Assessing energy performance of smart cities

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Abstract

The massive urbanization process registered since 1950's and projected to continue for the coming decades, is posing a crucial issue for the management of existing cities and for the planning of future ones. Smart cities are often envisioned as ideal urban environments where the different dimensions of a city, such as economy, education, energy, environment, finance, etc., are managed in an effective and proactive way. Nevertheless, in order to reach this remarkable and challenging objective, analysis tools are required to create scenarios that are able to inform policy makers' decisions.

Focusing on energy, this paper proposes an analysis method, based on exergy, to support smart city planning. It may help the decision makers to assess the energy-smartness of different scenarios, and to address energy urban policies. Possibilities and limitations of the analysis method are discussed via the application to the cities of London, Milan and Lisbon that committed to become smart cities.

Key words

Smart city; exergy; energy efficiency; extended exergy analysis; energy policies

Practical Application

The paper summaries a study on the possibilities and limitations of adopting an assessment technique, based on exergy, in order to evaluate the energy-smartness of policies in existing and future smart cites. As highlighted in the paper, building's related energy uses have a huge share of many cities' energy breakdown. Thus, professionals in the building industry will be interested in the paper not only because it refers to smart cities, but because the built environment plays a pivotal role in them. Professionals may also refer to this study to perform similar analysis in other urban environments to support decision makers.

Introduction

According to the Population Division of the Department of Economic and Social Affairs at the United Nations Secretariat, the world population living in cities has grown rapidly since 1950, from 746 million to 3.9 billion in 2014 [1], [2]. In 2008, for the first time in history, the urban population equaled the rural population of the world, and in 2014 already 54 % of the world's population was residing in urban areas [1], [2]. It is a trend expected to continue in the coming years. In 1950, 30 % of the world's population was urban, whereas by 2050, 66 % of the world's population is projected to be urban [2]. Some geographical distinctions nevertheless exist. Data referred to 2014 shows different shares of urban population in different world's regions [2]: 82 % in Northern America, 80 % in Latin America and the Caribbean, 73 % in Europe, 48 % in Asia and 40 % in Africa. All regions are expected to urbanize further over the coming decades. However, Africa and Asia are urbanizing faster than the other regions and are projected to become 56 % and 64 % urban, respectively, by 2050 [2]. Projections show that urbanization combined with the overall growth of the world's population could add another 2.5 billion people to urban populations by 2050, with nearly 90 % of the increase concentrated in Asia and Africa [2]. This is particularly important, since Asia, despite its current lower level of urbanization, is home to 53 % of the world's urban population, followed by Europe (14 %) and Latin America and the Caribbean (13 %) [2].

Almost half of the world's urban dwellers resides in relatively small settlements of less than 500 000 inhabitants, while around the 12.5 % of them live in the 28 mega-cities with more than 10 million inhabitants [2]. By 2030, the world is projected to have 41 mega-cities with more than 10 million inhabitants. However, the fastest growing urban agglomerations are medium-sized cities and cities with less than 1 million inhabitants located in Asia and Africa [2].

In the coming decades, we will therefore experience a continuous expansion of the major cities in Northern America, Europe and Latin America and the Caribbean, whereas this trend will be mixed in Asia and Africa with the fast expansion of mid and small size settlements and sometimes also the foundation of new towns. By 2050, a large portion of new buildings, equivalent to 40 % of the world's current building stock, will be built in cities in emerging and developing economies, which will also account for 85 % of the increase in urban passenger travel globally [3].

Cities currently account for about two-thirds of global primary energy demand and 70 % of total energy-related carbon dioxide (CO_2) emissions. The energy and carbon footprint of urban areas will increase with urbanization and the growing economic activity of urban citizens, which in 2013 accounted for about 80 % of the world's GDP [3].

Under current energy system trends, the urban primary energy demand could rise up to about 620 exajoules (EJ) by 2050, when it will account for 66 % of the total [3]. In parallel, carbon emissions from energy use in cities (including indirect emissions from power and heat generation) would increase by 50 % [3].

Mass urbanization presents therefore one of the most urgent, worldwide challenges of the 21st century. Cities and urban communities have to cope with poor air quality, urban heat island effect, low urban environmental quality, energy shortage and other interrelated issues. Moreover, urban services substantially rely on energy availability and on the reduction of harmful emissions as consequence of energy use. Key challenges for smart and sustainable cities are hence to provide solutions that may significantly increase cities' overall energy and resource efficiency through actions addressing mostly the building stock, the energy systems and mobility [3].

Local policy makers have the levers to drastically shape or reshape the cities where a huge part of world's population will live in the coming decades. However, they need adequate analysis tools, able to provide them with reliable forecasting scenarios.

Smart cities projects and technical committees are at the very heart of the development of these tools.

ITU, the United Nations specialized agency for information and communication technologies (ICTs) created a focus group on smart sustainable cities (FG – SSC) acting as an open platform for smart-city stakeholders to exchange knowledge with the aim of identifying the standardized frameworks needed to support the integration of ICT services in smart cities [4]. The FG-SSC concluded its work in May 2015 by approving 21 technical specifications and reports [4]. ITU also created a parallel study group, the ITU-T Study Group 5, about environment, climate change and circular economy [5].

The International Organization for Standardization (ISO) also created a technical committee about sustainable cities and communities, the ISO/TC 268, which already published four standards, and it is developing six new ones [6], and a subcommittee about smart community infrastructures, which published three standards and is developing six new ones [7]. The most relevant standards are ISO 37120 [8] about indicators for city services and quality of life and ISO/TS 37151 [9] about principles and requirements for performance metrics. A lot of expectation is also on ISO/NP 31722 and 37123 standards, about, respectively, indicators for smart cities and indicators for resilient cities, currently under development.

The technical reports and standards produced by ITU and ISO, and other similar organizations, provide, so far, a list of key performance indicators (KPIs) concerning the different aspects of a city (e.g., economy, education, energy, environment, finance, etc.), but they do not provide specific analysis tools able to support the development of local policies. In the case of energy, these KPIs are, moreover, quite general and do not allow for a detailed energy breakdown of the city energy uses.

Although a comprehensive and holistic approach is in the end required to address local policies for sustainable development and planning of smart cities, this must be based on different analysis tools specific for each city's dimension. According to the fast urbanization scenario depicted above, energy is one of the dimensions that most urgently need such a kind of tool.

Analysis methods and indices are necessary to assess the energy performance of cities and to determine if energy is used with appropriate and smart approaches. Almost no indication is provided in the literature about the effectiveness of using different energy carries to provide different services and about the quality of the conversion processes, that is how smartly energy is used within the city. Targeting this gap, the present paper proposes an analysis approach for smart cites, founded on energy and exergy efficiencies, with the aim to provide the decision maker with a useful tool to understand the energy-smartness of different scenarios, and to address urban energy policies.

Exergy is an indicator of the energy quality, and, specifically, it provides a quantitative basis to measure the degradation of energy (i.e., the decrease of its capacity to generate useful work) in conversion processes [10], [11], [12]. By means of the so-called *extended exergy analysis* [13], exergy has also been adopted to evaluate and compare countries, regions and economic sectors [14], [15], [16], [17], [18]; early example are available also for districts [19], [20], [21], [22].

The present work uses data from three relevant European cities participating to Sharing Cities [23], a lighthouse smart city project, as a case study to assess the possibilities and limitations of the proposed analysis method, and to evaluate its applicability to different urban scenarios

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Nomenclature

η	energy efficiency
ψ	exergy efficiency
o	overall
pr.en	primary energy
use	final energy use
Subscript:	
carr	energy carrier
sec	sector

Method

The goal of the analysis is to estimate the overall energy and exergy efficiencies of a city, in order to compare the energy-smartness of different urban policy scenarios. To this purpose, the approach presented by Dincer and Rosen [14], [24] has been assumed as a reference for the calculations. London, Milan and Lisbon, have been selected as case studies, since they substantially committed to become smart cities [23]. Starting from the final energy use for each sector (e.g., space heating, public lighting, transport, etc.) and from the associated energy carriers[1], energy and exergy efficiencies have been

[1] In order to simplify the communication of results, the definition of energy carrier provided by ISO 13600 is here adopted, that is an energy carrier is defined as either a substance or a phenomenon that can

calculated as weighted average, applying a two-step process. For each energy carrier, the weighted means of energy and exergy efficiency have been obtained, where the weighting factor is the ratio of energy input for each use to the total energy input for all uses (Eq. 1 and 3). Further, the overall weighted mean has been obtained for both energy and exergy efficiency, considering all energy carriers; in this case, the weighting factor is the ratio of the primary energy input of the considered energy carrier to the total primary energy input from all carriers (Eq. 2 and 4).

Energy efficiency by carrier:

$$\eta_{carr} = \frac{\sum_{i=1}^{n} (use_{sec,i} \cdot \eta_{sec,i})}{\sum_{i=1}^{n} use_{sec,i}} \quad (1)$$

Overall energy efficiency:

$$\eta_{o} = \frac{\sum_{i=1}^{m} (pr.en_{carr,i} \cdot \eta_{carr,i})}{\sum_{i=1}^{m} pr.en_{carr,i}} \quad (2)$$

Exergy efficiency by carrier:

$$\psi_{carr} = \frac{\sum_{i=1}^{n} (use_{sec,i} \cdot \psi_{sec,i})}{\sum_{i=1}^{n} use_{sec,i}} \quad (3)$$

Overall exergy efficiency:

$$\psi_{o} = \frac{\sum_{i=1}^{m} (pr.en_{carr,i} \cdot \psi_{carr,i})}{\sum_{i=1}^{m} pr.en_{carr,i}} \quad (4)$$

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be used to produce mechanical work or heat or to operate chemical or physical processes. It includes therefore both fuel oil, diesel oil, gasoline, natural gas, typically labelled as energy sources, and electrical energy and thermal fluids, more commonly defined as energy carries.

To obtain the overall energy and exergy efficiencies according to equations 1 to 4, data on city energy breakdown and efficiencies related to each urban sector is necessary. The different energy uses at city level may be available from the Sustainable Energy Action Plan (SEAP), a key document in which a Covenant of Mayor signatory outlines how it intends to reach its CO_2 reduction target by 2020 [25]. It defines the activities and measures set up to achieve the targets, together with time frames and assigned responsibilities.

The SEAP of Milano has a good level of detail and contains the description of the methodology and references adopted to gather data for past and on-going conditions (up to year 2013) [26]. The SEAPs of London and Lisbon, unfortunately, do not show the same level of detail; for the present study, we had consequently to refer to alternative databases.

In the case of London, we referred to the database of the Department for Business, Energy and Industrial Strategy, of the UK government [27], in particular to the sub-national total final energy consumption statistics for the period 2005-2014, where London's data is included. For Lisbon, we referred to the *Matriz Energética de Lisboa* for year 2014 [28], prepared by Lisboa E-Nova, *Instituto Superior Tecnico and Camara Municipal de Lisboa* and published in July 2016.

The *Baseline* scenario adopted in the present study refers, therefore, in the case of London and Lisbon to data for year 2014, whereas in the case of Milan to data for year

2013. The reference to three different databases required to slightly rework some data in order to establish a common initial point to perform our analysis. In particular, London and Lisbon data did not show a distinction between public and private mobility; we thus decided to apply the sharing reported in the SEAP of Milan to London and Lisbon too. Moreover, diesel oil and fuel oil used for buildings' heating have been grouped together under the general label "fuel oil" to limit the number of energy carriers.

Five additional scenarios have been then developed and simulated for the three reference cities: *Mob*, *DH*, *EE Build*, *LED*, and *EE Appl*. Each one of them has been prepared to evaluate the effect of a single action or policy on the energy-smartness at city level, by changing either some energy use values or energy and exergy efficiencies with respect to the *Baseline*.

In the *Mob* scenario, the focus is on urban mobility only; it includes a reduction of the final energy use for transport by 35 %, and a shift toward electric mobility. The sharing of public transport per carrier is: 58 % electric, 0 % natural gas, 42 % fuel oil, 0 % gasoline, whereas the sharing for private transport is: 2 % electric, 4 % natural gas, 49 % fuel oil, 45 % gasoline. The percentages of reduction and shift are taken from the scenario pictured for 2020 in the SEAP of Milan. In the *DH* scenario, 10 % of the total final energy use for buildings' heating is assigned to district heating. It is necessary to point out that in the *Baseline* scenario the sharing of district heating is 5 % for Milan, and 0 % both for London and Lisbon. Actually, a very small district heating network does exist in Lisbon, but energy data is not available. It means that the *DH* scenario pictures a spreading of an existing technology in Milan and to a rather limited extent in Lisbon, while the inception of a new technology in London. The *EE Build* scenario assumes the adoption of energy efficiency (EE) measures (i.e., renovation measures) on building envelopes and energy systems, resulting in an overall reduction of the final energy use by 20 %, with respect to the *Baseline* scenario. The EE measures on energy systems include the complete substitution of old fuel oil boilers with new natural gas furnaces and the use of exergy efficient systems such as radiant panels and condensing gas boilers, but they do not include interventions on residential appliances (i.e., refrigerators, washing machines, etc.). The final energy use for space heating refers to residential buildings only for all the three cities. The fourth scenario, named *LED*, is obtained by switching all the public lighting lamps, assumed as metal halide, to light-emitting diode (LED) lamps, resulting in a reduction of the final energy use and in an improvement of energy and exergy efficiencies. The Municipality of Milan effectively implemented this action, as from 2014 to present date, and 97 % of the public lighting in Milano has already been converted to LED. Unfortunately, data on public lighting was not available for London, and this scenario could not be simulated for this city. Finally, the *EE Appl* scenario envisions an improvement for residential appliances only, in terms of energy and exergy efficiency. The final energy use is assumed to decrease by 10 %, compared to the *Baseline*, following the efficiency improvement. The criteria adopted to build the scenarios are summarized in Table 1.

Table 1. Simulated scenarios

	Mob	***DH***	***EE Build***	***LED***[2]	***EE Appl***
Actions on energy use	The final energy use for transport is globally reduced by 35% and partially shifted from fuel oil and gasoline to natural gas and electricity[1]	A share equal to 10% of the total final energy use for buildings is shifted to district heating	The final energy use for buildings is globally reduced by 20% and shifted from fuel oil to natural gas and electricity	The final energy use for public lighting is reduced by 52%[3]	The electrical use of buildings (which is assumed to be function of appliances only) is reduced by 10%
Actions on efficiencies	None	None	Improved efficiencies for heating systems	Improved efficiencies due to LED technology	Improved efficiencies for new appliances

[1] The reduction and shifting follow the scenario proposed by Milan's SEAP for year 2020. In particular, for public transport, the share is: 58% electric, 0% natural gas, 42% fuel oil, 0% gasoline; for private transport the share is: 2% electric, 4% natural gas, 49% fuel oil, 45% gasoline.

[2] This scenario cannot be applied for London because data on public lighting energy use is not provided.

[3] This is the energy use reduction observed in Milan after the real switch of public lighting to LED technology.

Energy and exergy efficiencies should be evaluated with a common and shared procedure, adopting the same reference conditions and starting from a detailed characterization of the energy conversion processes and systems within the city. These include: the private and public transport fleet with a comprehensive breakdown for energy carrier and engine power, the public lighting system with an accurate description of terminal devices (including ballast), the entire (private and public) building stock, including specifications of building envelopes and energy systems (generation, storage, distribution, emission and control), residential appliances and equipment adopted by other sectors, etc. Average values for each sector may be eventually derived. This approach would nevertheless require an exhaustive and coordinated work, including interviews and surveys to operators, on-site inspections and measurements. It could be implemented only with a substantial commitment of the municipalities and a coordinated involvement of local public and private actors such as energy providers, research centers, local committees, professional organizations and other stakeholders. Since it was not possible to establish in a short time such a kind of exhaustive and coordinated analysis for the three reference cities, and since the aim of the study was just to report possibilities and limitations of the analysis method proposed to assess energy-smartness at city level, the values of energy and exergy efficiencies adopted in this work (Table 2) are taken from the literature, trying to choose the most appropriate ones. The validity of the analysis method is independent of the efficiency values adopted, and following results and discussion will focus on the method and possible outcomes of the procedure, and not on the specific numbers resulting from the application of the analysis to the given case studies.

Electrical energy and exergy efficiencies of residential appliances are critical values to be estimated, since they cover a large variety of applications, as highlighted in studies for Japan [29]. Lighting systems show an energy efficiency ranging from 20 % to 27 % and an exergy efficiency ranging from 17 % to 22 % [30]. Electrical cooking appliances may have an average energy efficiency of 32 % and an average exergy efficiency of 6 % [29]. Air conditioning appliances may reach energy efficiency up to 200 % and exergy efficiency of 5 % [29]. Since no specific study was found for Europe, average values for year 2013 and 2030 were set up, assuming an energy efficiency improvement of 50 % and an exergy efficiency improvement of 25 %. For district heating, natural gas and different couplings of generation and emission systems, energy and exergy efficiencies come from Ref. [31]. Values for fuel oil boilers were taken from Ref. [26]. No specific data was found in the literature for public lighting; values used in this paper come from Ref. [30], assuming the efficiencies of existing street lighting (mostly metal halide lamps) to be similar to values for fluorescent lamps, since their range of luminous efficacy is comparable. Furthermore, this shows to be a conservative approach [32]. The energy efficiency for electric engines come from Ref. [33], while the exergy efficiency come from Ref. [34]. Energy and exergy efficiencies for natural gas and gasoline engines are taken from Ref. [35], whereas their values for Diesel engines come from Ref. [36].

In order to calculate the overall efficiencies, it was necessary to convert the final energy use into primary energy for each energy carrier, by applying the related primary energy factor (PEF) valid for each city. The PEF of electricity is 2.92 for London [37], 2.42 for Milan [38] and 1.91 for Lisbon [28]. The PEF for natural gas, fuel oil and gasoline is assumed to be 1 in all of three cities. The PEF of district heating for Milan is 0.8, according to the local energy provider declaration. In the *Baseline* scenario, London and Lisbon do not have energy use related to district heating, the PEF reported for Milan was instead used in the *DH* scenario, where a district heating system is considered for London and Lisbon as well. Final energy use and primary energy for the considered scenario are summarized in Table 4, Table 5, and Table 6 that are reported in the Appendix, including the share for energy carrier. Values derived from SEAP for Milano and from Ref. [27] and Ref. [28], for London and Lisbon, respectively, have been slightly reworked to fit the purpose of this study and to make the results for the three cities comparable.

Table 2. Energy and exergy efficiencies for each energy use

DOMESTIC APPLIANCES		
	η	**ψ**
Average for 2013	50.0%	6.0%
Estimate for 2030	75.0%	7.5%

HEATING + DOMESTIC USES		
	η	**ψ**
District Heating	90.0%	31.9%
Gas boilers + radiators	86.0%	6.7%
Condensing gas boilers + radiant panels	105.0%	8.5%
Fuel oil boilers + radiators	75.0%	6.7%

LIGHTING		
	η	**ψ**
Fluor.	20.0%	17.5%
LED	27.3%	21.8%

TRANSPORT		
	η	**ψ**
Electric	80.0%	33.5%
Natural gas	27.0%	31.0%
Diesel fuel	36.7%	34.4%
Gasoline	27.1%	30.6%

The analysis is applicable only if the boundary of the system, in this case the city, is clearly established. The consulted databases provided final energy values within the cities, excluding power plant generation. This is especially important for the case of district heating. The efficiencies reported in Table 2 depend only on the thermal fluid distribution and heat transfer at the building's heat exchanger, but do not include the generation systems such as combined heat and power, or more traditional thermo-electric plants. The system's boundary considered in the present analysis is graphically sketched in Figure 1.

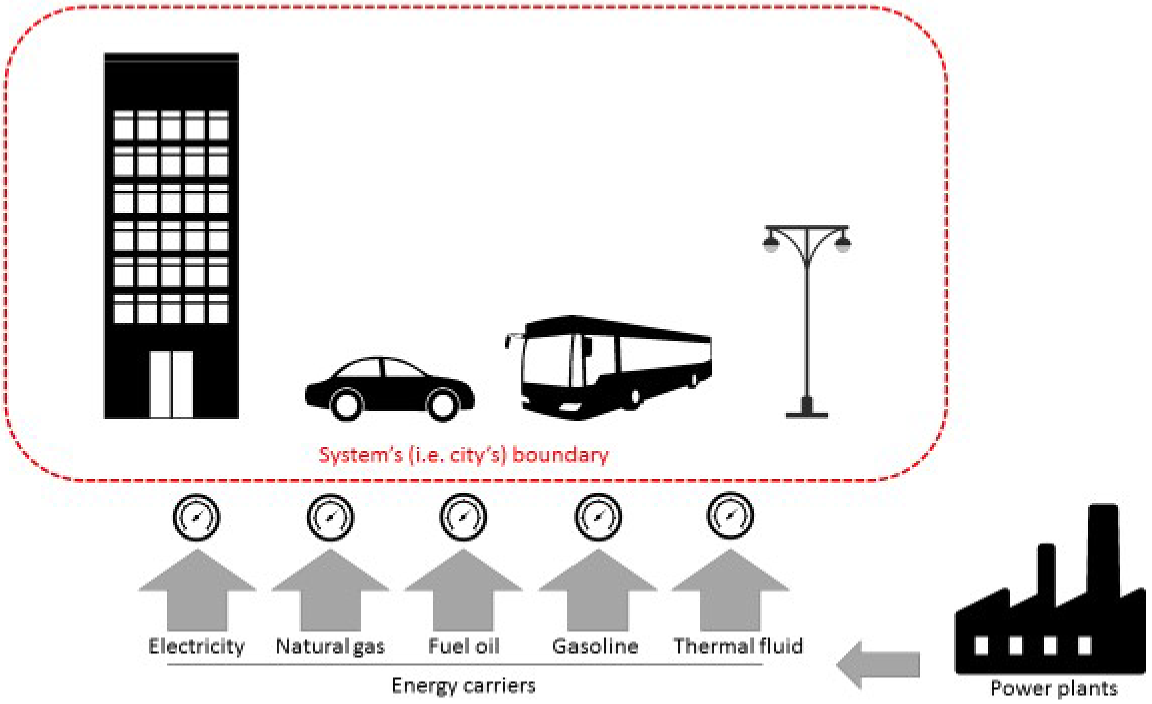

Figure 1. System's boundary adopted for the analysis

Results

Table 3 and Figures 2 to 4 summarize the analysis results in terms of energy and exergy efficiency and total primary energy for each considered scenarios. The energy efficiency shows the extent of the entering energy flows that is actually transformed in a useful energy output within the system (i.e., the city). Whereas the exergy efficiency shows the degradation of energy flows within the system by comparing exergy outputs to exergy inputs. In scenarios with a higher exergy efficiency, the degradation of the energy flows due to conversion processes into the city is low, the city is therefore exploiting better the potential of high quality services inherent to the input exergy flows. In this sense, the exergy efficiency may be assumed as an indicator of energy-smartness. However, a very high exergy efficiency applied to a small energy flow does not affect considerably the city's overall exergy efficiency. Thus, in terms of energy-smartness, it is important to couple high exergy efficiencies to the largest final energy uses.

Table 3. Primary energy use, energy and exergy efficiencies for different scenarios

		Baseline	***Mob***	***DH***	***EE Build***	***LED***	***EE Appl***
London	η_o	59%	63%	61%	65%	59%	68%
	ψ_o	13%	13%	15%	15%	13%	14%
	Primary energy (TWh)	107.3	107.3	101.2	91.6	107.3	103.5
Milan	η_o	66%	68%	67%	75%	67%	71%
	ψ_o	13%	13%	14%	15%	13%	14%
	Primary energy (TWh)	16.3	15.7	16.2	14.7	16.2	16.0
Lisbon	η_o	45%	50%	46%	46%	42%	52%
	ψ_o	22%	20%	23%	24%	21%	23%
	Primary energy (TWh)	5.0	4.2	4.9	4.7	5.0	4.9

An early comparison of results gathered in Table 3 and Figures 2 to 4 shows that the total primary energy use of Lisbon is roughly one third of the Milan's one, and that the latter is roughly 15 % of the primary energy use of London. Lisbon primary energy use represents thus just the 5 % of London's value. Slight, but not substantial variations are reported for the five scenarios. The size of the city is not a limit for the analysis method that is applicable to cities with substantially different energy use and size, as in the present example.

The variation of exergy efficiency among different scenarios is limited. The largest variation is registered in Lisbon and it is equal to 4 % (Table 3), whereas both in London and Milan the variation is limited to 2 %. This is linked to the energy breakdown by carrier (Figure 5) and by sector (Figure 6), which are very similar for London and Milan and slightly different for Lisbon. The primary energy use in residential buildings represents just 37 % of the total in the Portuguese capital, whereas it accounts for 74 % and 80 % of the total primary energy use in London and Milan, respectively. The share of primary energy due to private transport is therefore substantially higher in Lisbon (52 %) than in London (20 %) and Milan (14 %).

Exergy efficiencies reported in Table 2 are much higher for transport than for space heating, because the useful output of the energy conversion in transport is mechanical work, having a substantially higher exergy value than thermal energy at buildings' indoor air temperature that is the useful output of the energy conversion for building's space heating. It is then evident that in Lisbon, where transport has a higher share of primary energy, the overall exergy efficiency results higher.

It is worth nothing that in Lisbon the exergy efficiency of the *Mob* scenario is lower than the one of the *Baseline* scenario. This happens because in *Mob* the share of primary energy use due to buildings' heating substantially increases to compensate the decrease of the mobility share, and the exergy efficiency of building's heating processes is very low. The overall performance of Lisbon is consequently much more sensitive to changes in the mobility sector than in the case of London and Milan.

Conversely, Table 2 shows much higher energy efficiencies for buildings' heating than for transport, thus both London and Milan present overall energy efficiencies higher than Lisbon. In particular, the *EE Build* scenario reports the lowest primary energy use for both London and Milan, and substantially higher energy efficiencies.

A more accurate analysis of Table 3 shows that, for all of the three considered cities, the highest overall exergy values are achieved in the case of *DH*, *EE Build* and *EE Appl* scenarios. This means that the only way to increase the overall energy-smartness of a city is acting on the sector that shows the lowest exergy efficiency (i.e., buildings) and decreasing its overall energy use (*EE Build* and *EE Appl* scenarios), or promoting a switch to a technology that shows a higher exergy efficiency (*DH* scenario). The first solution is, however, more effective because it combines a rise of the exergy efficiency to a substantial reduction of the energy use.

As a direct consequence of these considerations, it is possible to state that local policies on mobility may have a higher impact in term of energy in Lisbon, whereas local policies on building's heating may have a larger energy impact in London and Milan, although they show to be effective in Lisbon as well. A further development of the analysis could provide projections also about harmful gas emissions related to the different sectors and carriers. Figure 6 shows that the electricity share of primary energy is 36 % in London, 21 % in Milan, and 32 % in Lisbon. The share of natural gas is instead 38 % in London, 52 % in Milan, and 11 % in Lisbon. Finally, the fuel oil share is 16 % in London, 18 % in Milan, and 42 % in Lisbon.

As already discussed, the *DH* scenario poses, moreover, an important economic issue because it corresponds to the extension of the exiting district heating system in the case of Milan, while to the inception of a new technology in London and of a substantially new technology in Lisbon as well. The economic value of these interventions may be considerably different.

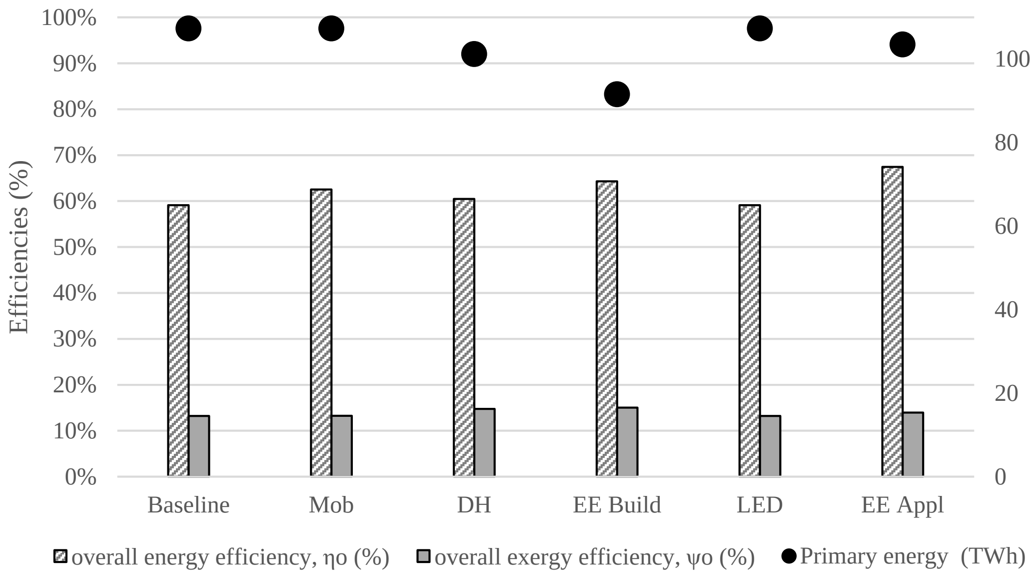

Figure 2. Scenarios for London

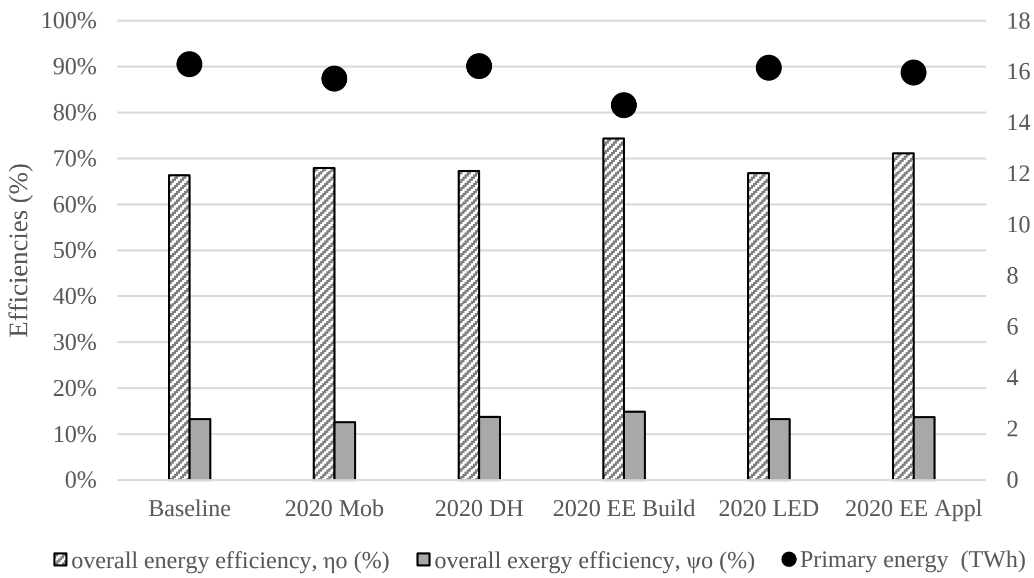

Figure 3. Scenarios for Milan

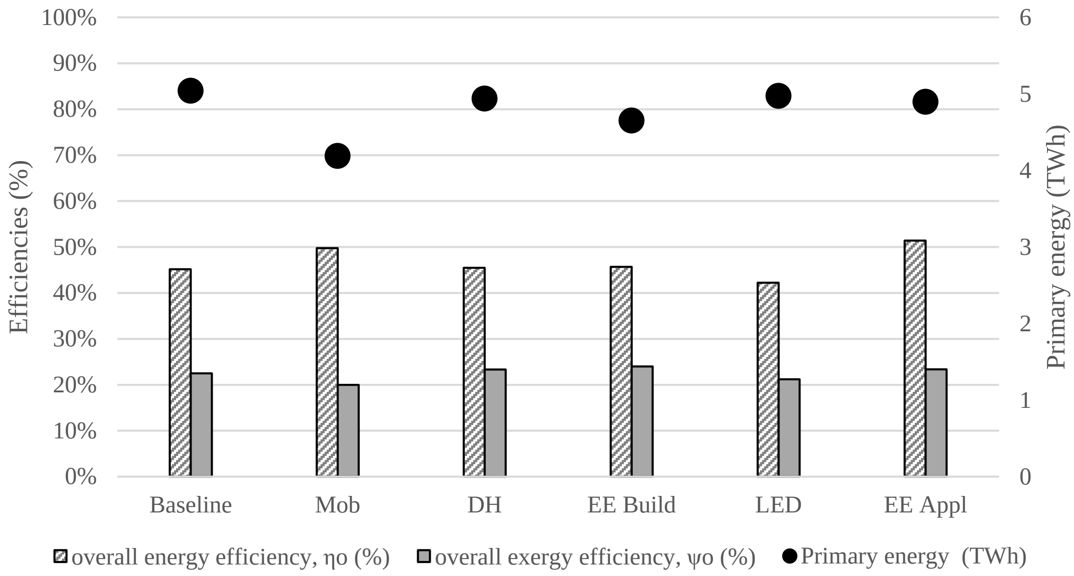

Figure 4. Scenarios for Lisbon

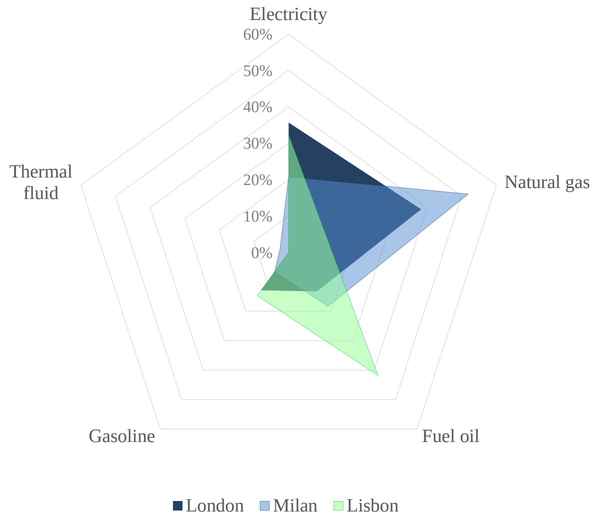

Figure 5. Primary energy breakdown by carrier for Baseline scenario

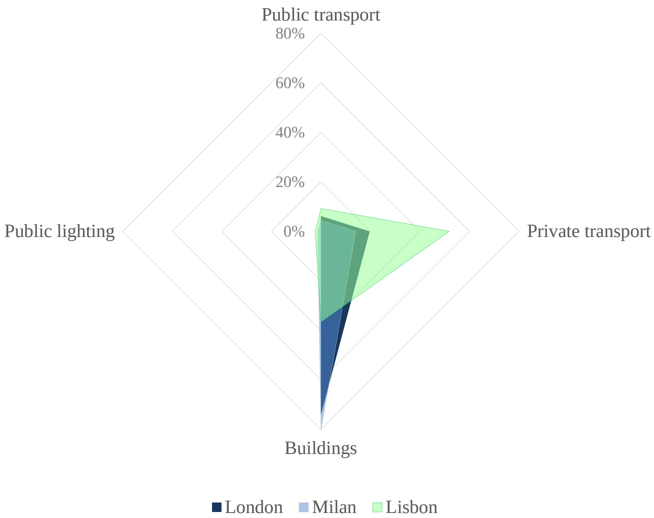

Figure 6. Primary energy breakdown by sector for Baseline scenarios

Discussions and Conclusion

The result of the analysis indicated some differences between the three cities. In particular, London and Milan showed to be more sensitive to local policies about buildings, electrical energy and natural gas, whereas Lisbon resulted more sensitive to local policies about transport, electrical energy and fuel oil. This depends on the different baseline scenarios used for the three cities. In Lisbon, the highest share of primary energy is due to the private transport, whereas buildings show a lower share (Figure 6). Actions on transport and on the energy carriers used for it (i.e., mostly fuel oil and electricity) show thus, in Lisbon, a larger effect. Both in Milan and London the largest share of primary energy is due to buildings (Figure 6). Actions on them and on the energy carriers mostly used for space heating and appliances (i.e., natural gas and electrical energy, respectively) show therefore a larger impact in Milan and London.

As already mentioned, policies meant to rise a city's energy-smartness, should target the sectors that present the highest share of primary energy and the lowest exergy efficiency.

Energy and exergy efficiencies of the single processes, are out of the control of local policy makers, as they depend on technological innovation. Local policies may nevertheless affect the overall energy and exergy efficiencies of the city (Eq. 2 and 4) by fostering energy saving (i.e., higher energy efficiencies and behavioral changes such as shifts from individual motorized vehicles to bicycle, pedestrian, public transport, car pooling and car sharing modes) in the sectors where energy uses are higher and by selecting and promoting the technologies that show higher exergy efficiencies.

Some limits are, however, peculiar of the single sector. The exergy efficiency of whatever space heating process will always be lower than the exergy efficiency of an engine for transport, because the useful output of the former process is thermal energy at the building's indoor air temperature, while the useful output of the latter is mechanical energy, subsequently transformed into kinetic energy (i.e., the vehicle motion). The only way to substantially increase the exergy efficiency for space heating processes, is to use energy carries with a low exergy content that is close to the exergy content of thermal energy at the building's indoor air temperature. District heating appears hence to be the best available solution in the present analysis. However, results could substantially change depending on the system's boundary (Figure 1): if the generation plants were included into the system's boundary, then the exergy efficiency of the district heating would substantially decrease. The choice of the system's boundary is therefore a key aspect of the entire process. We decided not to include the power plants into the analysis, (i) because data on the energy carries production is rather problematic to be gathered and would therefore increase the uncertainty of the analysis outcomes, and (ii) because it would include information that substantially exceeds the city's scale (e.g., the geographical origin of fuel oil or natural gas).

The preparation phase that aimed at collecting all data necessary for the analysis showed that energy data is not yet gathered in a shared and common way among cities. This is one of the major barriers hindering a systematic application of energy analyses at city level. In order to overcome this issue, a common database for at least European – and potentially worldwide– cities is required, which might gather all the fundamental energy uses in cities, measured with a common accuracy and harmonized procedures and metrics. Moreover, a similar database is required for energy and exergy efficiencies, evaluated with a common methodology.

A more comprehensive analysis approach would require information about economic and environmental aspects such as harmful gas emissions. Future extension of the analysis could therefore target the application of the Extended Exergy Accounting method [15] to smart cities. The issue about data quality and availability should, however, be tackled in advance.

Acknowledgment

The study was partially developed within the framework of the project SHAR-LLM, which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691895, and partially within the EU-GUGLE project funded by seventh framework programme under grant agreement No 314632.

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Appendix

In the following tables, highlighted data represents the final energy use values that characterize each scenario. They are obtained by changing either some energy use values or energy and exergy efficiencies with respect to the Baseline scenario.

Table 4. Final energy use and total primary energy (GWh) for each scenario, for London. Data reworked from [27].

BASELINE (2014)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	13102	41065	197	-	-
Transport	-	-	16530	11270	-
Public	-	-	4140	-	-
Private	-	-	12390	11270	-
Total final energy use	**13102**	**41065**	**16727**	**11270**	**-**
Total primary energy	**38257**	**41065**	**16727**	**11270**	**-**
% on total	36%	38%	16%	11%	0%

MOBILITY (Mob)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	13102	41065	197	-	-
Transport	2721	747	10768	8329	-
Public	2331	-	1676	-	-
Private	390	747	9093	8329	-
Total final energy use	**15823**	**41811**	**10966**	**8329**	**-**
Total primary energy	**46203**	**41811**	**10966**	**8329**	**-**
% on total	43%	39%	10%	8%	0%

DISTRICT HEATING (DH)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	10482	38445	-	-	5436
Transport	-	-	16530	11270	-

Public	-	-	4140	-	-
Private	-	-	12390	11270	-
Total final energy use	**10482**	**38445**	**16530**	**11270**	**5436**
Total primary energy	**30608**	**38445**	**16530**	**11270**	**4349**
% on total	30%	38%	16%	11%	4%

ENERGY EFFICIENCY BUILDINGS (EE Build)

Sector/Carrier	Electricity	Natural gas	Fuel Oil	Gasoline	Thermal fluid
Residential buildings	10560	32931	-	-	-
Transport	-	-	16530	11270	-
Public	-	-	4140	-	-
Private	-	-	12390	11270	-
Total final energy use	**10560**	**32931**	**16530**	**11270**	**-**
Total primary energy	**30836**	**32931**	**16530**	**11270**	**-**
% on total	34%	36%	18%	12%	0%

ENERGY EFFICIENCIES APPLIANCES (EE Appl)

Sector/Carrier	Electricity	Natural gas	Fuel Oil	Gasoline	Thermal fluid
Residential buildings	11792	41065	197	-	-
Transport	-	-	16530	11270	-
Public	-	-	4140	-	-
Private	-	-	12390	11270	-
Total final energy use	**11792**	**41065**	**16727**	**11270**	**-**
Total primary energy	**34431**	**41065**	**16727**	**11270**	**-**
% on total	33%	40%	16%	11%	0%

Table 5. Final energy use and total primary energy (GWh) for each scenario, for Milan. Data reworked from [26]

BASELINE (2013)

Sector/Carrier	Electricity	Natural gas	Fuel Oil	Gasoline	Thermal fluid
Residential buildings (domestic use)	1349	1061	-	-	-
Residential buildings (heating)	-	6239	1364	-	426
Public lighting	112	-	-	-	-

Public transport	281	-	218	-	-
Private transport	-	79	1454	1319	-
Total final energy use	1742	7379	3036	1319	426
Total primary energy	4216	7379	3036	1319	341
% on total	26%	45%	19%	8%	2%

MOBILITY (Mob)

Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings (domestic use)	1349	1061	-	-	-
Residential buildings (heating)	-	6239	1364	-	426
Public lighting	112	-	-	-	-
Public transport	281	-	202	-	-
Private transport	47	90	1096	1004	-
Total final energy use	1789	7390	2662	1004	426
Total primary energy	4329	7390	2662	1004	341
% on total	28%	47%	17%	6%	2%

DISTRICT HEATING (DH)

Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings (domestic use)	1349	1061		-	-
Residential buildings (heating)	-	7226	-	-	803
Public lighting	112	-	-	-	-
Public transport	281	-	218	-	-
Private transport	-	79	1454	1319	-
Total final energy use	**1742**	**8366**	**1672**	**1319**	**803**
Total primary energy	**4216**	**8366**	**1672**	**1319**	**642**
% on total	26%	52%	10%	8%	4%

ENERGY EFFICIENCY BUILDINGS (EE Build)

Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings (domestic use)	1349	1061	-	-	-
Residential buildings (heating)	-	5997	-	-	426
Public lighting	112	-	-	-	-
Public transport	281	-	218	-	-

Private transport	-	79	1454	1319	-
Total final energy use	**1742**	**7137**	**1672**	**1319**	**426**
Total primary energy	**4216**	**7137**	**1672**	**1319**	**341**
% on total	29%	49%	11%	9%	2%

LED					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings (domestic use)	1349	1061	-	-	-
Residential buildings (heating)	-	6239	1364	-	426
Public lighting	54	-		-	-
Public transport	281	-	218	-	-
Private transport	-	79	1454	1319	-
Total final energy use	**1684**	**7379**	**3036**	**1319**	**426**
Total primary energy	**4075**	**7379**	**3036**	**1319**	**341**
% on total	25%	46%	19%	8%	2%

ENERGY EFFICIENCIES APPLIANCES (EE Appl)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings (domestic use)	1214	1061		-	-
Residential buildings (heating)	-	6239	1364	-	426
Public lighting	112	-		-	-
Public transport	281	-	218		-
Private transport	-	79	1454	1319	-
Total final energy use	**1607**	**7379**	**3036**	**1319**	**426**
Total primary energy	**3889**	**7379**	**3036**	**1319**	**341**
% on total	24%	46%	19%	8%	2%

Table 6. Final energy use and total primary energy (GWh) for each scenario, for Lisbon. Data reworked from [28]

BASELINE (2014)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	660	500	4	-	
Public lighting	58	-	-	-	
Public transport	96	-	262	-	

Private transport	-	43	1749	707	
Total final energy use	**814**	**543**	**2015**	**707**	**-**
Total primary energy	**1774**	**543**	**2015**	**707**	**-**
% on total	35%	10,8%	40%	14%	0%

MOBILITY (Mob)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	660	500	4	-	
Public lighting	58	-	-	-	
Public transport	192	-	138	-	-
Private transport	32	61	747	684	-
Total final energy use	**942**	**562**	**889**	**684**	**-**
Total primary energy	**2053**	**562**	**889**	**684**	**-**
% on total	49%	13%	21%	16%	0%

DISTRICT HEATING (DH)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	594	450	-	-	120,44
Public lighting	58	-	-	-	
Public transport	96	-	262	-	
Private transport	-	43	1749	707	
Total final energy use	**748**	**493**	**2011**	**707**	**120**
Total primary energy	**1630**	**493**	**2011**	**707**	**96**
% on total	33%	10%	41%	14%	2%

ENERGY EFFICIENCY BUILDINGS (EE Build)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	528	403,7	-	-	-
Public lighting	58	-	-	-	-
Public transport	96	-	262	-	-
Private transport	-	43	1749	707	
Total final energy use	**682**	**447**	**2011**	**707**	**-**
Total primary energy	**1486**	**447**	**2011**	**707**	**-**

% on total	32%	10%	43%	15%	0%

LED					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	660	500	4	-	-
Public lighting	28	-	-	-	-
Public transport	96	-	262	-	-
Private transport	-	43	1749	707	-
Total final energy use	**784**	**543**	**2015**	**707**	**-**
Total primary energy	**1709**	**543**	**2015**	**707**	**-**
% on total	34%	11%	41%	14%	0%

ENERGY EFFICIENCIES APPLIANCES (EE Appl)					
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel Oil**	**Gasoline**	**Thermal fluid**
Residential buildings	594	500	4	-	-
Public lighting	58	-	-	-	-
Public transport	96	-	262	-	-
Private transport	-	43	1749	707	-
Total final energy use	**748**	**543**	**2015**	**707**	**-**
Total primary energy	**1630**	**543**	**2015**	**707**	**-**
% on total	33%	11%	41%	14%	0%

List of Figures

List of Tables