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MODEL-BASED DECISION SUPPORT FOR THE DESIGN AND OPERATION OF A NEW URBAN ENERGY SYSTEM IN "FIERA DEL LEVANTE" EXHIBITION COMPLEX

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ABSTRACT

The current centralised, fossil fuel-reliant energy system is experiencing a gradual transition to a more decentralised system, particularly in cities where decentralised energy resources (DER) largely based on renewable sources can help alleviate chronic environmental problems. This transition gave rise to the concept that the pervasion of sensors, embedded systems and ubiquitous network connectivity in urban energy systems (UES) could enhance the overall quality of life through so-called "smart cities" and "smart grids." A comprehensive analysis of recent reviews of EU-funded projects has elucidated a range of good practices, regarding stakeholder engagement, citizen participation, funding, technologies and demand-side management. Coupled with suitable modelling frameworks accurate analysis of synergies between generation assets, storage solutions and demand-side management (DSM) interventions is possible. Three dominant conceptual models have been identified: the energy hub, the microgrid and the virtual power plant. The technical characteristics can be transferred to the framework structure to be developed for optimising the energy system of the "Fiera del Levante" exhibition complex in the southern Italian city of Bari, which is characterized by a highly variable energy demand scenario. This paper describes the proposed methodology for this case study, which is strongly linked to the Technology Selection and Operation (TSO) model developed at Imperial College London.

Keywords: smart city; urban energy system; district heating and cooling; energy hub, micro grid, virtual power plant

NOMENCLATURE

Abbreviations

ASHP	Air source heat pump
CHP	Combined heat & power
DER	Distributed energy resource
DNO	Distribution network operator
DR	Demand response
DSM	Demand side management
EIP-SCC	European Innovation Partnership for Smart Cities and Communities
EU	European Union
EV	Electric vehicle
FDL	Fiera del Levante
GHG	Greenhouse gas
ICT	Information & communication technology
MES	Multi energy system
MILP	Mixed integer linear programming
ORC	Organic Rankine cycle
PV	Photovoltaic
RES	Renewable energy source
SNM	Smart network management
TOU	Time of use (tariff)
TSO	Technology selection & operation
UES	Urban energy system
UN	United Nations
UPS	Uninterrupted power source
VPP	Virtual power plant

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1. INTRODUCTION

Cities are the world's first energy consumption "hotspots," accounting for 75% of global energy use and 80% of global greenhouse gas (GHG) emissions (1). Around 55% of the world's population currently lives in urban areas and this number is expected to increase to 68% by 2050, according to the United Nations (UN) (2). If the traditional, fossil fuel-dependent energy paradigm continues to be adopted, cities' energy intensity and GHG emissions share will continue to rise. Climate change is only one of the concerns that have already set in motion a transition to the gradual adoption of decentralised energy resources (DER), heavily based on small-scale (less than 100 MWe), renewable and low-carbon energy generation at distribution-level voltages (3). Prevalent technological options are photovoltaic (PV) arrays, battery systems, combined heat and power (CHP) units in the form of turbines, engines or fuel cells (4). Other notable causes of this transition are greater national and regional energy security aspirations, falling costs and higher commercial value of DER, deteriorating urban air quality, recent advancements of information and communication technology (ICT), coupled with aging energy system infrastructures and the need for active control at the distribution network level to enhance the reliability and quality of power provision.

With the deeper penetration of DER in urban energy systems (UES), the energy supply chain is destined to shift almost entirely in the urban domain, as renewable energy sources (RES) are extracted, converted, distributed and exploited locally. If not integrated following a systems-based approach, DER can have the undesired effect of putting an additional operational strain on the already energy-dense UES that we have today. This combined with the uncontrolled electrification trend of heat (e.g. through electric heat pumps) and transport (e.g. through electric vehicles [EVs]) can ultimately have a crippling effect on urban distribution systems which were simply not designed for such generation capacities and margins. For this reason, enhancing the efficiencies of DER, particularly through the integration of different energy carriers in cogeneration and even trigeneration systems (e.g. CHP coupled with absorption chillers) and complimentary set of technologies (e.g. PV and battery systems) to satisfy the load requirements of clusters of buildings will be of paramount importance. Nonetheless, such practice proves to be harder when taking into account the intermittent nature of RES.

Carreón and Worrell (5) argue that despite the formation of several international sustainability networks in the last 30 years they have not been able to find a single comprehensive statistical appraisal of energy use at the urban level. This suggests that urban policymakers are overlooking the analysis of real-time energy flow data in their quest of solving their cities' environmental problems. These need to be integrated into holistic modelling frameworks of multi-carrier energy systems in order to assist them in their decision-making and help them identify and correct the current issues of UES. In line with the DER considerations in the previous paragraph, detailed, up-to-date techno-economic and operational data of the most promising technologies are to be included as well, in order to allow the models to optimise the technology selection and operation of retrofit or new build projects and create a sound business case with attractive returns.

Afterwards a methodological framework can be developed which can be adapted to technically different case studies and can be updated periodically with reliable input data. This approach is tested on the "Fiera del Levante" (FDL) exhibition centre in the southern Italian city of Bari which due to its seasonal demand variation represents a particularly interesting case study to demonstrate the usefulness of an appropriate optimisation framework for the objective of minimising the operational costs of its energy system and keeping GHG emissions to a suitable limit.

The rest of this paper is structured as follows. First, the relevant literature is analysed in Section 2. A more detailed description of the case study is undertaken in Section 3. Following this, some details on the methodological framework of the optimization model are presented in Section 4, along with some final discussion remarks in Section 5.

2. LITERATURE REVIEW

Adopting a holistic approach, an analysis of the overarching features of UES at three important levels of complexity (the entire city, a single district and a single grid) will follow, with a particular focus on the EU approach to smart cities development and the discussion of relevant literature on the topic. An evaluation of three dominant DER conceptual modelling frameworks will then be presented, backed up by a representative sample of optimisation studies using the models to test the flexibility of DER-dominated energy systems.

2.1 Smart cities, smart districts and smart grids

The terminology "smart city" was popularised in the late 1990s (7) to refer to a city characterised by highly technological initiatives aimed at improving the quality of life of the community and the efficiency of urban operations and services. In the scientific community, it was determined that the smart city paradigm lacks universality and is often characterised by multiple socio-technical facets, with the penetration of ICT infrastructures in the urban fabric (e.g. fiber optics, sensors, the Internet of Things, Big Data) seen as a common, determining feature (8–14). Among all the dichotomies that exist in the literature, the most relevant to this review is the mono-dimensional intervention logic, as opposed to an integrated approach uncovered in both (12,13). Only the energy domain is of interest, and the 2012 European Innovation Partnership for Smart Cities and Communities (EIP-SCC) (15) ideally exemplifies such approach, as it is aimed at achieving a future vision of low-carbon and sustainable EU economies, particularly in relation to their 20/20/20 climate action goals legislated in 2009 (16) and further long-term objectives.

In the quest of achieving such vision, the EU has brought together a community of more than 3,000 stakeholders belonging to different knowledge spheres (academic, private, governmental) and financial availabilities (13), raising significant logistical support and capital for the majority of the so-called "smart energy" projects in place in 199 cities as of 2014 (17). Such initiatives are particularly concentrated in Spanish, British, Italian, Dutch, Belgian and Nordic smart cities (e.g. Amsterdam, Barcelona, Copenhagen, Helsinki, Manchester), and consist primarily of two types, both ICT-enabled: smart neighbourhood units or districts aimed at creating carbon neutral and sustainable residential areas and resource management systems, consisting of smart grids, smart meters and smart DER integration (17). The EU-commissioned review (17) also highlights relevant good practices for the successful execution of the smart projects, such as the need for a strong and responsive local government partner and a firm business case, supported by the right mix of private and public funds depending on the typology of the project. Ultimately, such interventions must be deeply integrated in the city's comprehensive vision and approached by all stakeholders with a common, clear objective.

(18,19) argue that it is easier to implement successfully smart energy initiatives at the district-level rather than at a city-scale level, as small-scale integrated projects are seen as the most likely to succeed and be coordinated and can engage local citizens and raise awareness of the technological innovations to a greater extent. This view is in line with the district focus of the EIP-SCC, and with the EU strategy of launching multi-city sustainable district projects with a common vision and objectives. This approach based on replication helps spread the best design and retrofitting practices towards sustainable energy development throughout the bloc. The most up-to-date review of the best practices adopted throughout these projects is presented in "The making of a smart city: best practices across Europe" (20). An important takeaway of this review is that the first intervention in virtually all projects analysed regards the retrofitting of the building envelope, demonstrating that reducing final energy demand is more cost-effective than installing renewable or low-carbon energy capacity. It is no coincidence that the EU has set the ambitious goal to limit new buildings exclusively to zero energy building or near zero energy building types by 2020 (21). Common temporal demand side management (DSM) or demand response (DR) techniques that can assist in achieving such designs can be found at (22).

Aware of the reliability and flexibility constraints that aging electricity supply networks might pose as greater and greater proportions of electricity are generated in an intermittent fashion through DERs in increasingly liberal markets, the EU began promoting the mass deployment of the smart (power) grid concept, particularly among network operators and regulators, with the establishment of another multi-stakeholder partnership similar to the EIP-SCC: the 2005 SmartGrids Technology Platform (23). Their future aspirations are to ultimately create a unified European power market where customer-centric, actively managed grids would offer a wider choice of cost-effective energy services to the continent's citizens. The EU also saw it as an opportunity for testing innovative, cost-effective hardware and ICTs in end-of-life power infrastructures requiring maintenance. The EU-commissioned reviews (24,25) show that the political efforts have had a degree of success, as it is expected that almost 72% of European consumers will have a smart meter for electricity by 2020, accounting for a total of almost 200 million units, and overall 950 smart grid-related projects, divided almost evenly between R&D and demonstrations (57% vs. 43%), have been initiated in the 21st century, amounting to a total of almost €5 billion investment. This capital has been used mainly to finance the following project typologies: smart network management (SNM) through enhanced grid monitoring and control algorithms (34%), DSM schemes to shift consumption away from peak hours ("peak shaving") and to reduce energy level usage (25%) and finally control architectures to facilitate the integration of DERs (22%). Distribution network operators (DNOs) have invested particularly in SNM projects as they see it as one of the most promising techniques for reducing their planning and operational grid costs.

2.2 Review of modelling frameworks

Extensive reviews on recent research efforts on the suitability of modelling frameworks for the grids and energy systems of the near-future can be located at (26–29). In particular, Mancarella's exhaustive review on multi-energy systems (26) identifies three major conceptual modelling frameworks or general aggregation concepts: the energy hub, microgrid and virtual power plant (VPP). General characteristics and primary modelling objectives are described in Table 1.

Table 1: Principal DER conceptual frameworks (26)

Modelling framework	Description	Objective
Energy hub	Multi-carrier network structure of the future, optimized conversion of multi-energy vectors in matrix-based hubs	Reliability and flexibility of energy supply in future networks, real-time maximum efficiency of energy vectors conversion
Microgrid	Single controllable LV & MV smart grid embedded with DERs & interconnected loads, islanded or grid-connected	Autonomy of microgrid from external grid, optimal power balance and DER controllability, minimization of network constraints
Virtual Power Plant (VPP)	Electrical load aggregation (physical or virtual) platform to act as a "virtual power plant" in energy markets	Maximisation of profits from power and gas trading in energy markets, business case development

Following a review of case studies involving multi-technological mixes of distributed generation and storage in order to deal with the highly intermittent nature of RESs and implement appropriate DSM practices (30–41), all three frameworks seem to share a high degree of technical flexibility towards the integration of such complex energy systems. The energy hub model can be regarded as a general framework for MES aggregation, taking therefore into account more vectors simultaneously. The microgrid and VPP models instead only operate in the power domain, and occasionally also in the heat and cooling domain through the electrification trend (e.g. use of heat pumps). More specifically on the case studies, the energy hub seems to have been conceived fundamentally for the optimisation of the technological mix of local distributed energy generation in a spatial arrangement. If storage solutions, whether thermal or electrical, are factored in the mix, the model takes on a more sophisticated configuration due to the need of dynamic time series. However, it is also able to incorporate other more volatile elements from demand response (time of use tariffs [TOU], load shifting), as a result of its "black box" nature. The converter configuration allows to take advantage of the storage capacities in a hub and synergistically integrate their operation with local generation to achieve effective DR-based business models. The two last studies analysed (34,35) delve even deeper into the functionalities of the energy hub configuration for designing even more sophisticated DR-based operational strategies (stochastic-based customer behaviours, customer load managing by DNOs). To achieve this, the model needs to be subtly adapted to such applications and more elements and modules need to be added to the basic energy hub configuration.

It could be argued that microgrid and VPPs integrate such functionalities into their architectures more smoothly thanks to the use of advanced control algorithms. These two models share virtually the same architecture implications and the use of advanced control strategies (the latter is a distinctive feature that energy hub models rarely have); however, the main differences usually lie in their applications. Microgrid frameworks are usually used for assessing the coordinated control of all the distributed loads in the network and other power balance objectives: simulations of islanded operation, operational optimisation of multi-technological generation mixes with storage for greater autonomy. They can also incorporate demand response behaviours, but the studies concentrate more on the technical constraints of such operational strategies. In the case of VPPs, the focus is strictly more commercial and a discussion of network constraints is normally not the main concern, also because the level of aggregation does not necessarily have to be physical and many automated algorithms are implemented through a cloud base. The ultimate objective is usually the attainment of an ideal business case. For this reason, significant efforts are dedicated to modelling wholesale market price and incentive trends to a relatively high level of granularity. In conclusion, the microgrid and VPP can be considered more as operational concepts, also because they are not only used for simulation purposes but constitute effective physical assets. They are not restricted by rigid architectural technicalities and therefore relevant models can be constructed with different optimisation tools. On the other hand, the energy hub has a much more rigid, mathematical arrangement due to its input-output structure. It then describes energy flows in a more synthetic way, perhaps easier to conceptualise. In theory, this aggregation methodology can be used to model microgrid and VPP operational models and therefore combine the advantages of each different concept.

3. CASE STUDY

The Fiera del Levante (FDL) complex in Bari, Italy, is one of the largest exhibition centres in the Mediterranean, hosts around thirty large-scale events and other smaller-scale ones throughout the year (6), producing a strongly seasonal energy load scenario. As no local energy generation is currently present and the FDL centre contracts all electric loads from the grid, there is potential to introduce distributed energy generation, with the added challenge that low utilisation rates might hinder the proposal of a successful business case.

A planimetric map of the 280,000 m^2 FDL complex can be appreciated in Figure 1. The exhibitions and conventions tend to be organised in the multifunctional stands and modular spaces highlighted in colour in the map. In particular, the “Nuovo Padiglione” (also referred to as stand 216) is used more than other other stands, as it is of more recent construction and more energy efficient and is quite versatile as it can be subdivided into 4 modular 4,000 m^2 rooms (6). Most of the remaining buildings in the north of the complex are currently leased to permanent businesses and are therefore characterised by typical weekday and weekend load profiles. As a result, this district has a baseline energy consumption pattern of around 250 kW (42), which however increases dramatically when exhibitions and conventions are held, particularly in the summer months when the air conditioning requirements are significant. This strong seasonal demand variation results in electricity peak loads of up to 5 MW (42), as heat and cooling are provided through a network of air-source heat pumps (ASHPs) and natural gas boilers have been fully decommissioned. The only energy generation assets present are two PV arrays with a cumulative peak power capacity of 995 kW on top of stand 216 (6), which are however owned and operated by private ESCOs to whom FDL has leased the roof space.

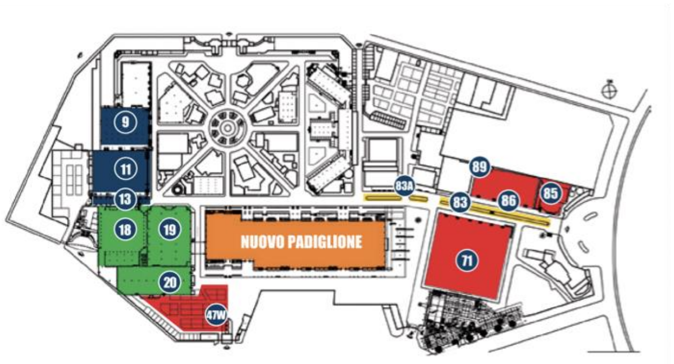

Figure 1: Planimetric map of the "Fiera del Levante" exhibition centre (6)

There is certainly an enormous potential for the introduction of power generating technology which could offset the particularly high peak demand loads during the exhibition periods, especially during the “Fiera Multisettore Campionaria Internazionale” (international multi-sector trade fair), the biggest event held here in September which attracts around 200,000 visitors every year (6). However, as a result of the low utilisation of the exhibition stands (between 0 and 50 days a year) and the low occurrence throughout the year of particularly high peak loads, some technologies might not be suited to such system and might result in low returns. Further PV arrays on the remaining roofs of the stands and a UPS-style standby diesel generator are seen as potentially attractive investment decisions. Battery or fuel cell storage solutions could also be suited to the variable load profiles but might result less economically competitive.

Another significant challenge of this case study is the lack of disaggregated load data (the FDL site is metered as a whole with the local DNO) and an hourly time resolution. The majority of the available power load data is characterised by monthly magnitudes, with a further subdivision in three time of use tariffs typical for small and medium enterprises. A high degree of heating and cooling demand estimations will be necessary on the basis of installed heat pump capacities, cubic meters of enclosed space and average ambient temperatures. To provide decision-support to the operator of FDL an optimisation model can compare different technologies and operating regimes and evaluate them against various metrics including costs and GHG emissions.

4. PROPOSED METHODOLOGY

The aggregation concepts discussed in section 2 are particularly applicable for the FDL case study, as they each give a significant insight into the technical and operational characteristics of an optimal retrofit intervention involving distributed RES and multi-generation, storage and even DSM practices (TOU above all). A good starting point for the design of such model is to identify a flexible open-source or accessible model which can be easily integrated with the pertinent input data of the FDL existing energy system. From here, more technical constraints can then be added in order to expand the modelling capabilities of the tool. Ringkjøb, Haugan and Solbrekke (43) provide a convenient flowchart exemplifying the selection criteria of an appropriate model. The following considerations on the general logic features are made:

- **Purpose:** the model should serve primarily as an investment decision support tool for new conversion and storage technology units in order to reduce operation costs, particularly during the summer peak load months during which events are held in the FDL centre. A secondary objective would be to provide operation decision support for the existing and proposed energy systems, as the operational schedules of all technologies must be predicted and understood in order to lower operating costs during the peak load periods. This however might be difficult to do for the installed ASHPs, as limited load data is available and might have to be treated as non-dispatchable loads. Such investment modelling will be mostly made with a myopic approach, which means that design decisions will be mostly made based on information from the current investment period rather than future periods as well (43). This is mainly due to the lack of such data and manpower hours to derive such information with suitable predictive tools.
- **Approach:** this characteristic refers to the analytical nature of the model. Bottom-up models rely on the specific technological details of energy systems in order to describe supply and demand trends (43). For this reason, they are quite suitable for building and district-scale systems such as the FDL one, where such data are more relevant for taking energy-related investment decisions. On the other hand, top-down models describe energy systems from the big picture, aggregating together macro-economic metrics and data to model technological advancements in response to policies, innovations and long-term changes (44). Because of their nature, they can be integrated more easily at a national and regional level, which is beyond the scope of the FDL energy system.
- **Mathematical formulation**: the general tendency of the optimisation models analysed in Section 2 is to maintain the constraints and objective function strictly linear, with the addition of integer variables if necessary, making the problem of the mixed integer linear programming type (MILP). The reason for this is that the addition of non-linearity does not ensure that the solution reached is the global optimum. However, part-load efficiencies, which are characteristic of prevalent technologies such as CHPs and heat pumps, are normally non-linear relationships and linear approximation techniques might be imprecise. Integer variables are also necessary to denote the installation and operation (or not) of specific technologies within the entire technical library and do not increase substantially the computational complexity of the problem.

The Technology Selection and Operation (TSO) optimisation model for DER energy systems designed at Imperial College London is characterised by the features just discussed and is therefore perfectly suitable as a starting point for the FDL case study. Its technology library contains combined heat and power (CHP) and organic Rankine cycle (ORC) engines, absorption chillers, photovoltaic panels and batteries, to which diesel generators and fuel cells can be potentially added. Further technical details of this model can be located at (45–47). Relevant data will be collected from FDL where possible, and combined with data from the literature as well as other comparable sites where required to construct a realistic picture of the loads and flexibility.

5. FINAL REMARKS

The proposed approach will allow a comparison of different interventions for the case study site, including the selection of suitable technologies, operating strategies for the hybrid energy system, the potential to link the site with surrounding areas (with FDL acting as a VPP) for further integration in a wider urban energy system, and finally can be used to experiment with different policies and incentives to support and guide this transition. The model relies in high temporal resolution to capture not just the seasonal variation, but also the day-to-day operation as well as the intermittency of RES. Finally, the case study will provide recommendations on the kind of data that needs to be collected on the site so building operators can best manage investments and control their assets. The full paper will show detailed results and analysis of relevant scenarios and reflect on the suitability of the methodology to provide decision-support for urban energy systems.

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