinning (the GAMES architecture) upon which many diverse energy scenarios can be created. As a consequence, existing solutions do not offer simple tools to create an energy scenario and to coordinate heterogeneous simulators: energy digital twins implement custom solutions where the problem is typically manually encoded, and co-simulation frameworks provide general-purpose programmatic interfaces that are not well suited for the diverse audience of researchers and practitioners we plan to reach. Instead, the COMET platform will build upon the deep domain knowledge offered by GAMES to drastically simplify the definition of scenarios, with tools that help design and validate energy scenarios.

The ***co-simulation layer*** will make the advantages of co-simulation available to researchers and practitioners in the energy sector. We build upon co-simulation frameworks to enable the analysis of complex MES scenarios employing reusable simulators. COMET will advance the state of the art thanks to the knowledge about the application domain and the simulators, which is encoded into the modules of the COMET integration layer. Not only this will simplify the definition of scenarios, as already discussed in the user interface layer, but it will also enable more efficient execution of co-simulations, which will be dynamically optimized for the specific scenario at hand. COMET will determine the best strategy to execute the simulation to make it more efficient (reduce execution time) and less expensive (reduce use of unnecessary resources). For researchers and players in the energy market that adopt the COMET platform, this translates to the possibility to explore a wider range of scenarios in a limited amount of time and in monetary savings due to a better exploitation of resources.

The ***simulators layer*** will exploit all the flexibility of a modular architecture to capture all the heterogeneous requirements of MES scenarios. We will support simulators with different paradigms (e.g., event-based and time-stepped), with multiple domains (e.g., simulators for the thermal model of building, for smart grids, for energy conversions systems, for socio-economic models, etc.), with different spatio-temporal scales (e.g., from a single household to a city, from microseconds to study new technologies to years to study the impact of policies and regulations). This is not possible in state-of-the-art digital twins for energy scenario: by relying on a monolithic approach, they are forced to a single simulation paradigm and build custom solutions that cannot easily integrate available simulators for various concerns (e.g., socio-economic behaviors). As a consequence, they either require a considerable amount of engineering time to integrate complex behavior, which is a tedious and error-prone task, or they trade accuracy for simplicity (e.g., they do not include models of socio-economic behaviors). Being specifically tailored to the energy sector, COMET will support digital real-time simulators and will allow interacting with real physical devices (hardware-in-the-loop). This will enable accurate analysis where the scenario is partially simulated and partially represented by real hardware components.

The ***data sources layer*** will provide both an integrated catalogue of ready-to-use sources, which current co-simulation frameworks do not offer due to their general-purpose nature, as well as a simple interface to plug new sources and extend the platform. Also in this respect, COMET advances the state of the art by exploiting the domain knowledge encoded in the modules of the COMET integration layer, which defines the core concepts of an energy system in a format that computers can understand and reason about. Users can always rely on this common conceptual framework to describe new data sources so that the platform can readily exploit them in the definition of scenarios.

There are ongoing projects in the area that aim to create digital twins of MES scenarios, such as the H2020 ERI-Grid2.0 [24], and we will build on their experience. The novelties introduced by COMET (automated and assisted scenario creation, pluggable simulators, support for multiple spatio-temporal resolutions, reference conceptual architecture, integrated data sources) will lead to a usable platform that may support heterogeneous stakeholders in a way that is simply not possible with current proposals, and will advance the state-of-the-art with respect to ongoing research efforts.

V. Conclusions

This paper presented ongoing work in the design and development of the COMET Digital Twin platform for the analysis

TABLE I
COMET ADVANCEMENTS

Solutions		Domain-specific frameworks (energy digital twin)	Co-simulation frameworks (Helics/Mosaik)	COMET
User interface layer	***Designed for MES***	Yes	No	Yes
	Reference scenario architecture	Yes (Solution dependent)	No	Yes (GAMES)
	Scenario creator	No (manual)	No (programmatic)	Yes (model-based)
Co-simulation layer	***Co-simulation***	No	Yes	Yes
	Reusable simulators	No	Yes	Yes
	Software architecture	Solution specific (monolithic, typically centralised)	Distributed on premise/on cloud inefficient	Distributed on premise/on cloud efficient
Simulators layer	***Simulation paradigms (e.g., event-based, time-stepped)***	Single	Multiple	Multiple
	Simulation domains (e.g., thermal, socio-economic models)	Solution specific	Multiple	Multiple
	Hardware simulators	Solution specific	No	Yes
	Spatio-temporal scale	Solution specific	Multiple/dynamic	Multiple/dynamic
Data Sources Layer	***Integrated data sources***	Solution specific	None	GIS Models
	Pluggable data sources	No	Yes	Yes

of multi-energy systems (MES). The platform exploits co-simulation to capture the complexity and multi-faceted nature of MES, supporting simulations at different spatio-temporal scales, and using distributed computing resources (including ad-hoc hardware) to speed up simulations. It promises a simple user interface that assists players in the energy market in building involved MES scenarios as a composition of building blocks taken from an existing library or developed ad-hoc. The high-level goal of COMET is to make MES easy to model and understand, thus assisting decision-making in the energy sector and making the development and assessment of innovative solutions faster and more accessible.

REFERENCES

[1] G. J. Schaeffer, "Energy sector in transformation, trends and prospects," *Procedia Computer Science*, vol. 52, pp. 866–875, 2015.

[2] E. Guelpa, A. Bischi, V. Verda, M. Chertkov, and H. Lund, "Towards future infrastructures for sustainable multi-energy systems: A review," *Energy*, vol. 184, pp. 2–21, 2019.

[3] P. Mancarella, "Mes (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, 2014.

[4] E. Commission, "Powering a climate-neutral economy: An eu strategy for energy system integration," 2020.

[5] D. Validzic, "Clean energy for all europeans-european union's new legislative framework," 2017.

[6] D. S. Schiera, L. Barbierato, A. Lanzini, R. Borchiellini, E. Pons, E. F. Bompard, E. Patti, E. Macii, and L. Bottaccioli, "A distributed platform for multi-modelling co-simulations of smart building energy behaviour," in *In Proc. of EEEIC 2020*. IEEE, 2020, pp. 1–6.

[7] D. S. Schiera, L. Barbierato, A. Lanzini, R. Borchiellini, E. Pons, E. Bompard, E. Patti, E. Macii, and L. Bottaccioli, "A distributed multi-model platform to cosimulate multienergy systems in smart buildings," *IEEE Transactions on Industry Applications*, vol. 57, no. 5, pp. 4428–4440, 2021.

[8] L. Barbierato, D. S. Schiera, E. Patti, E. Macii, E. Pons, E. F. Bompard, A. Lanzini, R. Borchiellini, and L. Bottaccioli, "Games: a general-purpose architectural model for multi-energy system engineering applications," in *In Proc. of COMPSAC 2020*. IEEE, 2020, pp. 1405–1410.

[9] Y. Fathy, M. Jaber, and Z. Nadeem, "Digital twin-driven decision making and planning for energy consumption," *Journal of Sensor and Actuator Networks*, vol. 10, no. 2, p. 37, 2021.

[10] X. Zhang, J. Shen, P. K. Saini, M. Lovati, M. Han, P. Huang, and Z. Huang, "Digital twin for accelerating sustainability in positive energy district: A review of simulation tools and applications," *Frontiers in Sustainable Cities*, vol. 3, p. 35, 2021.

[11] E. O'Dwyer, I. Pan, R. Charlesworth, S. Butler, and N. Shah, "Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems," *Sustainable Cities and Society*, vol. 62, p. 102412, 2020.

[12] G. Ji, J.-g. Hao, J.-l. Gao, and C.-z. Lu, "Digital twin modeling method for individual combat quadrotor uav," in *In Proc. of DTPI 2021*. IEEE, 2021, pp. 1–4.

[13] X. Wang, H. Song, W. Zha, J. Li, and H. Dong, "Digital twin based validation platform for smart metro scenarios," in *In Proc. of DTPI 2021*. IEEE, 2021, pp. 386–389.

[14] F. Perabo, D. Park, M. K. Zadeh, Ø. Smogeli, and L. Jamt, "Digital twin modelling of ship power and propulsion systems: Application of the open simulation platform (osp)," in *In Proc. of ISIE 2020*. IEEE, 2020, pp. 1265–1270.

[15] S. Schütte, S. Scherfke, and M. Tröschel, "Mosaik: A framework for modular simulation of active components in smart grids," in *In Proc. of SGMS 2011*. IEEE, 2011, pp. 55–60.

[16] M. Büscher, K. Piech, S. Lehnhoff, S. Rohjans, C. Steinbrink, J. Velasquez, F. Andrén, and T. Strasser, "Towards smart grid system validation: Integrating the smartest and the sesa laboratories," in *In Proc. of ISIE 2015*. IEEE, 2015, pp. 1144–1150.

[17] C. Steinbrink, M. Blank-Babazadeh, A. El-Ama, S. Holly, B. Lüers, M. Nebel-Wenner, R. P. Ramírez Acosta, T. Raub, J. S. Schwarz, S. Stark *et al.*, "Cpes testing with mosaik: Co-simulation planning, execution and analysis," *Applied Sciences*, vol. 9, no. 5, p. 923, 2019.

[18] B. Palmintier, D. Krishnamurthy, P. Top, S. Smith, J. Daily, and J. Fuller, "Design of the helics high-performance transmission-distribution-communication-market co-simulation framework," in *In Proc. of MSCPE 2017)*. IEEE, 2017, pp. 1–6.

[19] J. Zhang, J. Daily, R. A. Mast, B. Palmintier, D. Krishnamurthy, T. Elgindy, A. Florita, and B.-M. Hodge, "Development of helics-based high-performance cyber-physical co-simulation framework for distributed energy resources applications," in *In Proc. of SmartGridComm 2020*. IEEE, 2020, pp. 1–5.

[20] A. K. Bharati and V. Ajjarapu, "Smtd co-simulation framework with helics for future-grid analysis and synthetic measurement-data generation," *IEEE Transactions on Industry Applications*, 2021.

[21] J. Fitzgerald, P. G. Larsen, and K. Pierce, "Multi-modelling and co-simulation in the engineering of cyber-physical systems: towards the digital twin," in *From software engineering to formal methods and tools, and back*. Springer, 2019, pp. 40–55.

[22] R. Haberfellner, O. De Weck, E. Fricke, and S. Vössner, *Systems engineering: fundamentals and applications*. Springer, 2019.

[23] J. Bruinenberg, L. Colton, E. Darmois, J. Dorn, J. Doyle, O. Elloumi, H. Englert, R. Forbes, J. Heiles, P. Hermans *et al.*, "CEN CENELEC ETSI Smart Grid Coordination Group on Smart Grid Reference Architecture," *CEN CENELEC ETSI Technical Report*, pp. 98–107, 2012.

[24] H2020 European Project ERIGrid 2.0: European research infrastructure supporting smart grid and smart energy systems research, technology development, validation and roll out. [Online]. Available: https://erigrid2.eu