Energy Communities Digital Twin Platform

Thesis project

MSc Sustainable Energy Technology

Dominique Balassi

Delft University of Technology

TUDelft

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by

Dominique Balassi

Student Name	Student Number
Dominique Balassi	5617308

Thesis Committee:	Prof.dr. Peter Palensky
	Dr. Ir. Milos Cvetkovic
	Dr. Ir. Laura Ramirez Elizondo
MSc:	Sustainable Energy Technology
Institution:	Delft University of Technology

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Acknowledgements

This thesis marks the conclusion of the two most significant years of my personal and professional growth. TU Delft as a ship sailed me across the oceans of knowledge, allowing my curiosity to dive into the deepest seas of science. It took me to the edge of human understanding, providing me with the means to expand this frontier into the unknown. This experience has restored my confidence, showing me that hard work pays off and that there should be no limit to the magnitude of your dreams. Above all, it has enriched me with admirable and extraordinary people, who have freely offered their example, trust, support and loving care. I thank each of them for preserving that childlike openness and wonder towards others, so essential for living in peace and happiness together. I thank my family for bearing the burden of distance; with their love and sacrifice, they have given me the opportunity to shine to my full potential. I am immensely grateful for this good luck of mine and intend to pay back by maximising my positive impact on this world.

Dominique Balassi
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Abstract

This thesis focuses on advancing the digitization of socio-technical energy systems by facilitating the creation of Digital Twins of Energy Communities (ECs). A multi-layered architectural model was proposed to capture the different domains and interconnections within multi-energy and multi-agent ECs. Leveraging this framework, a flexible and modular co-simulation platform was realised as a tool that can be employed for enhancing research, decision-making, and policy analysis. Three study cases showcased the platform's capability to represent different ownership topologies, energy trading mechanisms and agents and control strategies. The study cases demonstrated that the holistic design and customisability of the platform allow for representing nuances and capturing cross-layer effects, thus unlocking a deeper understanding of ECs' dynamics and their members' outcomes.

Nomenclature

Abbreviations

Abbreviation	Definition
(L)EM	Local Electricity Market
DoF	Degrees of Freedom
DT	Digital Twin
EC	Energy Community
ECDT	Energy Communities Digital Twin
EMS	Energy Management System
EV	Electric Vehicle
GUI	Graphical User Interface
IoE	Internet of Energy
IoT	Internet of Things
MAS	Multi-Agent Systems
MECA	Multi-Layered Energy Community Architecture
MIMO	Multi-Input Multi-Output
P2P	Peer-to-Peer
RT	Realt-Time
SGAM	Smart Grid Architecture Model
SoC	State of Charge

Contents

1 Introduction

The transition towards the wide adoption of Distributed Energy Resources (DERs) necessitates a profound and comprehensive transformation of energy systems worldwide. This shift towards a sustainable energy paradigm requires the integration of renewable generation, flexible consumption and storage capacity, as well as the widespread adoption of advanced digital technologies across interconnected multi-energy infrastructures. With this challenge ahead, the power sector is poised for a monumental evolution, driven by the imperative to enhance sustainability, resilience, and efficiency.

To effectively address the challenges posed by the clean energy transition, a collaborative international effort is required to scale up investments in Smart Grids, particularly in emerging and developing economies (IEA, 2023b). These regions are experiencing rapid growth in electricity consumption, making it crucial to provide greater access to reliable and affordable energy, while accommodating the increasing deployment of renewable energy sources. Smarter grids, underpinned by advanced digital technologies, offer indispensable solutions to leverage data, optimize grid management, and enhance transparency and energy security (Yan et al., 2012).

The ongoing digitalization of energy systems has given rise to the innovative field of the Internet of Energy (IoE), which is ”highly likely to become ubiquitous as early as 2030” (Strielkowski et al., 2019). The IoE’s ability to collect and analyze data at a granular level, by leveraging real-time data from smart meters, sensors, and IoE devices, enhance community-level Energy Management Systems (EMS) to intelligently balance energy supply and demand. Furthermore, the IoE has created opportunities for a more equitable transition, by enabling the implementation of innovative solutions to address energy poverty, decreasing information asymmetry and ensuring energy access for all.

The creation of new digital platforms for multilateral data exchange has contributed to the spreading formation and integration of Energy Communities (ECs). These innovative socio-technical systems are legal entities composed of multiple shareholders, providing environmental, economic and social community benefits. By suggesting an inclusive paradigm, EC represents a revolution in the history of energy management (Gruber et al., 2021). Thanks to appropriate policy frameworks, such as the Clean Energy for All Europeans Package (Commission, 2019), ECs represent an opportunity to facilitate a just transition by increasing access to affordable and clean energy, promoting energy sovereignty, and empowering communities to play a more active role in defining and shaping their energy systems.

In this context, it is essential to recognize that ECs can be multi-energy entities, which is a crucial characteristic in the ongoing energy transition. Indeed, ECs encompass a diverse array of energy carriers, including electricity, hydrogen or heat. This multi-energy nature empowers ECs to intelligently manage energy generation, consumption, and storage across various vectors, fostering a more integrated, efficient and balanced energy landscape. ECs stand as exemplars of the dynamic convergence of different energy forms, underlining their significance in achieving a resilient and sustainable energy future.

The increasing size, diffusion and complexity of ECs have brought forward the importance of incorporating advanced technologies like Digital Twins (DTs). A DT is a virtual replica that simulates and mirrors the behaviour of real-world systems, whether they are tangible physical assets or intangible business processes (Palensky et al., 2022). DTs are a powerful tool for researchers and policymakers for modelling, analysing and forecasting ECs operations. By replicating in a unique virtual environment the dynamics determining the operation of ECs, it is possible to optimize their performance and enhance sustainability (Nguyen-Huu et al., 2022).

Despite the multiple advantages of the DTs, there still is not yet an open-source DT platform that holistically captures the complexity of various, multi-energy and multi-layered ECs. With such a platform in hand, it would be possible to foster research, decision-making and policy analysis in the field of ECs. Therefore, the following thesis poses its foundations on the following research question:

"With the aim of enhancing research, decision-making, and policy analysis, how can a holistic, modular, and flexible platform be designed to enable the creation and utilization of Energy Communities' Digital Twins?"

1.1. Research gap

The lack of a comprehensive DT platform that effectively encompasses the complex dynamics of diverse ECs, can be attributed to the following reasons:

- *Limited modelling approaches:* Current modelling approaches and simulation tools in the field of energy systems have primarily focused on either electricity networks or local energy systems, neglecting the intricate interplay between the utility grid, ECs and their members. Existing energy DTs have not adequately addressed this complex interaction (Nguyen-Huu et al., 2022).
- *Lack of generic solutions:* Although efforts have been made to address the research gap through the development of tools like NEPLAN (Bica et al., 2008), DEMKit (Hoogsteen et al., 2019), and multi-vector SEMS (O'Dwyer et al., 2020), these tools are often designed for specific cases and lack a generic approach that can be replicated in larger system areas with diverse services and market structures (Nguyen-Huu et al., 2022). This limitation underscores the need for a comprehensive DT platform that can cater to the heterogeneity of various ECs.
- *Complex stakeholder behaviours*: The integration of Multi-Agent Systems (MASs) in energy modelling has highlighted the importance of capturing stakeholders' behaviours in energy systems. MASs have facilitated research in energy-related behavioural studies, particularly through innovative participatory approaches like Companion Modeling (Étienne, 2013). However, there is a lack of research efforts that combine the advantages of MASs with those of physical DTs in the context of ECs.

1.2. Research objective

To overcome the existing research gap, **this thesis aims to realise a holistic, multi-energy, flexible and modular Energy Communities Digitial Twin (ECDT) platform that supports the comprehensive modelling, real-time simulation, and in-depth result analysis of the complex multi-layered structure of ECs**.

The primary goal is to develop an architecture that captures the interactions between all the possible elements of ECs, considering their specific behaviours and the intricate dynamics and dependencies within these socio-technical systems. This platform should enable the modelling and simulation of various scenarios, allowing for scalability and adaptability to different EC configurations. Such a platform should incorporate advanced modelling capabilities to accurately represent the physical and operational characteristics of the ECs elements, including the integration of various energy vectors and the consideration of physical and temporal constraints.

Another objective is the integration of MAS within the ECDT platform to enable a trustworthy representation of stakeholders, considering their interactions and decision-making processes. This includes capturing the interactions between energy suppliers, consumers, or prosumers while considering their strategies, preferences, and specific constraints. The MAS component should facilitate the analysis of different scenarios, the exploration of potential trade-offs, and the identification of optimal solutions for enhancing the inclusivity and social acceptance of ECs.

Additionally, the platform should support real-time simulation, allowing for the monitoring and control of real-world EC operations. This would enable the assessment in real time of the system performance, the identification of potential bottlenecks or vulnerabilities, and the evaluation of different strategies for load management, energy trading, and grid integration. Moreover, the platform shall provide in-depth result visualization, resulting in an effective decision-support tool to facilitate informed decision-making and policy development.

Finally, the performance and effectiveness of the platform in achieving the design objectives should be validated through rigorous testing on different study cases. This validation process would provide a coherent and robust demonstration of the capabilities and potential of the software.
By realizing such a holistic DT platform for ECs, researchers and policymakers will have a powerful tool at their disposal to better investigate the complexities of multi-energy systems, optimize their operations, and design effective policies and strategies for a sustainable and just energy transition.

1.2.1. Design criteria

To pursue the research objective, the ECDT platform should be designed according to the following design criteria:

- **Easy-to-use configuration**: The platform shall feature a user-friendly interface, ensuring accessibility and ease of configuration of cases for users.
- **Modularity and scalability**: The platform shall be designed with a modular architecture, allowing for flexible customization and expansion to accommodate varying system sizes and complexities.
- **Comprehensive set of assets**: The platform shall incorporate a wide range of multi-energy models representing various physical components of ECs.
- **Data series inputs**: The platform shall support the integration of time-series data inputs, enabling realistic modelling and simulation based on real-time data.
- **Multi-agent case definition**: The platform shall enable the definition of multiple agents representing different stakeholders within ECs, capturing their diverse behaviours and interactions.
- **Different ownership topologies**: The platform shall consider various ownership structures within ECs, allowing for the representation of different energy asset portfolios for each agent.
- **Utility metrics**: The platform shall provide relevant utility metrics to evaluate the performance and efficiency of agents, facilitating informed decision-making.
- **Agent strategies setup**: The platform shall allow for the configuration of different agent strategies and preferences.
- **Game configuration**: The platform shall support the configuration of game elements, enabling the study of strategic interactions and outcomes.
- **Controllable agent's visibility**: The platform shall provide options to control the visibility and information sharing among agents, reflecting their privacy and beliefs.
- **Forecasting capabilities**: The platform shall incorporate forecasting capabilities, allowing for the prediction of future energy availability, thus facilitating agents' strategic behaviours
- **Loop and comparison**: The platform shall facilitate iterative analysis and comparison of multiple scenarios, aiding in decision-making and optimization processes.
- **Result analysis:** The platform shall offer comprehensive result analysis tools, allowing for in-depth examination and interpretation of simulation outcomes.

1.3. Previous work

In the field of combining DTs and MASs, two notable works have demonstrated the significance of this approach and inspired its application to the field of ECs.

The first work, ”On the Integration of Agents and DTs in Healthcare” (Croatti et al., 2020), explores the integration of DTs with agents and MAS technologies in the healthcare domain. This paper highlights the disruptive impact of DTs in healthcare and presents a case study on the application of agent-based DTs for managing severe traumas. By showcasing the successful integration of agents and DTs, this work emphasizes the effectiveness of combining these technologies to enhance decision-making and improve outcomes in complex systems.

The second work, ”Multi-Agent Systems and DTs for Smarter Cities” (Clemen et al., 2021), focuses on the integration of IoT sensors, simulation modelling, and multi-agent systems to create DTs for smarter cities. The authors present an experimental setup where a simulation model of a city's traffic system is connected to real-time sensor data through a multi-agent framework. This integration enables real-time data-driven simulations and provides valuable insights for city planners and decision-makers. The work highlights the potential of combining MASs and DTs to improve understanding, optimize resource allocation, and make informed decisions in complex adaptive systems like big cities.

These two works effectively demonstrate the importance and benefits of combining DTs and MASs in different domains, and their successful applications inspire the adoption of a similar approach in the creation of the ECDT platform.

The most significant starting point for this thesis project is the work done, within the Intelligent Electrical Power Grids (IEPG) research group of TU Delft, for the development of The Illuminator (Saini, 2022). This toolkit facilitates communication among domain experts, educates students and communities, and addresses the challenges encountered during the energy transition. The kit demonstrates the workings of renewable energy technologies and their system-level integration while highlighting the complexities involved in transitioning to an energy system dominated by renewables.

For domain experts, The Illuminator toolkit plays a crucial role in fostering awareness and understanding of challenges faced in other domains, as interdependencies often exist. Through simulations and models, Illuminator can effectively demonstrate these challenges and support knowledge sharing among experts. Furthermore, as the toolkit is user-configurable, it allows for showcasing discoveries and advancements that can aid in the energy transition.

On the social side, The Illuminator toolkit serves as an educational resource for communities and students, providing insights into renewable energy and the intricate challenges associated with transitioning to a renewable-dominated energy system. By employing visual storytelling techniques, Illuminator enhances the communication process, making it easier for various stakeholders, including policymakers, government officials, energy companies, and consumers, to comprehend and engage with the challenges of the energy transition.

The Illuminator is relevant for the development of the ECDT platform based on its customizable, modular, and scalable structure, as well as the extremely flexible and powerful virtual environment it provides. However, the architecture of the ECDT platform should represent a substantial expansion of The Illuminator, incorporating multiple layers and models of the energy assets portfolio, while capturing many different domains.

1.4. Relevance of the Research

The proposed research on developing a holistic, multi-energy, and modular DT platform for ECs holds significant relevance in the context of the clean energy transition and the transformation of energy systems. Here are some key points highlighting the importance of this research:

Addressing the research gap: The research aims to address the existing research gap by developing a comprehensive DT platform that effectively captures the complexity of multi-layered ECs. By integrating various energy vectors, considering stakeholder behaviours through Multi-Agent Systems (MASs), and incorporating advanced modelling capabilities, the platform can facilitate a more accurate representation of the interactions and dynamics within ECs.

Boosting sustainable and just energy transition: The research objective aligns with the global objective of transitioning to a sustainable energy paradigm. By supporting the modelling, simulation, and analysis of ECs, the DT platform can contribute to enhancing the sustainability, resilience, and efficiency of different energy ecosystems. It can enable the exploration of optimal solutions for integrating renewable generation, flexible consumption, and storage management while promoting energy access, affordability, and equity.

Informing policy development for policymakers: The research outcomes can provide valuable insights and decision-support tools for policymakers. The DT platform's ability to simulate and evaluate different scenarios, assess system performance, and identify alternatives shall assist policymakers in developing effective policies and strategies for ECs. This includes the design and implementation of supportive regulatory frameworks, incentives, and market mechanisms that foster the integration of renewable energy sources, enable peer-to-peer energy trading, and enhance energy access and affordability for all. The platform can also aid in identifying barriers and addressing challenges related to grid integration, energy storage, demand response, and infrastructure planning.

Facilitating research across various disciplines for researchers: The DT platform opens up opportunities for researchers to conduct interdisciplinary studies within the field of ECs. The integration of MAS with DTs enables the exploration of various research subjects, including:

- *Game theory and strategic interactions*: The platform can allow researchers to study the strategic interactions and outcomes among different stakeholders within ECs. Game theory models can be developed to analyze the behaviour of agents, their decision-making processes, and the resulting equilibrium. This can provide valuable insights into incentive mechanisms, cooperation frameworks, and market design for efficient and equitable energy exchange.
- *Behavioral studies and social acceptance*: The platform can facilitate the incorporation of behavioural models into the decision-making process of agents. Researchers can explore different behavioural theories, such as bounded rationality, social norms, and pro-environmental attitudes, to understand the factors influencing stakeholders' choices and cooperation patterns. This can contribute to the development of strategies to enhance the social acceptance and inclusivity of ECs.
- *Artificial Intelligence (AI) and optimization*: AI techniques can be applied within the DT platform to optimize energy management strategies, load scheduling, and resource allocation in ECs. Researchers can develop AI algorithms to optimize the operation of ECs, considering factors such as energy demand patterns, renewable energy generation variability, and storage capacities.
- *Policy analysis and impact assessment*: The platform can enable researchers to evaluate the effectiveness of different policy measures and regulatory frameworks in promoting sustainable and just energy transitions. They can analyze the impact of policy interventions on energy access, affordability, environmental sustainability, and social equity within ECs.
- *Integration of advanced forecasting and data analytics*: The platform can incorporate advanced forecasting techniques and data analytics to enhance the accuracy of energy generation and consumption predictions. Researchers can explore the use of machine learning algorithms, statistical models, and data visualization tools to improve the forecasting of renewable energy generation, demand response potential, and energy market trends.

Improving energy system planning and operation: The DT platform's real-time simulation capabilities shall enable the monitoring and control of EC operations, allowing for the identification of potential bottlenecks or vulnerabilities. This aid in optimizing energy system planning, load management, energy trading, and grid integration strategies. The platform supporting forecasting capabilities, can facilitate proactive decision-making based on future energy availability.

Enhancing stakeholder engagement and empowerment: By integrating MASs into the DT platform, stakeholders' behaviours, preferences, and constraints can be captured and understood, facilitating a more inclusive and participatory energy transition. The platform enabling the representation of various agents can foster transparent and collaborative decision-making processes, thus empowering communities to actively participate in defining and shaping their energy systems.

Promoting usage: The design criteria of the DT platform emphasize ease of use, modularity, scalability, and customization. This shall enable the platform to accommodate different EC configurations, system sizes, and complexities. The platform's flexibility support its application in diverse contexts and settings, making it a valuable tool for various researchers, policymakers, and energy stakeholders globally.

1.5. Outline

This thesis report is structured as follows:

First, Chapter 2 will provide an explanation of the methodology adopted to address the research question. Section 2.1 will explore SGAM as a foundation for understanding smart grid systems and the creation of the MECA to cater to ECs' unique requirements. Subsequently, section 2.2 will illustrate the adopted virtual environment, focusing on the advantages of the co-simulation tool Mosaik implementation and explaining the role of The Illuminator toolkit as groundwork for the ECDT platform.

Then, Chapter 3 will detail the ECDT platform's software architecture, with a focus on exploring how the MECA's five layers are integrated into the ECDT platform (section 3.1), and its essential components (section 3.2). Subsequently, it will explain the functioning of the five interconnected layers: Environment, Energy Assets, Controls, Agents, and Games (sections 3.3-3.7),. Finally, the chapter will explain the steps of the configuration phase (section 3.8), and it will provide a detailed explanation of the Main file (section 3.9).

Subsequently, Chapter 4 will showcase the ECDT platform's versatility in the possible applications thanks to the various degrees of freedom (section 4.1). Three case studies will demonstrate its capabilities in exploring ownership topologies (section 4.2), trading mechanisms and agents' strategies (section 4.3), and control strategies (section 4.4).

Finally, the conclusion Chapter 5 will summarise the thesis's objectives, central research question, and key findings.

2
Methodology

This chapter explores the conceptual framework used to address the research question of how to create a holistic ECDT platform. Section 2.1 delves into the significance of the Smart Grid Architecture Model (SGAM) in representing smart grid systems, to provide a clear understanding of how the structural decomposition of energy systems can be performed. Additionally, the section provides an overview of how this research project, inspired by the SGAM approach, led to the development of a unique architecture tailored for ECs, the Multi-layered Energy Community Architecture (MECA).
Subsequently, section 2.2 aims to illustrate the virtual environment used for building the ECDT platform upon The Illuminator toolkit and employing the co-simulation tool Mosaik.

2.1. Conceptual Framework

To ensure a comprehensive representation of the complex structure of ECs, it is necessary to capture the different domains and the specific dynamics that determine their functioning.

In this regard, the European Commission's M/490 standardisation mandate (CEN-CENELEC-ETSI, 2012) played a pivotal role in establishing a comprehensive conceptual framework for the structural decomposition of energy socio-technical systems, thus resulting in the most effective guideline in the design of the ECDT platform. The collaborative efforts of CEN, CENELEC, and ETSI resulted in the development of the SGAM, which has gained significant recognition and traction within the research community (Dänekas et al., 2014).

The SGAM, as a pivotal framework in understanding the complex interconnections between elements of energy systems, assisted in structuring the MECA, a unique architectural framework which can overcome the challenge of designing a platform for the development of DTs of ECs.

2.1.1. Smart Grid Architecture Model (SGAM)

The SGAM, shown in fig 2.1, is a comprehensive framework used for designing and understanding the architecture of smart grid systems. It takes into account established energy domain models from organizations like the National Institute of Standards and Technology (NIST) and the International Electrotechnical Commission (IEC), as well as domain-independent architecture frameworks such as The Open Group Architecture Framework (TOGAF), while interoperability dimensions are addressed through the adoption of the GridWise Interoperability Context Setting Framework. (Dänekas et al., 2014)
The SGAM consists of different concepts that provide a structured approach to expressing architecture models, which shall be briefly introduced in the following.

Domains: The Domains represent the different stages of the energy conversion chain within the smart grid. They encompass generation (both conventional and renewable sources), transmission, distribution, DERs, and customer premises (end users and producers of electricity). (Dänekas et al., 2014)

Zones: The Zones reflect the hierarchy of power system management within the SGAM. They include:

- the process zone, which focuses on the physical and chemical transformations of energy:

- the field zone, which comprises equipment for protecting, controlling, and monitoring the power system;
- the station zone, which represents the aggregation level for the field zone;
- the operation zone, which deals with power system control operations;
- the enterprise zone, which covers commercial and organizational processes, services, and infrastructures;
- the market zone, which involves operations related to the market dynamics along the energy conversion chain. (Dänekas et al., 2014)

Interoperability Layers: The SGAM defines Interoperability Layers to express different entities and viewpoints within the architecture. These layers range from business objectives to physical components, ensuring traceability and interoperability between various concepts. The layers are:

- Business Layer: This layer focuses on the strategic and business aspects of the smart grid, considering market operations, regulations, and revenue models. It addresses the economic and financial aspects of the system.
- Function Layer: The function layer categorizes the operational functions of the smart grid, such as generation, transmission, distribution, metering, and demand response. It provides an overview of the different functions required for effective operation.
- Information Layer: The information layer deals with data collection, storage, processing, and sharing mechanisms within the smart grid. It addresses communication protocols, data formats, and information exchange requirements.
- Communication Layer: This layer focuses on the communication infrastructure and protocols for data transmission and control within the smart grid. It ensures reliable and secure communication between components.
- Component Layer: The component layer represents the physical devices and equipment that make up the smart grid, including power generation sources, substations, transformers, and meters. It includes both hardware and software components.
- Asset Layer: The asset layer addresses the management and optimization of physical assets within the smart grid. It includes asset monitoring, maintenance, and lifecycle management strategies. (Dänekas et al., 2014)

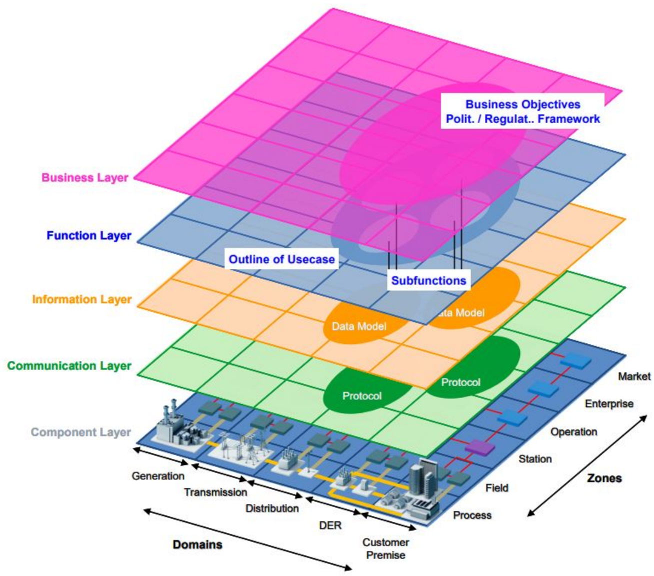


Figure 2.1: SGAM conceptual framework (CEN-CENELEC-ETSI, 2012)

2.1.2. Multi-layered Energy Community Architecture (MECA)

For this thesis project, the SGAM inspired the creation of an architecture model in the context of ECs with the aim to identify their essential domains, elements, functions, and interconnections. This process resulted in the realization of the MECA, the proposed conceptual framework for realizing the DTs of ECs. Leveraging the SGAM and following a bottom-up approach, from microscopic physical elements to macroscopic abstract dynamics, five different layers were structured. These layers are:

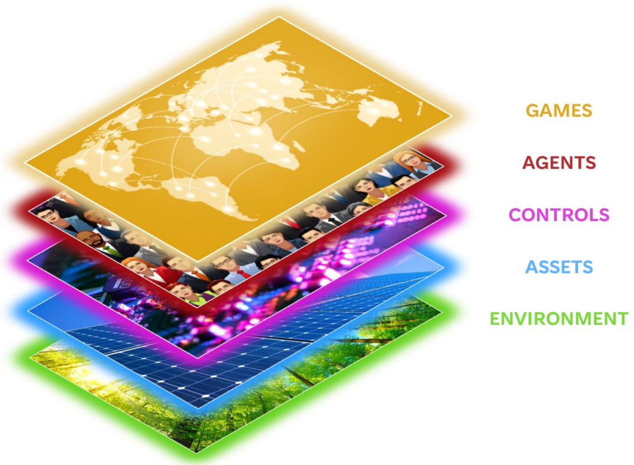


Figure 2.2: ECs multi-layered architecture

1. **Environment Layer**:

   To incorporate the functions of the Information Layer of the SGAM, the Environment Layer was introduced. This first layer allows for capturing the diverse and dynamic interactions between ECs and the external world. This layer represents the wide range of environmental inputs and outputs that are integral to the functioning of ECs. These inputs can encompass various physical resources, such as renewable energy sources like solar and wind, as well as natural conditions like temperature, humidity, and pressure.

   Moreover, the inputs and outputs of ECs extend beyond physical resources and include informational messages that are exchanged with external entities. This can include data related to electricity market prices, grid conditions, communication signals, and other relevant information. These inputs and outputs are crucial for the proper functioning and optimization of ECs, as they influence decision-making processes and system behaviour.

   One key aspect to consider within the Environment Layer is the contextual dependence of these inputs and outputs. The specific location of each EC can significantly impact the environmental factors it interacts with. For instance, the availability of solar energy will vary based on geographical location, climate conditions, and time of day. Similarly, the wind patterns and intensity will vary depending on the local topography and weather patterns.

   Furthermore, within a single EC, there may be variations in environmental inputs and outputs among its individual components. Consider an EC equipped with multiple PV systems. Due to factors such as shading from nearby structures or vegetation, the solar irradiance and energy generation may differ for each system. The ECDT platform shall be capable of accurately representing these variations and capturing the complex interplay of environmental dynamics within the DT.

   By effectively modelling and simulating the Environment Layer, the ECDT platform can provide insights into the behaviour, performance, and optimization of ECs in response to different environmental conditions.

2. **Energy Assets Layer**:
   To capture the SGAM's Component Layer, with a focus on the domains of Customer Premises and DER, the Energy Assets Layer was implemented. This represents a fundamental layer that encompasses various energy assets responsible for transforming energy into different forms, such as electricity, heat, and hydrogen. These energy assets deeply determine the overall dynamics of ECs by capturing energy from the environment and converting it for various purposes.

   Within this layer, a diverse range of devices and technologies are included. These devices have the capability to extract energy from the environment and convert it into usable forms or facilitate internal energy conversions. Examples of energy assets commonly found within this layer include loads, photovoltaic systems (PVs), wind turbines, electrolyzers, heat pumps, boilers, and energy storage systems. Each of these assets contributes to the overall energy consumption, generation, distribution, and management within ECs.

   In the ECDT platform, each energy asset within the Energy Assets layer shall be modelled to accurately represent its characteristics, functionalities, and interactions with other components of the EC. The modelling process may involve capturing parameters such as energy generation capacity, efficiency, operational constraints, and response to external factors. The level of complexity in modelling these assets may vary depending on their specific parameters and technologies involved.

   By incorporating the energy assets layer into the ECDT platform, it becomes possible to simulate and evaluate assets portfolios, assess energy generation and consumption patterns, optimize energy flows, and make informed decisions regarding energy management strategies.

3. **Controls Layer**:
   To incorporate in the MECA the Function Layer of the SGAM, the Controls Layer was created. This layer, within the EC architecture, encompasses various control systems and their specific control strategies that are responsible for effectively managing and optimizing the operation of energy assets. This layer allows for controlling power flows, regulating energy transformations, and ensuring efficient energy management within ECs.

   The components within the Controls Layer can include EMSs, controllable inverters, and other embedded control devices. These components are equipped with specific control strategies and techniques tailored to the energy assets they oversee.

   One of the key responsibilities of the Controls Layer is to route power flows and manage energy transformations. For example, a control system may be implemented to regulate the operation of an electrolyzer and a fuel cell. This control strategy allows excess electrical energy to be transformed into hydrogen, which can then be stored for future use. When needed, the stored hydrogen can be converted back into electricity. This dynamic control of energy transformation enables effective utilization and management of available resources within the EC.

   Additionally, the Controls Layer incorporates all the automated monitoring platforms, representing the interface between users and their assets. These platforms collect real-time information on the status and performance of the energy asset portfolios. Consequently, they provide structured data to users, enabling them to monitor, analyze and take decisions in a structured and informed manner.

   An accurate ECDT platform shall be capable of representing the Controls Layer as it acts as the crucial link between the physical domain of energy assets and the energy management domain. It allows for the simulation and evaluation of different control strategies, enabling stakeholders to optimize energy management, enhance system reliability, and achieve sustainable energy outcomes.

Given the ongoing evolution in the complexity of control strategies, the Controls Layer embraces advanced algorithms such as Artificial Intelligence, Machine Learning, Neural Networks and Model Predictive Control (MPC) (Holkar & Waghmare, 2010). These advanced techniques offer the potential to enhance the efficiency, responsiveness, and adaptability of control systems within the EC. The ECDT platform should provide the capability to test and assess the performance of these advanced control algorithms to ensure the continuous improvement of EC operations.

4. **Agents Layer**:
The Agents Layer within the MECA represents the individual members or entities participating in the community. These agents, representing the community shareholders, interact with the control systems and play a critical role in shaping the dynamics of the EC. Each agent can be modelled with unique beliefs, desires, and intentions, commonly referred to as BDI. (Kinny et al., 1996)

Beliefs refer to an agent's perception and understanding of the world, including its knowledge about the EC, energy assets, market conditions, and system behaviours. Desires represent the goals or preferences of an agent, reflecting what they aim to achieve or prioritize within the EC. Intentions are the specific actions or plans that an agent develops to satisfy its desires within the given context. (Kinny et al., 1996)

The members of the EC can have diverse and specific needs, which influence the way their energy assets are controlled. For example, consider an EC member who owns an electric vehicle (EV) and requires it to be charged for the day ahead. This subjective need of having a fully charged EV can significantly impact the operation of the control system. The control system needs to take into account this individual need while managing the overall energy flow and ensuring the optimal use of available resources.

In addition to specific needs, agents within the EC can have utility functions that guide their decision-making process. Utility functions represent the preferences of agents in terms of the outcomes they seek to maximize or minimize. Examples of utility functions can include cost minimization, revenue maximization, or emission abatement. Each agent takes actions and makes decisions to optimize their utility function, which can have implications for energy management and trading within the EC.

The representation of different types of agents within the Agents Layer is essential for understanding how they interact with each other and influence the overall functioning of the EC. The way agents manage and trade their energy resources is highly dependent on their forecasting capabilities. Agents with better forecasting abilities can anticipate potential excess electricity, for instance, and make informed decisions on whether to store it or trade it with other members. The effectiveness of these decisions relies on the agents' knowledge of future energy availability and market dynamics.

For the ECDT platform, the Agents Layer is essential to include Multi-Agent Systems (MAS) and conduct behavioural studies. MAS enables the platform to simulate and analyze the interactions, decision-making processes, and behaviours of the agents within the EC. By modelling agents in a realistic manner, using approaches like Companion Modeling (Étienne, 2013), the platform can capture the complexities and nuances of their behaviours and their impact on the overall EC dynamics.

The Agents layer is crucial for comprehending the real functioning of ECs as interconnected systems. By representing the diverse agents and their interactions, the ECDT platform can provide insights into the social, economic, and behavioural aspects that shape the EC's overall performance, and that are usually neglected in classical energy DTs. This understanding is vital for designing effective policies, optimising energy management strategies, building consensus and fostering cooperation among ECs members.

5. **Games Layer**:
   To capture the Business Layer of the SGAM, the Games Layer was introduced in the MECA. The Games Layer represents the diverse ways in which agents interact and engage with each other. Given the varied nature of these interactions, it is crucial to capture the different forms of engagement within a dedicated layer.

   One significant aspect of the EC's dynamics is the conduct of energy transactions, where agents exchange energy resources, services, or financial assets. These transactions involve the trading of electricity, heat, or hydrogen, as well as the negotiation of energy contracts or participation in market frameworks. Through these exchanges, agents collaborate, compete, and allocate resources within the EC.

   To facilitate these interactions, agents within the EC communicate using specific game structures. These game structures establish the rules, strategies, and outcomes of the engagements. Examples of such structures include market mechanisms, auctions, contracts, and other negotiation frameworks. Each game structure operates under distinct rules and protocols, determining how agents interact and make decisions.

   The types of engagements within the EC can be classified into various categories based on the number of participants involved. These categories encompass one-to-one interactions, where two agents directly engage with each other, one-to-many interactions, where a single agent interacts with multiple counterparts, and many-to-many interactions, where multiple agents simultaneously interact with each other. Understanding and modelling these diverse forms of engagement are essential for capturing the intricate dynamics and emergent behaviours within the EC.

   Incorporating the Games layer into the ECDT platform is vital as it embraces the field of Game Theory. Game Theory provides a theoretical framework for analyzing strategic interactions among agents, examining outcomes and equilibrium points. By integrating the Games layer, the platform can facilitate the exploration and identification of novel game structures that enhance sustainability, fairness, and efficiency within the EC.

   By simulating these games within a comprehensive environment, the ECDT platform can enable a deeper understanding of how micro-level changes impact macroscopic dynamics. For example, the seasonal variation in sun irradiation can influence the prices in the electricity market. By simulating and analyzing these connections, the platform can allow for the exploration of diverse scenarios and the evaluation of different strategies, policies, and market mechanisms to optimize the functioning of the EC and achieve desired sustainability goals.

2.2. Virtual enivronment

This section aims to illustrate the virtual environment choosed for the development of the software of the proposed ECDT platform. To pursue this objective this section first provides an overview of the Mosaik co-simulation tool (Steinbrink et al., 2019), so as to understand its role as an essential element for compliance with the design criteria of simplicity, modularity and scalability. Subsequently, an examination of The Illuminator toolkit's role as the cornerstone of the ECDT platform is undertaken. This exploration aims to provide insight into the initial software architecture upon which the ECDT platform is constructed.

2.2.1. Mosaik

Mosaik is a co-simulation framework that facilitates interaction between different simulation tools to create consolidated Smart Grid scenarios (Schloegl et al., 2015).

While in its initial versions, it used to operate on a discrete-event simulation basis, executing simulators in an event-based manner, the latest release Mosaik 3 also supports time-based and hybrid simulators (Ofenloch et al., 2022).

One of its key advantages is the ability to manage and integrate specialized and multidisciplinary simulation platforms, enabling the creation of customized scenarios based on user requirements.

Mosaik enables simulators to exchange data based on their required attributes. For example, a grid simulator and a household simulator can share the attribute ”power” and connect with each other, allowing the household simulator to provide power consumption information to the grid simulator. (Schloegl et al., 2015)

The Mosaik framework consists of four fundamental components. The *Mosaik SimAPI* serves as the communication protocol between simulators and Mosaik, providing low and high-level interfaces. The low-level API requires users to set up socket connections and JSON serialization, while the high-level API already includes network components within Mosaik, simplifying simulator implementation.

The *scenario API* in Mosaik allows users to create simulation scenarios by defining an environment that encompasses information about the integrated simulators. This environment called a World, specifies the time frame of the simulators. Simulators are started using the World.start() function, and entities are instantiated from models, which are then connected to each other based on defined topology rules. Finally, the defined scenario can be executed, resulting in the simulation process.

The *Simulator Manager* in Mosaik facilitates communication and initiation of simulator processes. It supports importing and executing simulators directly within the Mosaik simulation process, starting new simulator processes and connecting to them, or interconnecting with existing simulation processes.

The *Scheduler* component in Mosaik controls the operation of simulators and manages data flow between them. It utilizes the SimPy simulation library which allows it to handle simulators with different and variable step sizes. (Schloegl et al., 2015)

Among the various and interesting features of Mosaik, some of the most relevant for the development of The Illuminator and the ECDT platform are:

1. **Distributed computational units**: The library allows the execution of the simulation process on a cluster of distributed computational units. This means that simulators and models can be allocated on different computers, and the results of each step can be shared via LAN or via the Internet. Thanks to this feature, The Illuminator software can be installed on multiple Raspberry Pis, each of them representing an individual model. By doing so, The Illuminator bridges the gap between the virtual representation of a Smart Grid and the physical world, providing a miniaturized replica that facilitates the understanding of its functioning.
2. **Scalability**: Mosaik can support thousands of simulated entities per simulation run, enabling the representation of large-scale smart grid scenarios (Steinbrink et al., 2019). This feature resulted as crucial for the ECDT platform, due to the necessity of capturing its multiple layers and the many different models within each, thus making it compliant with the scalability requirements.
3. **Modularity**: The library architecture offers the possibility to establish connections between an unlimited number of simulators. Moreover, thanks to the high-level API, new simulators can be added through small changes in the code. This feature fostered the creation of a large open-source depository of building blocks created by the community, allowing developers to share their modelling efforts.
4. **Real-time operation**: A key feature of Mosaik is the possibility to execute the simulation in real-time. This is an essential characteristic for the realization of DTs that collect measurements from the real world at each time step.

2.2.2. The Illuminator

The Illuminator toolkit, introduced in section 1.3, thanks to its unique features was chosen as the starting point for the development of the ECDT platform. This toolkit, built upon the Mosaik environment, fosters communication among domain experts and educates students and communities, whit the aim of facilitating the challenges posed by the energy transition (Saini, 2022). The kit showcases the functionality of renewable energy technologies and how they can be integrated into a larger energy system, emphasizing the challenges that come with transitioning to a renewable energy-dominated system.

The Illuminator general architecture is represented in figure 2.3. On the left side, different entities from the default set of models are shown. For each study case, the models that have to be simulated and the respective locations of each simulator process (local or remote) must be listed in an XML configuration file. Similarly, the specific interconnection between each mode must be described in an XML connection file.

Some of the models require receiving data from an external source. For instance, this is the case of a PV model to receive the sun irradiation data to perform a simulation step and calculate the power produced. In The Illuminator, these inputs are in the form of data series stored in CSV files. The set of input data and the time horizon on which they are analyzed define a Scenario.

At the core of The Illuminator's architecture, there is a Main file, that has the role of reading the XML files, initialising the Mosaik environment and starting each simulator with its specific parameters. The Main file is the control interface because it allows the configuration of simulation settings, such as the start and end time or the step size. (Saini, 2022)

At run-time, it is possible to track the flow of information between the simulators through an online dashboard while the final results are collected into a CSV file.

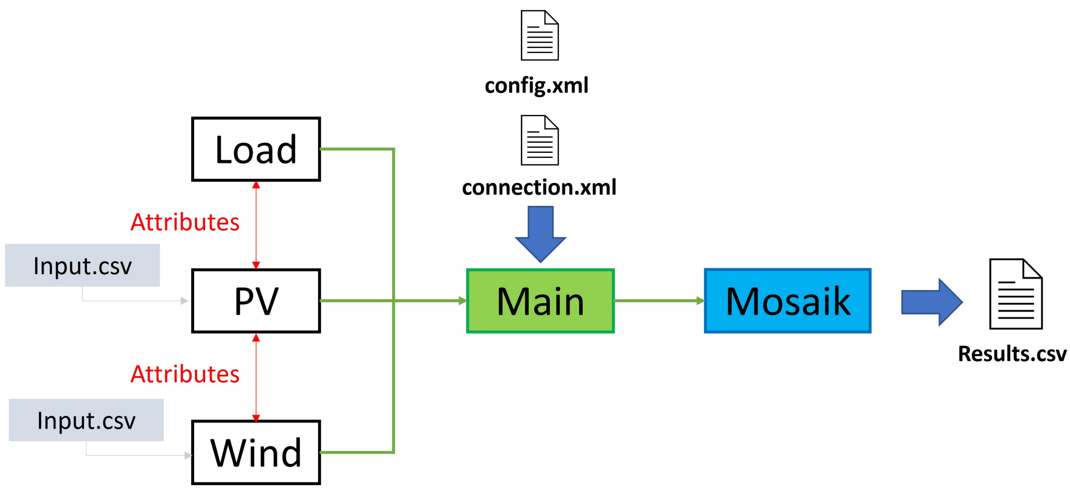


Figure 2.3: The architecture of The Illuminator

The architecture described here shows substantial compatibility with the design criteria chosen for the realisation of the ECDT platform. Although the purpose of The Illuminator is substantially different, its modular co-simulation structure offers such flexibility that it can be expanded to represent the various layers of the MECA, so as to be adapted to the ECs' requirements. Moreover, the support of Mosaik features, as well as the ease with which case studies can be defined, represent an ideal starting point for the realisation of the ECDT platform.

3
Implementation

This chapter focuses on a detailed description of how the ECDT platform's architectural elements were realized and implemented, while providing a comprehensive analysis of the main design choices that led to the creation of the software. To this aim, section 3.1 is an overview of the implementation of the MECA in the ECDT platform, so as to facilitate a comprehensive understanding of how the conceptual framework is implemented in the software architecture. Subsequently, section 3.2 explains the essential structure of the componets of the platform so to provide the knolwedge needed for the comphrension of each layer functioning, explained in sections 3.3-3.7. Furthermore, section 3.8 explains how the configuration of the platform can be conducted by the user, with the aim to facilitate the platform utilization. Lastly, Section 3.9 elucidates the pivotal role of the Main file as the central point for aggregating and orchestrating all the elements within the platform.

3.1. Energy Communities Digital Twin (ECDT) platform software

The software structure of the ECDT platform was meticulously crafted through a series of design choices to effectively incorporate the MECA (section 2.2) within a unified virtual environment built upon The Illuminator. This process involved extending The Illuminator's architecture with a bottom-up approach, carefully considering the nuances and specificities of the conceptual framework.

The key design choice was to encapsulate the entire layer stack within the co-simulation environment and populate it with a diverse set of simulators. While this choice may not have been the only option, it was carefully selected after exploring several viable alternatives.

For instance, an alternative approach could have involved implementing the Agents layer and Games layer outside the simulation run-time, resulting in a turn-based system where each turn triggered a new simulation run. In such a configuration, agents could have decided how to interact in the games based on the results of the previous simulation. Each decision made by each agent would have resulted in a change in the software parameters and the start of a new simulation session, thus initiating the next turn.

Although this approach allows the system to fully implement the MECA, it does not maximise compliance with the design criteria. In fact, such a structure would have resulted in the loss of Mosaik's scalability feature, hindering the ability of future researchers to extend and enhance the proposed software effectively.

In figure 3.1 the ECDT platform software architecture is illustrated. The figure clearly shows the distinct layers and interconnected blocks that form the layer stack.

Except for the Environment layer, which consists of several inputs that are fed to the DT platform, the other four layers are instead composed of multiple instances of different simulators. As a result, a large part of this research project was devoted to the implementation of new simulators and to the definition of their communication protocols.

Similarly to The Illuminator, each simulator of the ECDT platform exists inside of the Mosaik co-simulation world, it is instantiated in the Main file and can be executed in real-time. Moreover, the Main file, working as a simulation creation interface, translates the XML configuration and connections files so as to represent different study cases. Finally, the results can be monitored through the online dashboard or the respective CSV file.

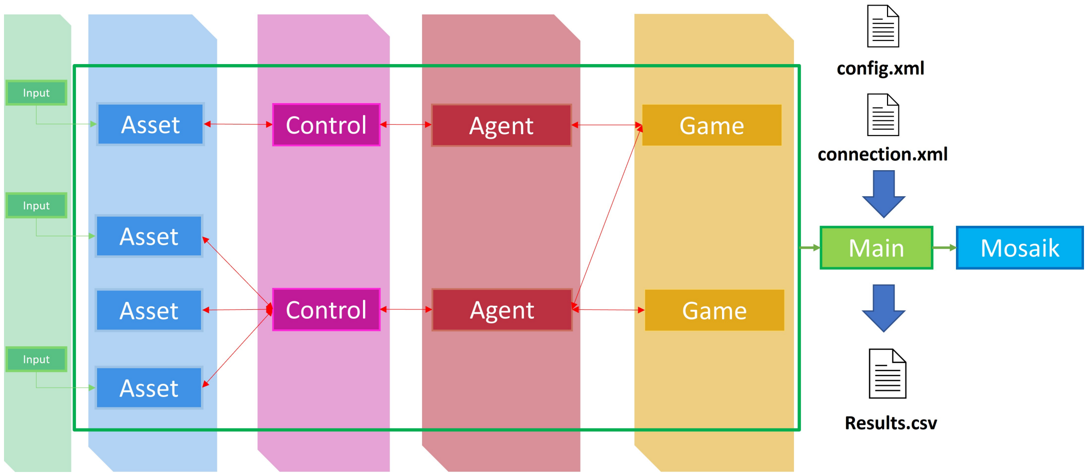


Figure 3.1: Implementation of the MECA in the ECDT platform software architecture

3.2. Components

In the ECDT platform, a simulator is a program that contains the implementation of one or more simulation models. It provides the environment and infrastructure to execute these models, manage the simulation execution, and handle data exchange between other simulators, through the Mosaik environment. The simulation model represents a system or process in programming code, encapsulating its logic, rules, and behaviour. It defines the variables, parameters, and equations that govern the system's dynamics. Together, the simulator and the model form the core components of a simulation process, thus representing a tile of the co-simulation mosaic.

Simulators are basically implemented through the Mosaik high-level API. This is responsible for encapsulating all the various networking functions, such as socket handling, event loop management, and message serialization and deserialization. It provides an abstract base class that serves as a blueprint for creating specific simulator subclasses. These subclasses must implement a set of required methods defined by the base class. By doing so, the simulator establishes the necessary framework for handling network communication and ensures that the essential functionalities are present in the implementation of the subclasses.

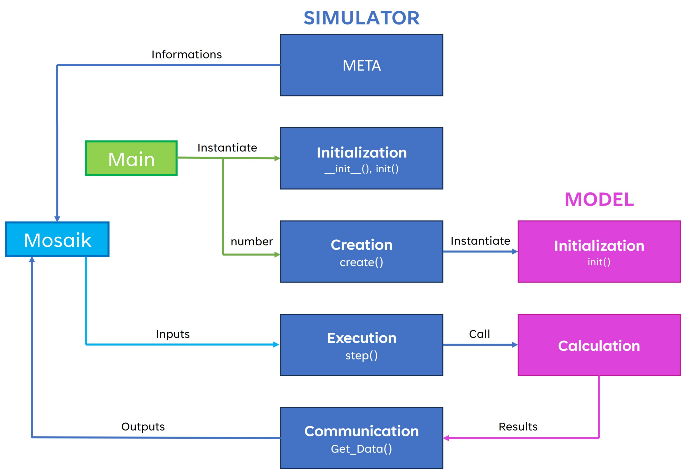


Figure 3.2: Flowchart of a single simulation process

Figure 3.2 is a flowchart that describes the process of configuration, instantiation and execution of simulators and models. According to the Mosaik syntax, each simulator file has to be provided with a META global variable. This is a JSON data structure that contains all the essential information that allow Mosaik to correctly execute and synchronize each simulator in the co-simulation process. The META variable has the following structure:

```
META = {
    'type': 'hybrid',
    'models': {
        'MODEL_NAME': {
            'public': True,
            'params': [...],
            'attrs': [...],
            'trigger': [...],
        },
    },
}
```

The first information contained in the META data structure is the type of simulator. Mosaik identifies three types of simulators, namely:

- **Time-based simulators**: These simulators independently determine the points in time at which they should be stepped forward, following a predetermined schedule.
- **Event-based simulators**: These simulators rely on specific events or the availability of new input to trigger a step forward in the simulation. They are reactive and wait for external events or data updates to prompt their advancement.
- **Hybrid simulators**: These simulators combine the features of both time-based and event-based approaches. They can individually make decisions based on time increments and also react to external events or input changes, providing a flexible and adaptive simulation modelling approach.

The META data frame also informs Mosaik about the publicity of each model and provides the names of the possible parameters, attributes and triggers. Parameters are provided from the Main file to correctly instantiate models in the configuration phase, while attributes and triggers are the inputs and outputs exchanged at simulation run-time.

During the configuration phase, the Main instantiates each simulator and transfers to the API function *create()* the number of model instances that have to be created within a study case. Each model instance is a unique object of the model class and is characterized by specific parameters.
At simulation run-time, Mosaik calls the simulator *step()* function that operates the deserialization of inputs. The function includes a translator code section that assigns specific inputs to each model object. This translation process converts the inputs into appropriate data structures that the respective models can properly understand and process.

The ECDT platform, building upon the capabilities of The Illuminator, incorporates a translator component responsible for converting input JSON variables into Pandas data frames. This design decision holds significant significance as it aims to streamline the implementation process of the higher layers within the ECDT platform, specifically the Controls, Agents, and Games layers.
The models in these particular domains exhibit unique characteristics that set them apart from the others, primarily due to the varying velocities of their dynamics and the types of data they involve. For instance, in the case of Energy Assets, the simulation primarily focuses on managing a limited number of lightweight inputs and outputs to accurately represent rapid physical transformations. On the other hand, the Game layer models demand meticulous classification and leverage powerful analysis tools to effectively handle potentially thousands of diverse inputs. By capturing the inputs in Pandas data structures, the classification and analysis are facilitated by leveraging the tools supported by this library.

It is fascinating to observe how the shift across different domains within the ECDT platform is inherently reflected in the data structures they employ. The translator component bridges the gap between the input JSON variables and the specific data formats required by each model. The fact that the lower layers predominantly deal with lightweight inputs and outputs, while the upper layers necessitate sophisticated analysis of numerous diverse inputs, highlights the adaptability and flexibility of the ECDT platform.

This observation underscores the platform's ability to cater to the unique requirements and characteristics of various domains within the ECs. By accommodating diverse data structures and handling them appropriately, the ECDT platform ensures that simulations accurately capture the dynamics and complexities of each domain. This aspect adds depth and realism to the simulations, ultimately enhancing their usefulness in decision-making processes and facilitating a deeper understanding of the interconnected ECs.

When the main model function is executed, the model calculation is performed and the results are returned to the simulator. In the *get_data()* function the results are serialized and passed to the Mosaik scheduler that transmits the outputs to other simulators.

3.3. Environment Layer

The Environment Layer represent the foundation of the ECDT platform, providing essential inputs that shape the simulation scenarios and drive the behaviour of the energy system.

Within the Environment Layer, the platform incorporates diverse data series inputs that are fundamental for creating realistic and dynamic simulation scenarios. These inputs include weather data such as temperature, solar radiation, and wind speed, which directly influence the performance of the energy assets. Additionally, consumption curves depict the energy demand patterns over time, while control signals provide information about how energy assets are controlled over time. Sensor measurements capture real-world data from physical assets, enabling the platform to respond to actual conditions and support accurate analysis. Furthermore, inputs can also encompass market conditions, such as quantity or price, providing the possibility to study the EC reaction to external market changes.

The set of inputs within the Environment Layer defines the specific scenario in which the energy system is simulated. By selecting and configuring the appropriate data series, users can create study cases that accurately reflect different operating conditions and environmental factors. These inputs serve as the foundation for simulating and analyzing the behaviour of the energy system under varying circumstances.

The Environment Layer supports both real-time and forecasted data inputs. Real-time data acquisition allows the platform to operate in real-world environments, capturing current conditions and making dynamic decisions based on actual measurements. On the other hand, forecasted data, such as predicted wind speed, enables the platform to simulate and analyze the behaviour of the energy system in the near future. This capability supports proactive decision-making, allowing stakeholders to anticipate and plan for upcoming events and optimize system performance in advance.

In summary, the Environment Layer of the ECDT platform is responsible for providing crucial inputs and data series that define the simulation scenarios and influence the behaviour of the energy system. By incorporating weather data, consumption curves, control signals, and sensor measurements, this layer enables realistic simulations and informed decision-making. It supports both real-time and forecasted data, empowering users to analyze the performance of the energy system under different conditions and plan for the future. As a result, the Environment Layer ensures the platform's adaptability and relevance in addressing the challenges of the energy transition.

3.4. Energy Assets Layer

The Energy Assets Layer replicates the physical domain of the EC multi-layered model within the ECDT platform. It encompasses a diverse range of energy assets, including demands, renewable energy sources, energy storage systems, and other infrastructure elements. This layer plays a vital role in simulating and representing these assets' physical characteristics, operational behaviours, and interactions within the energy system. Indeed, it serves as an interface between the components' physical world and the ECDT platform's virtual environment. As a result, it, facilitates the integration of several types of energy assets into the simulation of different study cases, allowing for a detailed examination of their impact on the overall energy system.

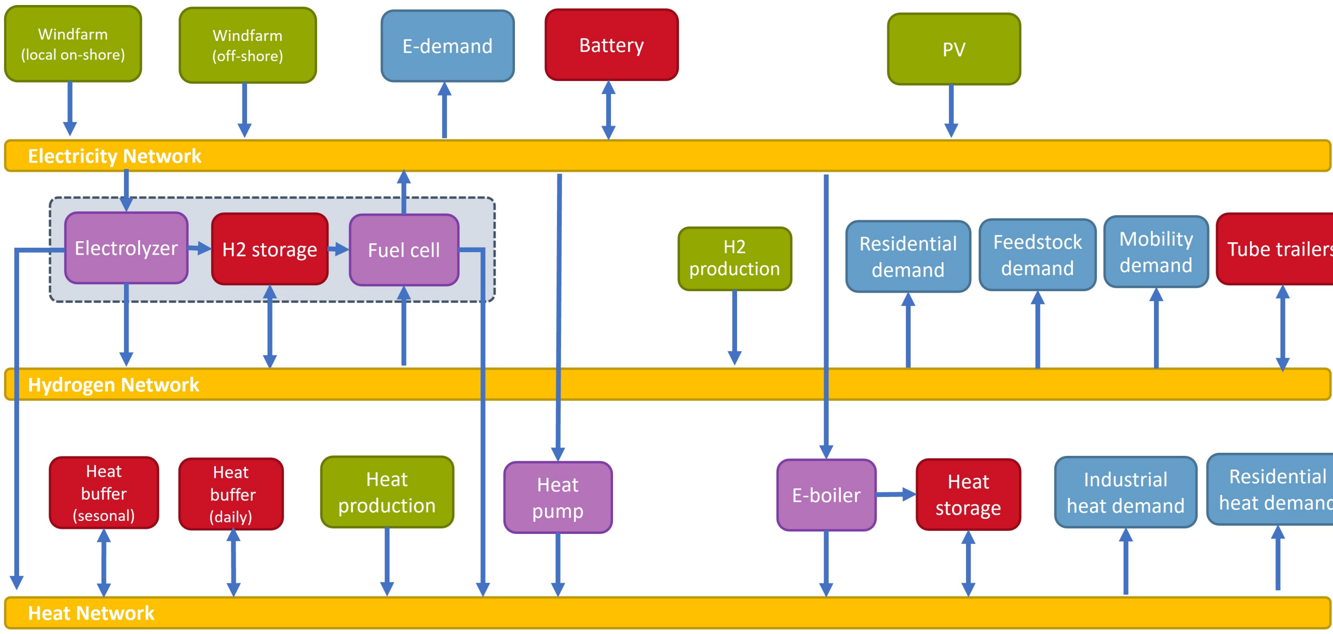


Figure 3.3: Energy assets layer components and possible interconnections

Figure 3.3 visualizes the intricate network of physical interconnections among the default set of models within the Energy Assets Layer. The complexity of this network posed a significant challenge during the research process, requiring substantial effort to establish robust communication protocols and expand the portfolio of assets.
The task of defining efficient protocols was vital to ensure seamless information exchange and coordination between the interconnected models. Additionally, considerable attention was devoted to expanding the range of available assets in order to enhance the realism and diversity of the simulations. To map efficiently the available models and their exchangeable attributes an appropriate table was realised, and it can be consulted in appendix A.

As shown in figure 3.3, one key aspect of the Energy Assets Layer is its coverage of three essential energy carriers: electricity, hydrogen, and heat. By considering these carriers, the layer provides a comprehensive framework for analyzing the dynamics of energy generation, distribution, and transformation across multiple vectors.
In the subsequent sections, this report will delve into each specific carrier, explaining the respective models and functionalities, and providing a comprehensive understanding of their functioning.

3.4.1. Electricity

The global trend towards electrification is gaining momentum, driven by various factors. According to the International Energy Agency (IEA), electricity supplied 20% of the final energy in 2019, up from 16% at the turn of the century (IEA, 2023a). This trend is expected to continue due to the improving cost competitiveness of low-carbon generation options and the attractiveness of electricity as a high-quality, emission-free energy vector (IEA, 2023a). The transition from fossil fuels to renewables is also a key driver of electrification, with the IEA reporting that 90% of rural electrification, particularly off-grid systems, will be powered by renewable energy. The transport sector is also moving towards electrification, as it accounts for a significant portion of worldwide CO_2 emissions and petroleum consumption.

The shift towards electrification has resulted in fundamental changes in energy demand, resource use, and infrastructure needs globally. However, challenges remain, as there are still millions of people without access to electricity, particularly in Sub-Saharan Africa, and current policies may not achieve universal electricity access by 2030 (Zapata et al., 2023).

This highlights the imperative for collaborative research efforts aimed at addressing the challenge of shaping tomorrow's electricity infrastructure. thus developing innovative solutions for unprecedented problems. In the dynamic field of energy systems, where complexities and uncertainties abound, it is crucial to foster a collaborative environment that brings together diverse expertise and perspectives.

This process can be facilitated by platforms like the ECDT, which harness the power of cyber-physical electricity system modelling. The platform offers a broad portfolio of electricity assets simulators for renewable energy generation, consumption and storage, which will be illustrated in the following.

E-Demand

In the ECDT platform, the E-Demand simulator replicates the consumption curves of electrical utilities. To achieve this, power consumption data series are stored in a CSV file, which is then read and scaled by each model instance at every simulation step.

The CSV file serves as a repository of historical power consumption data, capturing the patterns and variations in electricity usage over time. Each model instance within the E-Demand asset accesses this file to obtain the relevant consumption data.

At each simulation step, the E-Demand model retrieves the corresponding consumption values from the CSV file and scales them appropriately. Scaling is necessary to ensure that the simulated power consumption aligns with the specific characteristics and requirements of each model instance.

The E-Demand asset accurately replicates the consumption curves of electrical utilities. This enables the ECDT platform to simulate realistic power consumption scenarios and analyze the impact of various factors on energy usage.

In recent years, there has been a significant increase in research focusing on power demand, surpassing the level of attention given to electric energy consumption (Grandjean et al., 2012). This shift in focus can be attributed to the inherent challenges associated with predicting power demand, particularly due to its fluctuating nature. Unlike electric energy consumption, which can be relatively stable, power demand exhibits greater variability and complexity.

One of the primary complexities in modelling power demand lies in the fact that a single demand curve cannot adequately represent a cluster of households, even if they share similar characteristics such as household size, building construction type, or appliances. Each household's consumption profile is influenced by various factors, including human behaviour, lifestyle, and occupation. For instance, the consumption profile of a bachelor who works part-time will differ from that of a full-time employed couple with two children. The individual usage patterns are highly dependent on the unique behaviours and preferences of the occupants.

In conclusion, the ECDT platform's integration of the E-Demand simulator, along with its ability to replicate consumption curves and simulate power demand for thousands of different entities, demonstrates its effectiveness in addressing the challenges associated with modelling and understanding electricity usage.

PV

The PV (Photovoltaic) asset, which is inherited from The Illuminator in the ECDT platform, is designed to model and simulate PV systems by considering various real-world inputs. These inputs include irradiance (the amount of sunlight falling on the solar panel), wind speed, ambient temperature, elevation and azimuth of the sun, and the tilt of the PV module.

By incorporating these inputs and representing the underlying working principles of the technology, the PV model can capture important phenomena such as changing irradiance, resulting variations in output power, the influence of wind speed on module temperature, and the impact of module temperature on module efficiency. These concepts and modelling capabilities allow for accurate representation and analysis of PV systems within the ECDT platform.

Windfarm

The ECDT platform and The Illuminator feature a Windfarm asset, which enables users to simulate and analyze wind farm scenarios. This asset allows users to customize the wind farm configuration, including the number of wind turbines and their specific parameters. Some of the parameters that can be specified for each wind turbine include:

- *Rotor diameter*: The diameter of the wind turbine's rotor, which affects the swept area and the amount of wind captured by the turbine.
- *Cut-in speed*: The minimum wind speed at which the wind turbine starts generating power.
- *Cut-out speed*: The wind speed at which the wind turbine stops generating power and goes into a shutdown mode for safety.
- *Rated wind speed*: The wind speed at which the wind turbine achieves its maximum rated power output.

The Windfarm asset in the ECDT platform receives wind speed as an input, which is used to calculate the power output of the wind turbines. The power curve profile, as shown in figure 3.4, depicts the relationship between wind speed and power output. The power output is determined through the following equation:

$$P = \frac{1}{2}\rho\eta r^2 v^3$$

Where:

- P is the power output
- ρ is the air density
- η is the coefficient of performance
- r is the radius of the wind turbine rotor
- v is the wind speed

By incorporating this power curve profile and considering the wind speed input, the Windfarm asset in the ECDT platform accurately simulates the power output of the wind farm, allowing users to analyze the performance and behaviour of the wind turbines under different wind conditions.

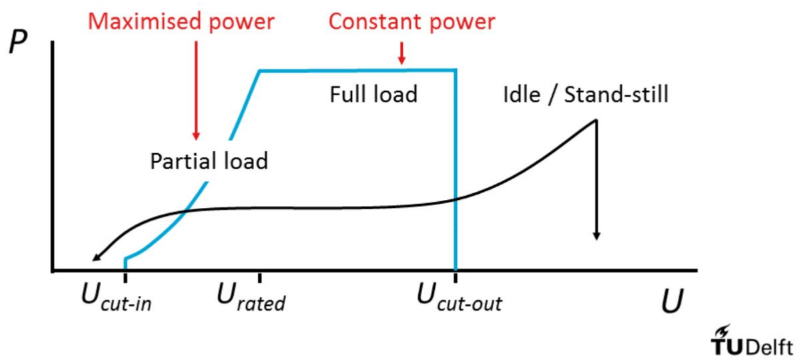


Figure 3.4: The power curve of a wind turbine

The Windfarm is provided in two variants on-shore and off-shore, so that different parameters and data series can be utilized to model the two different conditions.

Battery

The use of batteries in electricity grids is crucial for improving grid resiliency, integrating renewable energy sources, and ensuring grid stability. Grid-scale and household-scale energy storage systems, such as battery systems, can assist in peak shaving, load levelling, voltage and frequency regulation, and emergency power supply (Wheeler et al., 2022). Lithium-ion batteries, in particular, have seen significant penetration in power systems due to their ability to decarbonize, digitalize, and democratize the electricity grid (Vykhodtsev et al., 2022). Additionally, the batteries of EVs and plug-in hybrid electric vehicles (PHEVs) can support the smoothing of the intermittency of renewable energy sources and enhance grid stability (Monteiro et al., 2011). However, the economic viability, technical reliability, and appropriate assessment of battery projects are essential due to high capital expenditures and regulatory uncertainties (Vykhodtsev et al., 2022). While there may be additional costs associated with employing batteries in the electricity sector, their use can contribute to the reduction of greenhouse gas emissions and provide distributed energy storage benefits (Schmidt et al., 2019).

In the ECDT platform, the Battery asset, which is adapted from The Illuminator, allows modelling and analyzing the behaviour of general electrical storage systems. By simulating the State of Charge (SoC) evolution, users can gain insights into the performance and dynamics of batteries in various scenarios.
The Battery asset is characterized by several model parameters that define its capabilities and limitations. These parameters include:

- *max_p*: This parameter represents the rated charging power of the battery, indicating the maximum power at which it can be charged.
- *min_p*: Conversely, *min_p* denotes the rated discharging power, which represents the maximum power at which the battery can be discharged.
- *max_energy*: The *max_energy* parameter defines the capacity of the battery, representing the maximum amount of energy it can store.
- *soc_min* and *soc_max*: These parameters specify the minimum and maximum SoC limitations of the battery, respectively. They define the lower and upper thresholds of the battery's charge level, thus identifying the Depth of Discharge (DoD).
- *flag_e*: The *flag_e* parameter indicates the status of the battery. A value of 1 signifies a fully charged state, -1 represents a fully discharged state, and 0 indicates that the battery is ready for charging and discharging.
- *resolution*: The resolution parameter determines the time step of the simulation in minutes. It defines the granularity of the battery model and influences the accuracy of the results.

The Battery asset receives an input called *flow2b*, which represents the power flow to or from the battery. A positive *flow2b* value indicates power flowing into the battery for charging, while a negative value indicates power discharge from the battery.

To effectively control and optimize the battery's operation, a dedicated control system can be employed. This control system is designed to manage the dynamic models and regulate the power flow to the battery based on specific objectives. These objectives can include peak shaving, load levelling, minimizing grid interactions, and enabling efficient energy trading to maximize profits.

By incorporating the Battery asset into the ECDT platform, users can gain a comprehensive understanding of battery behaviour and its impact on ECs operation. The simulation results provide valuable insights into the performance and potential benefits of utilizing battery storage in different energy management strategies.

Electricity Network

In the ECDT platform, the Electricity Network asset allows monitoring and analyzing the power injection and ejection from a grid. This asset provides the functionality to track the flow of electricity within the network, calculate power losses, and detect congestion.

The Electricity Network asset offers several key features and capabilities that contribute to its effectiveness in simulating and analyzing grid behaviour. These include:

- Power Loss Calculation: The algorithm integrated into the asset allows for the calculation of power losses occurring within the grid. The asset takes into account the length of the grid when calculating power losses. Longer grid segments tend to have higher resistance, resulting in increased power losses. Considering grid length helps users evaluate the impact of transmission distances on system efficiency and make informed decisions regarding grid expansion and infrastructure upgrades.
- Congestion Detection: The Electricity Network asset facilitates the detection of congestion within the grid. Congestion arises when power demand exceeds the network's capacity, leading to bottlenecks and operational challenges. By identifying congested areas, users can implement strategies to alleviate congestion, such as load balancing, grid reinforcement, or rerouting of power flows.

By integrating the Electricity Network asset into the ECDT platform, users gain a comprehensive understanding of grid behaviour, performance, and limitations. This asset supports the analysis of power losses and congestion, enabling users to optimize grid operations, improve efficiency, and ensure a reliable electricity supply. It also serves as a valuable tool for grid planning, decision-making, and the integration of renewable energy sources into the network.

3.4.2. Hydrogen

Hydrogen has gained significant attention as a potential alternative carrier for various applications. Recent developments in hydrogen technologies have focused on fuel refining, hydrocarbon processing, materials manufacturing, pharmaceuticals, aircraft construction, electronics, and other applications (Qazi, 2022).

The integration of hydrogen into a multi-energy complementary system based on renewable energy sources has been identified as a global research hotspot, offering advantages such as improved consumption of renewable energy and reduced impact on the power grid system (Li et al., 2020).
Research in hydrogen production technologies aims to find methods that are as productive as mature technologies like reforming and gasification, while also being environmentally friendly (Martínez-Rodríguez & Abánades, 2020). Additionally, hydrogen technologies have been explored for both stationary and mobility applications, with a focus on hydrogen production from sustainable resources and the development of storage solutions (Khzouz & Gkanas, 2020).

The ECDT platform offers a comprehensive environment that supports research in the field of hydrogen. It provides a range of hydrogen-related assets that enable users to explore and analyze various aspects of hydrogen technologies. These assets contribute to a holistic understanding of hydrogen systems and their potential applications within ECs. The hydrogen-related assets that are available within the platform are discussed in the following.

Electrolyzer

The Electrolyzer asset is a component within the ECDT platform that simulates the process of electrolysis, which is used to produce hydrogen by splitting water molecules into hydrogen and oxygen. Users can simulate and analyze the performance of different types of electrolyzers and study their efficiency, hydrogen production rates, and operating characteristics. The electrolyzer asset is instantiated with the following parameters:

- *eff*: Efficiency of the electrolyzer, representing the conversion efficiency from input power to hydrogen production.
- *resolution*: Time resolution of the simulation in minutes.

The calculation method of the Electrolyzer asset takes the input power flow *flow2e* as a parameter. It calculates the hydrogen production based on the input power flow and the efficiency of the electrolyzer. If the input power flow

flow2e is greater than zero, indicating a positive power flow to the electrolyzer, the asset calculates the amount of hydrogen produced. It converts the input power flow to energy in kilojoules (kJ) based on the time resolution. Then, using the Higher Heating Value (hhv) of hydrogen (286.6 kJ/mol), it calculates the number of moles of hydrogen produced. Finally, it converts the moles of hydrogen to kilograms per minute and returns the hydrogen generation as an output parameter *h2_gen*.

Due to the relatively low energy yield of the electrolysis process, a significant portion of the electrical power input is converted into heat power as a byproduct. Recognizing this, the model provides the capability to effectively utilize this heating power by directing it towards the heat network or other components that require thermal energy. This approach ensures that the generated heat, which would otherwise be wasted, can be harnessed and contribute to the overall efficiency and sustainability of the system. By integrating the heat power generated during electrolysis into the broader energy network, the model maximizes the utilization of resources and promotes a more efficient and effective energy conversion process.

Hydrogen Storage

Similar to the Battery, the Hydrogen (H2) Storage asset within the ECDT platform allows users to model and simulate different hydrogen storage technologies and analyze their behaviour. It is provided in two variants, as H2 Storage or Tube Trailers. The first is the static version that can be interconnected with the grid, the electrolyzer and the fuel cell. The second instead represents specialized transport vehicles used for the transportation of compressed gases and it supports only the connection with the grid. The hydrogen storage asset is instantiated with the following parameters:

- *initial_set*: A dictionary containing the initial SoC of the storage system.
- *h2_set*: A dictionary containing attributes related to the hydrogen storage system, such as the minimum and maximum SoC limits, maximum and minimum hydrogen storage capacities, and the system's overall capacity.

The hydrogen storage asset provides three main methods: *charge_h2*, *discharge_h2*, and *output_h2*, which handle the charging, and the discharging, and determine the overall output of hydrogen from the storage system.

The *charge_h2* method calculates the amount of hydrogen to be charged based on the input power flow, taking into account the maximum storage capacity and efficiency of the system. It updates the state of charge and returns the amount of hydrogen stored.
Similarly, the *discharge_h2* method calculates the amount of hydrogen to be discharged based on the output power flow, considering the minimum storage capacity and efficiency. It updates the state of charge and returns the amount of hydrogen given out.
The *ouput_h2* method is responsible for calling the charge and discharge methods ensuring that the safety conditions are respected. It provides as outputs the current SoC and the quantity of hydrogen stored or given out.

Overall, the Hydrogen storage asset allows users to model and analyze different hydrogen storage technologies, taking into account capacity, efficiency, and safety considerations. This enables users to evaluate and optimize the behaviour of hydrogen storage systems within the ECDT platform.

Fuel cell

The Fuel Cell asset simulates the operation of fuel cells, which generate electricity through the electrochemical reaction between hydrogen and oxygen. Users can analyze the performance and efficiency of different types of fuel cells, by specifying the conversion efficiency. By considering the energy density of 1 Kg of hydrogen, which is 120 MJ/kg, the fuel cell model provides as output the electrical power produced.

Hydrogen Valve

The Hydrogen Valve asset ensures the proper flow of hydrogen between the Electrolyzer, H2 Storage, Fuel Cell assets, and the hydrogen network. Its purpose is to control and direct the flow of hydrogen based on the input signals received from each asset.

The assets in the system can be controlled through different inputs, which can be stored in CSV files. These control signals influence the behaviour of each asset and, consequently, the amount of input and output gas they require. Since the assets are interconnected, the specific operating state of each asset determines the path of the hydrogen flow.

For instance, if the fuel cell requires a certain amount of hydrogen and the storage asset has enough supply, the hydrogen will be directed from the storage asset to the fuel cell without the need to draw from the grid. However, if the storage asset cannot meet the hydrogen demand, the valve ensures that hydrogen is sourced from the grid to fulfil the requirements.

The presence of the hydrogen valve guarantees that the hydrogen flows are correctly directed under all operating conditions. It acts as a control mechanism to regulate the flow of hydrogen between the different assets and the network. Additionally, the valve enables the user to monitor the various flows within the system throughout the simulation, allowing for better analysis and understanding of the hydrogen distribution.

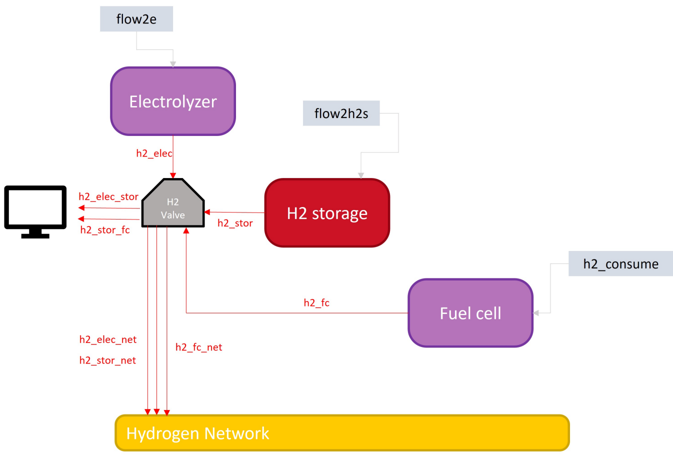


Figure 3.5: The Hydrogen Valve

Hydrogen production and demand

The Hydrogen production asset in the ECDT platform is a versatile entity that can produce hydrogen and distribute it within the hydrogen network or to other assets. It reads data series from a CSV file, allowing users to input specific parameters and profiles for hydrogen production. This feature enables the modelling of various hydrogen production technologies and processes by incorporating real-world dynamics and variations.

Similarly, the Hydrogen demand simulator allows for the representation of hydrogen consumption patterns in the ECDT platform. It is provided in three versions, residential, feed-stock and mobility so that each of them can be initialized with different parameters and data series.

Hydrogen Network

The Hydrogen network in the ECDT platform operates similarly to the Electricity Network asset but with some key differences. Instead of using power, it utilizes gas input and output mass flow rates, which are measured in kilograms per minute. The network's parameters include the pipe cross-sectional area, gas density, maximum pressure, and leakage rate.

One of the important output parameters of the hydrogen network is the total flow, which represents the sum of all the mass (inflow and outflow) rates within the network. It provides insights into the overall movement of hydrogen within the system. From the total flow, it is possible to calculate the congestion, which is a boolean value indicating whether any congested conditions exist within the network. Congestion can occur when the flow rates exceed the network's capacity or when there are bottlenecks in the distribution.

The internal pressure of the hydrogen network is also a significant output parameter. It is calculated using an adaptation of the ideal gas formula :

$$p_{\text{int}} = \frac{(\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}}) \cdot R \cdot T}{M \cdot V}$$

where represents p_{int} the internal pressure, $(\sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}})$ is the difference between the total flow rate of the incoming and outgoing gas, V is the pipe volume, R is the gas constant, T is the temperature and M is the molar mass.

3.4.3. Heat

The integration of heat energy in multi-energy systems is a crucial component for optimizing energy efficiency and leveraging the benefits of renewable energy sources. In this context, Integrated Energy Systems (IESs) play a significant role by integrating various forms of energy, including electricity, heat, gas, and cold, to establish local networks for energy supply and demand. IESs are instrumental in advancing the transition towards a fossil-free future, as they facilitate the effective utilization and management of different energy resources in a coordinated manner (J. Wu et al., 2016).
These systems can achieve high energy efficiency, with IESs having the potential to exceed 80% efficiency compared to the 35% efficiency of traditional energy systems, which supply power and heat separately (Ma et al., 2021). The integration of heat pumps and thermal storage in these systems can provide flexibility to accommodate fluctuating power generation from renewable sources (Steinle et al., 2020).

In the context of the ECDT platform, various models for the transmission, storage and transformation of heat energy are available. These models allow simulating and analyzing the performance of IESs and their components. The following paragraphs will delve into these heat-related models and explore their importance in advancing research and development in the field of IESs for ECs.

Heat Storage

The Heat Storage asset is designed to store thermal energy within the ECDT platform. It shares similarities with the storage assets examined so far but incorporates specific considerations to correctly represent the thermal dynamics. In addition to the other storage assets, the Heat Storage parameters are:

- Storage insulation thickness (d): The thickness of the insulation layer surrounding the storage system.
- Internal temperature (T_{int}): The temperature within the storage system.
- External temperature (T_{ext}): The ambient temperature outside the storage system.
- Thermal conductivity (k): The material's thermal conductivity.
- Area (A): The external surface area of the storage system.
- Mass (m): The mass of the storage medium.
- Thermal capacity (c): The specific heat capacity of the storage medium.

The temperature increase within the heat storage asset is determined by the formula:

$$T_2 = \frac{Q}{mc} + T_1$$

where T_1 is the initial temperature, T_2 represents the final temperature and Q is the thermal energy input. This formula is derived from the fundamental equation of heat transfer:

$$Q = mc\Delta T$$

The equation for power loss due to thermal losses is derived starting from the heat transfer equation:

$$Q = \frac{kA\Delta T}{d}$$

The power loss P_{loss} can be expressed as:

$$P_{\text{loss}} = \frac{Q}{t}$$

where t is the time duration, Substituting the value of Q from the heat transfer equation:

$$P_{\text{loss}} = \frac{kA\Delta T}{dt}$$

Considering cylindrical heat storage with diameter D and height h, the area A can be expressed as:

$$A = \pi Dh$$

Substituting the value of A back into the equation:

$$P_{\text{loss}} = \frac{k\pi Dh\Delta T}{dt}$$

The asset is provided in three variants, two representing daily or seasonal heat buffers and one that can be directly fed by the E-Boiler asset.

E-boiler

The E-boiler asset serves as a link between the electricity and heat domains within the ECDT platform. Its primary function is to facilitate the conversion of electrical power into heat energy. By specifying the efficiency of the transformation process, the E-boiler asset works as a blueprint for a vast number of possible devices for the utilization of electrical energy for heat generation purposes.

Heat Valve

Similar to the Hydrogen Valve asset, the Heat Valve asset's aim is to direct energy flow between different components within the ECDT platform. Its primary function is to ensure that heat energy generated by the E-Boiler asset is appropriately distributed based on the operational requirements of the system.

When the Heat Storage asset requires heat energy, the Heat Valve directs the flow from the E-Boiler asset towards the storage unit. This ensures that the heat produced by the E-Boiler is locally utilized and stored for later use. On the other hand, when the Heat Storage asset does not require additional heat, the Heat Valve redirects the flow towards the heat network, enabling the distribution of heat energy to other components within the system.

The Heat Valve asset plays essential for maintaining the balance and efficiency of the heat energy exchange within the ECDT platform. Its functionality is depicted in figure 3.6, illustrating the exchange of attributes and the routing of heat energy based on the operational conditions of the system.

Heatpump

In the list of assets supported by the ECDT platform also appears the Heat Pump simulator within the Mosiak package. One of the best features of this library is that it is open-source, which has enabled the creation of a wide range of components developed by the community. These models have different levels of complexity but are easily implemented in the co-simulation environment. This gives the ECDT platform remarkable characteristics of modularity and scalability and provides the user with the possibility of representing reality and its various domains with a flexible level of detail.
The model enables the simulation of two types of heat pumps:

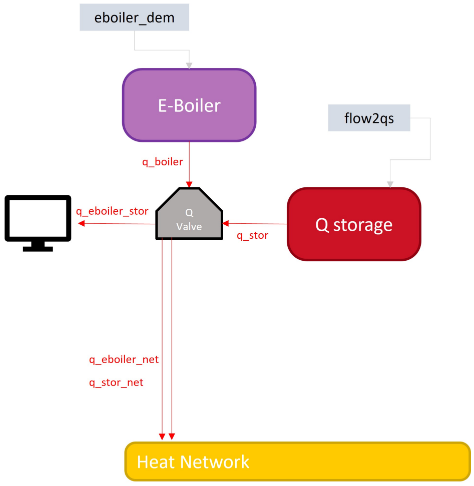


Figure 3.6: The Heat Valve

1. Water/Water Heat Pump: This type utilizes underground water as the heat source and water as the consumer fluid.
2. Air/Water Heat Pump: In this type, ambient air serves as the heat source, while water is used as the consumer fluid.

The model offers two calculation modes: detailed and fast. In the detailed mode, system calculations are performed based on a set of inputs. The fast mode uses pre-calculated data from the detailed mode to compute outputs instead of performing the calculations.
During initialization, the following parameters need to be set:

1. Heat source: Specify whether the heat source is water or air.
2. Calculation mode: Choose between detailed and fast.

For each time step of the simulation, the model requires the following inputs:

- Consumer heat load
- Heat source temperature
- Condenser inlet temperature

The model provides the following outputs for each time step:

- Heat supplied by the heat pump
- Coefficient of Performance (COP) of the heat pump
- Power requirement of the heat pump
- Condenser water mass flow rate
- Condenser water outlet temperature

Heat production and demand
The Heat production asset within the ECDT platform is designed to represent various heat sources. It has the flexibility to supply heat to the heat network and other components as needed. Users have the ability to input specific profiles for heat production using data series from a CSV file. This capability ensures that the simulations accurately capture dynamics and variations from the real world.

Complementing the Heat production asset, the Heat demand simulator focuses on capturing heat consumption patterns within the ECDT platform. It offers two distinct versions: residential and industrial, catering to these different contexts and scenarios. Each version can be customized with different parameters and data series, enabling the simulation of heat consumption patterns in specific settings.

Heat Network

Similar to the other networks in the ECDT platform, the Heat Network allows the distribution of heat energy. It serves as a conduit for transferring heat from various sources to the intended destinations within the system. The Heat Network allows users to monitor the inputs and outputs of the network. This monitoring capability enables users to gain insights into the flow of heat energy and ensure its efficient utilization. Additionally, the asset simulation incorporates factors such as thermal losses and a measure of the internal temperature of the network.

Considering the heat transfer into the storage system as positive and the heat transfer out of the system as negative, it is possible to write the energy balance equation as:

$$\sum Q_{\text{in}} - \sum Q_{\text{out}} = mc(T_2 - T_1)$$

Dividing both sides of the equation by $m \cdot c$

$$\frac{\sum Q_{\text{in}} - \sum Q_{\text{out}}}{m \cdot c} = T_2 - T_1$$

Substituting the density of the medium ρ, diameter D, and length L of the pipework:

$$\frac{\sum Q_{\text{in}} - \sum Q_{\text{out}}}{\rho \cdot D \cdot L \cdot c} = T_2 - T_1$$

Finally, rearranging the equation to solve for T_2:

$$T_2 = T_1 + \frac{\sum Q_{\text{in}} - \sum Q_{\text{out}}}{\rho \cdot D \cdot L \cdot c}$$

This equation is used to estimate the internal temperature T_2 of the network, taking into account the heat input and output, as well as the physical parameters of the model. Furthermore, similar to the Heat Storage asset, the power loss is calculated with the following formula:

$$P_{\text{loss}} = \frac{k}{d} DL(T_{\text{int}} - T_{\text{ext}})$$

3.5. Controls Layer

The Controls Layer within the ECDT platform plays allows for facilitating effective energy control asset representation, management and optimization. It serves as a vital link between the physical domain of energy assets, such as generators, storages, and demands, and the energy management domain, where control strategies and techniques are implemented.

One of the key components within the Controls Layer is the Energy Management System (EMS). The EMS acts as the central control hub, responsible for monitoring, controlling, and optimizing the operation of energy assets within a given portfolio. It gathers real-time data from various sources, such as sensors, meters, and communication interfaces, to assess the current state and performance of the energy system.

In addition to EMSs, the Controls Layer can encompass a diverse range of controllable devices, including inverters, battery management systems, and other embedded control units. These devices are equipped with specific control strategies and techniques tailored to their respective energy assets. For example, inverters regulate the conversion of DC power from renewable sources, such as solar panels, into AC power suitable for consumption or grid connection.

To ensure seamless integration and interoperability among the different control systems and devices within the ECDT platform, a General-Purpose (GP) controller asset has been developed. The GP controller acts as a flexible

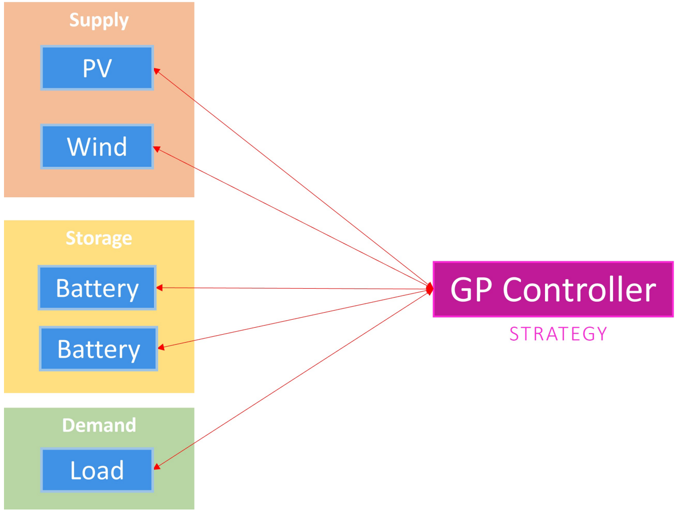


Figure 3.7: The GP controller asset

and adaptable control module that can interact with various energy assets and implement control strategies based on the specific requirements of each asset. It serves as a blue-print for researchers to simulate, evaluate, and fine-tune different control strategies to optimize energy management, improve system reliability, and achieve sustainable energy goals.

The design process of the GP controller involved abstracting the common features and communication protocols of the control systems within the Controls Layer. This abstraction allows for the creation of a standardized framework for exchanging information and commands between the GP controller and the connected assets.
The GP controller is equipped with a translator tool that disentangles and organizes the incoming data from different assets, facilitating efficient data processing and analysis. Inputs are categorized as demands, generators and storages.
The collected data, organized within Pandas data structures, form the knowledge base of the GP controller. It provides a comprehensive view of the current state of the energy assets, including their operating parameters, performance metrics, and status information. This knowledge base enables the GP controller to make informed decisions and implement control actions to optimize energy flows, ensure demand response, and maintain system stability.

3.5.1. Incremental attributes

The implementation of the GP controller within the ECDT platform brought to the forefront several implementation challenges and shed light on certain limitations of The Illuminator. While the toolkit initially supported simulators capable of handling inputs from multiple instances of the same model, it became evident that this approach was insufficient to fully realise the platform's capabilities. The platform's capability to link control systems to different energy assets necessitated the ability to control each asset independently.

Indeed, a significant complexity emerged when considering the diverse nature of control systems within the Controls Layer. Each control system needed to be able to connect to and effectively control various types of energy assets independently. Furthermore, the ECDT platform provided the flexibility to create multiple instances of its models, including controllers. This introduced an additional complexity, as each controller instance had to properly and separately manage its assigned energy asset portfolio, which could differ from the portfolios of other controller instances. As a result, controllers needed to function as Multiple Input Multiple Output (MIMO) systems, with a variable number of outputs.

This realization prompted the development of a new feature called incremental attributes. The goal was to overcome the limitations of the existing simulators and enable independent control of each energy asset within a controller's portfolio. By incorporating incremental attributes, the platform could effectively represent the dynamic nature of the Controls Layer and cater to the specific control requirements of different energy assets.

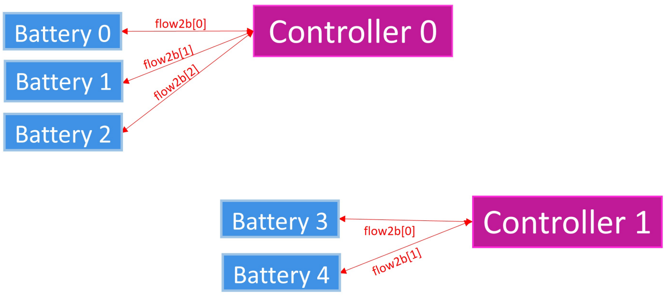


Figure 3.8: Incremenatal attributes example

To illustrate the concept of incremental attributes, let's consider a scenario depicted in figure 3.8. Each block represents a specific energy asset, and these blocks can be instantiated during the configuration phase through the connection matrix, which specifies attribute exchanges between assets. The incremental attribute *flow2b* denotes the power sent to different batteries, and multiple instances of this attribute can be defined for each controller in the connection matrix.

This incremental attribute allows for the development of control logics that enable independent battery management within each controller instance. By utilizing this feature, each controller instance can accurately control the assigned number of batteries within its portfolio, regardless of its size.
To ensure that each simulator receives the appropriate number of incremental attributes, the META variables need to be dynamically modified during runtime. This task is carried out by the Main file, which analyzes the connection matrix, identifies the required list of incremental attributes for the simulation, accesses each simulator, and adjusts the META variables accordingly.

In general, the incremental attribute resulted as an essential feature to realize simulators also in other layers, such as the MIMO networks of the Energy Assets Layer or the games within the Games Layer.

3.5.2. Control strategy

The Controls Layer within the ECDT platform provides users with the flexibility to implement multiple control strategies, catering to the diverse needs and objectives of ECs. These control strategies serve as the foundation for effectively managing and optimizing the operation of energy assets within the ECs.

The availability of multiple control strategies empowers users to customize their approach to energy management, taking into account factors such as energy source availability, demand patterns, congestion management, and environmental goals. For instance, one control strategy may prioritize maximizing the utilization of renewable energy sources, aiming to minimize reliance on non-renewable resources and reduce carbon emissions. Another strategy may focus on cost optimization, aiming to minimize energy expenses by intelligently balancing generation, storage, and consumption.

Implementing multiple control strategies within the Controls Layer allows users to experiment with different approaches and compare their performance. This capability fosters innovation and enables continuous improvement in energy management practices. Users can evaluate the effectiveness of each strategy based on key performance indicators such as energy efficiency, system reliability, economic viability, and environmental impact.
The ECDT platform supports the integration and testing of diverse control strategies, ranging from rule-based ap-

proaches to more advanced techniques utilizing artificial intelligence and machine learning. This empowers users to explore cutting-edge methodologies and leverage emerging technologies to enhance the efficiency, responsiveness, and adaptability of their energy systems.

The ECDT platform equips users with the tools to design, simulate, compare and evaluate different control strategies for their ECs, analyzing how these affect the other layers. For example, consider an EC that incorporates PV panels for energy production and EVs for energy consumption. The control strategies implemented in the Controls Layer can significantly influence the operation of this EC.

Suppose the user wants to evaluate the impact of different control strategies on maximizing the utilization of solar energy and optimizing EV charging patterns. They can simulate and compare two control strategies: Strategy A, which prioritizes charging EVs during periods of high solar energy generation, and Strategy B, which focuses on grid stability and balances the energy exchange between the PV panels and EVs.

Within the ECDT platform, these strategies can be holistically analysed. Indeed, users can explore how these strategies influence multiple domains within an EC, including agents' utility and market prices. With this capability, the ECDT platform empowers users to gain a holistic understanding of the impact of each strategy on the entire EC in a single simulation run.

By considering the effects on agents' utility, users can assess how these control strategies influence the decisions and behaviours of various entities within the EC. This includes consumers adapting their consumption patterns, prosumers optimizing energy generation and consumption, and energy suppliers adjusting their trading strategies. The platform enables users to examine how each strategy drives changes in these agents' actions and overall satisfaction. Additionally, the ECDT platform allows users to study energy trading mechanisms, like local electricity markets, and analyze how these are affected by control strategies.

3.6. Agents Layer

The Agents Layer within the ECDT platform incorporates features of MASs, which are computational systems comprising multiple autonomous agents that interact with each other and their environment to achieve defined objectives. These agents can be software entities or physical robots, each possessing unique knowledge and decision-making abilities. MAS has emerged as a prominent approach in diverse domains, due to its capacity to model complex systems, enable decentralized decision-making, and facilitate coordination among agents.

In the energy sector, MASs has been widely applied to address various challenges with the aim to optimize energy systems. The authors of (McArthur et al., 2007a) and (McArthur et al., 2007b) provide an extensive review of the topic, shedding light on the advancements and methodologies employed in developing MAS applications for energy systems. Their work of mapping the technical challenges, approaches, defining concepts, standards, and tools, was essential in the process of creation of the Agents Layer. Another added value to this project was provided by the various efforts of using MAS for the control of microgrids (Han et al., 2017).

Within the Agents Layer, bidirectional information and energy interaction are effectively facilitated through the use of the MAS-based architecture, leveraging the features of *autonomy*, *communication*, and *coordination* (Han et al., 2017).

- The *autonomy* of individual agents in the ECDT platform allows them to independently make decisions based on their internal state, goals, and local information. This autonomy enables agents to dynamically respond to changes in energy supply and demand within their energy assets portfolios. They can adapt their energy consumption or generation patterns, participate in energy trading, and collaborate or compete with other agents.

- The *communication* feature allows agents to exchange information and coordinate their actions. Agents can communicate with each other to share relevant data, execute energy transactions, and coordinate their energy-related activities. The communication facilitates the efficient allocation and distribution of energy resources within the EC, ensuring the dynamic balancing of supply and demand.

- The *coordination* mechanisms within the ECDT platform enable agents to synchronise their actions and work together towards common goals. Agents coordinate their trading activities to effectively manage energy flows, optimize resource utilization, and achieve overall system efficiency. Through coordination, agents ensure a more reliable energy supply and reduce wastage, thus maximising sustainability.

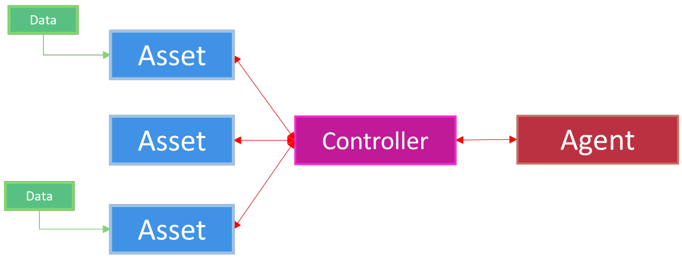


Figure 3.9: Agent integration in the ECDT architecture

The architecture of the ECDT platform has been carefully designed to facilitate a seamless transition across different domains, with an increasing level of abstraction. This can be observed in figure 3.9, where each agent in the Agents Layer possesses a specific portfolio of energy assets but does not directly interface with each asset. Instead, the agents rely on constant communication with the controllers responsible for managing their assets. These controllers provide the agents with structured information that simplifies their decision-making processes.

For instance, the GP controllers in the ECDT platform communicate important information to the agents, such as the total net, excess or deficit power, for each time step. This enables the agents to have an overview of the operation of their portfolio and make appropriate adjustments to their strategies. By receiving this information from the controllers, the agents can effectively manage their energy needs and make informed decisions.

This shows how within the ECDT platform the flow of information, which originates in the Environment Layer, undergoes several abstraction steps in the subsequent layers. This ensures that the information is correctly manipulated and processed within each domain. As the information flows through the layers, it becomes more structured and tailored to the specific needs of the different models, such as the agents or games. This hierarchical organization of information allows for an efficient and holistic representation of the ECs' dynamics.

3.6.1. Forecaster

In a structured co-simulation environment like the ECDT platform, an effective forecaster engine is crucial for providing the platform components with accurate forecasting capabilities. This was a significant focus of the thesis project, involving extensive research into various approaches to enable agents to anticipate the behaviour of the assets in their portfolios.

The challenge of incorporating forecasting capabilities stems from the heterogenic nature of energy assets, which often exhibit dynamic evolution of their states. One of the goals was to equip agents with knowledge about the future behaviour of assets right from the start of the simulation. Moreover, a key design criterion was to ensure deterministic knowledge, ruling out options based on hypothetical estimates. The objective was to eliminate any solution that would introduce uncontrolled errors, as this would severely impact the effectiveness and potential of the platform.

Instead, the emphasis was on developing a deterministic forecaster capable of determining the expected behaviour of assets with complete certainty, so to allow for unambiguous analyses. Moreover, the deterministic forecaster enables the gradual and targeted introduction of error, providing insights into the impact of errors on the overall operation.

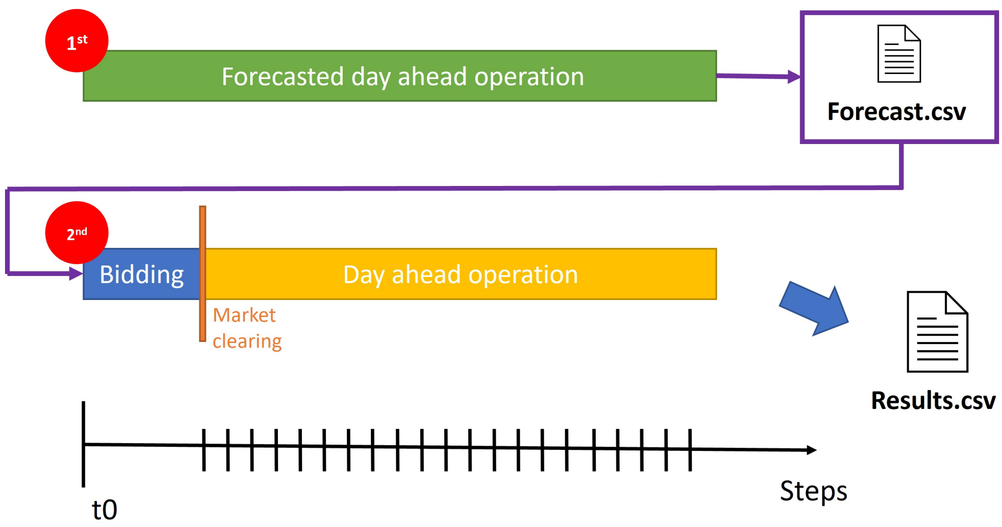


Figure 3.10: Deterministic Forecaster process

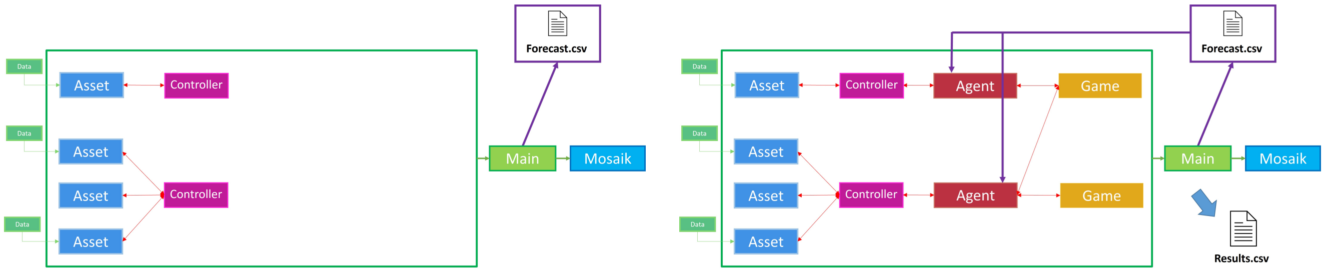
To successfully create a deterministic forecaster for the ECDT platform, it came to help the striking realisation that the platform can itself be used to forecast the future. In fact, the platform can be provided with forecasted weather conditions to predict, for instance, the production pattern of a PV system. This capability of simulating individual assets and determining their expected behaviour laid the foundation for developing a forecaster engine that leverages the ECDT platform in an iterative manner.

In fact, the co-simulation process in the ECDT platform consists of two distinct runs. The first run focuses solely on the physical assets, analyzing their behaviour and evolution. Therefore, during the first run, only the simulators within the study case related to the Energy Asset and Controls Layers are executed, excluding those from the Agents and Games Layers. This allows for tracing the behaviour of static physical systems and the state evolution of dynamic systems, which deeply depends directly on the control strategies implied. This is the case of the SoC of batteries evolving according to the specific logic of the connected controller. The results of this first run are stored in the *Forecast.csv* file in the Results repository.

In the subsequent step, the Main extracts the relevant curves from the results of the first run and assign each to the corresponding agent. This process involves determining the topology of the study case, so as to correctly provide each agent with the knowledge about the expected behaviours of the assets within their own portfolio. With this knowledge about the future, each agent gains a clear understanding of energy availability for the day ahead and can then proceed to schedule energy tradings right from the start of the second run. This includes the components of the study case from all the Layers of the ECDT platform so that the case is completely simulated and the final results can be examined.

3.6.2. Prosumer

The Agents Layer was populated by a multivalent simulator called Prosumer. It is capable of owning and managing all possible portfolios of energy assets, behaving as a consumer, if it only owns loads, as a producer, if it owns renewable energy assets, and as a prosumer, if it owns both. The Prosumer model was developed according to a classical Bliefs-Desires-Intentions (BDI) paradigm, which are fundamental psychological concepts of human cognition. As ex-



(a) First simulation run

(b) Second simulation run

Figure 3.11: Simulation runs schematics

plained by Kinny et al., 1996, beliefs represent the agent's knowledge about the world, including information about its environment, other agents, and its own internal state. Desires represent the agent's goals or preferences, indicating what the agent wants to achieve or obtain. Intentions, on the other hand, represent the agent's plans or commitments to perform certain actions in order to achieve its desires.

In the Agents Layer, the Prosumer's beliefs are encapsulated in the memory of each instance. At each simulation step, the prosumer instance receives up-to-date information from the connected controller, ensuring that it has a comprehensive understanding of the present state. This information is stored and forms the basis of the prosumer's past knowledge. However, the beliefs about the future are the ones that primarily drive the actions of the prosumer. These future-oriented beliefs are derived from the forecaster engine, as described in the previous section, which provides the prosumers with insights into the expected behaviour of their energy assets.

The Prosumer's desires in the ECDT platform are shaped by the metrics used for participation in the various games. During the configuration phase, specific values for these metrics can be specified for each prosumer instance, so that they can be used to formulate bids for energy trading. The chosen metrics can vary depending on the objectives of the prosumer. For example, economic metrics can be used to maximize revenue and minimize costs, guiding the prosumer's decisions towards optimizing their financial outcomes. On the other hand, environmental impact metrics can be employed to minimize the prosumers' carbon footprint, influencing their choices towards more sustainable energy practices. By adjusting these metrics, the prosumer can align their actions and decision-making processes with their desires.

As said, metrics play a crucial role in formulating supply or demand bids that agents can submit to participate in various games. To illustrate this process, let's consider an instance of a Prosumer with two generators. The formulation of supply bids can be broken down into the following steps:

- Analyzing the expected *excess* power available for sale within a specific *time* frame.
- Assigning specific metrics to each production asset based on user-defined parameters. For example, we can assign the marginal cost MC_1 to generator 1 and MC_2 to generator 2, assuming MC_1 is less than MC_2.
- Analyzing the expected power output of the generators, denoted as P_1 and P_2. Based on the analysis, two scenarios can arise:
  - a. P_1 is greater than the excess power. In this case, the Prosumer can attempt to sell the entire excess power at the lowest marginal cost (MC_1). The bid will be formulated as:

$$[\textit{time}, \textit{excess}, MC_1]$$

  - b. P_1 is less than the excess power. In this case, the Prosumer can only sell P_1 at MC_1, and the remaining excess power will need to be sold at a higher price MC_2. Therefore, two bids are formulated:

$$[[\textit{time}, P_1, MC_1], [\textit{time}, \textit{excess} - P_1, MC_2]]$$

In the ECDT platform, the intentions of Prosumers are shaped by the interaction protocols established with the implemented games. These protocols consist of communication phases designed to meet the requirements of the game structure. The flexibility of each Prosumer lies in the choice of the order and number of communications, allowing the platform to accommodate different intentions of game participation.

Furthermore, Prosumers have the freedom to allocate their resources or energy needs differently. For example, one Prosumer may choose to invest its entire energy surplus in a single game, while another Prosumer may allocate its resources to multiple games simultaneously. To capture this heterogeneity while ensuring scalability and flexibility, the Prosumer simulator in the ECDT platform was designed with a special structure.

Within the Prosumer simulator of the ECDT platform, an abstract class was created to house the initialization and game interaction methods. This abstract class also features the abstract method *play()*, which serves as the foundation for implementing the prosumer strategy. By extending the abstract class and implementing the *play()* method, subclasses were developed to represent specific prosumer strategies. Each subclass defines a unique sequence of method calls to participate in the different games, reflecting the prosumer's decision-making process. This design approach allows the ECDT platform to accommodate diverse prosumer strategies, catering to the varied preferences, objectives, and constraints of different agents.

The design choice to decouple the implementation of game interaction methods from their calling process minimizes code redundancy and enhances scalability. Indeed, introducing a new game in the ECDT platform only requires defining a new participation method in the abstract class and including its call in the relevant subclasses. This modular approach allows for easy extension of game functionalities without impacting the overall structure of the Prosumer simulator.

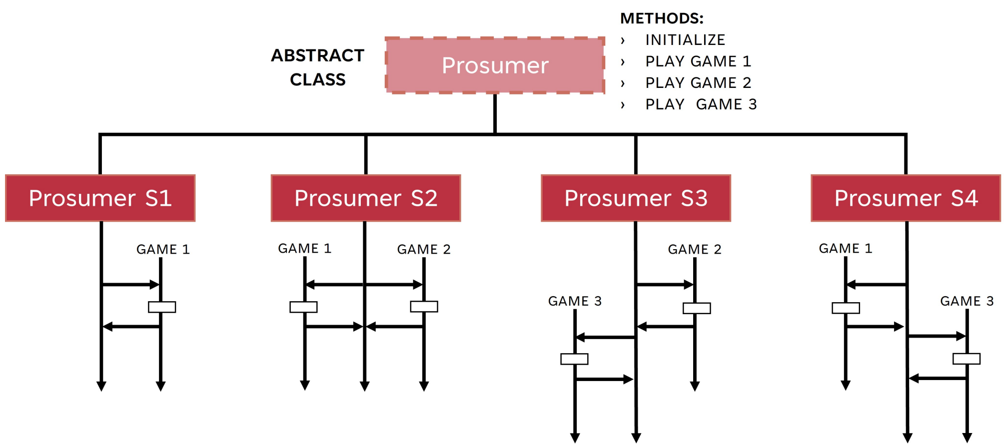


Figure 3.12: Prosumer simulator structure

3.7. Games Layer

The Games Layer plays a crucial role in the ECDT platform, as it enables the modelling and simulation of various energy-related games that may exist within an EC. This layer encompasses different types of Games simulators that replicate the interaction among different agents, according to specific rules and mechanisms.

One of the key objectives of the Games Layer is to enable the analysis and optimization of energy transactions and resource allocation among agents. By simulating different game scenarios, users can assess the economic efficiency, environmental impact, and overall system performance within the EC. The Games Layer also allows for the evaluation of different policy interventions, market mechanisms, and regulatory frameworks to understand their impact on agent behaviour and system-level outcomes.

In the next sub-sections, three types of games within the Games Layer will be illustrated: the Electricity Market, P2P Trading, and RT price. These games have been selected as they effectively capture various dynamics of energy trading and represent three distinct types of interactions: Many-to-Many, One-to-One, and One-to-Many.

By including these three types of games within the ECDT platform, it becomes possible to study and simulate a wide range of energy trading dynamics and interactions. These games offer flexibility in representing different market structures, transactional models, and pricing mechanisms, enabling users to explore various scenarios and evaluate the performance of different trading strategies within ECs.

3.7.1. Electricity Market

The Electricity Market (EM) simulator attempts to replicate the basic mechanisms of electricity markets. It is a MIMO simulator as it can receive information from various agents and can send different messages to each of them. The communication protocol between the agent and EM is depicted in figure 3.13. Following the bid formulation process, explained in section 3.6.2, each agent sends the bids to the EM, where they are collected in Pandas data structure. At the end of the bidding period, the clearing function is called for each of the time periods of the day ahead.

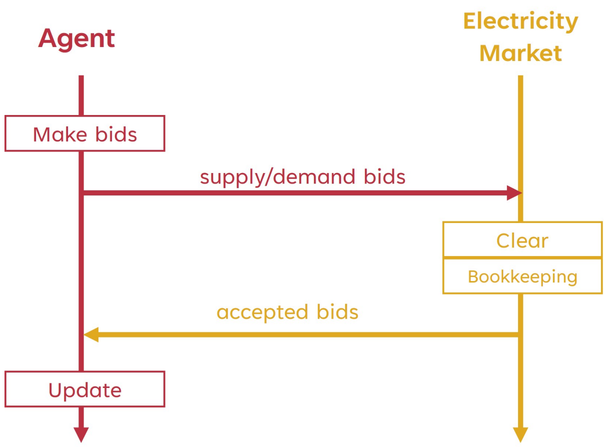


Figure 3.13: Communication protocol between agent and EM

The EM clearing mechanism aims to match the total electricity supply with the total electricity demand, determining the equilibrium price and quantity of electricity traded in the market.

The clearing process in the EM of the ECDT platform begins with the sorting of submitted bids based on their prices. This sorting creates the supply and demand curves, with the lowest price supply bid and the highest price demand bid considered first, respectively. The sorting of bids based on prices establishes the order in which the bids will be evaluated during the market clearing process.

Once the bids are sorted, the market clearing mechanism compares the total quantity of electricity offered by sellers with the total quantity demanded by buyers at each price level. Starting from the lowest bid price, the mechanism determines the quantity of electricity that can be traded at that price. This process continues until the quantity supplied equals the quantity demanded, reaching the point of equilibrium where the supply and demand curves intersect.

At the point of intersection, the market clearing price is determined. This price represents the equilibrium price at which all transactions can be executed without any excess supply or unmet demand. It reflects the agreed-upon price at which buyers are willing to purchase and sellers are willing to sell electricity.

After the market clearing process, the resulting market clearing bid, along with its corresponding partial quantity traded, is appropriately identified. The market clearing price, quantity, clearing bid, and partial quantity are the variables returned by the clearing method.

The market clearing function in the EM has been designed to handle various scenarios, including cases where the supply and demand bids do not intersect. This ensures that the clearing process can handle special situations and provide accurate results even in complex market conditions.

Following the clearing operations, the EM model performs bookkeeping operations to record and track the outcomes. This includes saving the results in a CSV file, which provides a comprehensive overview of the submitted bids, accepted bids, total cost, and total revenues for each participating agent. This record-keeping feature allows for transparent tracking and analysis of market transactions, enabling further evaluation from the users.

Upon completing the bookkeeping operations, the accepted bids are accurately communicated back to the participating agents. This step is crucial as it enables each agent to identify the energy trades that have been executed and update their knowledge about future power surpluses and deficits. By receiving this information, agents gain insights into their trading outcomes and can make decisions regarding unmet bids.

Overall, the ECDT platform's EM ensures a robust and reliable market-clearing process and enhances transparency and accountability, thus enabling users to assess the performance and investigate market-related dynamics.

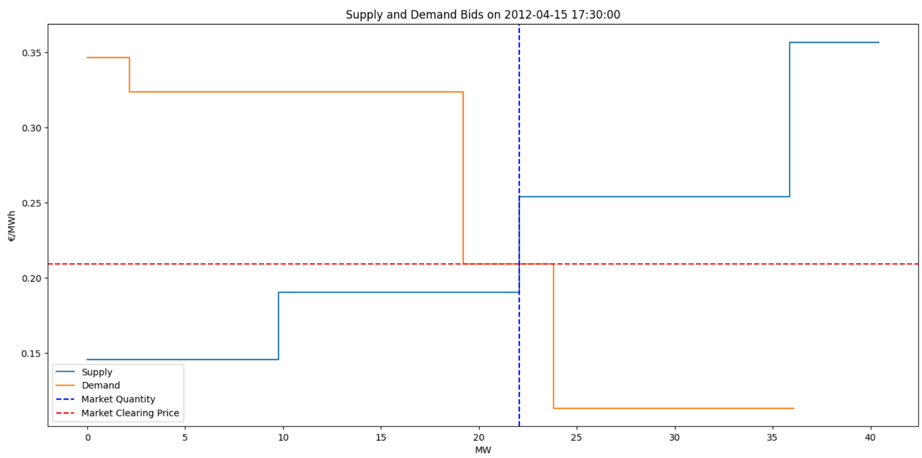


Figure 3.14: EM clearing in the ECDT platform

3.7.2. P2P Trading

Peer-to-peer (P2P) energy trading is a promising approach for decentralized energy exchange among users in a community or microgrid. It allows for the direct exchange of energy between peers without the need for intermediaries (Guerrero et al., 2018).

By participating in local P2P electricity trading mechanisms, households can benefit from reduced electricity costs through direct trading with their peers within a specific community or neighbourhood (Y. Wu et al., 2023). They can sell excess energy they generate from renewable sources to neighbours who may have a higher demand or who prefer to source their energy locally. This not only promotes the use of renewable energy but also fosters a sense of community and cooperation among participants.

Moreover, local P2P electricity markets contribute to the overall stability and resilience of the electricity distribution and transmission systems. By enabling local balancing of electricity supply and demand, these markets help to alleviate strain on the grid, reduce transmission losses, and minimize the need for costly infrastructure upgrades (Guerrero et al., 2018).

Although these types of energy trade mechanisms are widely investigated in the literature, each has its own unique peculiarities and there are no widely established methods yet. Therefore, the ECDT platform was equipped with a P2P Trading simulator that could adapt to this heterogeneity, providing a blue-print for the implementation of new and different methods.

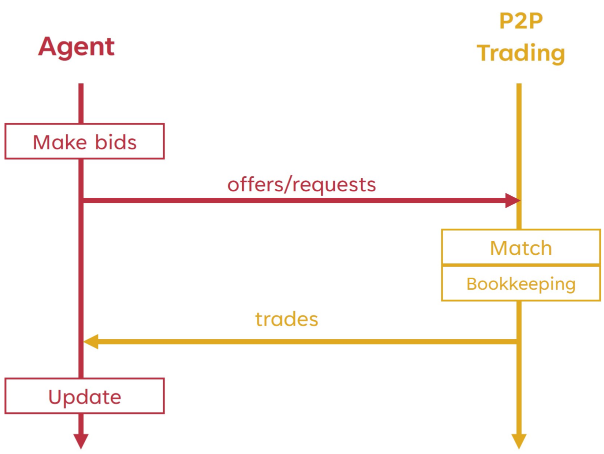


Figure 3.15: Communication protocol between agent and P2P Trading

Similar to the EM simulator, the P2P Trading simulator operates as a MIMO system that receives supply and demand bids, referred to as offers and requests, from participating agents, and informs each of them, about the executed transactions. Each bid is characterized by the capacity that an agent is willing to provide or receive at a chosen price and a specific time for the following day. It is important to note that this price can be more than just a monetary value. Indeed it is possible to imagine coupling P2P Trading with carbon credit mechanisms, aimed at encouraging environmentally responsible energy behaviour as proposed by Y. Wu et al., 2023.

As shown in figure 3.15, the P2P Trading model, after receiving the bids, performs a matching operation. As depicted in figure 3.16, each request is examined individually, and the simulator assesses the availability of bids that can meet its requirements. If there is at least one offer capable of fully or partially satisfying the request, a transaction is executed. In cases where a request has multiple feasible offers, the one with the smallest price is considered first. The price of the transaction is determined by the price of the request itself. This approach ensures that consumers' energy security is maximized, while simultaneously incentivizing the active participation of energy producers.

After the matching process in the P2P Trading simulator, a dedicated bookkeeping section comes into play. This section carefully analyzes the list of transactions that have taken place, calculating the total costs and revenues for each participating agent. The results of these calculations are then saved in a CSV file, providing a comprehensive record of the trades made by each agent.

Furthermore, the simulator ensures that the updated information regarding the trades is sent back to the respective agents. This step is crucial as it allows each agent to adjust their knowledge about the future based on the transactions that have occurred. By receiving this information, agents can make informed decisions and update their strategies for future trading activities.

Overall, the P2P Trading simulator enables the study of the effects of direct energy exchanges among participants, facilitating the exploration of local energy trading schemes that enhance energy resilience within communities.

Transactions

Request	Offer	Capacity	Price
Agent 0	Agent 1	30	80
Agent 0	Agent 2	70	80

Figure 3.16: P2P bids matching mechanism

3.7.3. Real-time Price

The Real-Time (RT) price simulator of the ECDT platform enables the representation of different types of energy tariffs for buying and selling energy. This simulator facilitates Many-to-One interactions, where multiple agents enter into contracts with an energy provider to determine energy rates. The RT price simulator allows the platform to simulate various energy contracts, each characterized by different pricing mechanisms.

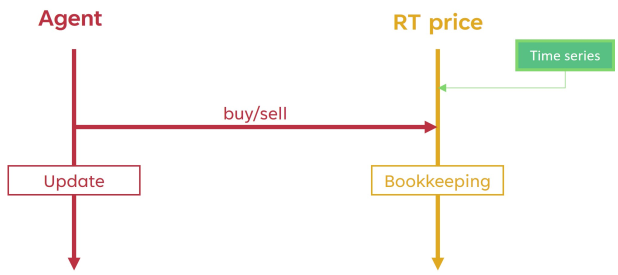


Figure 3.17: Communication protocol between agent and RT Price

One type of energy contract is the constant rate, where the price for buying and selling energy remains fixed and predetermined. Such contracts are often seen in retail agreements. Another type of contract is the scheduled rate, where the price varies according to a specific schedule, typically distinguishing between off-peak, shoulder, and peak hours. The scheduled rate contracts offer more flexibility in price adjustments based on time of use. Lastly, the RT price simulator can also handle completely dynamic pricing, as observed in energy markets, where the price fluctuates in real-time based on supply and demand dynamics.

To accommodate the diverse range of tariff options, the RT price simulator can draw price time series from a CSV file. This feature enables the platform to conduct tests using real-time series or energy bills, allowing the study of the EC's behaviour under different scenarios and the assessment of financial flows for each agent.

Similar to other games in the ECDT platform, the RT price simulator includes a dedicated bookkeeping section. This allows for tracking the quantities bought and sold, as well as the total costs and revenues, for each agent participating in the real-time price market. This bookkeeping function is essential for evaluating the performance of different agents, understanding market dynamics, and making informed decisions related to energy trading within the community.

In summary, the RT price simulator is a crucial tool that enables the ECDT platform to represent various energy rate structures and assess the financial implications of different energy contracts.

Figure 3.18: Example of a real price time series from Europe Power Exchange (EPEX)

3.8. Configuration

The configuration process of the ECDT platform involves several steps, each contributing to the definition of the study case. This is achieved through the utilization of three key files: *config.xml*, *connection.xml*, and *buildmodelset.py*, accompanied by XML and Python formats.

The *config.xml* file serves as a reference matrix, providing Mosaik with essential information about each simulator involved in the study case. This includes details such as the simulator's name, programming language, and specific location. By leveraging this file, the platform can accurately identify and incorporate the necessary simulators into the study case.

The *connection.xml* file defines the interconnections between the different instances of the models whithin the study case. It presents a matrix format that specifies the sender and receiver names, as well as the attributes being sent and received. This connection matrix, utilized in the Main file, assists in determining the number of entities for each simulator and it is used to correctly call the Mosaik Scenario function *connect()*, which informs the engine of the topology of the studycase

The *buildmodelset.py* file holds the parameters for each simulator. It is imported into the Main file and used to instantiate the models with the appropriate setup. This file allows for the specification of various parameters related to physical energy assets, like the initial SoC of batteries or the rated power of wind turbines. Additionally, economic parameters, such as the marginal cost or benefit of each asset in agents' portfolios, can also be defined among the available parameters.

Through the utilization of the *config.xml*, *connection.xml*, and *buildmodelset.py* files, the ECDT platform offers a highly flexible and intuitive configuration process. Researchers can explore different combinations of simulators, test various interconnections between models, and analyze the outcomes of ECDTs with different settings.
This modular approach to configuration empowers researchers to define various scenario configurations without the need to hardcode specific details. By leveraging the provided simulators and models, the ECDT platform offers flexibility in investigating different aspects and configurations, facilitating the creation of Digital Twins for diverse real-world cases. This capability opens up new possibilities for researchers to explore and analyze various domains, gaining insights into the behaviour and performance of ECDTs under different conditions.

The ECDT platform offers multiple approaches to facilitate the configuration process. While the configuration and connection matrix can be directly written in Python files, the platform goes a step further by incorporating a user-friendly approach inherited from The Illuminator. This approach allows users to define their simulation cases by visually drawing them in an online workspace or using tools like PowerPoint.

The translation of these visual representations into the necessary XML format is achieved through the *readppt.py* file. This enables the schematic to be seamlessly utilized by the Main file of the ECDT platform. This flexible and intuitive configuration method showcases the platform's strong accessibility and scalability characteristics.

Looking ahead, the ECDT platform has the potential to further enhance its usability by incorporating a graphical user interface (GUI), as depicted in figure 3.19. Such a GUI would enable users to insert models into a workspace and define their connections in a straightforward manner. With the configuration process just needing the three mentioned files, the implementation of such a GUI is greatly facilitated. This scalability and adaptability of the platform pave the way for future enhancements aimed to make it accessible to a wider range of researchers and stakeholders.

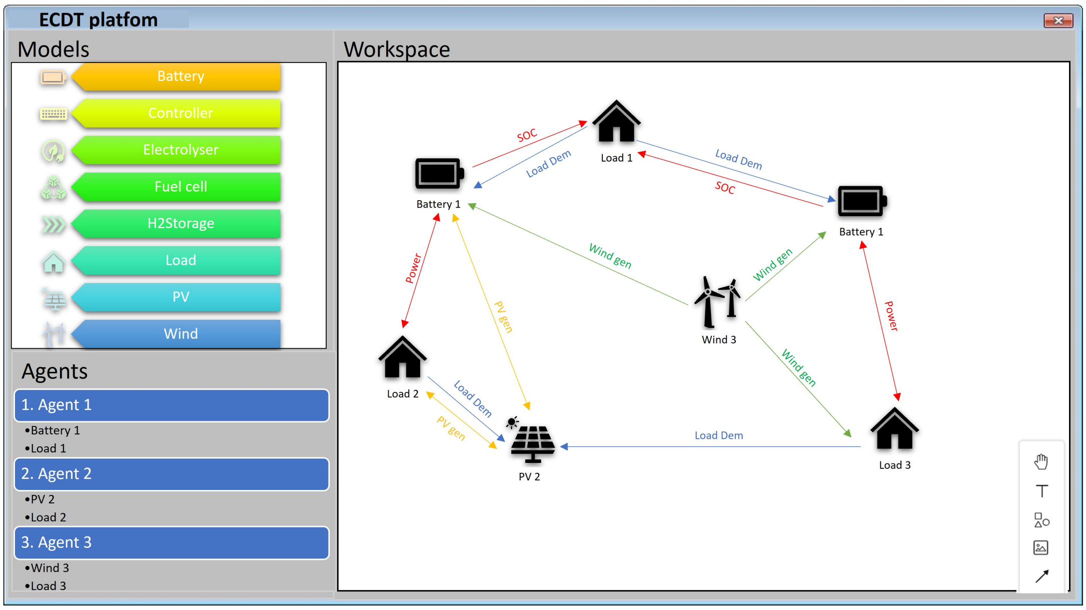


Figure 3.19: A possible GUI

3.9. Main

As described in earlier sections and chapters, the Main file serves a pivotal role within the ECDT platform. It acts as the central component responsible for interpreting the configuration files and facilitating the interaction with Mosaik for the configuration and initialization of the co-simulation. To provide a clearer understanding of the structure and functioning of the Main file, it can be dissected into the following key elements:

1. **Import**: The Main file begins with importing essential resources required for the program's functioning. One of the most crucial imports is *mosaik.util*, which provides methods for controlling and setting up the Mosaik environment. Additionally, the file imports other libraries such as *numpy*, which offers advanced mathematical functions and array manipulation capabilities, *pandas*, a powerful data analysis and manipulation tool, and *datetime*, which provides functionalities for working with dates and times.
   The Main file also includes the *wandb* library, which stands for "Weights and Biases". This library provides a platform for real-time monitoring and visualization of the co-simulation process. With the integration of the *wandb* library, researchers and users of the ECDT platform gain the ability to monitor the simulation progress, track performance metrics, and visualize the results in an online platform. This real-time monitoring capability enhances the overall experience of running simulations, as it allows for quick insights and analysis of the co-simulation process.
   Furthermore, the matrixes contained in the *config.xml* and *connection.xml* files are imported in pandas data frames with the method *read_xml()*, and the *buildmodelset.py* file is imported for access to the models' parameters.

2. **Set-up**: The Main file includes a section where several co-simulation configuration parameters can be modi-

fied according to the specific requirements of the simulation. One of these parameters is the start date, which informs the simulators about the beginning point from which the respective input time series should be analyzed. By specifying the start date, users can control the temporal scope of the simulation and ensure that the co-simulation is processed accurately.
Another important configuration parameter is the end date, which is used by Mosaik to determine the termination point of the co-simulation. By setting the end date, users can define the duration of the simulation and ensure that it runs for the desired time period.
Additionally, in this section of the Main file, users have the flexibility to specify the file paths of the CSV files that contain the various data series used in the simulation. By providing the correct file addresses, the ECDT platform can access and feed to each simulator the necessary data during the simulation run.

3. **Instantiation**: The next section of the Main file begins with the instantiation of the Mosaik world object, which is created by assigning the variable obtained by analyzing the *config.xml* file. This step sets up the foundation for the co-simulation environment.
   Following that, the program proceeds to analyze the connection matrix. This crucial step involves identifying the models being used and determining the number of instances for each model. By understanding the connections between the models, the program establishes the framework for data exchange during the co-simulation process.
   Among the models, the first one to be initialized is the collector. This simulator is responsible for tracking and recording the information exchanged between the various models throughout the co-simulation. With each step of the simulation, the collector transcribes the data into the *Result.csv* file and also sends it to the online Weight & Biases dashboard. This allows real-time monitoring and visualization of the co-simulation progress and results.
   Subsequently, each of the possible simulators and models must be initialised individually. This is done by calling the method *start()* of the world object specifying the name of the simulator that has to be instantiated. After that, the model instances are obtained by calling the *create()* function of the simulator. This method requires as input the number of instances to be created, as well as the start date and the model parameters. For clarity, the code for simulator 'Battery' is shown:

```
batterysim = world.start('Battery')
battery = batterysim.Batteryset.create(number, sim_start=START_DATE, params=Battery_params)
```

4. **Connection**: During this section of the code, the connection matrix is analyzed to establish the interconnections between simulators and models. Each line in the connection matrix corresponds to a connection between a sender and a receiver, with specific attributes being exchanged between them.
   To establish these connections, the *connect()* function of the world object is utilized. Within the *connect()* function, the sender, receiver, and exchanged attributes are specified. This information is crucial for informing Mosaik about the interconnections, enabling it to orchestrate the co-simulation process effectively.
5. **Execution**: The final portion of the Main file is dedicated to the execution of the co-simulation initialization command. This step is accomplished by invoking the *run()* method of the world object. The *run()* method takes parameters such as the end time of the co-simulation and a flag indicating whether it should be executed in real-time or not.
   By calling the *run()* method, the co-simulation process is initiated, and the simulators and models start exchanging data and progressing through time. This command enables the coordinated execution of the interconnected components within the ECDT platform, ensuring that the simulation progresses according to the defined parameters and time constraints.

4 Applications

This chapter aims to showcase the vast potential of the ECDT platform in facilitating a wide range of study cases, which can be represented by leveraging the platform's Degrees of Freedom (DoF) (section 4.1). Therefore, the primary purpose of this chapter is not to present specific analysis results but rather to provide a demonstration of the platform's capabilities.
In this context, the study cases presented in sections 4.2-4.4 represent specific scenarios carefully crafted to exemplify various research activities and policy impact evaluations, which can be enabled by the ECDT platform. These examples serve as illustrations of the versatile structure and functionality of the platform, demonstrating its capacity to support diverse analyses and investigations.

4.1. Degrees of Freedom (DoF)

The ECDT platform empowers researchers, policymakers, and stakeholders to conduct a wide array of studies, exploring the complex interactions and dynamics of ECs. By providing a realistic and customizable simulation environment, the platform offers valuable insights into optimizing energy systems, fostering sustainable practices, and enhancing the overall resilience and efficiency of ECs.

Based on the presented software architecture, some of the applications of the ECDT platform are:
Energy System Analysis:

- Realizing the DT of complex multi-energy ECs
- Monitoring and controlling EC operations in real-time
- Exploring optimal solutions for integrating energy assets in different ownership topologies
- Forecast or back-test the behaviour of ECs in specific environmental conditions
- Assessing the effects of control strategies on ECs operations

Policy Analysis and Decision Support:

- Fostering transparent and collaborative decision-making processes in ECs
- Analyzing the impact of different policy measures and regulatory frameworks on ECs
- Assessing the effects of decisions related to the change in the management of ECs

Game Theory and Behavioral Studies:

- Integrating MASs to capture stakeholders' behaviours and preferences
- Studying strategic interactions and outcomes among stakeholders within ECs
- Evaluating the effectiveness of energy trading schemes
- Assessing the financial flows of ECs' members in real-world conditions
- Exploring the possible factors influencing stakeholders' choices and cooperation patterns
- Investigate the social acceptance within ECs and their inclusivity

The versatility of the ECDT platform allows for endless possibilities as each of the described applications can be explored in combination with others. This aspect exponentially increases the potential uses and research opportunities that the platform offers. For instance, the ECDT platform can be utilized to study the influence of policies on the strategies adopted by agents in energy trading schemes throughout different seasons. By leveraging the platform's capabilities, researchers and policymakers can gain valuable insights into the complex interactions between various components.

The interconnectivity among the platform's Layers fosters a holistic approach to ECs analysis, making it possible to investigate the intricacies of trading schemes, the decisions of individual agents, the deployment of DERs and the application of advanced control strategies, all in an integrated manner.

The extensive versatility of the platform stems from its ability to capture the different domains of the EC multi-layered architecture and the implemented **DoF** that each layer offers. These are:

- **I. Environment Layer**
  - **I-A.** Modify environmental/external conditions
- **II. Energy Assets Layer**
  - **II-A.** Modify parameters of assets
  - **II-B.** Modify assets set
  - **II-C.** Modify assets ownership
- **III. Controls Layer**
  - **III-A.** Modify control strategy
- **IV. Agents Layer**
  - **IV-A.** Modify games participation
  - **IV-B.** Modify agents' strategy
- **V. Games Layer**
  - **V-A.** Modify games parameters
  - **V-B.** Modify games metrics

The study cases in the following sections aim to highlight the significance for research purposes of the ECDT platform's holistic architecture, also emphasizing the added value of representing its various domains. A key focus of these study cases is to demonstrate how modifications in one or more **DoF** can have simultaneous impacts across all the represented layers. This approach allows users to examine the cross-layer effects and interactions, illustrating how decisions and changes made in one domain can influence the overall operation and performance of the entire EC. Therefore, this chapter underscores the importance of the ECDT platform's comprehensive design, which enables a deeper understanding of the complex dynamics and interdependencies within an EC.

4.2. Study Case 1: Ownership Topologies

The first case study demonstrates how the ECDT platform can facilitate studies focused on evaluating the effectiveness of different ownership topologies within an EC. The study begins by establishing a base case (1A) as a reference, which represents a multi-agent EC with varying energy asset portfolios. Three additional Scenarios are then developed to assess the impact of introducing PV systems with different ownership topologies.

In Scenario 1B, the evaluation focuses on the introduction of household rooftop PV panels for each agent within the EC. This Scenario allows for an examination of the effects of distributed PV generation at the individual agent level.

Scenario 1C explores the introduction of a community-scale PV park, with a specific agent assigned the responsibility of trading energy within a medium-scale electricity market. This Scenario enables an assessment of the collective impact and market dynamics resulting from a centralized PV generation facility.
Scenario 1D investigates the introduction of an Aggregator that trades the excess energy produced by each agent in the medium-scale electricity market. This Scenario demonstrates how the flexibility of the ECDT platform allows for the representation of innovative forms of ownership and energy management.

The results of these Scenarios are meticulously documented and compared to the base case, showing how the ECDT can provide insights into the effects of different ownership topologies on the overall performance of the EC.

Importantly, it is noteworthy that these Scenarios were achieved without the need for any major hard code modifications to the ECDT platform. The Scenarios were constructed solely by utilizing the platform's configuration tools, such as defining the connection matrix and simulator parameters. This showcases the accessibility and effectiveness of the ECDT platform as a versatile tool for presenting and studying diverse case Scenarios within the context of ECs.

4.2.1. Scenario 1A: Base Case

Imagine a User who intends to use the ECDT platform to study how to introduce PV capacity in an EC called the Green Community.

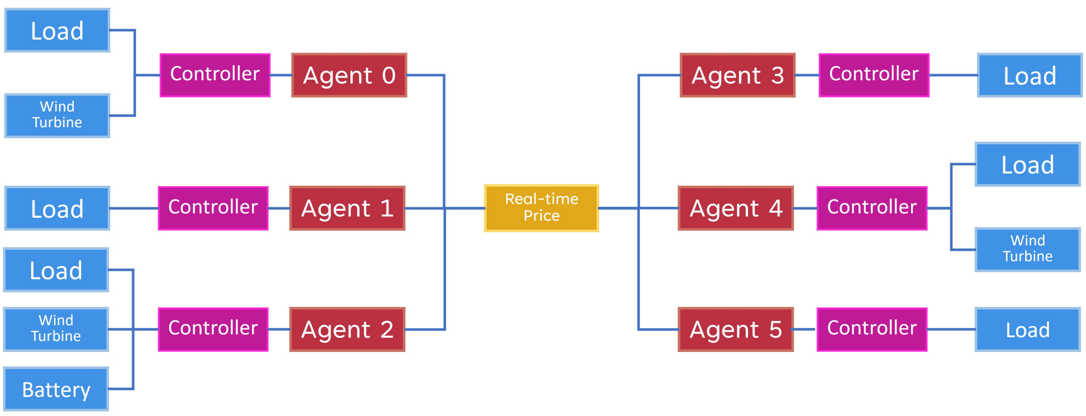
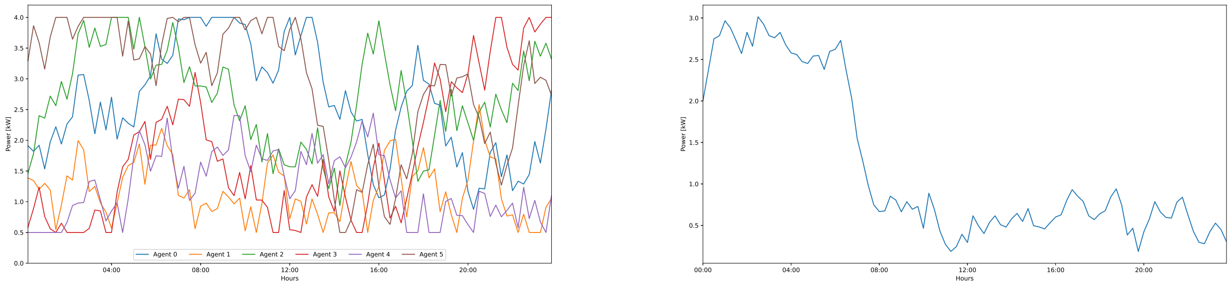


Figure 4.1: Scenario 1A: The Green Community

As depicted in figure 4.1, the base case comprises six agents, each with a distinct load profile representing their energy consumption patterns, as shown in figure 4.2a. Among these agents, Agents 1, 3, and 5 are simple consumers, while Agents 0, 2, and 4 are prosumers. The latter group possesses identical micro wind turbines, whose generating power profile is illustrated in figure 4.2b.



(a) Loads **(b)** Wind tubine

Figure 4.2: Consumption and production patterns

Notably, Agent 2 stands out due to its possession of a battery storage system, which serves as a buffer due to the peak-shaving logic integrated into the controller.

In this base case of The Green Community, each agent is engaged in the same contract with an energy provider, offering a dynamic tariff scheme with a sell-back rate equivalent to half of the buy rate for every time step, as shown in figure 4.3. The User could use **DoF I-A and V-A** to choose a different tariff or to examine the case on a different day.

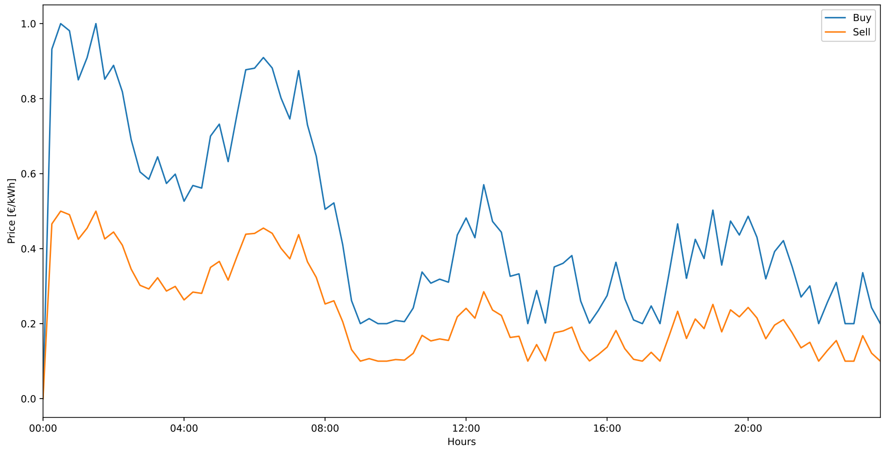


Figure 4.3: RT dynamic rates for Study Case 1

4.2.2. Scenario 1B: Household PV

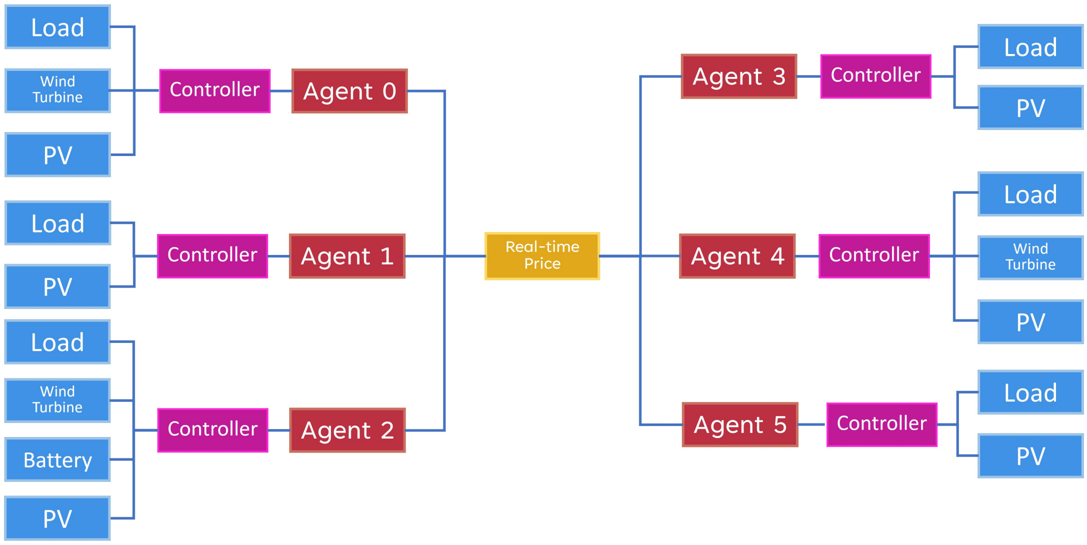


Figure 4.4: Scenario 1B: Household PV

The second Scenario involves assigning each agent an identical PV system installed on the rooftop of each household. The User can represent this situation by leveraging the **DoF II-B**. Each system has a rated power of 5kWp and under the climatic conditions considered the power production curve is shown in figure 4.5. While conducting this type of study, the User can leverage **DoF I-A** to test the PV asset in different environmental conditions.

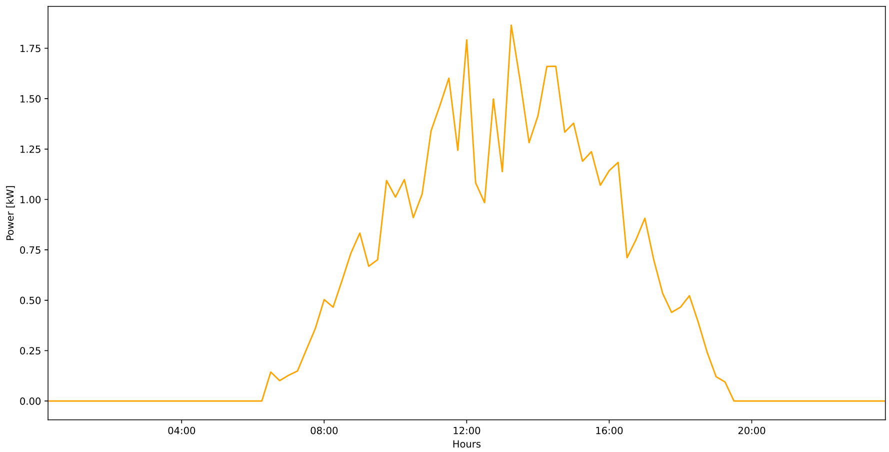


Figure 4.5: Housold PV system production curve

4.2.3. Scenario 1C: Community PV

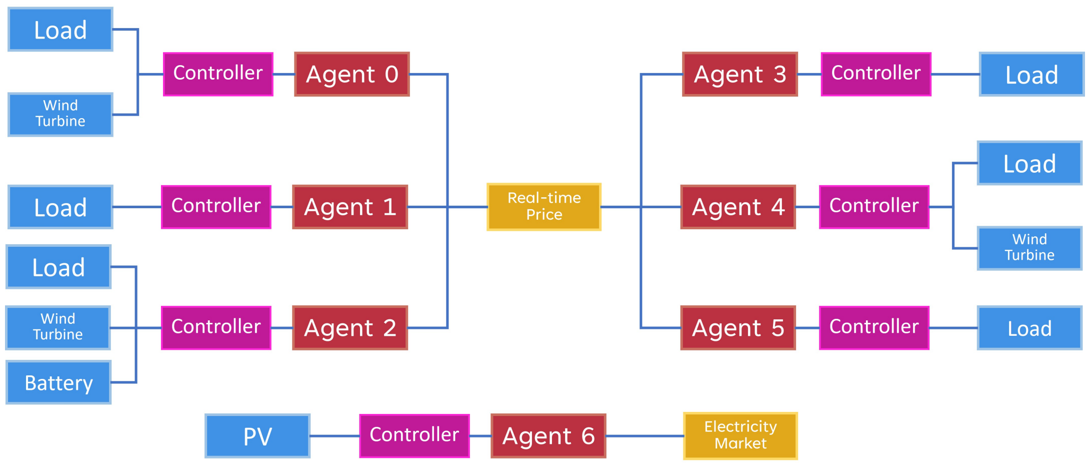


Figure 4.6: Scenario 1C: Community PV park

In the third Scenario, the User evaluates the introduction of a community-scale PV park with a rated power output of 30 kWp. Thi is possible due to the **DoF II-A**, which allows for the modification of assets' parameters. As a result, the power output of the energy generator asset is a scaled version of that of the PV household introduced in Scenario 1B, as shown in figure 4.7. The PV park is assigned to a seventh agent that implements the strategy of bidding on the energy produced in a small-scale electricity market. This change is facilitated by **DoF IV-A and IV-B**, which allow for the introduction of agents and the choice of their strategy, and it is done by simply customizing the connection matrix. The electricity market is pre-loaded with a set of initial bids, which can be chosen by the User thanks to the **DoF V-A**.

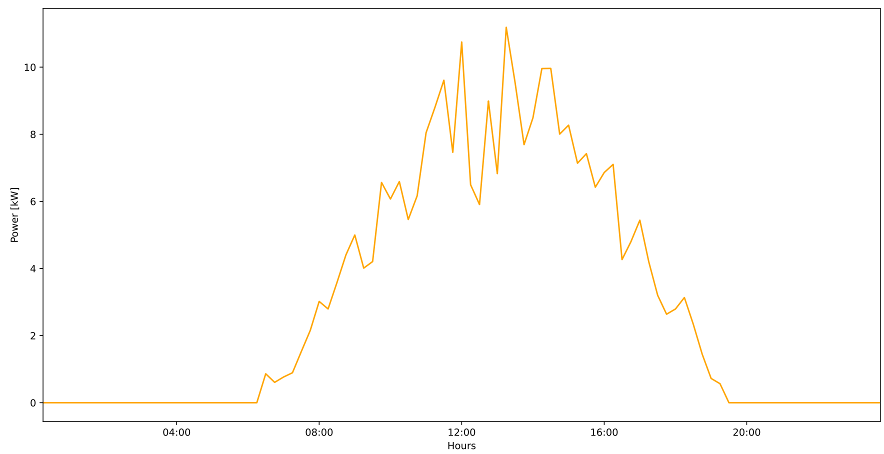


Figure 4.7: Community-scale PV park production curve

4.2.4. Scenario 1D: Aggregator

The User sets the fourth Scenario to evaluate the effect of introducing an Aggregator in the Green Community, which can trade the surplus energy of each member on the medium-scale electricity market introduced in Scenario 1C. This is done by adding a seventh Agent to the connection matrix of Scenario 1B and specifying the correct controllers' interconnections.

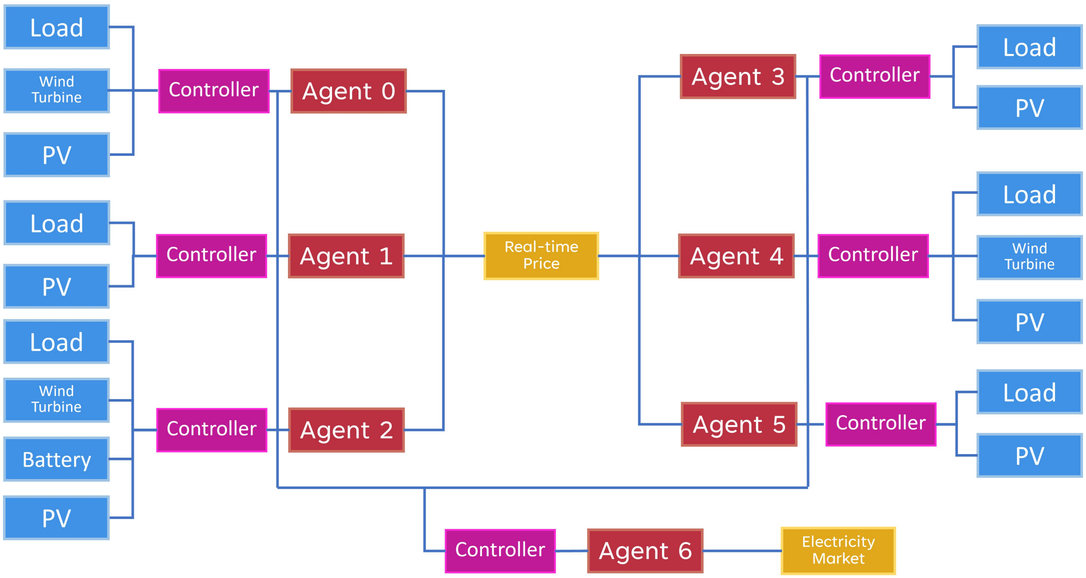


Figure 4.8: Scenario 1D: Aggregator

The Aggregator, during the simulation, sells the aggregated energy surplus, in figure 4.9, with the electricity market, bidding at MC equal to zero. The value of the Marginal Cost can be chosen by the User by specifying it the parameter configuration file, thanks to the **DoF V-B**. The market is preloaded with the same set of bids used in Scenario 1C.

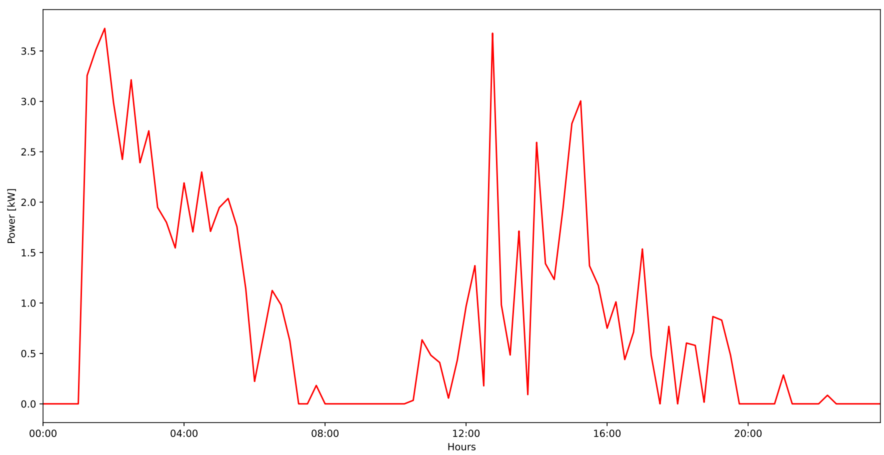
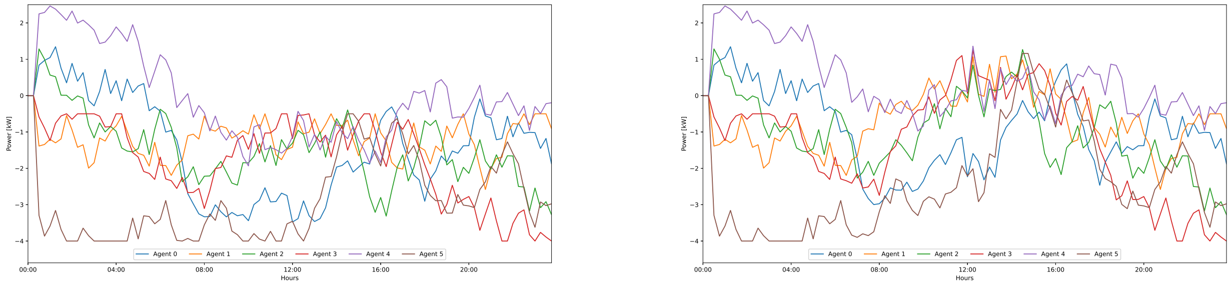


Figure 4.9: Power traded by the Aggregator in the electricity market

4.2.5. Results

The outcomes of the various runs can be visualized and compared using the online dashboard provided by the ECDT platform. When comparing the different Scenarios, a crucial factor to consider is the evolution of the net power for each agent. Figure 4.10a illustrates the net power for the six agents in Scenarios 1A and 1C, while figure 4.10b shows the same for Scenario 1B and 1D. The introduction of household PV systems in Scenario 1B leads to an upward shift in power patterns during the midday hours, resulting in energy surplus situations for all agents at various times.

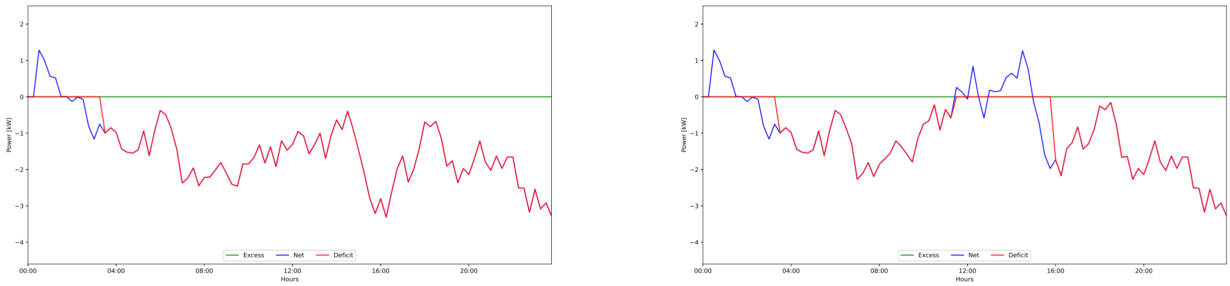


(a) Scenarios 1A-1C

(b) Scenarios 1B-1D

Figure 4.10: Evolution of the net power of the Agents

A closer examination of Agent 2, the only one equipped with a battery, provides interesting insights. Indeed, due to the presence of the battery, Agent 2 exhibits an unmatch between its net, excess, and deficit power, evident in all the Scenarios in figure 4.11.

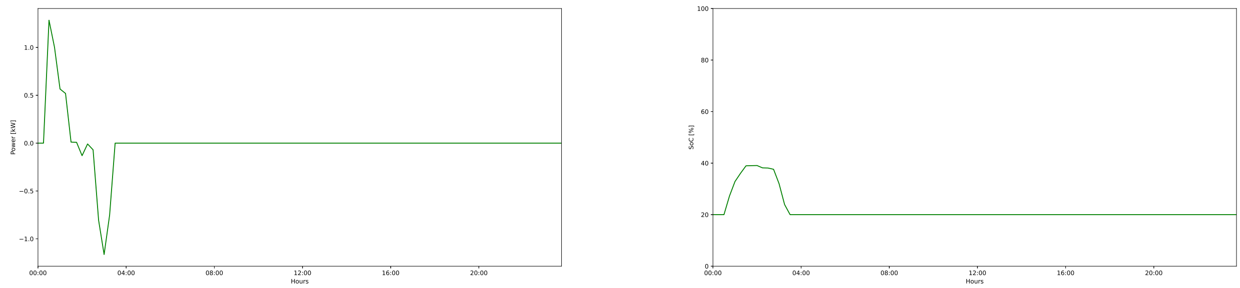


(a) Scenarios 1A-1C

(b) Scenario 1B-1D

Figure 4.11: Agent 2 net, excess and deficit power

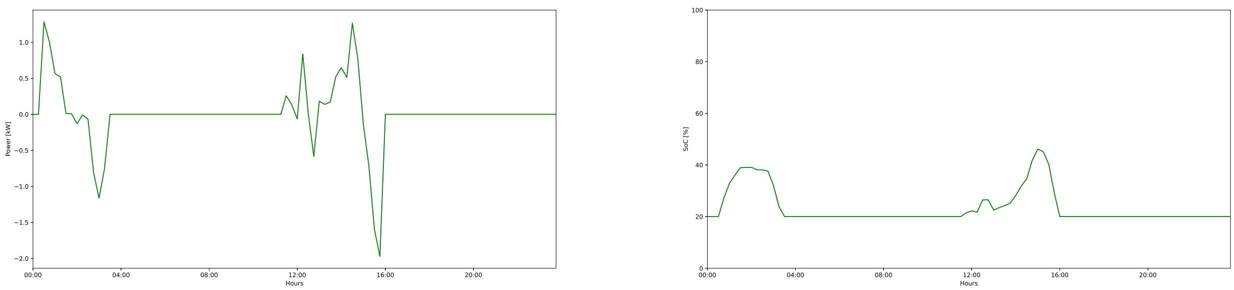
For Scenario 1A the charging and discharging power of the battery are depicted in figure 4.12a, and the evolution of the SoC over time is illustrated in figure 4.12b. From figure 4.11b it can be seen that the addition of the PV system is reflected in an increase in the net power of Agent 2 compared to the base case. This allows for an additional battery charging phase in the afternoon hours of the day under consideration, as illustrated in figure 4.13.



(a) Power flow

(b) SoC

Figure 4.12: Battery of Agent 2 in Scenario 1A and 1C



(a) Power flow

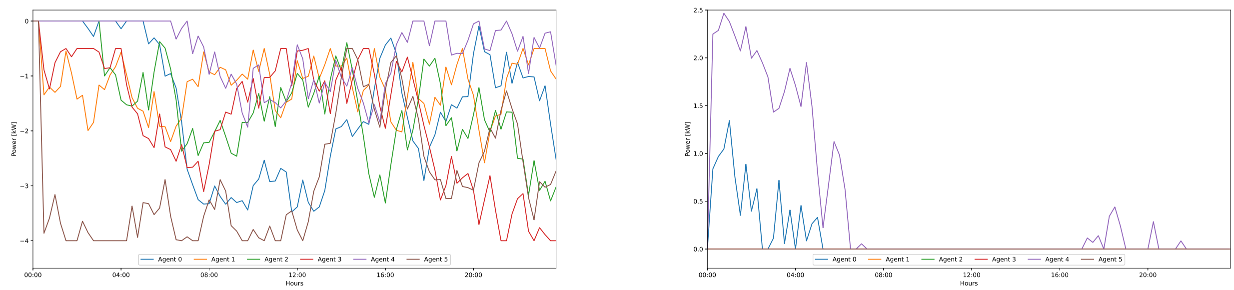
(b) SoC

Figure 4.13: Battery of Agent 2 in Scenarios 1B and 1D

The analysis of the effectiveness of the different ownership topologies is fostered by the possibility of representing the economic dynamics of the Scenarios under consideration.

Through the online dashboard, the User can visualise the amount of power sold or purchased by each member of the Green Community from the energy provider.

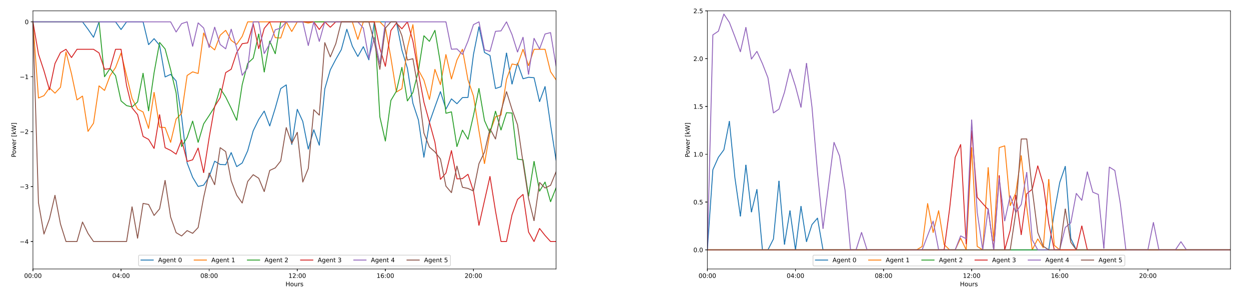
Comparing Scenario 1A, in figure 4.14, and 1B, in figure 4.15, it is possible to see a substantial increase in the amount sold and a decrease in the amount purchased by the agents owning a household PV compared to the base case. This is supported by the analysis of the total costs and revenues reported in table 4.1, which can be easily obtained by the User consulting the CSV files containing the RT Game results. Table 4.1, shows a significant decrease in the costs of each agent owning a household PV, also resulting in a net profit for Agent 4.



(a) Buy

(b) Sell

Figure 4.14: RT power exchange Scenario 1A



(a) Buy

(b) Sell

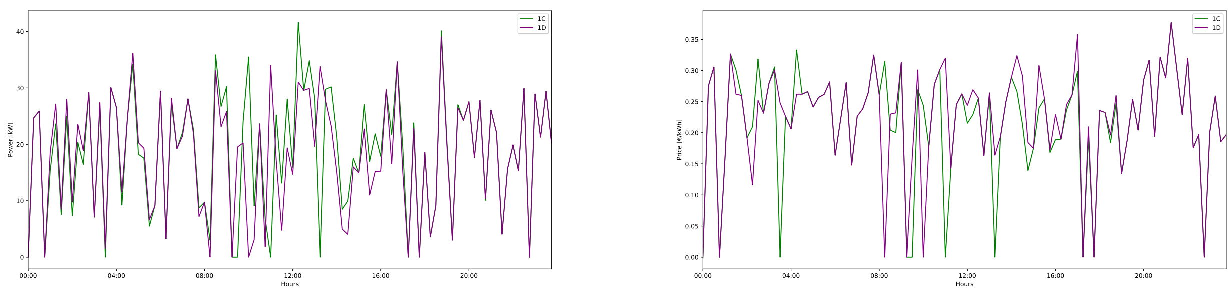
Figure 4.15: RT power exchange Scenario 1B

Table 4.1: RT price cashflow Scenarios 1A and 1B. [€]

	1A			1B			
Player	**Total Costs**	**Total Revenue**	**NET**	**Total Costs**	**Total Revenue**	**NET**	**VAR**
Agent 0	14.41	1.02	-13.39	10.70	1.10	-9.6075	28.26%
Agent 1	13.81	0.00	-13.81	10.98	0.35	-10.6225	23.10%
Agent 2	14.13	0.00	-14.13	10.32	0.00	-10.315	26.98%
Agent 3	18.82	0.00	-18.82	16.01	0.46	-15.5475	17.37%
Agent 4	4.36	4.11	-0.25	1.38	4.56	3.175	1381.50%
Agent 5	35.22	0.00	-35.22	32.43	0.16	-32.2725	8.36%
Community	100.74	5.13	-95.61	81.81	6.62	-75.19	247.59%

Through the dashboard, the User can analyze Scenario 1C noticing that the power exchange with the energy provider for Agents 0 to 5 is the same as Scenario 1A, shown in figure 4.14. On the contrary, Scenario 1D corresponds to Scenario 1B only for the power bought from the RT price game, shown in figure 4.15a. This is because the aggregated power excess, in figure 4.9, is completely traded by the Aggregator (Agent 6) in the electricity market.

To compare Scenarios 1C and 1D, the User can study how the electricity market quantity and price variate analyzing figure 4.16. Finally, the User can notice that the total revenues of Agent 6 are 56.98€ in Scenario 1C and 20.14€ in Scenario 1D.



(a) Quantity **(b)** Price

Figure 4.16: Evolution of the Electricity Market dynamics in Scenarios 1C and 1D

To enhance the analysis, the ECDT platform allows testing the Scenarios across different seasons of the year, enabling a comprehensive investigation of the Green Community's behaviour under diverse environmental conditions. The collected data provides valuable insights, empowering the User to develop and utilize essential metrics such as the Levelized Cost of Electricity (LCOE), Net Present Costs (NPC), and Return on Investment (ROI).

The LCOE metric offers a standardized approach to evaluating the average cost of electricity generation over the lifetime of energy assets. By considering the various ownership topologies, the User can identify the most cost-effective and sustainable options for energy production within the Green Community.

The NPC metric allows users to assess the total costs of a project, encompassing both initial investments and future revenues. By considering the present value of costs and returns over the project's lifetime, the User can make financially informed decisions regarding energy infrastructure investments.

The ROI metric helps gauge the profitability of specific investments within the EC. By analyzing potential returns and financial benefits under different scenarios, the User can prioritize investments that yield the highest returns.

Through the utilization of these metrics, the User can determine the most suitable ownership topology for the Green Community. The ECDT platform thus serves as an invaluable resource, enabling researchers, policymakers, and stakeholders to make well-informed decisions in EC planning.

4.3. Study Case 2

The second Study Case aims to demonstrate how the ECDT platform facilitates the study of introducing different trading mechanisms within an EC. Additionally, it allows investigation of the possibility of assigning different game strategies to each member of the EC. This setup enables an analysis that tests various trading patterns, considering different agents' attitudes while accounting for the physical dynamics involved in the case.

Building upon the findings from Study Case 1, suppose the User determines that the configuration of Scenario 1B is the optimal one for the Green Community. At this stage, the User can explore the introduction of two Games: a Local Electricity Market (LEM) and a P2P trading. To configure this Scenario, the User can utilize **DoF IV-A**, defining the connection matrix to realize the configuration shown in figure 4.17.

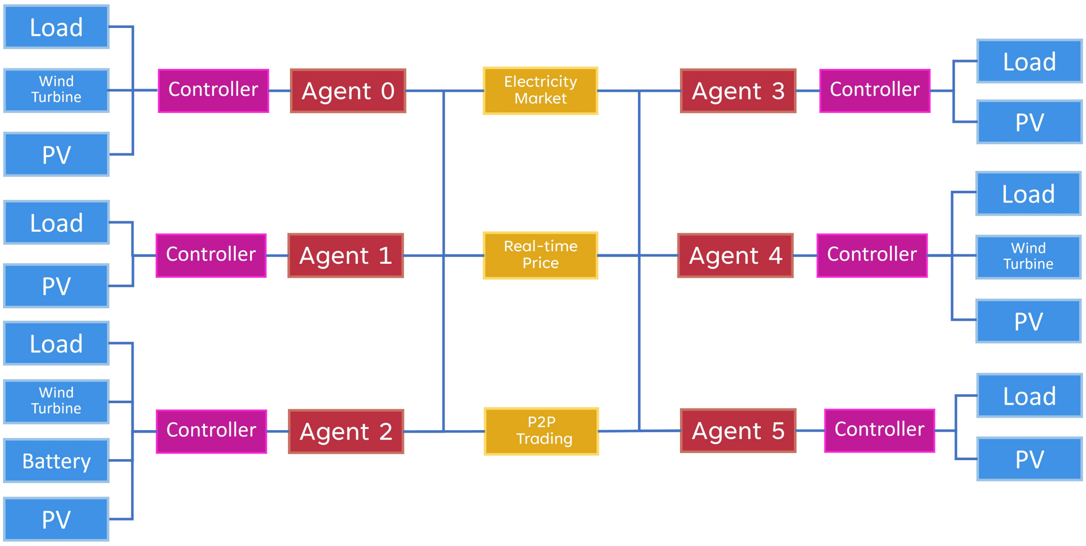


Figure 4.17: Study Case 2

The LEM is an instance of the Electricity Market simulator which is not preloaded with a set of bids. As a result, the clearing operations are solely determined by the bids sent by the EC's agents, thus enabling energy exchanges exclusively within the community.
In the Study Case under consideration, P2P Trading is configured as an alternative platform to classical forms of energy trading. It operates based on a system of credits that are appropriately assigned to agents, promoting and incentivizing sustainable practices. This approach encourages energy exchange and cooperation within the community, fostering the use of renewable energy sources and promoting energy resilience.

According to the BDI paradigm, each agent can be individually configured by the User, who has the flexibility to specify the values of the metrics for participation in the games. The Companion Modelling approach suggests that these metric values could be directly obtained from interviews or real-agent interactions, ensuring a more representative simulation. Table 4.2 presents the metrics adopted for the two Games.
First, in the LEM, two standard economic metrics are used: the Marginal Cost (MC), associated with each generator, and the Marginal Benefit (MB), representing the maximum value at which each agent is willing to pay to match their load.
Secondly, for P2P Trading, the metrics include the Marginal Offer (MO) and the Marginal Request (MR), which indicate the amount of credits at which each agent is willing to make energy transactions for each asset.

Table 4.2: Metrics adopted for Study Case 2

	Electricity Market [€]		P2P Trading [Credits]	
Player	**MC**	**MB**	**MO**	**MR**
Agent 0	0.07 -0.1	0.12	0.05-0.25	0.4
Agent 1	0.27	0.2	0	0.33
Agent 2	0.33-0.7	0.18	0.09-0.22	0.15
Agent 3	0	0.5	0	0.5
Agent 4	0.10-0.7	0.44	0.01-0.20	0.2
Agent 5	0.12	0.28	0.17	0.19

4.3.1. Scenario 2A: First LEM then P2P

In Scenario 2A, the User is testing the two introduced Games by assigning each agent the Strategy S1, as shown in figure 4.18. This strategy involves agents attempting to trade their entire amount of energy surplus and energy deficit in the LEM Game during the bidding phase. They are currently generating demand and supply bids, which are being sent to the game to initiate the clearing operations.

After the clearing process, the LEM sends each prosumer instance the accepted bids, allowing them to update their knowledge regarding their expected energy needs. Once these operations are completed, each agent seeks to trade the remaining expected energy surplus or deficit within the P2P trading mechanism. To do this, each agent is developing another set of supply offers and demand requests to be sent to this second Game. The P2P Trading Game then match the requests with the offers and send the feasible trades back to each of the agents, enabling them to update their expectations once again.

Throughout the phases of bidding, clearing, matching, and in moments where no trades were possible in either game, energy is being managed entirely through the RT price game, representing the tariff offered by an energy provider.

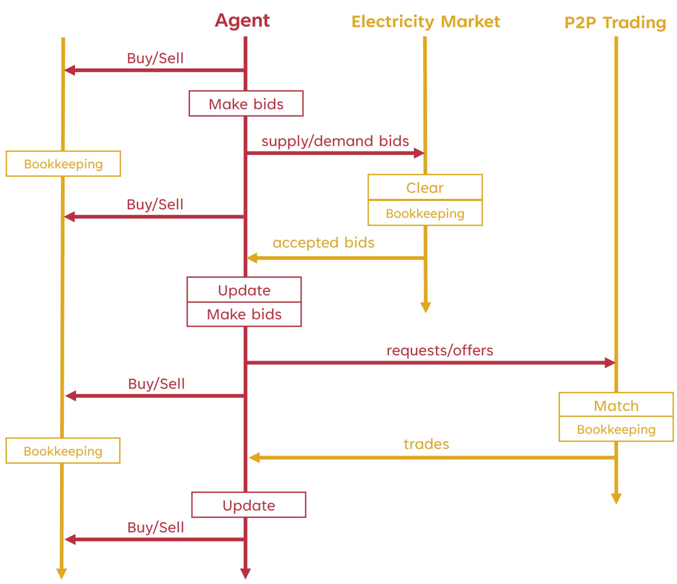


Figure 4.18: Strategy S1 of Scenario 2A

4.3.2. Scenario 2B: First P2P then LEM

In Scenario 2B, the User continues to explore the two introduced Games with a different approach, where each agent adopts Strategy S2, as depicted in figure 4.19. The possibility to assign different strategies to each of the agents is possible thanks to the **DoF IV-B**. The S2 strategy entails agents first engaging in P2P trading before participating in the LEM Game. This change in sequence alters the dynamics of the energy trading interactions and can lead to distinct outcomes compared to Scenario 2A.

During the bidding phase, agents now focus on trading all their energy surplus or deficit within the P2P trading mechanism. They develop supply offers and demand requests that are sent to the P2P trading game for matching. After the matching process, the feasible trades are returned to the agents, enabling them to update their knowledge and expectations based on the outcomes of P2P trading.

After completing the P2P trading phase, the agents proceed to the LEM Game, where they prepare new demand and supply bids. These bids are then submitted to the LEM Game to initiate the clearing process. Once the clearing is complete, the LEM communicates the accepted bids to each prosumer instance. As a result, the prosumers can update their knowledge about their expected energy needs based on the outcomes of the LEM Game clearing.

The RT price game acts as a fallback mechanism, ensuring that energy needs are met even when direct peer-to-peer exchanges or the LEM Game cannot fully satisfy the agents' requirements.

The integration of P2P trading before LEM Game participation introduces a different energy exchange sequence, potentially leading to varied trading patterns and resulting in diverse energy supply and demand scenarios within the Green Community.

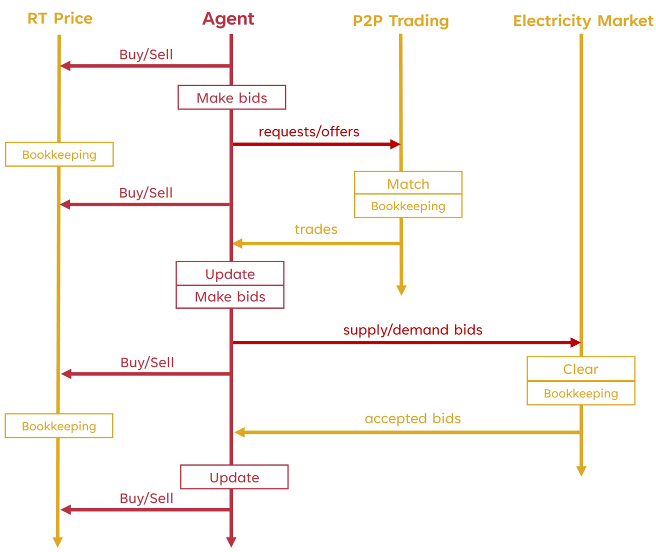
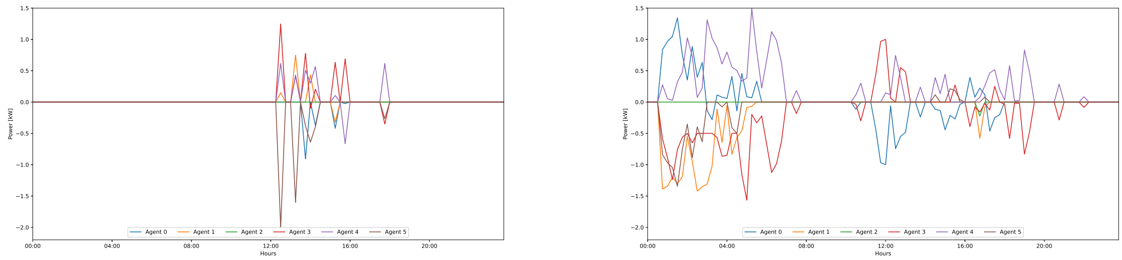


Figure 4.19: Strategy S2 of Scenario 2B

4.3.3. Results

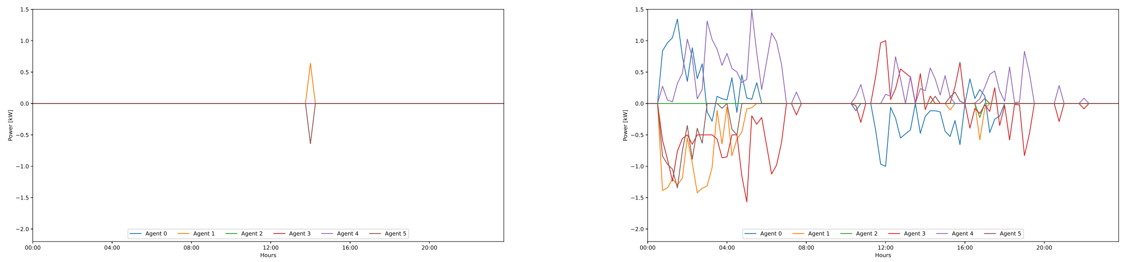
The results of the two scenarios presented above demonstrate the powerful capabilities of the ECDT platform in evaluating and comparing different energy trading strategies within the Green Community. Through the platform's flexible design and incorporation of various games, the User is able to explore the impact of different trading strategies on the overall community's energy dynamics and on the agents' financial outcomes.

In Scenario 2A, where the agents play the LEM Game first and then proceeded to the P2P Trading Game, the User observes how the bidding and clearing processes in the LEM influence the subsequent interactions in the P2P Trading Game in comparison with Scenario 1B. This is clearly visible comparing figure 4.20 with figure 4.21, where it is possible to appreciate the power exchanged by each agent in the two Games.



(a) LEM **(b)** P2P Trading

Figure 4.20: Scenario 2A power exchanges with LEM and P2P trading



(a) LEM **(b)** P2P Trading

Figure 4.21: Scenario 2B power exchanges with LEM and P2P trading

The quantities traded in the RT price, the quantities and prices in the LEM and the financial outcomes of agents in each game are shown in Appendix B.1 for Scenario 2A and in Appendix B.2 for Scenario 2B. The comparison of the financial outcomes in Scenario 2B versus 2A, shown in table 4.3, allows the user to have quantitative elements to determine the best strategy.

Table 4.3: Percentual variation of Scenario 2B compared to Scenario 2A

	Electricity Market [€]			**P2P Trading [Credits]**			**RT Price [€]**		
Player	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**
Agent 0	-100.00%	0.00%	100.00%	54.39%	0.00%	-327.05%	-3.27%	0.00%	3.27%
Agent 1	-100.00%	-52.04%	-46.29%	0.52%	0.00%	-0.52%	0.20%	10.92%	0.30%
Agent 2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Agent 3	-100.00%	-100.00%	-100.00%	1.77%	47.29%	4.85%	0.00%	113.96%	0.99%
Agent 4	-100.00%	-100.00%	-100.00%	0.00%	6.42%	6.42%	3.32%	0.00%	-3.42%
Agent 5	-86.89%	0.00%	86.89%	0.00%	65.20%	7.86%	1.72%	-9.40%	-1.77%
Average	-81.15%	-42.01%	-9.90%	9.45%	19.82%	-51.41%	0.33%	19.25%	-0.10%

From the results obtained, the User can clearly see that in Scenario 2A the amount traded in the LEM is greater than in Scenario 2B in which only one transaction is made. In economic terms, the comparison between Scenario A and Scenario B indicates an average decrease in NET economic flows, suggesting that Strategy S2 is, on average, less effective than Strategy S1. However, to gain a more comprehensive understanding, the User can conduct a detailed analysis by studying the individual performance of each agent. This approach allows the User to determine which strategy is best suited for each specific agent in the Green Community.

By examining the economic outcomes of each agent under different strategies, the User can identify patterns, trends, and variations that may not be apparent in the aggregated results. This level of granularity offered by the ECDT platform enables the User to tailor the best trading mechanisms and strategies to better suit the unique characteristics of the EC. Consequently, the ECDT platform provides a powerful tool for optimizing the energy ecosystem within the Green Community, ensuring that the chosen strategies align with the individual goals and requirements of its members.

4.4. Study Case 3

The third Study Case demonstrates how the ECDT platform's holistic architecture enables the evaluation of control strategies' impact on EC dynamics. Specifically, the focus is on understanding the cross-layer effects resulting from changes in the Controls Layer's logic and functioning. In particular, the focus is on how the development of a control algorithm sensitive to a dynamic tariff generates chain effects that propagate both in the lower Energy Assets Layer and in the upper layers, i.e. the Agents Layer and the Games Layer.

To this aim, let's suppose that the User, seeking to expand the analysis of the Green Community from Scenario 1B, decides to explore a different market condition not previously considered in Study Cases 1 and 2. In this new scenario, the User investigates the behaviour of the community and its financial outcomes when the RT price (shown in figure 4.22) becomes negative at certain times of the day.
This situation often arises in areas with high renewable energy penetration and insufficient energy infrastructure. During periods of excessive renewable energy generation, grid congestion may occur, leading to negative market prices. This creates a paradoxical situation where users are paid to consume energy from the grid and are required to pay for injecting their excess power back into it.

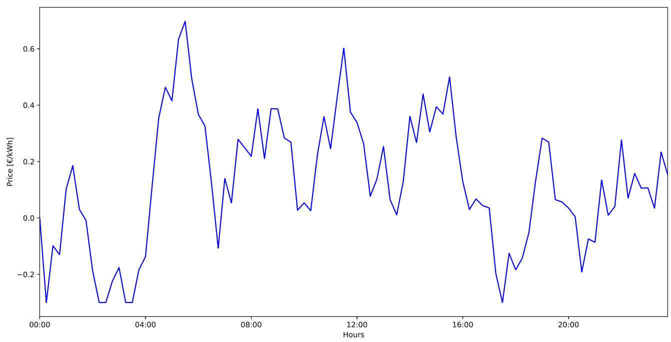


Figure 4.22: RT dynamic rates for Study Case 3

Given the significance of this scenario for policy-makers and market stakeholders, the User aims to develop a control mechanism that enhances agents' flexibility in response to negative prices. Prosumers also have a vested interest in adapting their energy management strategies to minimize costs and maximize revenues under such conditions.

To address this, the User implements curtailment logic in the Energy Management Systems (EMSs) of the Green Community, leveraging the **DoF III-A**. The algorithm, depicted in figure 4.23, allows the EMSs to adapt their energy management based on two regimes depending on an input ON/OFF signal sent by an Energy Provider or Grid Operator.

When the signal is OFF, meaning normal operation condition. the EMS controls the battery as an energy buffer, charging it during surplus periods and discharging it to meet agent consumption needs. If the battery is fully charged or discharged, the EMS determines the energy surplus and deficit.
On the other hand, when the signal is ON, indicating negative prices, the EMS resets renewable energy production to zero and eventually maximizes consumption by charging the battery.

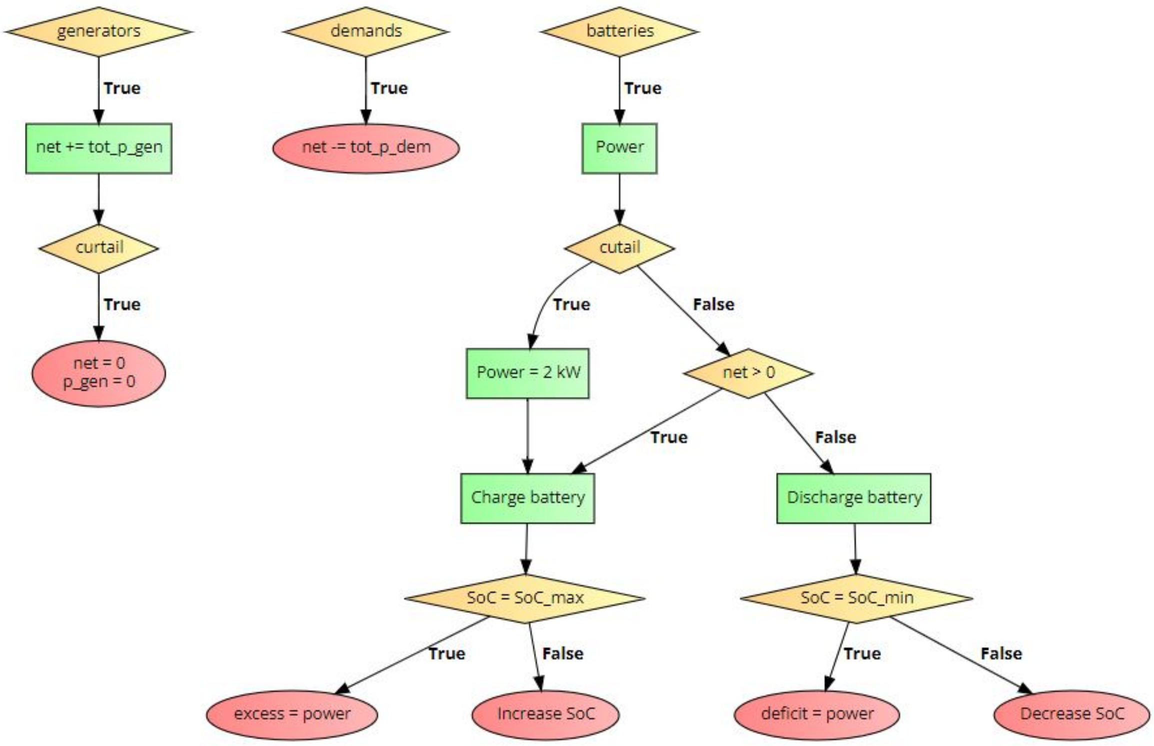
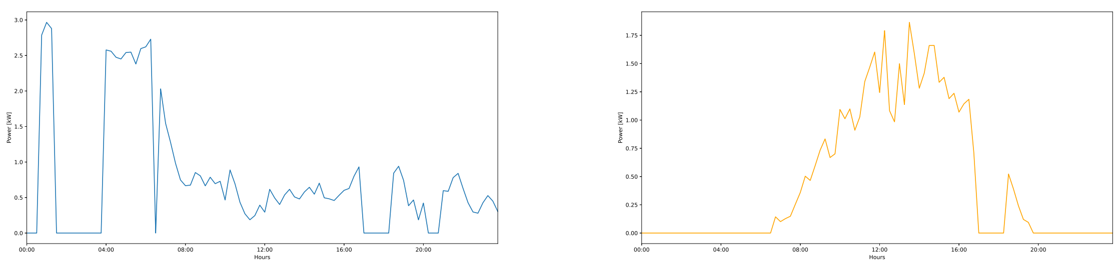


Figure 4.23: Curtailment strategy

4.4.1. Results

The simulation results, obtained with and without the curtailment strategy, provide essential insights for the User to evaluate the effects of this approach on different layers of the EC.

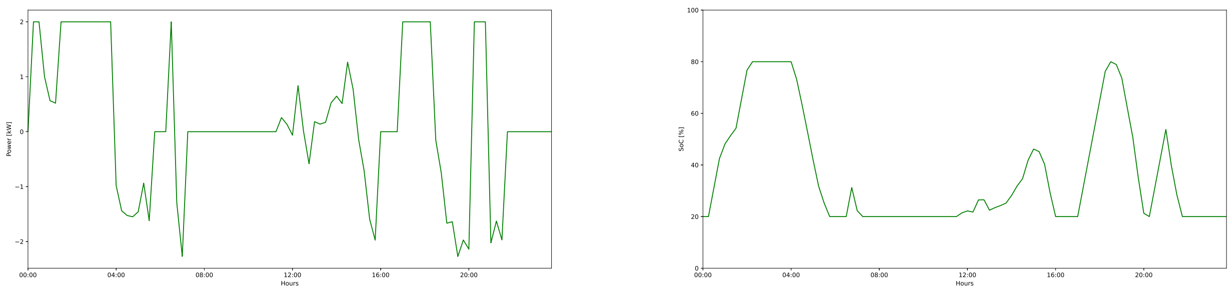
Firstly, focusing on the Energy Asset Layer, a comparison between the energy production profiles of renewable sources in figure 4.24 with figures 4.2b and 4.5 can be conducted. The User can observe how the curtailment strategy alters the energy production patterns of renewable sources, enabling a deeper understanding of its impact on the EC's energy generation dynamics.



(a) Wind Turbine **(b)** PV

Figure 4.24: Study Case 3 power production profiles

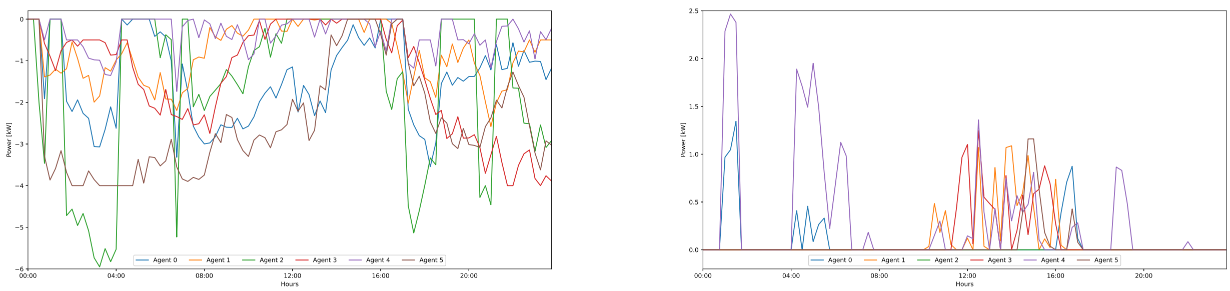
An important aspect to investigate is the energy directed to Agent 2's battery. By comparing figures 4.25a and 4.13a, it becomes evident that during curtailment phases, the EMS actively charges the battery with 2 kW of power. As a result, the evolution of the SoC, depicted in figure 4.25b, experiences significant growth compared to the case without the curtailment strategy (figure 4.13b). This enhancement in energy storage capacity offers Agent 2 greater energy availability and reduced reliance on the grid during periods of positive prices.



(a) Power Flow **(b)** SoC

Figure 4.25: Battery of Agent 2 in Study Case 3

Analyzing figure 4.26, the User can quantitatively assess the impact of the curtailment strategy on the Games Layer, specifically evaluating the variation in power exchanged by each Agent with the RT price. Comparing this with figure 4.15, it is evident that during curtailment phases, no sell transactions occur, and the quantities purchased by prosumers increase. To precisely evaluate the financial outcomes resulting from the implementation of the strategy, the User can generate a table 4.4 using data from the results CSV files of the simulation runs.



(a) **(b)**

Figure 4.26: RT power exchange Scenario 3

Table 4.4: Financial flows with and without the curtailment strategy [€]

	OFF			ON			
Player	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**	**VAR**
Agent 0	4.19	0.06	-4.13	2.38	0.28	-2.09	49.31%
Agent 1	1.44	0.51	-0.93	1.26	0.51	-0.75	18.95%
Agent 2	3.37	0.00	-3.37	-2.23	0.00	2.23	166.07%
Agent 3	4.21	0.71	-3.50	4.05	0.73	-3.32	5.02%
Agent 4	0.53	0.63	0.10	-0.27	1.86	2.14	2052.12%
Agent 5	7.04	0.33	-6.71	6.87	0.33	-6.53	2.62%
Community	20.78	2.25	-18.53	12.06	3.72	-8.34	382.35%

In conclusion, the ECDT platform enables the User to comprehensively analyze the effects of the curtailment strategy on the EC, shedding light on how this control mechanism influences energy generation, energy storage, and financial outcomes for individual agents. The platform's holistic architecture allows for a detailed investigation of cross-layer effects, making it a powerful tool for studying the dynamic behaviour of ECs.

5
Conclusions

The upcoming chapter will revisit the key points discussed in the earlier sections, reinforcing the thesis's objectives, and emphasizing the main conclusions and areas of discussion.

Chapter 1 provided a comprehensive overview of the challenges posed by the ongoing energy transition and the crucial role played by ECs in shaping the future of socio-technical energy systems.
Following this, the concept of DT, offering virtual representations mirroring real-world systems, emerged as a compelling approach to address the ECs' intricacies.
However, a critical gap was identified - the absence of an open-source DT platform that can holistically capture all the domains of various multi-energy and multi-layered ECs. Such a platform could be instrumental in fostering research, supporting decision-making, and enabling policy analysis in the field of ECs. Consequently, the central research question driving the entire thesis was formulated as follows:

"With the aim of enhancing research, decision-making, and policy analysis, how can a holistic, modular, and flexible platform be designed to enable the creation and utilization of Energy Communities' Digital Twins?"

In order to address this research question, **this thesis realised a holistic, multi-energy, flexible and modular ECDT platform that supports the comprehensive modelling, real-time simulation, and in-depth result analysis of the complex multi-layered structure of ECs.**

Chapter 2 shifted the focus to the need for a conceptual framework for the realization of the software architecture of the ECDT platform.
To establish a structured foundation for understanding smart grid systems, the SGAM was introduced.
Inspired by SGAM, the creation of the MECA became possible, enabling the platform to cater to the unique requirements of ECs.
The MECA's five critical layers - namely, Environment, Energy Assets, Controls, Agents, and Games, allowed to holistically capture the diverse domains and interactions within ECs. These dynamics range from environmental inputs, energy asset management, and control systems to the behaviour and decision-making of individual agents, and their strategic interactions into games.
A main design choice to address the research objective was the choice of utilizing a co-simulation environment. The integration of Mosaik as the core library to orchestrate the co-simulation stood out as a cornerstone of the platform's strength. Enabling real-time simulation, modularity and scalability, Mosaik gave the ECDT platform the capability of modelling large-scale ECs scenarios effectively. The Mosaik's capacity to handle thousands of simulated entities per run empowered the ECDT platform to provide valuable insights into real-world interactions among agents and energy assets.
Lastly, in chapter 2, it is discussed how at the heart of the ECDT platform lies the innovative groundwork laid by The Illuminator toolkit. The Illuminator's unique features and architecture made it an ideal starting point for the development of the ECDT platform. While The Illuminator fostered divulgation about renewable energy technologies and their integration into energy systems, the ECDT platform goes further by providing a powerful tool for addressing the intricate challenges of transitioning to an ECs-centered paradigm.
As a result of chapter 2, the first main conclusion is:
To design a holistic, modular, and flexible ECDT platform a structural decomposition of ECs' architecture shall be performed and a robust co-simulation virtual environment shall be employed.

Chapter 3 illustrates how the MECA was cast in the software architecture of the ECDT platform and presents a detailed overview of its five interconnected layers.
The Environment Layer emerged as the core foundation, integrating real-world data and external factors that influence energy systems within ECs.
The Energy Assets Layer proved fundamental, representing the physical energy infrastructure within ECs and encompassing various components for the generation, storage and conversion. By simulating multi-vector energy networks, the platform provided a comprehensive representation of energy flows and a deeper understanding of energy asset behaviours.
The Controls Layer supported the platform's capability to represent and facilitate the study of a wide range of strategies for energy management. The concept of Incremental Attributes, which is the feature of the ECDT platform that allows it to support MIMO models, enables granular control over each energy asset.
The Agents Layer implemented the features of the MAS on the ECDT platform. Through this layer, it was possible to simulate autonomous agents representing different stakeholders within the ECs. Agents were modelled according to a BDI paradigm, where they were provided with predictive capabilities thanks to an apposite-developed Deterministic Forecaster. Each agent was given the capabilities to interact, make informed decisions, and optimize strategies for energy trading.
Lastly, the Games Layer introduced energy-related games that simulated the agents' interaction mechanisms within the ECs. By providing insights into energy market dynamics, economic efficiency, and environmental impact, these games enabled users to evaluate trading schemes and optimize resource allocation. More specifically, the Electricity Market simulator in the ECDT platform replicated the mechanisms of electricity markets, allowing users to evaluate their impact on ECs' dynamics. Subsequently, the P2P Trading simulator facilitated the analysis of direct energy exchange among agents, promoting renewable energy use and fostering community cooperation. Lastly, the Real-Time Price Simulator enabled the representation of various energy tariffs for buying and selling energy, allowing users to study different pricing mechanisms and assess financial flows within the ECs.
As a result of chapter 3, the second main conclusion is:
To comprehensively encompass the diverse domains and complexities of ECs, the ECDT platform shall be able to reliably and extensively represent the physical dynamics, the agents' behaviours and their interactions.

Chapter 4 of the thesis starts exploring the vast range of applications the ECDT platform enables. By providing a realistic and customizable simulation environment, the platform empowers researchers, policymakers, and stakeholders to conduct various studies and explore the complex cross-layer effect within ECs. Some of the identified applications include energy system analysis, policy analysis, decision support, game theory and behavioural studies. These applications can be combined to create endless possibilities, greatly expanding the research opportunities offered by the platform.
The versatility of the ECDT platform stems from its ability to capture different domains of the EC's multi-layered architecture and the implemented Degrees of Freedom (DoF) that each layer offers. The identified DoFs include modifications to environmental conditions, energy asset parameters, ownership topologies, control strategies, agent strategies and participation and game parameters and metrics. By leveraging these DoFs, researchers can create and analyze various scenarios and explore the impacts of different configurations on the EC's performance and dynamics.
To demonstrate the exceptional capabilities of the ECDT platform, three case studies were created, each with a specific objective.
The first case study aimed to show how the ECDT platform can be used to study different ownership topologies within an EC and evaluate their effectiveness. The case showcased how the modifications in ownership, such as introducing household rooftop PV panels, community-scale PV parks or Aggregator programs, can influence the overall performance of the EC.
The second case study focused on demonstrating how the ECDT platform features can be leveraged for exploring different trading mechanisms and strategies within ECs. This was done by comparing the effects of playing Local

Electricity Market (LEM) and P2P trading games in different sequences. The study demonstrated how these different strategies impact agents' energy dynamics and individual financial outcomes.
The third case study showcased how the ECDT platform supports the analysis of the effects of control strategies on the EC's dynamics. The case focused on the introduction of a curtailment strategy in response to negative prices, showing how this control mechanism altered energy generation patterns, improved stored energy availability and minimized the costs for each agent.
These case studies highlighted the power of the ECDT platform in capturing and identifying cross-layer effects within ECs. They proved that, by simulating and analyzing different scenarios, researchers can gain valuable insights into the intricate interplay of ECs' various components.
Overall, Chapter 4 emphasizes the immense potential of the ECDT platform in facilitating a wide range of study cases and investigations. As researchers continue to explore and combine different applications using the platform's DoFs, the knowledge and insights gained can contribute significantly to enhancing energy systems, fostering sustainable practices, and promoting the overall resilience, sustainability and efficiency of ECs.
As a result of chapter 4, the third main conclusion is:
The ECDT platform's comprehensive design and customizability foster a holistic approach to ECs' analysis, allowing for the capture of cross-layer effects, thus unlocking a deeper understanding of these socio-technical systems.

5.1. Recommendation and future work

In the spirit of expanding the functionality of the ECDT platform, it is strongly recommended to integrate a user-friendly GUI into the ECDT platform. This will enhance usability, making it more accessible to researchers and stakeholders. The addition of a GUI will democratize access to the powerful simulation and analysis features of the ECDT platform, allowing even those without extensive technical expertise to explore its capabilities. This inclusivity will foster collaboration and knowledge exchange, contributing to a more sustainable future.

Additionally, it is highly recommended to enhance the level of detail in the physical models within the Energy Asset Layer. This improvement should not only focus on power exchanges but also encompass essential physical dynamics, such as voltage and frequency evolution, so as to provide a greater understanding of the physical constraints. To achieve this, the ECDT platform can leverage the capabilities of the Pandapower library thanks to its inclusion in the Mosaik environment. Pandapower is an open-source Python tool specifically designed for power system modelling and analysis, providing comprehensive functionalities to simulate and analyze various power grid components. By integrating Pandapower into the ECDT platform, it can achieve a more accurate and realistic representation of electricity assets and grids, enabling it to gain valuable insights into system stability and overall performance.

Furthermore, it is recommended to introduce more sophisticated strategies, such as AI, Machine Learning, and Model Predictive Control, within the Controls Layer and Agents Layer of the ECDT platform. These techniques will enhance the platform's capabilities, enabling agents to make more informed and adaptive decisions in response to changing conditions. This will empower researchers and stakeholders to explore cutting-edge energy trading and management solutions, optimizing resources and promoting sustainability. By leveraging these advanced strategies, the ECDT platform will foster research, drive innovation, and address real-world energy challenges more effectively.

Lastly, it is highly recommended to fully exploit the ECDT platform's unique features in the study of the most creative solutions, with the aim of shaping tomorrow's energy systems. Embracing the platform's holistic architecture and exploring its diverse applications will undoubtedly pave the way for a more resilient and sustainable energy future.

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A

Models Maps

Table A.1: Map of the models and the exchanged attributes in the ECDT platform

Model	CSV	Enetwork		Gnetwork		Qnetwork		H2 Valve		Q Valve	
	↓	↑	as	↑	as	↑	as	↑	as	↑	as
Wind_on	u	wind_gen	p_in[1]								
Wind_off	u	wind_gen	p_in[2]								
Load	load	load_dem	p_out[0]								
Battery	flow2b	p_out	p_out[1]								
PV	G_Gh’, ’G_Dh’, ’G_Bn’, ’Ta’, ’hs’, ’FF’, ’Az’	pv_gen	p_in[0]								
Electrolyser	flow2e	flow2e	p_out[2]			q_product	q_in[0]	h2_gen	h2_elec	h2_gen	h2_elec
H2 storage	flow2h2s							h2_flow	h2_stor	h2_flow	h2_stor
Tube trailers	flow2h2s							h2_flow	h2_stor	h2_flow	h2_stor
Fuel cell	h2_consume	fc_gen	p_in[2]			q_product	q_in[1]	h2_consume	h2_fc	h2_consume	h2_fc
H2 Valve				h2_elec_net	flow_in[0]						
				h2_stor_net	flow_in[1]						
				h2_fc_net	flow_out[0]						
H2 product	h2_product			h2_product	flow_in[2]						
H2 demand residential	h2_consume			h2_consume	flow_out[1]						
H2 demand feedstock	h2_consume			h2_consume	flow_out[2]						
H2 demand electric vehicle	h2_consume			h2_consume	flow_out[3]						
Heat demand residential	qdemand					qdemand_dem	q_out[2]				
Heat demand industrial	qdemand					qdemand_dem	q_out[3]				
Heat product	q_product					q_product	q_in[2]				
Heat Pump	Q_Demand	P_Required	p_out[3]			Q_Supplied	q_in[3]				
Heat storage seasonal	flow2qs					flow_out	q_out[0]				
Heat storage daily	flow2qs					flow_out	q_out[1]				
Heat storage	flow2qs									flow_out	q_stor
E-boiler	eboiler_dem	eboiler_dem	p_out[4]							q_gen	q_eboiler
Q Valve						q_stor_net	q_in[5]				
						q_eboiler_net	q_in[4]				

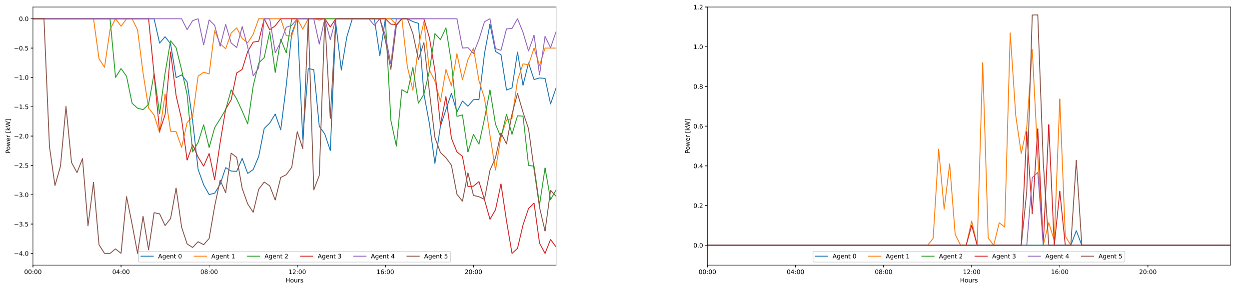
B

Study case 2 results

B.1. Scenario 2A

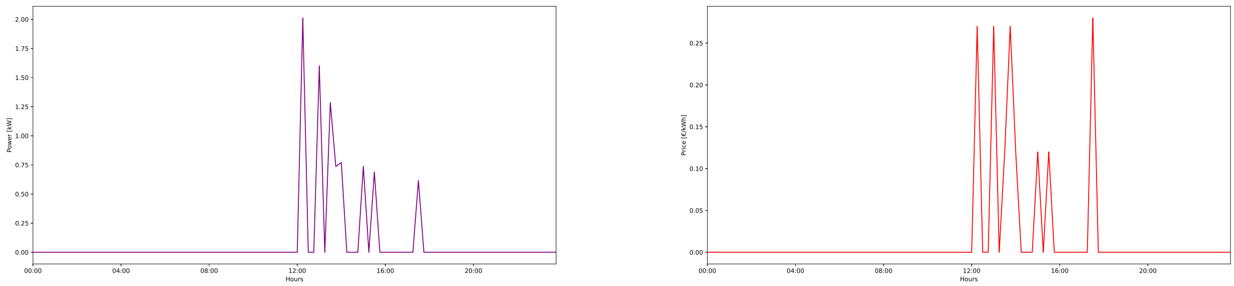
Table B.1: Total financial flows Scenario 2A

	Electricity Market [€]			P2P Trading [Credits]			RT Price [€]		
Player	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**
Agent 0	0.052	0.000	-0.052	0.903	0.753	-0.150	8.672	0.002	-8.670
Agent 1	0.010	0.090	0.080	1.645	0.000	-1.645	6.933	0.310	-6.624
Agent 2	0.000	0.000	0.000	0.008	0.000	-0.008	9.548	0.000	-9.548
Agent 3	0.031	0.182	0.151	3.166	0.402	-2.764	10.527	0.091	-10.436
Agent 4	0.020	0.170	0.150	0.000	5.075	5.075	1.176	0.033	-1.143
Agent 5	0.329	0.000	-0.329	0.569	0.061	-0.507	27.891	0.144	-27.747



(a) **(b)**

Figure B.1: RT power exchange Scenario 2A



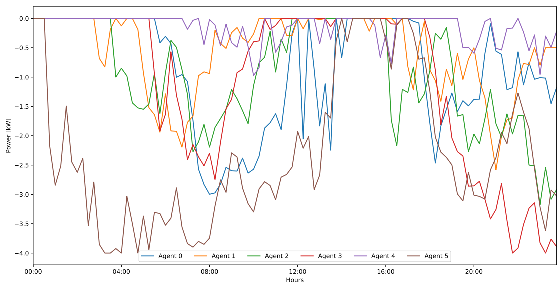
(a) **(b)**

Figure B.2: local Electricity Market in Scenario 2A

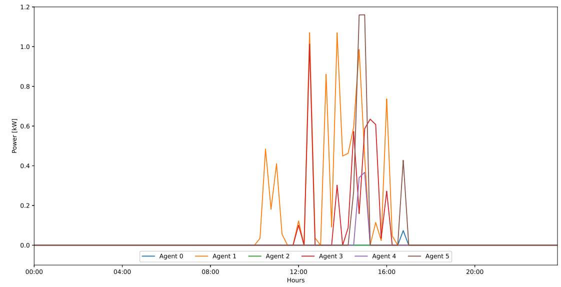
B.2. Scenario 2B

Table B.2: Total financial flows Scenario 2B

	Electricity Market [€]			**P2P Trading [Credits]**			**RT Price [€]**		
Player	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**	**TC**	**TR**	**NET**
Agent 0	0.000	0.000	0.000	1.394	0.753	-0.641	8.388	0.002	-8.387
Agent 1	0.000	0.043	0.043	1.654	0.000	-1.654	6.948	0.343	-6.604
Agent 2	0.000	0.000	0.000	0.008	0.000	-0.008	9.548	0.000	-9.548
Agent 3	0.000	0.000	0.000	3.222	0.592	-2.630	10.527	0.195	-10.333
Agent 4	0.000	0.000	0.000	0.000	5.401	5.401	1.215	0.033	-1.182
Agent 5	0.043	0.000	-0.043	0.569	0.101	-0.468	28.370	0.131	-28.239

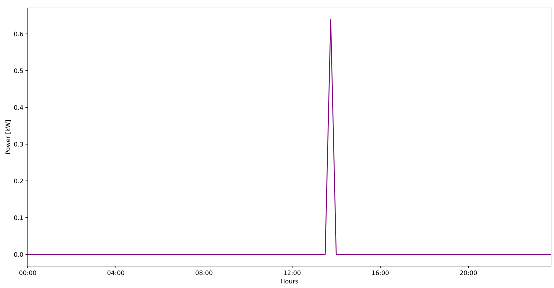


(a)

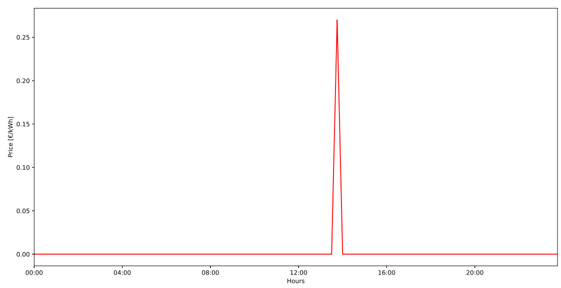


(b)

Figure B.3: RT power exchange Scenario 2B



(a)



(b)

Figure B.4: local Electricity Market in Scenario 2B