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Abstract: In recent years, many governments are promoting a widespread deployment of Renewable Energy Sources (RES) together with an optimization of energy consumption. The main purpose consists on decarbonizing the energy production and reducing the CO_2 footprints. However, RES imply uncertain energy production. To foster this transition, we need novel tools to model and simulate Multi-Energy-Systems combining together different technologies and analysing heterogeneous information, often in (near-) real-time. In this paper, first we present the main challenges identified after a literature review and the motivation that drove this research in developing MESsi. Then, we propose MESsi, a novel distributed infrastructure for modelling and co-simulating Multi-Energy-Systems. This infrastructure is a framework suitable for general purpose energy simulations in cities. Finally, we introduce possible simulation scenarios that have different spatio-temporal resolutions. Space resolution ranges from the single dwelling up to districts and cities. Whilst, time resolution ranges from microseconds, to simulate the operational status of distribution networks, up to years, for planning and refurbishment activities.

1 INTRODUCTION

Nowadays, one of the main challenges in our societies consists on reducing greenhouse gas emissions as highlighted during the international conference on climate changes (United Nations, FCCC, 2015). Many countries are investing on developing and deploying Renewable Energy Source (RES) to reduce the dependence on fossil fuels for energy generation. Moreover, novel ICT (Information Communication Technology) solutions can increase the demand flexibility by managing the uncertain production of RES and by optimizing the energy consumption in cities.

In this paper, we propose a distributed infrastructure, called MESsi, for modelling and simulating Multi-Energy-Systems (MES) by exploiting novel ICT solutions, such as cyber-physical-systems, Internet-of-Things (IoT), cloud computing and cognitive computing. As pointed out by (Mancarella, 2014), an in-depth simulation and analysis of MES is required to increase the flexibility of energy systems by integrating different resources for both electric and thermal energy. Furthermore, ICT and MES offer valid options to foster novel services for smart energy management. For example they can foster events of Demand Response (DR) and Demand Side Management (DSM) by integrating buildings equipped with heat pumps, CHP (Combined Heat Power) or HVAC (Heating, Ventilation and Air Conditioning) systems (Molitor et al., 2014). The scope of this paper consists on presenting the methodology and the conceptual overview of MESsi, which is under development and only some modules have been validated.

The rest of the paper is organized as follows. Section 2 presents motivations and challenges that drove our research on developing such infrastructure. Section 3 reviews relevant state of the art solutions for modelling and simulating Multi-Energy-Systems. Section 4 introduces the MESsi platform and possible simulation scenarios. Finally, Section 5 discusses our concluding remarks.

2 MOTIVATIONS AND CHALLENGES

This research aims at developing a distributed infrastructure to model and co-simulate Multi-Energy-Systems (a.k.a. MESsi) in urban context.

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MESsi combines together different technologies and heterogeneous information to model the energy flows and to simulate the impact of novel control strategies in cities and distribution networks. It also can exploit information coming in (near-) real-time from Internet connected devices installed across the city. Furthermore, MESsi provides features to simulate how such novel policies affect the energy marketplace and to analyse the effects and/or limitations of regulatory frameworks. On these premises, MESsi is an infrastructure for simulations as a service that can be used by different stakeholders to build and analyse new energy scenarios for short- and long-term planning activities and for testing and managing the operational status of Multi-Energy-Systems. Examples of scenarios that combine together thermal and electricity trends (load and/or generation) to simulate the energetic behaviour of buildings, districts and cities are: i) Installation of Renewable Energy Sources, ii) Grid reconfiguration, iii) Demand Response and iv) Demand Side Management. To achieve this purpose, MESsi needs to combine novel or already existing modelling and simulation tools together with real-time simulator (e.g. OPAL-RT or RTDS). At the same time, it needs to correlate heterogeneous information, such as: i) measurements retrieved in (near-) real-time from IoT devices deployed across the city (e.g. information on multi-vector energy trends, weather, indoor temperature in buildings, status of the distribution grids); ii) Building Information Models (BIM), grid models and Geographical Information Systems (GIS); iii) topology of energy distribution networks; iv) urban cartographies and information on population censuses.

To realize the MESsi infrastructure, we identified the following key challenges from a literature review (Mancarella, 2014; Molitor et al., 2014; Allegrini et al., 2015; Keirstead et al., 2012; Van Beuzekom et al., 2015) that needs to be addressed:

i) *Simulation of buildings dynamics*: MESsi has to provide features for analysing both thermal and electrical dynamics in buildings. For example, modelling and simulating thermal dynamic includes also the analysis of indoor temperature variations related to power consumption. In this view, information on thermal inertia and/or heat storages can be given as input to control policies for shaving demand peaks in district heating networks (Brundu et al., 2017; Verda et al., 2016) or for DR and DSM if heating and cooling systems are supplied by electric generators or CHPs.

ii) *Simulation of novel energy management policies*: Novel control policies needs to be evaluated in a realistic environment before being applied in a real-world context. Thus, the effects in terms of energy efficiency, energy optimization, distribution network reliability and economic value can be evaluated in-depth.

iii) *Simulation of distribution networks*: MESsi must be able to simulate the energy distribution network to provide energy management policies with information on the status of the network itself. For example, from these simulations possible congestions, failures and unbalances can be evaluated in a realistic scenario. For this purpose, simulators like OPAL-RT and RTDS need to be integrated in the infrastructure to perform real-time simulations of the distribution network with microseconds time-steps.

iv) *Evaluation of RES impacts on the marketplace*: The impact of Renewable Energy Sources needs to be evaluated to better design and apply novel control policies and actions that affect the energy marketplace, such as signal pricing and load balancing. Moreover, these results can be analysed to better understand the the limitation of current regulatory frameworks.

v) *Simulations with different spatio-temporal resolutions*: MESsi has to provide features to simulate energy phenomena with different time and space resolutions. Time resolution ranges from the microseconds, for analysing the operational status of distribution systems, up to years, for planning and refurbishment activities. Whilst, space resolution ranges from the single dwelling up to districts and cities.

vi) *(Near-) real-time integration of real-world information*: Real-world information sent in (near-) real-time by heterogeneous Internet connected devices are needed to develop more accurate event-based models for analysing the operational status of the grid, for developing ad testing more efficient control policies and for planning and refurbishment activities (Bottaccioli et al., 2017a).

vii) *Modularity and extendibility in integrating data, models and simulators*: Modularity and extendibility are two main features for Multi-Energy-Systems. In particular, MESsi needs to be designed to integrate in a plug-and-play fashion heterogeneous data-sources, models and simulators. This makes the overall infrastructure suitable for simulating different energy scenarios, becoming a general purpose framework for energy simulations in cities. Modularity and extendibility are also two main requirements to allow future extensions with low cost and small architectural impacts.

viii) *Scalability of the infrastructure*: Horizontal and vertical scalability of the infrastructure is another key requirement of MESsi. Indeed, it needs to scale up quickly and easily because simulating a city or a dis-

trict implies the interaction of thousand of concurrent entities. This becomes critical if real-time simulations of power distribution network must be performed.

3 STATE OF THE ART

In the last years, the study of Multi-Energy-Systems is becoming crucial to de-carbonize energy production and also to foster a widespread deployment of RES. To achieve it, we need tools for an in-depth analysis and simulation of MES for both electrical and thermal energy (Mancarella, 2014). In (Molitor et al., 2014; Allegrini et al., 2015; Keirstead et al., 2012; Van Beuzekom et al., 2015), authors present a complete overview of literature tools and models for MES analysis. In this section, we report relevant state of the art solutions on modelling and simulation platforms for Multi-Energy-Systems, identifying challenges and limitations as well.

DER-CAM (Firestone, 2004) is a useful tool for planning and operational analysis of power distribution networks. It aims at providing guidelines for future investment. The input can be given with a resolution up to 5 minutes. HOMER (Lambert et al., 2006) helps on studying different micro-grid configurations based on hourly input data. EnergyPLAN (Lund, 2011) is another solution useful for both operational and planning activities. It receive input data up to hourly values. However, none of these solutions provides features for detailed power flow analysis or thermal simulations in buildings. Moreover, they are not flexible in integrating new scenarios in the simulation process and they do not exploit data coming in (near-) real-time from real devices installed across the city.

GRIDSpice (Anderson et al., 2014) is a distributed platform that co-simulate power flows and data communication in smart-grid scenarios. It integrates third-party software like MATPOWER and GridLAB-D to simulate power generation, demand and distribution. It exploit a cloud-based architecture to parallelize the computation of large scale models. Also in this case, GRIDSpice neglects thermal simulations in buildings and does not exploit (near-) real-time information from real devices.

DIMOSIM (Riederer et al., 2015) is a platform to perform MES simulations in urban districts. It enables thermal simulations in buildings but it lacks of electrical flows simulations in power grids. MOSAIK (Schütte et al., 2011) is a distributed platform for co-simulation of electrical flows in smart grid scenarios. It provides an integration of their Matlab models with PowerFactory, a third-party software, to exploit Photovoltaic (PV) and Load generation profiles. IDEAS (Baetens et al., 2015) is an open source platform based on Modelica modelling language. It co-simulate Demand Side Management strategies where thermal request of buildings affects power distribution networks. MESCOS (Molitor et al., 2014) is a co-simulation platform for district energy systems. It simulates Demand Response and Demand Side Management policies by integrating both electrical and thermal loads. The main limitations of these solutions are summarized as follows: i) they do not integrate (near-) real-time information from real devices; ii) they do not exploit a real-time simulator (e.g. OPAL-RT and RTDS); iii) the integration with other simulation tools is not easy. In addition to that, MOSAIK lacks in simulating thermal behaviours in buildings.

In (Abrishambaf et al., 2017), authors present a distributed platform for real-time co-simulation of Demand Response events in microgrids. The platform integrates the OPAL-RT simulator and exploits information coming in real-time from real devices. However, the platform does not simulate thermal behaviours in buildings.

HUES (Bollinger and Evins, 2015) platform aims at facilitating the integration of different models for MES analysis. It implements a repository layer that includes all the platform modules whose functionalities are described in a semantic wiki. However, HUES neglects on an interconnection among the platform's modules and lacks on integrating data coming in (near-) real-time from devices installed across the city.

In our previous work (Bottaccioli et al., 2017b), we presented a real-time architecture for co-simulation of novel control policies in smart grid with RES. In its core, it leverages upon an OPAL-RT simulator and exploits real-time information from real devices. However, this solution neglects in simulating thermal behaviours in buildings.

With respect to literature solutions, we propose MESsi, a distributed infrastructure for modelling and simulating Multi-Energy-Systems. It aims at overcoming the highlighted limitations and addressing the main challenges identified in Section 2 to evaluate general purpose simulation scenarios. In particular, MESsi performs simulations for both thermal and electrical distribution networks with different spatio-temporal resolutions. It exploits the OPAL-RT real-time simulator that allows in-depth simulations with microseconds time-steps. It provides features to perform detailed power flow analysis, thermal simulations in buildings and evaluation of RES impacts on the marketplace. Furthermore, MESsi integrates data

coming in (near-) real-time from real devices installed across the city. Finally, it eases the interconnection among MESsi components and third-party models and simulators in a plug-and-play fashion.

4 INFRASTRUCTURE FOR MES MODELLING AND CO-SIMULATION

In this section, we present MESsi, a distributed infrastructure for real-time modelling and co-simulation of Multi-Energy-Systems in cities (see Figure 1). This infrastructure exploits the microservice design pattern (Fowler and Lewis, 2014; Newman, 2015) to increase both scalability and extendibility of the system, and to ease its maintenance. Indeed, the microservice approach defines software architecture as a set of loosely coupled and collaborating services. Thus, our solution is flexible in modelling and co-simulating different energy flows in a single solution made of different interoperable components or modules that can be deployed in a plug-and-play fashion.

The proposed infrastructure consists of five layers. From left to right in Figure 1, both *Environmental and Physical Layers* includes the heterogeneous data-sources needed by the different components in the system. The *Cyber Layer* enables the communication among the different modules in the five layers by exploiting either the request/response or publish/subscribe (Eugster et al., 2003) communication paradigms. The *Modelling and Simulation Layer* consists of different components that simulate energy phenomena and multi-energy-flows. Finally, the *Simulation Scenarios Layer* provide end-users with a set of tools and API (Application Programming Interfaces) to build and run their MES simulation scenarios. At this layers, end-users can easily access to all the information made available by the modules in the previous layers.

4.1 Data sources

The proposed solution integrates heterogeneous data-sources needed by the simulation components. In particular we group them in two layers, *Environmental Layer* and *Physical Layer* (see Figure 1).

The **Environmental layer** integrates all the information needed to describe a city. Among the others this layer includes:
i) *Geographical Information Systems* (GIS) integrate georeferenced information about the different entities (e.g. devices, buildings and pipelines) in cities. It also includes cartographies cadastral maps and Digital Elevation Models.
ii) *Building Information Models* (BIM) are parametric 3-Dimensional models, where each model describes a building, both structurally and semantically.
iii) *System Information Models* (SIM) describe size and structure of energy distribution networks. SIM is built by exploiting parametric and topological data.
iv) *Weather Data* are retrieved by third party services, such as (Weather Underground, 2017). This information is georeferenced and collected by personal weather stations deployed in cities.
v) *Census data* are information about different characteristics and behaviours of citizens, such as population distribution, dwelling size and appliances distribution.

On the other hand, the **Physical layer** integrates data coming from physical systems and Internet connected devices in (near-) real-time. Among the others this layer includes:
i) Measurements of energy production from *Distributed Generation*.
ii) Status of *Distribution Grid* that are needed to simulate energy flows and evaluate the integration of RES. Thus, information sampled by devices monitoring the energy distribution network.
iii) Information sent by *IoT devices*, such as *Ambient sensors*, multi-vector *Smart Meters* (i.e. electricity, gas, heating and water) and *Actuators*.

4.2 Data Communication

The **Cyber layer** is in charge of enabling data exchange among the different components in our infrastructure. It exploits both the synchronous and asynchronous communication paradigms adopting both request/response and publish/subscribe (Eugster et al., 2003) approaches, respectively. Request/response allows a fast bidirectional communication to send/access information to/from different components in our infrastructure (either hardware or software), using, for instance, REST Web Services (Fielding and Taylor, 2002). Whilst, publish/subscribe is complementary to request/response and allows (near-) real-time data transmission. Publish/subscribe removes the interdependencies between producer and consumer of information. This allows developers in creating distributed software components that are independent from data-sources and can react in (near-) real-time to certain events. Thus, publish/subscribe enables a data-driven and event-based communication that also increases the scalability of the system as pointed out in (Patti et al., 2016). In the proposed solution, we adopted MQTT

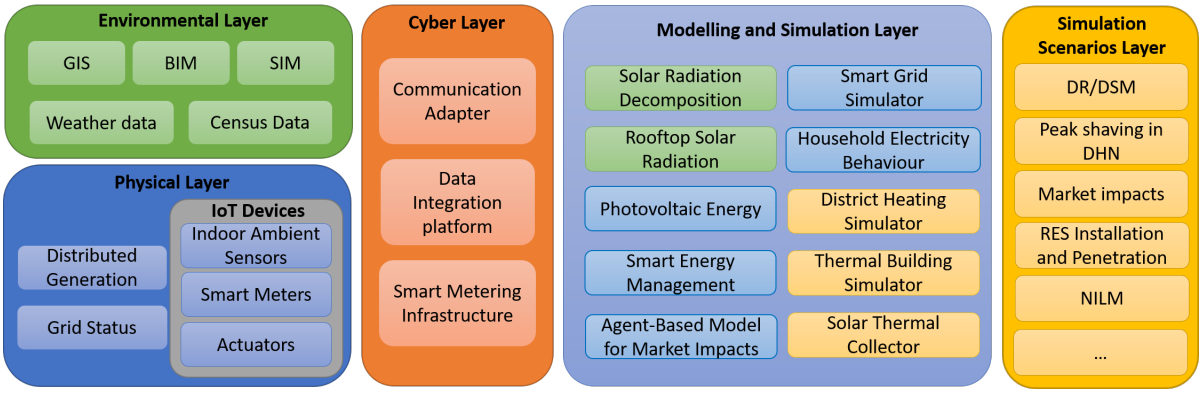

Figure 1: Schema of the proposed MESsi infrastructure

protocol (MQTT, 2017), which is an implementation of publish/subscribe.

As shown in Figure 1, the **Cyber layer** consists of three main modules the *Communication Adapter*, the *Data Integration Platform* and *Smart Metering Infrastructure*. The Communication Adapter enables the interoperability across the heterogeneous devices in the Physical Layer. Whilst, the *Data Integration Platform* integrates third party software and platforms in the Environmental Layer. Both act as a bridge between the components of infrastructure and the underlying technologies, either hardware or software. In this view, each technology needs a specific *Communication Adapter* or a *Data Integration Platform* to provide common and unified interfaces to access low-level functionalities through REST Web Services and/or MQTT. Thus, both *Communication Adapter* and *Data Integration Platform* are key component to access each low-level technology transparently. Finally, MESsi provides features to integrate also third party *Smart Metering Infrastructure*, such as (Pau et al., 2017), that makes available historical data collected from real distribution networks and post-processed information output of its services.

4.3 Modelling and Simulation

The **Modelling and Simulation Layer**, in Figure 1, consists of different software components to simulate environmental conditions (green boxes), electrical energy (light blue boxes) and thermal energy (yellow boxes).

The *Solar Radiation Decomposition* is a software module that decompose Global Horizontal radiation (GHI) into Direct Normal Incident radiation (DNI) and Diffuse Horizontal Incident radiation (DHI) by applying mathematical models such as (Ruiz-Arias et al., 2010). The inputs are meteorological information retrieved by *Weather Data* module in the Environmental Layer. Often, weather stations sample only GHI. Thus, this module is crucial because DNI and DHI are needed to evaluate the solar heating gains and to simulate incident solar radiation on tilted surfaces (e.g. buildings' rooftops).

The *Rooftop Solar Radiation* (Bottaccioli et al., 2017c) module exploits GIS cartographies, real *Weather Data* and results from *Solar Radiation Decomposition* module to simulate incident solar radiation on rooftops. Simulations are done in real-sky conditions with a resolution of 15 minutes. It is able to detect roof encumbrance (e.g. chimneys and dormers) and to estimate their shadowing effects.

The *Photovoltaic Energy* module exploits the methodology described in (Bottaccioli et al., 2017c). It exploits both *Rooftop Solar Radiation* and *Weather Data* modules to estimate the incident solar radiation and the effects of the air temperature on the efficiency of PV arrays. By exploiting GIS cartographies, it also identifies the suitable areas for PV deployment on rooftops and simulates the energy production with a resolution of 15 minutes.

The *Smart Energy Management* module offers an environment fully integrated in MESsi to simulates novel control policies for energy optimization suitable for battery management, Demand Response and Demand Side Management.

The *Agent-Based Model for Market Impacts* module simulates the impact of RES (e.g. PV arrays) and novel control policies on the electrical marketplace. It aims at evaluating the role of emerging energy aggregators to better understand the feasibility of such actions in residential sectors from both regulatory and economical viewpoints.

The *Smart Grid Simulator* module integrates a Real-Time Simulators (e.g. Opal-RT or RTDS) as depicted in (Bottaccioli et al., 2017b). It simulates power distribution networks with different time resolutions ranging from microseconds to hours. Ex-

ploiting the *Communication adapters* in the *Cyber layer*, it is able: i) to access information from IoT devices deployed across the real distribution network in (near-) real-time and ii) to exchange data with the *Smart Energy Management*, the *Photovoltaic Energy* and *Household Electricity Behaviour* modules. The *Smart Grid Simulator* module enables a more accurate analysis of distribution network when different control strategies are applied. Moreover, this module can be used together with the *Agent-Based Model for Market Impacts* module to simulate congestions and unbalances, and to evaluate the electrical implication of Demand Response events on distribution networks.

The *Household Electricity Behaviour* module reproduces realistic electrical consumptions in residential houses. It builds a virtual model of households occupancy and their activity patterns by exploiting a Markov chain Monte Carlo simulation. The input needed by this module are the information given by *Census Data* (i.e. statistical information on the distribution of population and appliances). In particular, it uses results of the last national census that provides statistical information on households occupancy and citizens activities over the day. Once the virtual model is built, it translates these information into electrical usages for each appliance in each single virtual home. This module can build scenarios involving a single house up to a full city. During the execution of the simulation, the results are continuously made available to the other modules of MESsi through the *Cyber Layer*.

The *District Heating Simulator* provides an environment fully integrated in MESsi to simulates novel control policies for Heating Distribution Networks (HDN) accounting also for their impacts on building comfort (Brundu et al., 2017; Verda et al., 2016). Additionally, this module provides tools to analyse and predict the thermal behaviour of buildings connected to HDN exploiting the KPIs and the methodology described in (Acquaviva et al., 2015).

The *Thermal Building Simulator* follows the methodology described in (Bottaccioli et al., 2017a). It provides tools to simulate and analyse the thermal behaviour of buildings. It combines information about *BIM* and *GIS* together with real *Weather data* and environmental information coming from *IoT Devices* deployed in the corresponding real buildings. This module allows: i) (near-) real-time visualisation of energy consumptions in buildings; ii) simulation of indoor temperature trends and iii) evaluations of building performances through energy models.

The *Solar Thermal Collector* module simulates the behaviours of solar thermal panels in heating water. It needs as input *Weather Data* and the results from the *Rooftop Solar Radiation*.

4.4 SIMULATION SCENARIOS

The *Simulation Scenarios Layer*, the last in our infrastructure (see Figure 1), provides end-users with a set of tools and API to build and run different energy scenarios. This layer allows end-users to easily access to information made available by the other module in MESsi. Among the others this layer includes simulation scenarios described in this section for which MESsi as been designed.

Simulations can be performed to evaluate the operational states of distribution networks. For example, events of DR and DSM in a urban MES can be analysed taking into account RES (e.g. PV arrays) and buildings equipped with electrical HVAC. These scenarios involve different MESsi modules: i) *Smart Grid Simulator* to simulate the power network: ii) *Photovoltaic Energy* to estimate generation profile of PV systems; iii) *Thermal Building Simulator* to analyse the indoor temperature trends and to avoid discomfort in case HVAC is switched off. Furthermore, the *Smart Metering Infrastructure* can be used to retrieve historical data and to schedule DR and DSM events that also involve common appliances (i.e. washing machine, dishwasher and boilers). Otherwise, if real data are not available, *Household Electricity Behaviour* generates realistic load profiles for different dwellings. These simulations span different spatio-temporal resolutions at the same time. Simulations of indoor temperature trends involve the single dwelling or building with 15 minutes time resolution. Whilst, grid behaviour simulations involve the whole district or city with microsecond or second time resolution.

Thermal peak shaving is another scenario to evaluate the operational states of HDN. In this case, an high request of hot water from buildings connected to HDN causes a power peak at the thermal power plant. This issue is normally managed with heat storages or with additional gas heaters that are used only during this peak period. To avoid it, control policies can be tested to shift in time the request of each single building (Verda et al., 2016). This scenario involves the *Thermal Building Simulator* to evaluate the indoor temperature trends in each building and the *District Heating Simulator* to evaluate the peak shaving. Both modules needs 15 minutes time resolution.

As mentioned in the previous sections, MESsi can be used also for strategic planning activities. For example, it can simulate scenarios that involves the Energy Aggregators, a new rising actors in the electrical marketplace. In this case, Energy Aggrega-

tors exploit the proposed infrastructure to analyse the customers participation and the effects of regulatory frameworks in DR/DSM events. Consequently, Energy Aggregators can evaluate their impact on the marketplace. This scenario is a long-term planning activity. Thus, simulations needs monthly or yearly time resolution. This scenario exploits the following modules: i) *Agent-Based Model for Market Impacts*, ii) *Household Electricity Behaviour*, iii) *Smart Metering Infrastructure*, iv) *Photovoltaic Energy*, v) *Smart Grid Simulator* and vi) *Thermal Building Simulator*.

City managers can use MESsi to evaluate the solar potential and its impact on the distribution network considering also load profiles and network constrains. This scenario involves the following modules: i) *Photovoltaic Energy* to estimate the generation profile for each PV system installed in building rooftops; ii) *Smart Metering Infrastructure* to retrieve real load profiles or *Household Electricity Behaviour* to generate realistic energy consumption patterns, iii) *Solar Thermal Collector* to simulate the behaviours of solar thermal panels in heating water for domestic use or for heat pumps. If the simulation scenario includes building heating systems supplied by solar thermal panels, the *Thermal Building Simulator* is needed to evaluate the impact on indoors temperature behaviours. The scenarios needs monthly or yearly time resolution.

MESsi can also be used for testing or validating already existing algorithms, such as Non-Intrusive Load Monitoring (NILM). NILM is a signal processing technique, which discerns the energy consumption of the appliances from the aggregated data acquired from a single point of measurement, i.e. the *Smart Meter* (Zoha et al., 2012). In this case, the input needed by the NILM algorithm are historical households load profiles retrieved from *Smart Metering Infrastructure*. As an alternative, the NILM service can exploit the *Household Electricity Behaviour* module to create realistic electrical consumption patterns. Time resolution for this scenario ranges from microseconds to 1 second.

It is worth noting that, thanks to the microservice design pattern, MESsi is opened to build and run new simulation scenarios to meet latest requirements from the end-users.

5 CONCLUSION

In this paper, we presented MESsi, which is a novel distributed infrastructure for modelling and co-simulating Multi-Energy-Systems in cities. First, we discussed the motivations and challenges we addressed to design such infrastructure. Then, we introduced our proposed framework that is suitable for general purpose energy simulations with different spatio-temporal resolutions. MESsi combines different technologies and correlates heterogeneous information, also sent in (near-) real-time, to simulate multi-energy-flows and to evaluate the impact of novel policies in cities and distribution networks. Finally, we discussed possible simulation scenarios i) for analysing the operational status of energy distribution systems, ii) for planning and refurbishment activities, and iii) for testing or validating already existing algorithms.

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