Modelling and Co-simulation of Multi-Energy Systems: Distributed Software Methods and Platforms

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Modelling and Co-simulation of Multi-Energy Systems

Distributed Software Methods and Platforms

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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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 toward a low-carbon future. Unfortunately, the inherent complexity of MES makes them extremely difficult to analyze, understand, design, and optimize.

This dissertation addresses this problem by applying Information and Communication Technology (ICT) and proposing different distributed software methods and platforms for modelling and co-simulating MES. These solutions will enable the definition of a virtual representation of the real world as a composition of models by applying co-simulation techniques, permitting the analysis of a MES scenario from multiple viewpoints and at different spatio-temporal scales, providing a structured basis to design, develop and validate novel solutions and technologies for MES.

Firstly, this dissertation proposes GAMES, a General-purpose Architecture model for MES, which helps designers in describing a MES scenario by applying Model-Based System Engineering (MBSE) and Model Driven Architecture (MDA) strategies. GAMES builds a solid conceptual framework of the energy sectors and aspects involved in MES offering a guided and semi-automated definition of complex MES scenarios. Then, it proposes three variants of a co-simulation infrastructure to address the interconnection of heterogeneous General-purpose Programming Language (GPL), software, and hardware simulators. Depending on the interconnected simulators, a MES designer could choose among: *i)* the Pure Software Co-simulation

Infrastructure when the MES scenario presents models developed in GPL and software simulators with slow temporal evolution, i.e. their time step duration is equal or greater than one second; *ii)* the Digital Real-Time Co-simulation Infrastructure when the MES scenario presents models developed with hardware simulators with fast temporal evolution, i.e. their time step duration is around tens of microseconds with strict real-time requirements for Hardware-In-the-Loop (HIL) and Power Hardware-In-the-Loop (PHIL) testing; and, finally, *iii)* the Hybrid Co-simulation Infrastructure that joins together the previous infrastructures to simulate complex MES scenarios with both slow and fast temporal evolution of involved simulators. To conclude, the Distributed Event-Driven Infrastructure is proposed with the purpose of scaling a simulated MES application and/or service from a testing environment to a real-world scenario.

The proposed solutions will ultimately promote and accelerate the energy transition by making the simulation of complex MES scenarios easier, more accurate, and more efficient. Ease of use of such a solution comes from tools that automate and validate the definition of involved energy scenarios. Accuracy instead comes from the inclusion of heterogeneous simulators that capture the multifaceted nature of the scenario under analysis. Finally, efficiency comes from distributed simulations and support for dedicated hardware.

This promises a broad impact for both academic researchers and practitioners working in the energy sector. Indeed, the solutions proposed in this dissertation offer a common playground where both researchers and companies can share knowledge and assess their solutions. Different actors may benefit from the outcome of this dissertation: *i)* distribution system operators, who manage the distribution grids; *ii)* energy aggregators, who manage the resources and loads of both consumers and prosumers to generate savings and offer ancillary services to the grid; *iii)* public administrators and decision-makers, who are in charge of drawing policies to plan the energy transition; *iv)* energy managers, who manage energy flows in a building/small district; *v)* energy communities, which are a new emerging actor of the energy sector consisting of single citizens, companies, and public administration, and aim to adopt renewable energy sources and storage systems to produce and consume energy locally and share it in a peer-to-peer market.