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An exergy analysis for Milano smart city

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Abstract

Cities represent fundamental hubs in the world's energy-flow network, and their role is expected to gain further relevance in the next decades, following the ongoing urbanization process.
Reducing energy use and increasing energy efficiency are crucial aspects for both existing and planned cities, and many policies have been established to pursue these objectives. However, in smart cities, as the ones envisioned in many on-going research projects, energy should also be used in a smart way, that is reducing the energy degradation in terms of capacity to generate useful work.
Starting from the literature, the paper proposes an analysis method, based on exergy, to support smart city planning, with the aim to provide the decision maker with a useful tool to compare and understand the energy-smartness of different scenarios, and to address future energy urban policies. Possibilities and limitations of the analysis method are discussed via the application to the city of Milano that committed to become a smart city.

Keywords: Smart city; exergy; energy efficiency; extended exergy analysis

1. Introduction

According to the Growing Urbanization of the World (GRUMP) data, urban areas occupy roughly 3% of the Earth's land surface [1]. Moreover, the global map of accessibility released by the European Commission's Joint Research Centre for the World Bank's World Development Report 2009, indicates that 95% of world's population is concentrated on just 10% of world's land surface, and that only 10% of the world's land is classified as remote or

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more than 48 hours from a large city [2]. A large majority of the population therefore inhabits only 10% of world's land, another 10% of it may be considered remote to urbanization, whereas the remaining 80%, although considered as a rural environment, is well connected to the major cities by roads, highways, railways, etc. [2]. Approximately 54% of the world's population now resides in urban areas (7% in the largest mega-cities), a proportion that is expected to increase to 66% by 2050, accounting for 60 to 80% of global energy use and around the same share of carbon dioxide (CO_2) and other harmful gas emissions. 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 [3]. Currently, 75% of EU and 81% of US population already lives in urban areas, whereas, according to a United Nations report, the largest urban growth by 2050 will take place in Asia and Africa [4].

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, 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 therefore to provide solutions to significantly increase cities' overall energy and resource efficiency through actions addressing the building stock, energy systems, mobility, water and air quality.

Analysis method and indices are necessary to assess the energy performance of cities and to determine if energy is used with appropriate and smart approaches. Current standards provide, unfortunately, a limited set of indices for smart cities, mostly focused on the energy intensity in different sectors [5, 6]. Almost no indication is provided about the effectiveness of using different energy carries to provide different services and about the quality of the conversion processes, i.e. how smartly energy is used within the city.

According to the second principle of thermodynamics, not all the forms of energy have the same potential to generate useful work. Exergy has been introduced as an indicator of energy quality. In particular, exergy provides a quantitative basis to measure the degradation of energy (i.e., the decrease of its capacity to generate useful work) in conversion processes. By means of the so-called *extended exergy analysis*, exergy has also been adopted to evaluate and compare countries, regions and economic sectors [7, 8]; early example are available also for districts [9]. However, no reference is available in the literature to understand how energy-smart an entire city may be, and how current and future policies may improve or decrease its global energy-smartness. Targeting this gap, the present paper proposes an analysis approach for smart cites, founded on exergy, with the aim to provide the decision maker with a useful tool to understand the energy-smartness of different scenarios, and to address future energy urban policies.

Nomenclature

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

2. Method

The goal of this analysis is to calculate overall energy and exergy efficiencies at city level, in order to compare the energy-smartness potential of different urban policies scenarios. To this aim, the method presented in Ref. [9] was applied. Starting from the final energy use for each sector (e.g., space heating, public lighting, transport, etc.) and from the associated energy carriers, energy and exergy efficiencies were calculated as weighted average, applying a two-step process. For each energy carrier, weighted means of energy and exergy efficiencies were 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 was obtained both for 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

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

To obtain the overall energy and exergy efficiency 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. It defines the activities and measures set up to achieve the targets, together with time frames and assigned responsibilities. This document is available for the city of Milano since 2015 [10], as developed by AMAT (Agenzia Mobilità Ambiente e Territorio), the local agency for transport, environment and habitat, according to Covenant of Mayors indications. Since the city of Milano committed to be among the leading smart cities in Europe, both participating to relevant research projects such as Sharing Cities [11], and by implementing many dedicated actions and policies, it has been chosen as a relevant case study to test the analysis method proposed in this paper, which aims at evaluating the energy-smartness at city level.

The SEAP contains the description of the methodology and references adopted to gather data for past and on-going conditions, respectively 2005 and 2013, since 2013 data is the last available one. The document includes also the definition of two future scenarios, i.e. Business As Usual (BAU), in which only the actions already approved at municipal level are taken into consideration, and the 2020 scenario, including all the actions planned to reach the CO_2 emission target by 2020. In the present study, the four scenarios contained in the SEAP are considered as a starting point, and named in the following as: *SEAP 2005*, *SEAP 2013*, *SEAP 2020, SEAP 2020 Baseline*. The first two report actual data for 2005 and 2013, *SEAP 2020* is the scenario including actions targeting the CO_2 emission reductions by 2020 and, eventually, *SEAP 2020 Baseline* corresponds to the SEAP BAU, and it is used as a baseline for further scenarios. *2020 Mob*, *2020 DH*, *2020 EE Build*, *2020 LED*, *2020 EE Appl* are the five additional scenarios, based on *SEAP 2020 Baseline*, and prepared to evaluate the effect of a single action or policy on the energy-smartness at city level. These scenarios are created changing either some final energy use values or energy and exergy efficiencies with respect to *SEAP 2020 Baseline*. In *2020 Mob* the focus is on urban mobility only, it includes, in fact, the improved energy uses for transport described in *SEAP 2020*, that is a reduction of private transport energy use, and an initial shift toward electric mobility. The *2020 DH* scenario pictures a massive switch to district heating (DH); half of the total energy use for buildings' heating is assigned to DH, whereas the remaining half is assigned to natural gas. *2020 EE Build* assumes the adoption of energy efficiency (EE) measures (renovation measures) on building envelopes and energy systems, resulting in an overall reduction of the energy use by 20%, with respect to *2020 Baseline*. The EE measures on energy systems include the complete substitution of old fuel oil boilers with new natural gas ones and the use of low exergy systems such as radiant panels and condensing gas boilers, but it does not include interventions on appliances. This scenario includes the energy use for heating of the entire building stock (i.e., residential, commercial, service and public buildings). The fourth scenario deriving from *SEAP 2020 Baseline*, and named *2020 LED*, is obtained switching all the public lighting, assumed as metal halide, to light-emitting diode (LED) lamps, resulting in a slight reduction of energy use and in an improvement of energy and exergy efficiencies. Indeed the Municipality already implemented this kind of action, as from 2014 to present date, 97% of the public lighting in

Milano was converted to LED [12]. The *2020 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 53%, compared to baseline, following the efficiency improvement. Finally, *2020 Best Overall* includes all the measures described in the previous five scenarios, together.

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 at city level. 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, distribution, emission and control), residential appliances and equipment adopted by other sectors, etc. Average values for each sector may be eventually derived. This approach requires an exhaustive and coordinated work, including interviews and surveys to operators, on-site inspections and measurements. It may be implemented only with a substantial commitment of the municipality and a coordinated involvement of local public and private actors such as energy providers, universities, local committees, professional organizations and other stakeholders. Since it was not possible to establish such a kind of exhaustive and comprehensive analysis in a very short time, without the contribution and the support of many actors, and, since the aim of the present paper is just to show possibilities and limitations of an analysis method to assess energy smartness at city level, the values of energy and exergy efficiencies adopted in this study (Table 1) are taken from the literature, trying to choose the most appropriate ones. The validly of the analysis is therefore independent from 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 study.

Electrical energy and exergy efficiencies for domestic uses (i.e. residential appliances) for different years, come from actual values of year 2005 and projections based on data for Japan [13]. Data was considered reliable for Milano, as the overall exergy efficiencies for Italy and Japan, in the household end-use sector, are proved to be similar, that is 0.02 for Italy and 0.03 for Japan [14]. For district heating, natural gas and different couplings of generation and emission systems, energy and exergy efficiencies come from Ref. [15]. Values for fuel oil boilers were taken from Ref. [10]. No specific data was found in the literature for public lighting; values used in this paper come from Ref. [16], 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 similar. Furthermore, this shows to be a conservative approach [17]. The energy efficiency for electric engines come from Ref. [18], while the exergy efficiency come from Ref. [19]. Energy and exergy efficiencies for natural gas and gasoline engines are taken from Ref. [20], whereas their values for Diesel engines come from Ref. [21]. 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 Milano. For electricity PEF is 2.18, for the thermal fluid PEF is 0.8, according to the local energy provider declaration, and finally, for natural gas, fuel oil and gasoline PEF is 1. Final energy use and primary energy for the considered scenario are summarized in Table 2, including the share for energy carrier. Values from SEAP were slightly reworked to fit the purpose of this study.

Table 1. Energy and exergy efficiencies for each energy use.

DOMESTIC APPLIANCES			HEATING + DOMESTIC USES			LIGHTING			TRANSPORT		
	η	ψ		η	ψ		η	ψ		η	ψ
SEAP 2005	38.0%	5.3%	**District Heating from cogeneration**	90.0%	31.9%	**Fluoresc.**	20.0%	17.5%	**Electric**	80.0%	33.5%
SEAP 2013	49.3%	6.0%	**Gas boilers + radiators**	86.0%	6.7%	**LED**	27.3%	21.8%	**Natural gas**	27.0%	31.0%
SEAP 2020 Baseline[1]	49.3%	6.0%	**Condensing gas boilers + radiant panels**	105.0%	8.5%				**Diesel fuel**	36.7%	34.4%
SEAP 2020	59.2%	6.6%	**Fuel oil boilers + radiators**	75.0%	6.7%				**Gasoline**	27.1%	30.6%
2020 EE Appl, 2020 Best Overall	73.3%	7.4%	**Photovoltaic + air-to-water heat pump**	27.0%	2.4%						

[1]Comprising also *2020 Mob*, *2020 DH*, *2020 EE Build*, *2020 LED* scenarios

Table 2. Final energy use and total primary energy (GWh) for each scenario, as elaborated from SEAP.

	SEAP 2005					***SEAP 2013***				
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**
Buildings	1525	8874	3813	-	263	1349	10474	2058	-	642
Domestic use	1525	1021	-	-	-	1349	1061	-	-	-
Heating	-	7853	3813	-	263	-	9413	2058	-	642
Public lighting	108	-	-	-	-	112	-	-	-	-
Public transport	301	-	217	-	-	281	-	218	-	-
Private transport	-	13	1725	1934	-	-	79	1454	1319	-
Total final energy use	**1934**	**8887**	**5755**	**1934**	**263**	**1742**	**10553**	**3730**	**1319**	**642**
Total primary energy	**4216**	**8887**	**5755**	**1934**	**210**	**3798**	**10553**	**3730**	**1319**	**514**
% on total	20%	42%	27%	9%	1%	19%	53%	19%	7%	3%

	SEAP 2020 Baseline					***2020 Mob***				
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**
Buildings	1501	11487	1195	-	647	1501	11487	1195	-	647
Domestic use	1501	1091	-	-		1501	1091	-	-	-
Heating	-	10396	1195	-	647	-	10396	1195	-	647
Public lighting	112	-	-	-	-	112	-	-	-	-
Public transport	281	-	208	-	-	281	-	202	-	-
Private transport	-	109	1360	1167	-	47	90	1096	1004	-
Total final energy use	**1894**	**11596**	**2763**	**1167**	**647**	**1941**	**11577**	**2493**	**1004**	**647**
Total primary energy	**4129**	**11596**	**2763**	**1167**	**518**	**4231**	**11577**	**2493**	**1004**	**518**
% on total	20%	57%	14%	6%	3%	21%	58%	13%	5%	3%

	2020 DH	***2020 EE Build***

Sector/Carrier	Electricity	Natural gas	Fuel oil	Gasoline	Thermal fluid	Electricity	Natural gas	Fuel oil	Gasoline	Thermal fluid
Buildings	1501	6409	-	-	6647	1501	10364	-	-	518
Domestic use	1501	1091	-	-	-	1501	1091	-	-	-
Heating	-	5318	-	-	6647	-	9273	-	-	518
Public lighting	112	-		-	-	112	-	-	-	-
Public transport	281	-	208	-	-	281	-	208	-	-
Private transport	-	109	1360	1167	-	-	109	1360	1167	-
Total final energy use	**1894**	**6518**	**1568**	**1167**	**6647**	**1894**	**10473**	**1568**	**1167**	**518**
Total primary energy	**4129**	**6518**	**1568**	**1167**	**5318**	**4129**	**10473**	**1568**	**1167**	**414**
% on total	22%	35%	8%	6%	28%	23%	59%	9%	7%	2%

	2020 LED					***2020 EE Appl***				
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**
Buildings	1501	11487	1195	-	647	791	11417	1195	-	647
Domestic use	1501	1091	-	-	-	791	1021	-	-	-
Heating	-	10396	1195	-	647	-	10396	1195	-	647
Public lighting	54	-	-	-	-	112	-	-	-	-
Public transport	281	-	208	-	-	281	-	208	-	-
Private transport	-	109	1360	1167	-	-	109	1360	1167	-
Total final energy use	**1836**	**11596**	**2763**	**1167**	**647**	**1184**	**11526**	**2763**	**1167**	**647**
Total primary energy	**4002**	**11596**	**2763**	**1167**	**518**	**2581**	**11526**	**2763**	**1167**	**518**
% on total	20%	58%	14%	6%	3%	14%	62%	15%	6%	3%

	2020 Best Overall					***SEAP 2020***				
Sector/Carrier	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**	**Electricity**	**Natural gas**	**Fuel oil**	**Gasoline**	**Thermal fluid**
Buildings	1434	5916	-	-	4895	2091	9734	115	-	1150
Domestic use	1434	1021	-	-	-	1434	1021	-	-	
Heating	-	4895	-	-	4895	657	8713	115	-	1150
Public lighting	54	-	-	-	-	54	-	-	-	-
Public transport	281	-	202	-	-	281	-	202	-	-
Private transport	47	90	1096	1004	-	47	90	1096	1004	-
Total final energy use	**1816**	**6006**	**1298**	**1004**	**4895**	**2473**	**9824**	**1413**	**1004**	**1150**
Total primary energy	**3959**	**6006**	**1298**	**1004**	**3916**	**5391**	**9824**	**1413**	**1004**	**920**
% on total	21%	32%	7%	5%	21%	29%	53%	8%	5%	5%

3. Results

Table 3, Figure 1 and Figure 2 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 output within the system (i.e. the city). The exergy efficiency shows instead the degradation of energy flows within the system. If the exergy efficiency is high, the "energy output" of the city has still a high potential to be used for other conversion processes, whereas, if it shows a low value, the energy output has a low potential to generate useful work, and thus it can hardly be used in other energy conversion processes. It is therefore possible to state that a city with a high overall exergy efficiency shows to be smarter, since the energy conversion processes, within its boundary, determine a low degradation of the entering energy flows, and this may be utilized for further conversion processes. In this sense, the exergy efficiency may be assumed as an indicator of energy-smartness.

Figure 1 reports the past and current situation (*SEAP 2005* and *SEAP 2013)*, the baseline scenario (*SEAP 2020 Baseline*), the *2020 Best Overall scenario*, including all the interventions envisioned in Section 2, and eventually *SEAP 2020*, the best scenario foreseen by SEAP. It shows that from 2005 to 2013 the overall primary energy decreased and the energy efficiency increased, however, no major change in terms of exergy is reported, since there is no evidence of a significant shift to energy processes that show a higher exergy efficiency. *SEAP 2020 Baseline* shows values very similar to *SEAP 2013* scenario, and an overall energy use slightly rising, due mostly to buildings and transport. Both *2020 Best Overall* and *SEAP 2020* show opportunities to decrease primary energy and to slightly increase energy efficiency. The former shows, nevertheless, a substantially higher primary energy reduction and a considerable improvement of exergy efficiency. Possibilities to rise energy-smartness and to decrease energy use do exist.

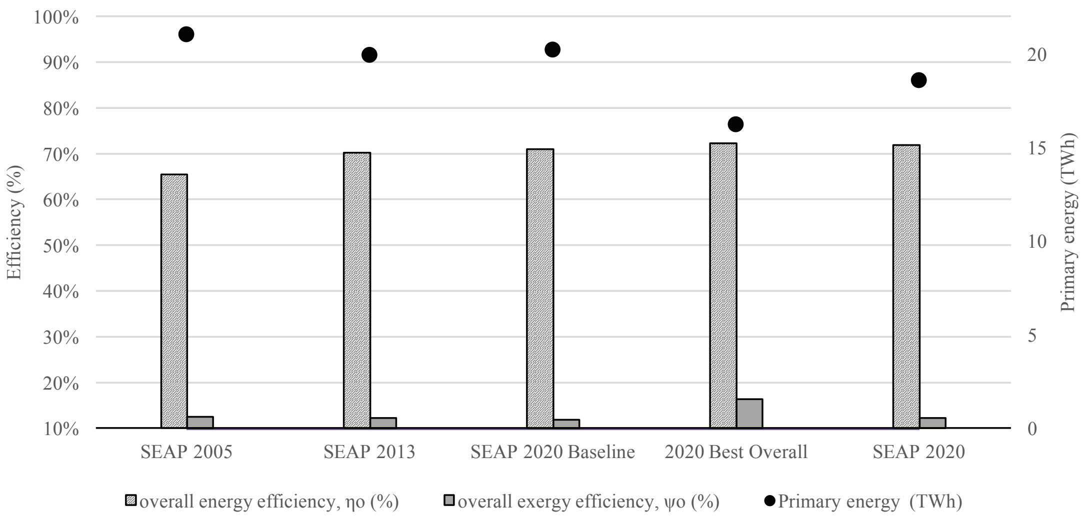

Fig. 1. Comparison of the energy and exergy performances of the SEAP scenarios and the *Best Overall* scenario.

Looking at the single interventions (Figure 2 and Table 3), the one providing the highest increase in exergy efficiency is the massive shift to district heating, depicted in *2020 DH*. *2020 EE Build* scenario, shows the lowest primary energy value and the highest energy efficiency; however, the exergy efficiency does not reach the value reported for *2020 DH*. It means that the shift to district heating should be considered a major energy-smart action to be pursued, unless technological improvement were able to provide new energy systems with even higher exergy efficiency.

Actions on public lighting alone did not show major improvments, since the sharing on the overall primary energy of this sector is very low and by applying LED it reduces further. Similar considerations may be made for mobility and appliances scenarios envisioned in this study. Unless a massive shift to new technologies that show substantially higher energy and exergy efficiencies is considered, no relevant results in terms of energy-smartness may be reported.

In general, since the largest share of primary energy reported in SEAP for Milano relies on buildings, no substantial change may be obtained if massive interventions in this sector are not considered.

The *2020 Best Overall* scenario that includes interventions on buildings, appliances, public lighting, mobility and district heating altogether, reports definitely the lowest value for primary energy. The energy and exergy efficiency show quite good values, though lower than the ones reported for *2020 EE Build* and *2020 DH* scenario respectively, because the final energy share per sector is different in the three scenarios.

Finally the *SEAP 2020* scenario, the best foreseen by SEAP, shows a lower exergy efficiency than the *2020 Best Overall* scenario, demonstrating that policy makers have still a large margin of action to increase the overall energy-smartness at city level.

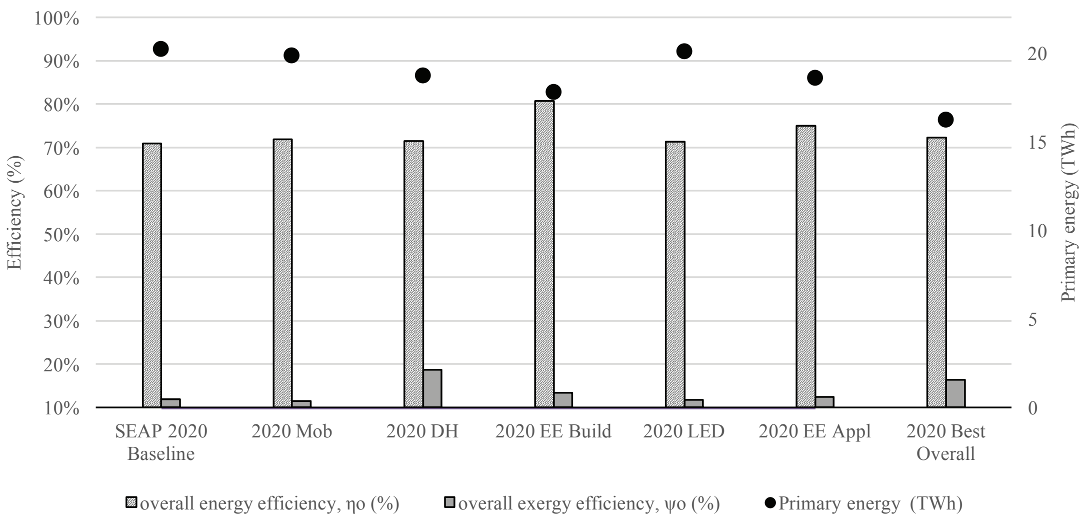

Fig. 2. Scenarios derived from *SEAP 2020 Baseline*.

Table 3. Overall energy and exergy efficiencies and primary energy for each analyzed scenario.

	SEAP 2005	**SEAP 2013**	**SEAP 2020 Baseline**	**2020 Mob**	**2020 DH**	**2020 EE Build**	**2020 LED**	**2020 EE Appl**	**2020 Best Overall**	**SEAP 2020**
η_o	66%	70%	71%	72%	72%	81%	75%	75%	72%	72%
ψ_o	12%	12%	12%	11%	19%	13%	12%	12%	16%	12%
Primary energy (TWh)	21.0	19.9	20.2	19.8	18.7	17.8	20.0	18.6	16.2	18.6

4. Discussion

Results reported in the former section are just an example of how the proposed analysis method may be used to assess energy-smartness at city level, and thus inform local energy policies.

As reported in Section 2, the energy and exergy efficiencies used as input in this study, derive from the literature and not from an accurate analysis of the actual conversion processes in the case study. Although such literature values may be considered reliable as a first order of approximation, substantial deviations might result from an accurate analysis of the energy conversions specific to the case study. Moreover, many energy use values reported in SEAP are projections or estimates. Hence, also these values require a more detailed definition before providing a sound reference to inform an energy-smartness analysis.

Despite of these *caveat*, the analysis method proved to be applicable at city level and it may provide useful output for decision and policy makers, about the best actions to be pursued.

Exergy alone is not, however, a comprehensive indicator. It may provide information on energy-smartness, but other key aspects, such as harmful gas emissions and economic estimates, are required to provide all the information necessary to take sound decisions at city level. A further analysis step could therefore target the application of the Extended Exergy Accounting method [8] to smart cities. The issue about data quality and availability should, however, be tackled in advance.

5. Conclusion

An analysis method to study and compare energy scenarios for smart cities has been proposed. It shows potentialities to evaluate energy smartness at the city level. However, the actual tools usability is hindered by low availability and quality of the data required to perform the analysis. In order to pursue this approach, a common database for at least European, and potentially worldwide, cities is required, which might gather all the fundamental energy flows 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 methodological approach. A further step would require a cross evaluation including economic and other indicators.

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