Smart City Energy Planning: Integrating Data and Tools

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ABSTRACT

This paper presents an innovative analytical framework to address incomplete interpretations and dispersed data of the energy system in cities, which usually generate multiple inefficiencies. Integrative city planning takes the city energy system from the supply to the demand while considering its spatial representativeness, and drives optimal cost-efficient assessment towards future sustainable energy targets. This holistic approach delivers more adequate policies and measures towards higher energy use efficiency.

The proposed analytical framework has been developed within the INSMART EU funded project and focuses on data gathering procedures and data processing tools and models, covering a wide range of city's energy consumers, as residential buildings, transport and utilities. The results, mapped into a GIS, can be further exploited either for awareness increase of citizens and for decision support of city energy planners.

Keywords

Integrative Energy Planning; GIS; Buildings; Transports and Mobility; Smart Meters

1. INTRODUCTION

Cities are vital for engaging with environmental issues since its activities affect the environment locally, regionally and globally in both negative and positive ways [5]. Climate change and the reduction of energy consumption are challenging topics for cities and their territorial organization. A number of initiatives (*e.g.* [1, 2]) have been set up to engage cities in efforts towards a low carbon future and an improved quality of life through sustainable economic development.

Smart cities appeal for a coordinated energy, water, transportation, public health and safety services towards an efficient management of the critical infrastructure to assure end-use services for all citizens. There is a critical need for integrated comprehensive city planning [12], focused on ex-ante cost-benefit assessment and using energy systems models towards urban sustainable energy use.

This allows moving from a reactive urban management to a proactive approach based on knowledge and supported by the increasing availability of the IoT (Internet of Things) and information and communication technologies (ICT) on cities.

Hence, innovative tools and models to assess and perform in-depth analysis of alternative measures, will help pave the way towards more efficient energy use, to fully capture the potential of each city in the most efficient (economical, technical) way. We argue that assessing the energy dimension of a city (from supply to distribution and to demand) in an integrated approach allows a better understanding of the overall urban environment for improved and coherent city planning.

The growing availability of advanced computing and sensing platforms facilitates the potential access to massive data repositories with city information at several levels [18]. Moreover, it is important to engage decision-makers to increase their trust and understanding of the indicators and tools. Both aspects require advancing on ICT and IoT solutions.

This paper presents an innovative framework to integrate multiple data sources, with different temporal and spatial resolution (e.g. door-to-door surveys, smart meters, stakeholders' involvement, and energy statistics), modelling (transport and mobility, buildings simulation, energy system optimization) and analysis tools (statistical, geographic information systems). The paper shows how this comprehensive data gathering and processing steps are key to the integrative energy planning to deliver future sustainable energy pathways.

The paper is organized in four sections. The following section describes the methodology for each step of the data framework. Section 3 presents and discusses selected results achieved for the data collection and modelling, while the final section concludes.

2. RESEARCH METHODOLOGY

The proposed methodology intends to address the gap regarding incomplete interpretations and dispersed data of the energy system in cities (e.g. [12]), which generate multiple inefficiencies.

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This work has been developed under the European project INSMART – Integrative Smart City Planning (FP7 Grant agreement no: 314164), that brings together four EU cities: Évora (Portugal), Cesena (Italy), Nottingham (United Kingdom) and Trikala (Greece), and scientific and technical organizations of the same countries, to establish a methodology for enhancing sustainable energy planning for future city needs through an integrative and multidisciplinary approach.

We use the city of Évora as a case study, located in the Alentejo region of Portugal, with a population around 57000 [8], and a per capita annual energy consumption of 17.5 GJ [17]. Évora was the first city in Portugal to implement a massive electricity smart metering system (near 35000 meters with 15 minutes' registries) [7].

A bottom-up approach is taken to gather data for the whole energy system from supply to distribution to demand, through a combination of different data sources, tools and methods to collect and analyse information regarding: 1) residential buildings, 2) transport and mobility, 3) other energy consuming sectors (waste, water and sewage management systems; public lighting, public administration buildings, services) and 4) energy supply system, including renewables potential.

In a graph theory-like vision, the assessment of previous defined sectors provides the description of "nodes" (demand centres), namely the quantification of the stocks of processes and technologies (*e.g.* buildings, space heating technologies ownership, number of vehicles) and characterization of energy services required in the selected geographical polygons of the city (*i.e.* districts). These data are then integrated into a Geographic Information System (GIS) platform, mapping spatial energy features, which in the end will feed an integrative city-energy planning tool, as illustrated in Figure 1. A short description of the data, tools and methods used for each component is portrayed in the next sections.

The combination and integration of multi-scale data granularity, including 15 minutes electricity consumption data from smart meters, monthly to annual statistical energy production and consumption data, detailed energy modelling of buildings typologies, city transport characteristics and mobility flows, door-to-door surveys, and GIS tools with the participation of different levels of city stakeholders (municipality, utilities, transport companies, citizen groups, market associations) brings forward the main advantages of this methodology. The stakeholders' participation at the different stages of the methodology is essential in assembling an acceptable, realistic and mostly beneficial city action plan.

A better appreciation of the energy flows within city districts and building level is necessary for the identification and assessment of energy measures, and for the improvement of urban sustainability governance, through the integration of various city departments. The most definitive aspect in energy planning and effective policy execution is the availability of adequate data. For this purpose, existent cultural and organizational barriers have to be broken down, putting the various stakeholders to work collaboratively. Capacity building, collection and processing of scattered data, making it openly available is one of the first steps for ambitious city planning.

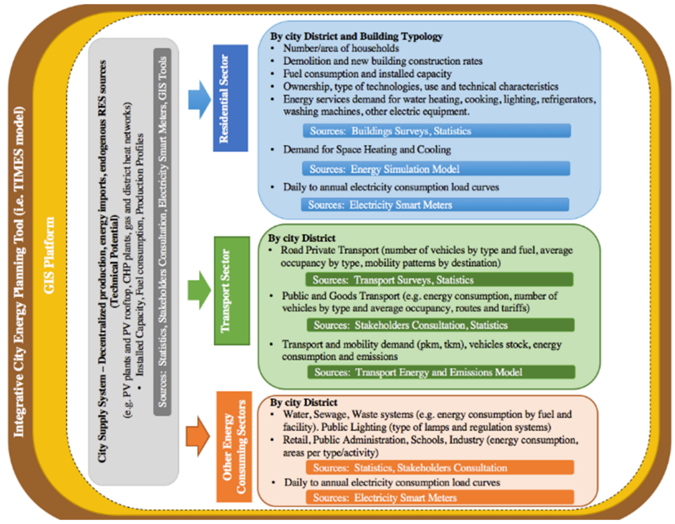


Figure 1 - General framework concept for an Integrative Energy City Planning

Energy city planning requires a significant spatial detail, in order to assess the spatial heterogeneity of energy flows and identify the underlying drivers. We divided the city of Évora in four districts to collect, describe and assess the energy indicators for residential buildings, public utilities and services buildings. For the transport sector, we identified the need to split the city into 21 zones to address adequately the mobility patterns. All the results are addressed in a GIS for an in-depth visualization and analysis.

2.1 Residential buildings

The city residential building stock was characterized with a selection of relevant building typologies (*e.g.* semi detached, built before 1945, one floor, sloped roof). A door-to-door survey was carried out in order to provide an exhaustive detail of the current situation of the city building stock compiling information not usually available in such spatial detail. The survey covered information about physical characteristics of the dwelling (*e.g.* load bearing structure, type of windows, insulation of external walls and roofs, etc.), socio economic details of the occupants (*e.g.* number of persons, income, age, gender), appliances characteristics, use and ownership.

The growing deployment of smart meters and real-time home energy-monitoring services, allow for increasing available data to characterize the electricity consumption in households. The socio-economic information from the buildings survey benefits from its combination with electricity smart meters data, whenever these are available, taking each building typology. The assessment of these data enables the identification of differentiated daily to annual electricity consumer profiles into the integrative city-energy planning tool where different energy policies and instruments can be evaluated.

Using the information collected in the surveys, we simulated the energy services demand for each of the residential building typologies [13] using DesignBuilder [3] and EnergyPlus [6] tools.

Simulated energy services demand data input the city GIS database, taking the location of each typology in each district, to provide spatial representations of the total energy demand from residential buildings, to identify regions of special interest (e.g. district heating network expansion; city blocks for renovation measures) and to visualize alternative energy savings potential in a comprehensive way.

2.2 Transport and mobility

Mobility analysis is supported by mobility flows within the city and conducted through a transport-based energy and emissions model [11]. The model developed as part of the INSMART project is a small, easy to use, but complex model, requiring minimal input data and computational time, but still providing sufficient sophistication to produce meaningful outputs for a variety of scenarios.

The spatial energy consumption, mobility demand and emissions data in each zone and between different zones of the city are essential to feed the integrative energy planning tool, which will provide a joint optimization of the overall city energy system to set up measures towards city sustainable mobility. The majority of the data needed as inputs to this model was collected through door-to-door surveys, national statistics and relevant stakeholders' meetings (*i.e.* municipality transport department, public transport companies). These dedicated transport and mobility surveys provide important contributions for the collection of socio economic households' characteristics, information on the number and type of vehicles and patterns of private transportation (locations and purposes) through travel diaries. The surveys also provide the characterization of mobility demand per vehicle, per person, journey purpose and distances covered on commuting, either within each zone or across the city zones. The key outcomes to feed the city-integrated energy-planning tool include the passenger and mobility demands by city zones.

2.3 Other energy consuming sectors

We extend the analysis of the energy demand centres to other relevant city services and technologies to properly operate the urban infrastructures. An in-depth description of the current city energy system requires to analyse a) Public Utilities (i.e. water/sewage and waste chain and public lighting) and b) Services Buildings (*i.e.* hospitals, retail centres, schools, public administration buildings).

The data collection for these sectors was made through the interplay of tools and procedures including literature review of existing reports; electricity smart meters' registries for public lighting, waste and water facilities; relevant stakeholders (*e.g.* utilities, municipality) inputs concerning water and sewage facilities and services sectors. The combination of different levels of information with stakeholders' engagement is crucial for detailed, updated and harmonized information collection.

2.4 Energy supply system

Besides energy demand sectors, the city energy system must acknowledge the energy supply system such as natural gas, district heating, electricity networks, oil products distribution, and local renewables potential. In this sense, the decentralized energy supply technologies and networks in the city as well as the potential for renewable energy sources were assessed.

A literature review, as well as a consultation with the appropriate stakeholders (*e.g.* electricity utility, municipality technical departments), and smart meters' data was taken to characterize the city supply system. Namely, to compile information on the current decentralized facilities (e.g. rooftop photovoltaic (PV) and solar thermal), the utility scale units (e.g. solar PV power plants, combined heat and power) and on the coverage of existing supply networks.

The estimation of the technical potential of local renewables is of outmost importance to offer cost-effective options for the sustainable city energy system. For the case of Évora, the solar PV technology was selected as the most important renewable and its potential was estimated for each city district at two levels: utility scale [13], and building integrated PV (rooftop and façade) considering local specific characteristics [4].

2.5 Geographic information system

The GIS platform holds all 'spatial' and 'spatially enabled' energy related information for the city (residential buildings, transport and mobility, city utilities and supply systems), facilitating decision making towards the sustainable city planning. The GIS plays a central role, in the sense that it connects spatially all the energy system components, while focusing into specific parts of the energy demand and supply of the city.

2.6 Integrative city energy planning tool

Whilst all the previous results and model outputs can be analyzed independently, the true advantage of our approach is the integration of all aspects of city energy usage. The abovementioned datasets, with multiple spatial and temporal dimensions, are combined to deliver detailed future sustainable energy scenarios for the city in the TIMES (The Integrated Markal-Efom System) technological optimization model [14]. The TIMES model is a technology-rich, bottom-up model that integrates the entire energy/emission system of the city and its different districts, into a single model, including the procurement, transformation, trade, and consumption of a large number of energy forms. TIMES model is implemented in each city district, departs from the current energy system (*i.e.* 2014) and generates future scenarios of cost-effective energy technologies and measures, taking into consideration city planning goals and policies (*e.g.* expansion of a services hotspot in a specific city district, reducing the city overall CO_2 emissions or achievement of a renewable target up to a horizon year, introduction of a CO_2 tax in selected city activities) while fulfilling the energy services of the various city districts, taken exogenously.

Examples of model outputs are: energy flows, energy commodity prices, greenhouse gas and air quality emissions; new supply infrastructures and demand device purchases, total installed capacity of technologies and energy expenditures. Detailed examples include the estimation of energy savings by component (walls, windows, and technologies), savings per building typology, the energy shift in electricity demand, and the increase of PV technologies. These outputs are expressed for each city district and organized into the city GIS depicting the spatial distribution of the impact of energy related policies and measures assessed at the city level.

We argue that effective sustainable energy planning requires detailed and spatially explicit datasets (preferably openly available), supporting the design and implementation of policies and measures targeted to local socio-economic profiles and specific infrastructures characteristics.

Otherwise, the implementation of policies and measures equally across all the city districts will be ineffective and resource wasted.

2.7 Multi criteria analysis

Scenarios of measures from the modelling work will be assessed with respect to non-technical criteria through a multi-criteria decision making method (MCDM). This process will be conducted in two one-day workshops with city stakeholders to ensure that other factors are considered in the identification of the measures to apply in the city. A wide spectrum of city stakeholders selected after an institutional analysis (*i.e.* citizen groups, municipality technical departments, private companies, city utilities) will be involved in determining the different sustainability concerns, the methodology for decision support and the evaluation of the results to address economic, environmental and social issues. We use PROMETHEE (Preference Ranking Organization Method for the Enrichment of Evaluations) tool [19].

Selected measures ranked after the MCDM, are subject to a detailed economic analysis, to identify relevant investment and other costs indicators. Finally, a detailed, realistic and applicable mid-term implementation plan will be developed to describe the necessary steps, required resources and monitoring procedures for each city.

3. RESULTS

In this section we present selected examples of the datasets and results to illustrate the several steps of our analysis supporting the integrative city energy planning tool. No results of this integrated assessment and selected measures will be presented at this stage.

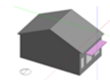
Almost 400 door-to-door, extensive 110–question surveys were performed between June and September 2014 across the entire municipality (37% of the surveys answers from rural area, and the remaining in urban areas) to collect information of a diverse but representative set of households from different typologies (#10).

Apart from allowing an in-depth characterization of residential building stock in Évora to be used in the buildings simulation, that otherwise was not available, the survey is key to spatialize the buildings characteristics at the city districts providing valuable insights for the design and assessment of targeted policy options, for example on energy efficiency and PV integration. Table 1 presents a sample of the data collected through the surveys for two typologies.

Electricity consumption registries from smart meters are available in Évora since 2010. From the combination of the surveyed households and smart meters data availability we were able to link 72% of the sampled households to detailed electricity consumption information.

One example of the type of results derived from the smart meters' data evaluation (from *e.g.* per number of persons per household, per building typology, per level of income) that can be used to input in the integrative planning tool for future energy policies evaluation is presented in Figure 2. The diversity of electricity consumption profiles arising from cluster analysis [10] and socio economic characteristics [9] show the diverse assessments that could be done for consumer segmentation, encompassing tailored energy reduction measures and distinct ICT integration at households.

Table 1 – Examples of buildings data collected for two representative typologies of Évora

	Typology	TP5	TP7
	External view of Design Builder model		
	Photo of an example property		
	Internal Zoning		
General	Location	Rural, Bacelo e Sra da Saude, Malagueira e Horta das Figueiras	Rural and S.Mamede, Sé e S. Pedro e St Antão and Bacelo e Sr da Saude
	Type of Dwelling	Semi Detached	Terraced
	Age of Construction	Between 1946 and 1990	Until 1945
	Average Area (m2)	112	83
	Set Point Temperature Heating	25ºC	25ºC
	Set Point Temperature Cooling	20ºC	20ºC
Geometry	Number of Floors	2	1
	Room in the Roof	No	No
	Infiltration rate (ach)	0,7	0,9
Construction	Exterior Walls Type	Brickwork Single Layer	Brickwork Single Layer
	Exterior Wall Thickness (cm)	27	48
	Roof type	Pitched	Pitched
	Roof Insulated	No	No
	Bearing Structure	Masonry wall (70%), Concrete (30%)	Masonry wall (82%)
	Window Framing Type	Aluminum	Aluminum
	Glass Type	Single Glazed	Single Glazed
Household Members	Occupancy Type	Owner (69%), Rented (31%)	Owner (38%), Rented (62%)
	Average Number of Occupants	2,8	2,4
	Average Monthly Income (€)	Less than 750€ (35%), between 751€ and 1500€ (40%)	Less than 750€ (68%)
Electrical Equipments Ownerhsip	Refrigerators	100%	100%
	Freezers	80%	33%
	Cloth Washing Machines	100%	100%
	Dish Washing Machines	51%	33%
Heating Equipments Ownership	Air Conditioning	24%	16%
	Electric Heaters	58%	62%
	Fireplaces	5%	2%
	FirePlaces with heat Recovery	15%	2%
	Solar Thermal	0%	0%
	Heat Pumps	0%	0%
Cooling Equipments Ownership	Air Conditioning	32%	14%
	Fan Coils	32%	14%

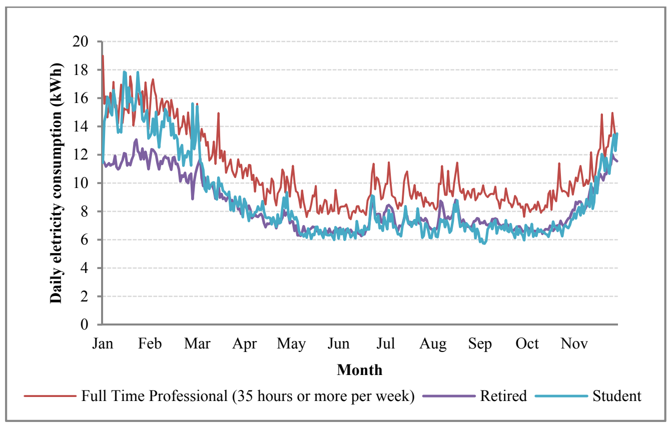


Figure 2 - Daily electricity consumption (2011-2014 daily average) by working status

The output of the simulation process using the EnergyPlus provide city specific data input of the representative building typologies to the GIS platform thus creating a building energy demand map of the city, identifying districts of special interest (e.g. natural gas or district heating network expansion) and to the integrative planning tool; *i.e.* the energy system optimization model (TIMES) of the city. The results of the buildings' simulations, showing differences in annual total energy use for heating, cooling and electricity, across the typologies, are shown in Figure 3.

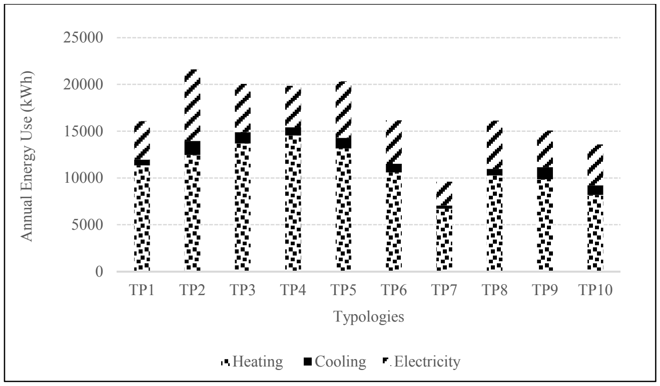


Figure 3 – Total energy use (kWh/annum) for residential building typologies

The analysis of the transportation system through the assessment of current traffic dynamics was done using the results of 460 door-to-door surveys. An example of the results derived from the survey is portrayed in Figure 4 regarding the purpose of the daily travels. This kind of information feeds both the transport model and the integrative planning tool allowing to estimate the impacts on mobility patterns underpinned by planning measures such as new cars restriction areas, new parking lots, new infrastructures as bike lanes, or new residential areas.

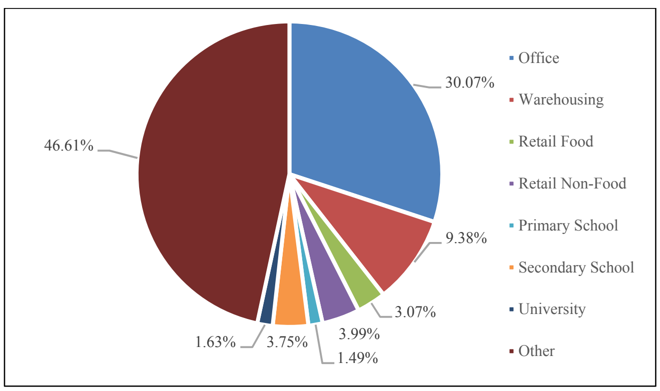


Figure 4 – Purpose splits of the daily trips in Évora

Figure 5 shows one example of the results obtained from the transport model, energy consumption per person by city zone. The zones furthest away from the center (where there are higher numbers of attractions) often have a high-energy usage due to the large travel distances, whereas zones with shorter trip lengths to the center of Évora have a low energy usage. The zones to the south of the historic centre contain large amounts of retail and industrial land use which act as attractors to trips within the model [14].

Regarding other energy consuming sectors, examples of results range from electricity consumption load curves (daily, seasonal, annual) differentiated by *e.g.* public lighting, water management facilities, industries, retail; to the energy consumption, number, size (when applicable), location of public lighting, schools, public buildings and waste facilities.

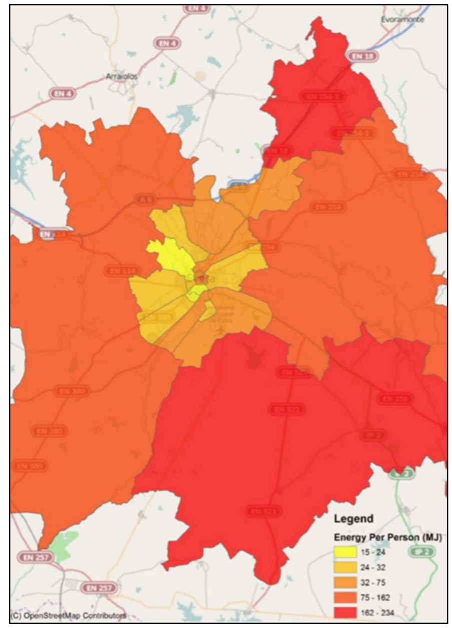


Figure 5 – Final energy use per person for transportation per city origin zone in Évora

Energy supply data collection and assessment are comprised in GIS maps, showing the best locations for electricity production from renewable sources, as rural areas and roof tops for PV production and how these connects with the current city energy supply infrastructure (*i.e.* electricity, oil products, and natural gas networks).

Data obtained within this framework steps is now feeding the integrative city-planning tool (TIMES_Évora) designed to meet the municipality needs. This model, as aforementioned will be used for the development and comparison of alternative city planning scenarios (e.g. one Reference scenario following recent trends vs. one more optimistic scenario - Smart_Évora) with different expectations of city development on population, economic sectors importance, city districts evolution and measures.

The city energy GIS will be used as a core tool to communicate with the stakeholders during the MCDM under development, showing that further applications are essential to interface the wide datasets and the city actors. The integrated city planning approach and exercise offers the opportunity to design new and innovative solutions to bring forward the value of multiple data to effective decisions, both at the citizen level and at the policy decision level.

4. CONCLUSIONS

The integrated framework presented in this paper illustrates how detailed and high-quality energy data should be gathered and integrated in a structured process. This work shows the added value of integrating multiple sources and type of data highlighting all the benefits in the outcomes.

The methodology shows how to combine and integrate spatially distinct and multi-scale data granularity into a common structure of an energy-planning tool to deliver future sustainable energy scenarios. The integration of all these results, while evaluating the entire city energy system, into a GIS platform for visualization purposes coupled with the valuable participation of different city stakeholders (municipality, utilities, transport companies, citizen groups, market associations) brings forward one of the main advantages of this methodology. The stakeholders' participation at different stages of the methodology is essential in assembling an acceptable, realistic and mostly beneficial city action plan.

The ability of an optimization model as TIMES serving the main concept of a core planning approach, while including inputs from relevant city stakeholders (e.g. municipality) along the data collection, methodology, scenario building and validation of results gives policy relevance.

In order to evolve into fully optimized smart cities it is crucial to collect and combine a plethora of information from energy statistics by city district or blocks; sensors and metering within households, services buildings, public spaces and city utilities; smart technologies for transport management and roads. Acquiring this knowledge and disseminating it to all the relevant city stakeholders will help to pave the way for a comprehensive and robust city planning and should be highly supported.

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