Multi-resource Optimized Smart Management of Urban Energy Infrastructures for Improving Smart City Energy Efficiency

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Abstract: This paper presents an innovative conceptual, technological and business framework for an energy-centred multi-resource optimized hub aimed at smart city infrastructure improved integration and improved energy efficiency and reduced carbon footprints. Early results show a cost-effective operation for the integration hub, as well as a 30% smart city/district energy efficiency overall increase when a synergistic operation management is carried out for those resource supply infrastructures which are integrated through the implemented hubs. Two major technological implementations have been presented and their current state of implementation has been discussed, the first one aimed at integrating smart electricity grid with hydrogen mobility infrastructure, while the latter one refers to a smart data centre hub interfacing with smart energy (both power and heat) grids and with telco networks.

1 INTRODUCTION

This paper presents an innovative conceptual, technological and business framework for an energy-centred multi-resource optimized hub aimed at smart city infrastructure improved integration and improved energy efficiency and reduced carbon footprints. Two major technological implementations for this framework have been presented and their current state of implementation has been discussed, the first one aimed at integrating smart electricity grid with hydrogen mobility infrastructure (and/or with natural gas grid), the latter one which refers to a smart data centre hub interfacing with smart energy (both power and heat) grids and with telco networks.

2 BACKGROUND AND MOTIVATION

Efficient management of urban infrastructure networks is becoming nowadays the cornerstone to deal with for achieving significant energy efficient gains and reducing carbon footprints in urban environments, when we face with larger penetration of fluctuating decentralized renewable energy generation.

Infrastructure is commonly referred to as the physical networks of energy supply, water, communication, transportation, and waste removal and treatment, including sewage. The current infrastructure operation consists of separate supply systems provisioning unconstrained demand, which is considered as the societal need to deal with (infinite resource mode).

Urban networks include:

- Energy distribution networks (smart electricity grid, district heating/cooling, gas grid), whose main purpose is to transport energy in whatever form from the generation to the end user delivery point, while consuming themselves energy.
- Beyond-energy Resource distribution networks (ICT, water, sewage, fuels as energy carriers aimed at mobility/transport, transport, including railways, motorways,…) which consume Energy to distribute/transport resources (data, water, wastes, people)

Major focus is on urban energy systems optimized management and their optimized interaction with other resource (beyond energy) infrastructures to achieve system-level energy

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efficiency. Urban energy systems have been defined as the combined process of acquiring and using energy to satisfy the demands of a given urban area (Keirstead, 2013).

Latest advancements of ICTs have made possible today to design and operate in a optimized way individual energy distribution networks, which include smart electricity grids, district heating/cooling networks, gas grids, and beyond-energy resource distribution networks, like ICT, transport /fueling networks.

The state of the art for Infrastructure integration implementation is for:

- Different limited-scale pilot applications have been implemented all over Europe (if not world)
- No synergies in place at any level among the different functional domains or infrastructures, which is the main reason for:
    - Ongoing applications are tailored to optimize resource efficiency in a single domain (i.e. either energy, either transport/mobility, either water, …)
    - Energy and resource-efficient district planning and retrofitting are very seldom cost-effective and very rarely citizens are fully engaged in decision making process
- Municipalities look at infrastructure networks as individual and unrelated systems, producing resource usage inefficiencies
- Governance is based on unconstrained growing demand results in inefficient and unsustainable
- Current design and operation do not integrate end users, in terms of the heterogeneity of their energy and other resources demand and behaviors (e.g. car ownership as unique transport mode) and their crucial role in selecting and using technological options (e.g. selection and appropriate operation of energy efficient technologies);
- Disjoint and parallel delivery of different infrastructure streams prohibits the development of potential joint solutions (e.g. co-treatment of waste and wastewater), or even substitutions (e.g. substitution of electricity with gas through micro-combined heat and power (CHP)), between infrastructure systems. These characteristics represent major barriers to technical innovation and longer term sustainability.

However the urban landscape nowadays is rapidly moving forward towards an overall sustainable system with embedded local energy generation from Renewable Energy Sources (power from PV, thermal energy from solar collectors) to be exploited, used and/or integrated in whatever form in the energy distribution networks aimed at reducing energy intensity of human activities and increase the smart city energy efficiency. The emerging paradigm is for a constrained demand, in which the basic assumption is the “limited natural resources availability”, which need to be exploited at largest possible extent when and where they are available and suitably managed.

Emerging ecological models represent cities as living self-sustainable organisms which pass trough different life stages, each of them with different level of energy consumption (and materials) to carry out human processes (Urban Metabolism). Leveraging on urban metabolism sustainable models, cities may take on a key role in nurturing an innovative smart sustainable development model, aimed at activating a circular economy through a synergistic approach, combining the city economic, logistic and industrial activities with citizens quality of life and overall energy efficiency and carbon footprint reduction.

Innovation can be stimulated by regarding cities as living organisms, with the continuous flow of inputs and outputs as their “metabolism.” More circular urban metabolism that treats outputs from one use as inputs to another would help cities increase resource productivity and adapt to a future of resource limitations and climate uncertainty.

Self-sustainability for cities means a “system-of-system” vision in which the objective is to consume locally generated resources as much as possible, with a view to reduce the energy cost necessary for transporting locally generated resources elsewhere. As such, different synergies may be found within energy consuming (transport, ICT) and energy transporting infrastructures (smart energy networks) stakeholders, ranging from planning stage (Co-Planning of a district-level decentralized CHP generation system to couple heat and power system), to the construction (es. digging sharing for telco and power networks), operation phase (es. sharing assets and facility among street lighting, telco networks, information access and electric vehicle recharging, billing IT systems sharing, coupled optimized operation) and at level of service delivery and business model (integrated services built upon data-level cross-resource interoperability, without any operational optimized multi-resource management, multi-utility value proposition like providing the requested thermal comfort level to the households).

Despite there have been a number of attempts for designing and operating multi-carrier systems, the large majority of these approaches are limited to deliver smart integration hubs for connecting energy networks or, where other resource infrastructures are considered, no systematic economic analysis is carried out within a real multi-utility integrated environment, nor any comprehensive modeling which would include energy usage-driven integration of beyond-energy resource supply infrastructures has been conceived (Bruno et al., 2014), (Geidl et al., 2007), (Hemmes et al., 2007), (Maroufmashat et al., 2014), (Lehnhoff et al., 2013). The urban landscape is characterized more and more by rising local (fluctuating) renewable energy generation, which aims at securing local energy supply at lower costs and reducing the energy intensity of natural resource usage. Such proliferation of decentralized renewable energy sources however would require increasing decentralized flexibility to deal with local technical constraints preventing energy (smart electricity grids and district heating) and beyond-energy networks to integrate larger shares of RESs. Accordingly decentralized flexibility becomes the key resource for instantiating the urban metabolism paradigm and the maximization of available natural resource potential deal with the societal need to fully exploit the local available energy generation potential, while reducing at the same time the cost of the investments for local energy generation. Along this roadmap an holistic design for coupled and interconnected operation of energy and beyond-energy infrastructures would rather allow to achieve larger system-level efficiency, while reducing energy and natural resource intensity of human activities. On the other hand end users, as final consumers of energy and other energy-consuming resources can play a significant role to reduce pressure on the energy and natural resource demand, through raising awareness and suitable education towards adopting more sustainable behaviors, which could bring significant overall energy and natural resource saving and better management. Humans behaviors and citizens potential contribution to a more sustainable development can be modeled as a further specific network which will be interconnecting with energy and other resource infrastructure in physical hubs where humans consume energy to carry out their own daily work or leisure activities. In particular citizens will be consuming energy at home for cooking, heating, watching TV, washing, will be consuming energy for the water they consume and finally they consume energy on the move by taking train (transport infrastructure consuming energy).

3 THE APPROACH

We propose to model the smart city as a multi-layered intertwined and coupled network infrastructures, consisting of energy and other resource (energy-consuming) infrastructures (like ICT, water, transport) and human networks which will be interacting and integrating one each other in local multi-network cyber-physical hubs, where either energy will be generated, either converted in whatever other energy form or other resource, with a view to secure and maximize local energy supply through the provisioning of the requested levels of flexibility. Suitable combinations of leading-edge ICT technologies, like near real time sensing and monitoring, intelligent processing, big data on line analytics may be enabling the holistic optimized operation of integrated coupled energy and other resources infrastructures with human networks with a view to achieve cost-effective optimal urban system management and enhancing energy efficiency, while reducing carbon footprint.

Decentralized flexibility could be provided by:

- demand-side management strategies (like load/demand flexibilization and active energy consumers/prosumers engagement)
- supply-side management (local decentralized energy storage and/or integration with other energy or resource networks)
- a combination of the above

It is worth to be said here that the integration of locally generated energy should be carried out through cost-effective integration in coupled energy infrastructures, complemented by local storage and active end users engagement for reducing their energy consumption and actively contributing to load flexibilization. In our model that non-energy infrastructures, like communication, transport and water ones could be used as further potential integration networks with a view to provide increased level of flexibility. The key assumption for our Integrated Sustainable Urban Model is for Smart Urban Infrastructures consisting of the application of recent advances in real time smart monitoring and processing technologies to support the optimized yet flexible operation of the energy and beyond networks (power, gas, district heating, water, ICT, transport, waste...).

The second dimension along which smart city is represented and implemented is the self-sustainable system-of-systems. The vision is for future urban systems moving away from traditional broadbandlike systems towards multi-directional networked cyber-physical systems of systems, consisting of smart decentralized multi-layered self-sustainable sub-systems which: (i) optimize the consumption of self-generated energy by distributed RES; (ii) exchange and make available the resulting surplus of energy to the upper connected layers (smart building, smart district, smart city/region/community); (iii) manage and solve locally (at district/city levels) the major operational challenges, reducing value chain length and costs (es. Sustainable agriculture, zero waste, local energy supply systems integrating fluctuating RES locally at the largest possible extent with a view to reduce transmission losses); (iv) are managed in a coordinated and integrated way, with a view to achieve holistic and synergistic resource efficient distribution (optimized management of multi-carrier energy networks, like Power2Gas systems); (v) are enabled by ICT proactive systems, which include finer-grained situational awareness and networked optimized control; (vi) include in the loop at the largest possible extents citizens, which are expected to become "socially educated" sensors (nodes).

Smart cities representation hence is for a cyber-physical Systems of Systems, consisting of large interconnected partly autonomous sub-systems, coupled by flows of electric power, steam, gas, and other resources, where larger local RES generation capability requires increased local-level network flexibility solutions (demand-response, storage, multi-utility integration…), which may be effectively achieved through a local control and decision-making, within the framework of a global large-scale coordinated networked control. In a nutshell our model aims at originally leveraging on synergies among resource infrastructures (resource supply side), while locally addressing flexible yet optimized energy consumption as core innovation to deploy cost effective Sustainable Smart Cities.

The expected outcome is to maximize synergies among resource infrastructures to enable improved systemic energy efficiency and optimal energy management at district/city level within a multi-resource synergistic management.

3.1 Technology Implementation

Within the proposed model we have developed a suitable IT architecture for a decentralized cyber-physical urban hub at the interplay among the different networks. Such node will be in charge for optimally manage and efficiently operate in real time with a view either

- to optimize a hub-level operational efficiency (for example maximization of usage of locally generated energy from RES, either power from PVs either thermal energy from solar collectors or micro-CHP, i.e. follow-the-sun strategy) or economic criteria (multi-energy generation)
- either to adapt real time hub operation with a view to achieve given set points within a multi-networks or coupled network optimization (multi-network optimization) paradigm.

3.2 Business Models and Innovation

To achieve long-term sustainability infrastructure needs to be designed and operated with the goal of providing essential service delivery at radically decreased levels of resource. This requires a new approach based on a more systemic view of the purpose of infrastructure.

This new approach will need to:

- be focused on the service provided (thermal comfort) rather than carrier supply (e.g. gas);
- incorporate the end-user, in terms of their energy and other energy-consuming resources demand, behaviors and technological choices;
- and above all will be enabled by recent advancements in smart Information and Communication Technologies (ICTs) able to provide tighter real time situational awareness and more effective capabilities for intelligent processing of large amount of data to integrate the operation of different infrastructures

The transition of urban infrastructure operation is moving away from supply of unconstrained demand and towards resource-efficient service delivery. This requires a fundamental change in the business model used to deliver effective infrastructure services. The current throughput based approach, where profit is made by increasing unit sales or utility products, is not longer sustainable and vulnerable to resource scarcity. It needs to turn on into a model where the provided service and infrastructure companies are incentivized to provide service at lowest possible resource use. In addition we need to exploit the benefits of infrastructure integration because one service is often provided by multiple utilities. New stakeholders are expected to emerge which can play the role of integrated infrastructure service companies (Multi-Resource Service Companies)

In order to better identify potential suitable service delivery and appropriate business models, we need to identify different yet increasing levels of integrations and synergies among the urban resource infrastructures:

- Integration of Facilities and Assets at construction and operation stage to avoid the underutilization of valuable fixed assets by integrating facilities conventionally separated by sectorial functions (sharing digging and construction material during construction, sharing equipment and/or facilities
- Integration of Services across Silos (Business or Service Integration) to break existing organizational barriers and provide cross-infrastructures service (Integrated Service Delivery Model). Here Integrated service delivery model is based on the IT cross-infrastructure interoperability and integration (es. Energy footprint of mobility patterns)
- System-level Integration (Technical Integration), where energy generation, resource supply and waste management are integrated either at design either at operational stage by establishing cascades and system-level cost-effective optimized multi-resource operation

The way in which innovation can be deployed at smart city level and the respective service delivery and business models will be strictly depending from the tailored integration level.

Despite in principle the proposed framework can instantiate whatever level of integration, the main purpose of our proposed framework is to tailor the third and highest level of integration, with a view to maximize energy efficiency of human activities at smart city level. In that respect integrated service delivery model and a multi-utility model, enabled by a system-level technical integration.

4 IMPLEMENTATIONS

At the current stage we carried out a number of preliminary implementations for the proposed infrastructure integration model, where we have delivered an instantiation of the hub IT architecture and a preliminary business analysis aimed at demonstrating the cost-effective operation of the integration hub, while considering the additional costs incurred due to the technology stack implementation (in terms of return on investments). Furthermore from the early calculations we conducted we demonstrated the 30% improved efficiency (and related overall energy saving) for synergistic management of resource supply infrastructures against a disjoint separated operation of the same infrastructures.

It is worth to be said that these implementations presents different levels of maturity: while for the case of INGRID we have already developed a preliminary business case for the storage-enhanced integration hub, in the case of the GEYSER project, we are about to deliver the early prototype for a smart integration hub able to couple energy and telco infrastructures. The following implementations have been partially developed so far: (i) Integrating smart electricity grids with gas grid and/or with hydrogen-based fuelling infrastructure for green mobility through Hydrogen Energy Storage (INGRID); (ii) Integrating smart energy grids and telco networks through net-zero energy smart Data Centres (GEYSER)

4.1 INGRID Implementation

Within the framework of the ongoing European FP7 INGRID project, a multi-network optimized management of a hydrogen energy storage enhanced-hub has been developed at the interplay between smart electricity grid and natural gas grid and/or green mobility infrastructure, whereas the surplus of hydrogen will be used as fuel for alternative mobility or in alternative can be injective in the nearby natural gas network.

INGRID (High-capacity hydrogen-based green-energy storage solutions for grid balancing) is a European R&D ongoing project which aims at demonstrating in a real life operational context the technical and economic feasibility of decentralized solid hydrogen energy storage supporting the joint optimized operation of a multi-carrier energy distribution systems, which includes the simultaneous optimal (technical and/or economic management) of electricity and hydrogen infrastructures. Main challenge is to make use of smart grids technologies for real time monitoring and optimized control combined with solid-state hydrogen energy storage systems for effectively balancing power demand and supply in the Medium and Low Voltage branches of the power network in a scenario of large (>25-30%) penetration of intermittent distributed Renewable Energy Sources at smart district level. Hydrogen energy storage coupled with distributed RES generation and onsite hydrogen use and/or nearby transportation may enable multi-utility systems to be efficiently and sustainably used to integrate larger shares of RESs in the overall energy distribution system, with a concrete increase in resource efficiency distribution, yet reducing the problem of the curtailment of the generation facilities to prevent unsecure power network operations.

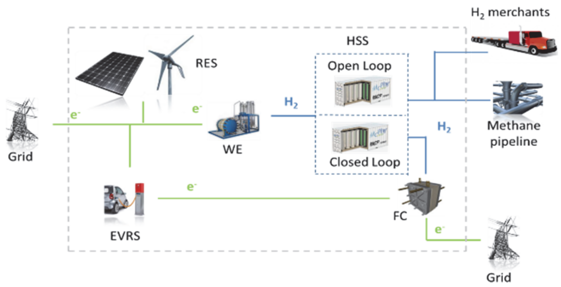

Figure 1: INGRID Implementation of the proposed model.

In that respect we have been developed a novel ICT-based cooperative storage-based inter-grid energy management and control strategies for the optimal behavior of the storage hub at the interface between multiple energy grids (INGRID Energy Management System), and respective stakeholders (Distribution System Operators, storage operators/service providers and hydrogen value chain operators (including natural gas distributors).

EMS will be deployed in a field demonstrator (actually in commissioning stage), which consists of a Water Electrolyser (WE), an Hydrogen Solid Storage (HSS) system, a Fuel Cell (FC), an internal RES based plant and an Electric Vehicle Recharge Station. The INGRID system is connected to the MV branch of the power network insisting on the Troia (Foggia, Italy) Primary Substation 150/20 KV, where a significant intermittent generation from PV and wind farms will be converging Two different families of Optimized Management. INGRID EMS will be operated through different optimization policies, which implies different business models:

(i) Multi-network operation, where the main objective will be to support local Power Distributors in Lower Voltage Grid stabilization by provisioning of network services. Here the local DSO will play an "incumbent" role, by defining the near real time set points for the storage-enhanced hub, which will be accordingly in charge for self-adapting their internal hydrogen surplus production and deployment. Local DSO-level electricity balancing markets can be implemented, where local DSOs can eventually procure ancillary services for local grid stabilization, while green hydrogen surplus can be locally used or transported for subsequent industrial or other uses;

(ii) Multi-generation, where hub-level multi-energy optimization will be carried out, enhanced by hydrogen energy storage, aimed at maximizing the local hub district-level economic result, based on the near real time monitoring input from local RES generation and on the economical stimuli from the smart power grid and from hydrogen market (or gas grid). Underlying business models will be based on: (i) local Third Party Independent Storage Service Operator within a Merchant Ownership Model and (ii) bundling different storage services with a view to achieve double reward for service deployment at Medium and Low Voltage levels, while reducing the high CAPEX for storage facility deployment. Early simulations shows a positive business case within five-six years, for a given bundling configuration. However more detailed analysis for a more extensive range of bundling configurations will be carried out during the demonstrator operation.

4.2 GEYSER Implementation

An implementation for a Net-zero Energy Data Center acting as energy-driven multi-resource hub at the interplay between Smart energy grids (either smart power grid either district heating or both) and telecommunication network for workload shifting has been developed within the GEYSER project.

Main background for this implementation is that no active links among Data Centers/ICT networks and Smart Cities and its respective energy utilities (either electricity either heating operators) and no energy or info exchange do exist among them and urban Data Centers are operated in uncoordinated way and their Energy efficiency has been so far addressed in an isolated way. However urban Data Centres have a large yet mostly unexploited flexibility potential to contribute to smart city local energy consumption optimization and smart energy grids optimized operation, at the extent of IT workload time and spatial migration through telecommunication networks. Our implementation provides a Resource Management System for a net-zero energy Data Center hub, which will be conveniently integrated with Smart City level Energy operators. Along such vision, data centers are expected to turn on into flexible energy players at the crossroads of Smart City and Smart Energy Grids, with a view to become adjustable adaptive power consumers. We can identify the GEYSER unique selling proposition as near real time energy flexibility service provisioning at local level, aimed at either alleviating power grid local (MV and LV) network constraints in real time caused by the imbalances derived by surplus/shortage of electricity generated by stochastic RESs, either optimizing nearby city/district level energy management with a view to prioritize green local produced energy. GEYSER builds its flexibility offer to the interested stakeholders (local DSOs, retailers, ESCOs, energy traders) though uniquely combining and optimizing internal (back up and intermittent renewable) generation capability with internal energy (either thermal either electric) storage and computational workload shifting techniques. In particular, local power generation and thermal storage (i.e. DER management) combined with workload management has a significant potential to shed the peak load and reduce energy costs, provided that adaptation, responsiveness and latency time will be matching with real time local utility operator requirements.

The unique combination of optimal internal back-up generation, with thermal storage and computational workload (temporal and geographical) shifting allow next generation Data Centers (i.e. “GEYSER-enabled Data centres”) to become active stakeholders in the energy market and smart city/local energy optimization affair. GEYSER DC flexibility offering will be conveyed and made available through local green energy marketplaces tailored to energy sellers/traders, ESCOs, municipalities for anticipated energy contracting and provisioning (energy services in time-ahead markets). Main stakeholder here is the smart city /district energy manager who will be in charge for procuring energy (in all the necessary forms and with an economically optimized portfolio of energy carriers/mix (power, heat, gas,…). Here both a multi-network optimization can be carried out if Smart City Energy Manager will place a bid on the scheduling marketplace (es. One day/hour ahead) for the energy mix requirement, otherwise a multi-generation scenario can be operated where the data-center hub will adapt its internal computational workload and local generation and storage with a view to achieve the best economic results. Eventually follow-the-sun strategy could be conveniently adopted by the data centers if suitable economic signals will be captured from the city-level DSO or district heating operator. For example, follow-the sun strategy local generation combined with thermal storage could be used for temporary thermal storage with a view to subsequently alleviating the later thermal network peak demand.

Otherwise Data Centers could be directly participating to Local Balancing Marketplaces by Network Service real time provisioning to alleviate their specific operational problems. For example data centers could provide flexibility services to DSO to manage peak shaving in the DSO network, provide a firm load diagram (load leveling), or provide local balancing service systems like voltage regulation or reactive power regulation.

Suitable business models have been specifically designed for Smart City viable value proposition,

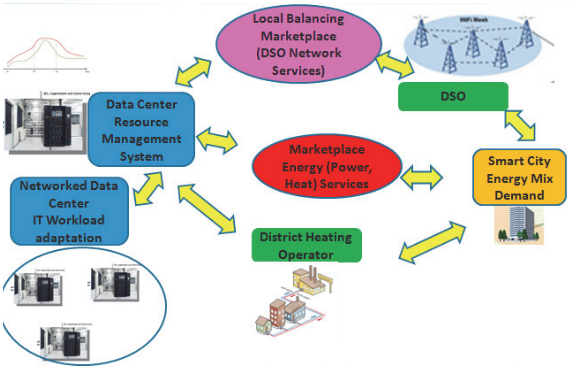

Figure 2: GEYSER Implementation of the proposed model.

based on Time based Service Level Agreements, intended as major or minor responsiveness of DCs to offer the required flexibility (by uniquely combining local generation and storage with computational workload shifting) with different latency times. For instance, a Data Centre may deploy a Premium, more expensive, service with a very low latency time and highest time responsiveness in the range of 1 to 5 minutes. Otherwise, we can imagine cheaper less responsive ancillary services tailored to DSOs in the range of 5 to 15 minutes.

5 CONCLUSIONS

An innovative model for energy-led smart urban resource infrastructure model has been proposed, which includes a conceptual, a technological and a business layer implementation. Two major implementations within the on-going FP7 European projects INGRID and GEYSER have been illustrated, despite they are at different maturity stages, which demonstrate the cost-effective operation of a resource management hub enhanced with storage, with a view to demonstrate cost effectiveness and improved energy efficiency of smart city when resource supply infrastructures are operated in a coupled way.

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