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Environmental driving forces of urban growth and development An emergy-based assessment of the city of Rome, Italy

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ABSTRACT

Large urban systems can be considered as the final point of convergence of resources, environmental services and human activities from rural settlements to villages to towns to small and big cities. The emergy synthesis method is applied in order to capture the complexity of urban systems from the point of view of the larger scale, the geobiosphere, where resources come from. Emergy is the total available energy of one kind (usually solar) directly or indirectly used up to drive a system or a process. It can be considered as a measure of a system's demand for environmental support. The population of Rome is 4.43% of total Italian population, with an emergy use of about 4% of total emergy supporting the Italian economy. Emergy use per capita is 5.50E+16 seJ/year, compared to an average value for Italy of 3.60E+16 seJ/year. An empower density of 1.09E+14 seJ/m^2/year was calculated for Rome, much higher than for average Italy, 6.86E+12 seJ/m^2/year. Finally, the emergy/GDP, an indirect measure of economic performance of the system, is 2.43E+12 seJ/€ for Rome compared to 1.64E+12 seJ/€ for Italy, suggesting that in an urban system (generally characterized by a larger fraction of tertiary activities) the required environmental support for the generation of economic results is much higher than for the whole economic system. Finally, comparison of above performance indicators with similar studies published by other authors (Taipei, San Juan and Macao) points out that Rome has the highest annual emergy per capita (suggesting higher potential standard of living).

1. Introduction

The world urban population reached 2.9 billion in the year 2000 according to an estimate by the United Nations (2001). Based on the same estimate, the 50% mark should have been reached in the year 2007 and – by the year 2030 – 60% of the world population will likely be urban, thus generating a huge change of lifestyle, land use, demand for energy and other resources, and environmental pressure. It is therefore of paramount importance to explore the driving forces and the consequences of such a trend, as far as environmental integrity and resource availability are concerned. Previous studies have already recognized the importance of the energy and material basis in support of urbanization trends and expressed concerns about their environmental and social consequences (Obernosterer et al., 1998a; Bongardt, 2003; Martinez Alier, 2003; Kenworthy and Laube, 2001; G.L.A., 2002; Barrett et al., 2002; B.C.C., 2003; Doughty and Hammond, 2004; Alberti et al., 2006).

Pointing out that cities are a special kind of ecological systems, Odum et al. (1995) suggested the need for a more comprehensive investigational approach from the point of view of the biosphere that supplies resources and environmental services (Odum, 1996; Brown and Ulgiati, 2004a). In particular, Odum stressed that quality of input resources and not only quantity, should also be taken into proper account. He suggested this be done by means of a special accounting and evaluation procedure named Emergy Synthesis. Odum and his collaborators applied the emergy synthesis method to explore the zonal organization of several American (e.g., Miami and Jacksonville, FL) and international cities (e.g., San Juan, Puerto Rico) as well as the energy systems basis for an urban society to be sustainable (Odum et al., 1995). Building on Odum's approach, Huang (1998) developed a framework of indicators in order to assess the urban sustainability of Taipei (Taiwan). Based on the same method, Lei et al. (2008) evaluated the urban dynamics and economic system of Macao (a rapidly developing urban system in Southern China).

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The starting point of Odum's approach was the awareness that, until recently, neoclassical economics has been incapable of understanding the role of biophysical support provided free of cost by the environment in the development of economic processes. Howard Odum's pioneering work since the 1960s pointed out that real wealth is not money but instead the environmental services as well as the resources provided free by nature. Economists and policy makers must recognize the role played by energy and other resource flows in support of human societies. Integration between economic and biophysical tools for a better management of available resources is urgently needed and may lead to a very different way of dealing with production processes, economic development, and their relationship to the environment.

Odum and Odum (2006), dealing with the dynamics of human societies, point out very strongly the assumption that "*resource scarcity and rising costs cause the global economy to contract*" and that the most important point is not the timing, but "*what can be expected and what our adapting strategies should be to conditions that force descent*". They focus on growth and decline of societies, characterized by such a long wave-length of the growth-descent pulsing (in the order of magnitude of thousands years) that we are most often unable to recognize the cycle of which we are part. This "pulsing paradigm" also applies to cities: concentration of population and economic activities are driven by the availability of cheap fossil fuels, with population densities largely surpassing the carrying capacity based on locally available renewable resources. Worldwide reliance on the same resource makes world civilizations more similar to each other, decreasing diversity and overall stability. Decreasing availability of fuels and strategic resources (minerals, water) will force cities to implement policies to decrease consumption to an amount compatible with local sustaining capacity and to rebuild strong relations to their surrounding regions. The Roman Empire and the city of Rome are often cited as clear examples of the rise and decline of powerful societies according to changes in resource availability (Tainter, 1988). A system driven by outside resources (be they renewable or not) is never "sustainable", although it can somehow be stable for a relatively long time, depending on the stability of the flow of resources from outside. According to Lotka-Odum's Maximum Power Principle (Lotka, 1922; Odum, 1996), systems grow in complexity in order to become able to draw-in and process more resources; support growth in size and functions; and displace competing systems. Do modern cities of industrialized countries follow the same trend and competition patterns? Is it possible to "forecast" the future evolution of urban systems based on their interaction with surrounding environment, competition for available resources, and the mix and the quality of resources attracted from outside? The present paper deals with the evaluation of the resource basis of the city of Rome. The main goal is to help understand what the direct and indirect environmental work that supports the urban development is and which portion of urban system assets, population and activity would be sustainable by relying solely on locally available renewable resources. Answering these questions provides both a way to design the future structure and dynamics of Rome and a challenging test for the emergy method, purported to be a comprehensive evaluation tool for quality and sustainability assessment.

2. Materials and methods

2.1. Accounting for donor-side resource quality. The emergy approach

The emergy method is known as "Emergy Synthesis". "Synthesis is the act of combining elements into coherent wholes. Rather than dissect and break apart systems and build understanding from the pieces upward, emergy synthesis strives for understanding by grasping the wholeness of systems" (Brown and Ulgiati, 2004a).

The rationale of the emergy method is the following. The same product may be generated via different production pathways and with different resource demand, depending on the technology used and other factors. In turn, different resources require a different environmental work for their production through natural processes. As a development of these ideas, Odum (1996) introduced the concept of *emergy*, i.e. "the total amount of 'available energy' (exergy) *of one kind (*usually *solar)* that is directly or indirectly required to make a given product or to support a given flow". In some way, this concept of embodiment supports the idea that something has a value according to what was invested into making it. This way of accounting for required inputs over a hierarchy of levels might be called a "donor system of value", while for example exergy analysis and economic evaluation are "receiver systems of value", i.e., something has a value according to its usefulness to the final user. *Solar emergy* is therefore suggested as a measure of the total environmental support to all kinds of processes in the biosphere, including economies. Flows that are not from solar source (geothermal heat and gravitational potential) are expressed as solar equivalent energy by means of suitable transformation coefficients (Odum, 1996).

The input emergy invested per unit output flow or product is named *solar transformity* and can be considered a "quality" factor which functions as a measure of the intensity of biosphere support to the product under study. If the product flow is measured in exergy units (although mass or energy units are also used), its total solar emergy is calculated as: solar emergy = exergy of the product × solar transformity. Solar emergy is usually measured in solar emergy joules (seJ), while the unit for solar transformity is solar emergy joules per joule of product (seJ/J). Sometimes emergy per unit mass of product or emergy per unit of currency are also used (seJ/g, seJ/$, etc.). In so doing, all kinds of flows to a system are expressed in the same unit (seJ of solar emergy) and have a built-in quality factor to account for the conversion of input flows through the biosphere hierarchy.

Values of transformities are available in the scientific literature on emergy. Based on a first set of transformities for very common items (rain, wind, fossil fuels, minerals, fertilizers, etc.) (Odum et al., 2000; Odum, 2000), other natural and economic processes can be evaluated by calculating input flows, "through-put" flows, storages within the system, and final products in emergy units (e.g., all manufactured products, such as food items, electricity, gasoline, construction materials, etc.) (Haukoos, 1995; Brandt-Williams, 2002; Cuadra and Rydberg, 2006; Rotolo et al., 2007, among others). As a result of the emergy accounting procedure, a set of indices and ratios suitable for policymaking can be calculated (Ulgiati et al., 1995; Brown and Ulgiati, 2004a). An overview of most recent findings on research in the field of emergy can be found in Brown et al. (2005) and Brown et al. (2007). A summary of published literature is provided in Brown and Ulgiati (2004b, Table 2), where several application fields are listed and selected papers are referred to. Finally, a very large number of past and recent emergy papers and reports can be downloaded from www.emergysystems.org.

2.2. Systems diagram

The purpose of the system diagram is to conduct a critical inventory of processes, storages and flows that are important to the system under consideration and are therefore necessary to be evaluated. Components and flows within diagrams are arranged from left to right reflecting more available energy flow on the left, decreasing to the right with each successive energy transforma-

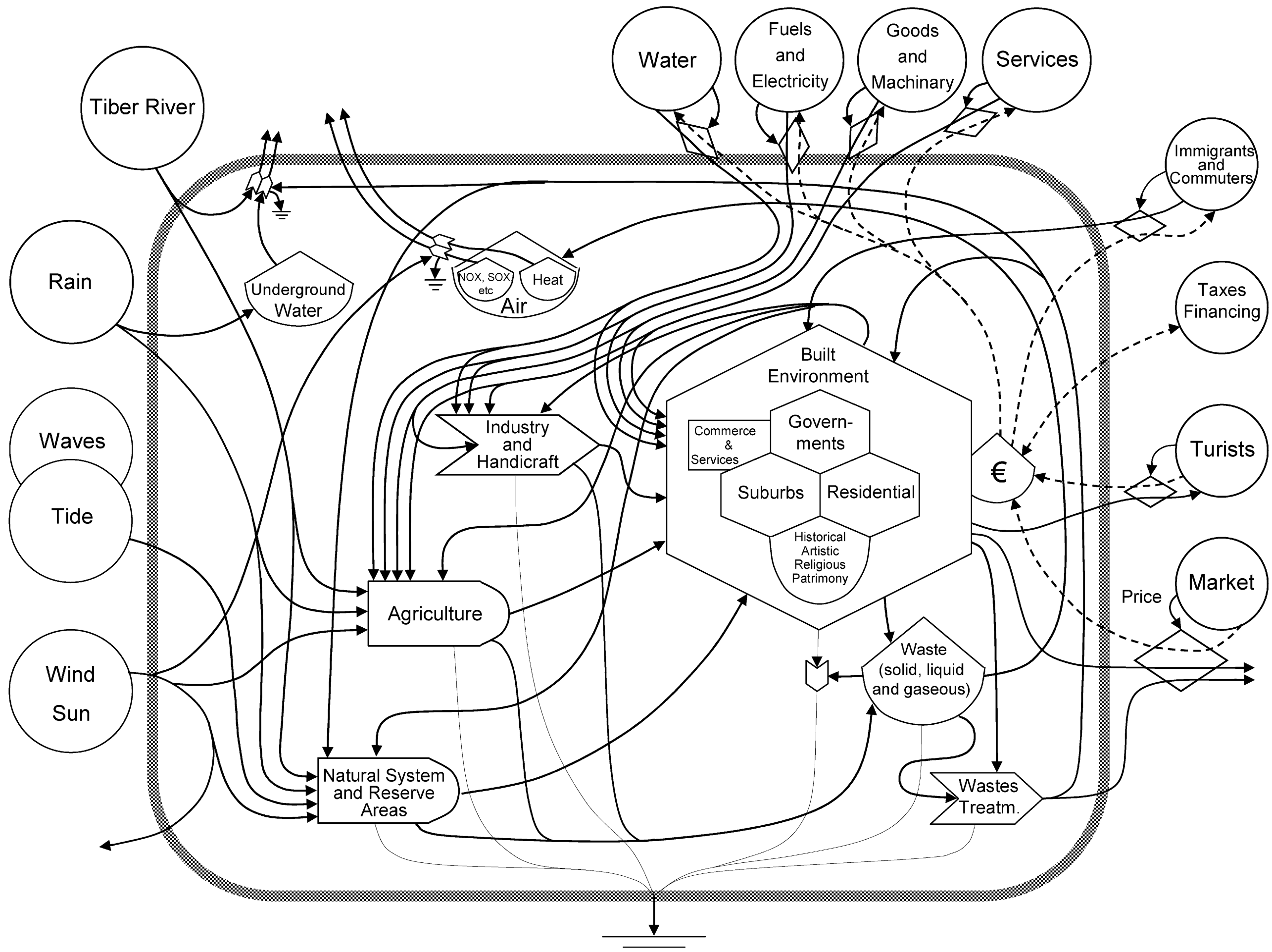

Fig. 1. Systems diagram, showing renewable and non-renewable resources driving the urban system of Rome, Italy. Systems symbols from Odum, 1996, according to the legend below.

	Generic resource flow (money flow, when dotted)		Primary production process (photosynthesis)
	Flow-limited energy or resource input		Interaction among flows with different quality
	Generic process box		Storage of resources or assets
	Generic consumer		Economic transaction (resources versus money)

tion. A system diagram of the city of Rome is shown in Fig. 1, and discussed later on in this paper.

2.3. Preparation of an emergy evaluation Table for inventory of input flows and emergy calculation procedure

Tables of the actual flows of materials, labor and energy are constructed from the diagram of the system investigated. Raw data on flows and storage reserves are converted into emergy units, and then summed for a total emergy flow to the system. According to the emergy algebra (Brown and Ulgiati, 2004a), inputs that come from the same source are not added, to avoid double counting. Only the larger input is accounted for, because the smaller flow is driven by the same emergy source that drives the larger one. If the table is for the evaluation of a process, it represents flows per unit time (usually per year). If the table is for the evaluation of reserve storages, it includes those storages with a turnover time longer than a year.

Separate tables are constructed for evaluations of flows and storages. Tables are usually constructed in the same format, as illustrated in the example (Table 1).

Collecting data at the local scale of a city is never an easy task, due to the fact that national and regional statistical offices very seldom publish data at such a disaggregated level. However, due to the fact that Rome is the capital of Italy and due to the fact that it is the largest Italian city, most data for the present investigation were

Table 1
Typical table format for emergy accounting.

1 Note	2 Item	3 Data	4 Units	5 Emergy/unit (seJ/unit)	6 Solar emergy (E+15 seJ/year)	7 em-Value (em$; em€; . . .)
1.	First item	xx.x	J/year	xxx.x	xxx.x	xxx.x
2.	Second item	xx.x	g/year	xxx.x	xxx.x	xxx.x
. . .						
.. . .						
n.	*n*th item	xx.x	J/year	xxx.x	xxx.x	xxx.x
O.	Output	xx.xx	J or g/year	xxx.x	$\sum_{n}^{1} Em_i$	xxx.x

Column #1 is the line item number, which is also the number of the footnote found below the table where raw data sources are cited and calculations are shown. Column #2 is the name of the item, which is also shown on the aggregated diagram. Column #3 is the raw data in joules, grams, dollars or other units. The units for each raw data item are shown in column #4. Column #5 is the emergy per unit used for calculations, expressed in solar emergy joules per unit. Sometimes, inputs are expressed in grams, hours, or currency units, therefore an appropriate conversion ratio is used (seJ/J; seJ/h; seJ/g; seJ/$, seJ/€). Column #6 is the solar emergy of a given flow, calculated as raw input times the transformity (column 3 × column 5). Column #7 is the "em-value" of a given item for a given year. This is obtained by dividing the emergy in column #6 by the "emergy-to-money ratio" (EMR) for the country and selected year of the evaluation (units are seJ/$, seJ/€, etc.). The EMR is calculated independently. The resulting values in this column express the amount of economic activity that can be supported by a given emergy flow or storage.

Table 2
Matter, energy and emergy flows supporting the urban system of Rome.

#[a]	Items	Units	Raw	Transformity (seJ/unit)	Reference for transformity	Emergy (seJ/year)
Locally available renewable input						
1	Solar radiation	J/year	8.04E+18	1	[a]	8.04E+18
2	Wind (kinetic energy)	J/year	2.22E+16	2.51E+03	[b]	5.58E+19
3	Evapotraspired rain (chemical potential)	J/year	1.48E+15	2.69E+04	[b]	3.97E+19
4	Run-in (river geopotential)	J/year	2.13E+15	4.66E+04	[b]	9.95E+19
5	Waves	J/year	7.62E+15	5.13E+04	[b]	3.91E+20
6	Tidal energies	J/year	1.27E+12	7.39E+04	[b]	9.41E+16
Locally available non-renewable input						
7	Top soil (erosion, weathering)	g/year	6.15E+11	2.87E+09	[b]	1.76E+21
Imports						
8	Gasoline	J/year	5.87E+16	1.11E+05	[a]	6.52E+21
9	Diesel fuel	J/year	7.02E+16	1.11E+05	[a]	7.80E+21
10	LPG (liquid petroleum gas)	J/year	8.92E+15	1.18E+05	[a]	1.05E+21
11	Heavy oil for domestic heating	J/year	5.42E+15	1.11E+05	[a]	6.02E+20
12	Natural gas					
12a	Domestic use for cooking	J/year	4.34E+15	8.05E+04	[a]	3.49E+20
12b	Domestic use for heating	J/year	1.76E+16	8.05E+04	[a]	1.42E+21
12c	Other uses	J/year	2.62E+16	8.05E+04	[a]	2.11E+21
13	Electricity	J/year	2.91E+16	3.11E+05	[c]	9.05E+21
14	Water (from aqueduct)	g/year	3.28E+14	3.76E+06	[d]	1.23E+21
15	Main Food Items					
15a	Fish	g/year	1.80E+10	2.78E+11	[a]	4.99E+21
15b	Meat	g/year	6.83E+10	3.00E+10	[a]	2.05E+21
15c	Fruits and Vegetables	g/year	2.43E+11	1.01E+09	[a]	2.45E+20
15d	Milk, cheese and other derivatives	g/year	1.49E+11	1.44E+10	[a]	2.15E+21
15e	Cereals and derivatives	g/year	1.33E+11	6.04E+08	[a]	8.03E+19
15f	Wine and alcoholics	g/year	3.83E+10	1.41E+09	[a]	5.38E+19
15g	Olive and seed oils	g/year	1.95E+10	4.25E+11	[e]	8.26E+21
16	Steel and iron	g/year	1.42E+12	3.16E+09	[f]	4.49E+21
17	Copper	g/year	4.98E+10	3.36E+09	[c]	1.67E+20
18	Aluminium	g/year	6.71E+10	7.76E+08	[g]	5.21E+19
19	Cement (Portland)	g/year	1.83E+12	1.73E+09	[d]	3.17E+21
20	Sand and gravel	g/year	1.35E+13	1.68E+09	[b]	2.27E+22
21	Rocks	g/year	3.00E+12	1.64E+09	[b]	4.92E+21
22	Glass	g/year	2.35E+11	3.50E+09	[c]	8.23E+20
23	Plastics	g/year	5.60E+11	9.68E+09	[d]	5.42E+21
24	Asphalt	g/year	1.46E+11	9.56E+09	[h]	1.40E+21
25	Chemicals	g/year	5.17E+11	6.38E+08	[a]	3.30E+20
26	Wood	g/year	5.94E+11	6.79E+08	[a]	4.04E+20
27	Textiles	g/year	8.32E+10	1.34E+11	[a]	1.11E+22
28	Paper and derivatives	g/year	4.88E+11	6.55E+09	[a]	3.20E+21
29	Fertilizers	g/year	7.67E+09	8.28E+09	[a]	6.35E+19
30	Services for imports	€/year	1.36E+10	1.64E+12	[i]	2.23E+22
31	Imported Labor (commuters)	People/year	2.54E+05	3.60E+16	[i]	9.15E+21
Size of specific sectors						
32	Governmental support (salaries, health services, schools, etc.)	€/year	6.19E+09	1.64E+12	[i]	1.01E+22
33	Tourism (from Italy and abroad)	$/year	4.91E+09	3.81E+12	[l]	1.87E+22

[a] Item numbers as well as references of transformities used are listed in the Appendix A.

available in the annual financial and environmental reports published by the City Administration. Additional data were available in selected reports from other Research or Administrative Institutions such as ENEA – National Energy and Environment Agency, Police, Tax Payment Offices, Environmental Deputy Office of Rome, Cultural and Environmental Associations, Chamber of Commerce, Professional Associations and the three Universities of Rome. Reference to these sources of data is given in table of footnotes. Data collected from different sources allowed for cross-checking of uncertain assumptions as well as educated guesses about data definitely not available.

An inventory of mass and energy flows is provided in Table 2, where primary locally renewable, locally non-renewable and imported flows are listed. Data sources and reference years are listed in the Appendix A. Input data were entered in Table 2 as energy (J) and matter (g) units. Input matter and energy flows were then multiplied by appropriate emergy intensity factors (transformities, seJ/J; specific emergy, seJ/g; emergy/GDP ratios, seJ/€) and converted into emergy flows. Highly aggregated items (such as food items) are multiplied by emergy intensities calculated as weighted averages of published data (Brandt-Williams, 2002; Odum, 1996; Brown et al., 2005; Brown et al., 2007). Finally, the total emergy (U) driving the system as well as a set of performance indicators based on fractions of renewable (R), non-renewable (N) and imported (F) emergy flows were calculated and are shown in Table 3. Money flows are used in the calculation procedure to estimate in emergy terms the indirect labor (services) embodied in imports as well as the emergy supporting imported labor of daily commuters (accounted for as import of their supporting emergy). Accounting for emergy supporting labor and services brings the efficiency and dynamics of the larger national economy into the evaluation of the local system (Franzese et al., 2009).

2.4. Understanding emergy indicators: what do they indicate

The total emergy use, U, measures the emergy that converges to produce the yield Y. Since U is a measure of the emergy cost of the yield, we commonly say that U is the emergy assigned to the yield Y or the environmental work supporting the yield Y. The latter expression translates into the statement that U is a measure of ecological footprint for the process or system investigated.

Transformities measure how much emergy it takes to generate one unit of output, regardless of whether the input is renewable or not. They are not sensitive to the renewable versus non-renewable alternative. According to the way they are defined and calculated, transformities measure the global conversion efficiency over the whole chain of processes from primary resources to the final product.

The emergy yield ratio, $EYR = U/F = (R+N+F)/F$ – where R is locally renewable emergy, N locally non-renewable emergy and F imported emergy –, is a measure of the ability of a process to exploit and make available local resources by investing outside resources. It provides a look at the process from a different perspective, its "openness". It provides a measure of the appropriation of local resources by a process, which can be read as a potential additional contribution to the economy, generated by investing resources already available. Processes with EYR equal to one or only slightly higher do not provide significant net emergy to the economy and only transform resources that are already available from previous processes. In doing so they act as consumption/conversion processes instead of making new resources available for system's growth.

The $ELR = (N+F)/R$ is designed to compare the amount of non-renewable and imported emergy ($N+F$) to the amount of locally renewable emergy (R). In the absence of investments from outside, the renewable emergy that is locally available would have driven the growth of a mature ecosystem consistent with the constraints imposed by the environment and characterized by an $ELR = 0$. Instead, the non-renewable imported emergy drives a different development, whose distance from the natural ecosystem can be indicated by the ratio $(N+F)/R$. The higher this ratio, the bigger the distance of the development from the natural process that could have developed locally without non-renewable investment from outside. The ELR is clearly able to make a difference between non-renewable and renewable resources, thus complementing the information that is provided by the transformity.

If we divide the EYR (sensitive to the outside versus local emergy alternative) by the ELR (sensitive to the non-renewable versus

Table 3
Aggregate emergy flows supporting the urban system of Rome and calculated performance indicators[§].

	Aggregate flows from Table 2	Units	Emergy flows	%
R	Renewable emergy (maximum among items 1–6)	seJ/year	3.91E+20	0.3%
N	Locally non-renewable (item 7)	seJ/year	1.76E+21	1.3%
$F1$	Imported emergy of fuels and electricity (sum of items 8–13)	seJ/year	2.89E+22	20.7%
$F2$	Imported emergy of water and food (sum of items 14–15)	seJ/year	1.91E+22	13.6%
$F3$	Imported emergy of goods and commodities (sum of items 16–29)	seJ/year	5.83E+22	41.7%
SL_N	Non-renewable fraction (94%) of imported labor and services for imports (items 30–31)	seJ/year	2.95E+22	21.1%
SL_R	Renewable fraction (6%) of imported labor and services for imports (items 30–31)	seJ/year	1.88E+21	1.3%
U	Total emergy without services and imported labor	seJ/year	1.08E+23	77.5%
U_{LS}	Total emergy with services and imported labor	seJ/year	1.40E+23	100.0%
		Units	Rome	Italy[a]
Products considered				
P	People supported in 2002	Persons/year	2.54E+06	5.73E+07
GDP	Gross domestic product in 2002	€/year	5.75E+10	1.26E+12
Performance indicators				
U_{LS}/GDP	Emergy/GDP	seJ/€	2.43E+12	1.64E+12
U_{LS}/P	Emergy/person	seJ/person	5.50E+16	3.60E+16
A	Area of Urban System	m^2	1.29E+09	3.01E+11
U_{LS}/A	Empower density	seJ/m^2/year	1.09E+14	6.86E+12
EYR	Emergy yield ratio: $U_{LS}/(F1+F2+F3+SL_N+SL_R)$		1.02	1.29
ELR	Environmental loading ratio: $(N+F1+F2+F3+SL_N)/(R+SL_R)$		60.43	16.13
ESI	Emergy index of sustainability (EYR/ELR)		0.02	0.08
U_{Rome}/U_{Italy}	Emergy of Rome/emergy of Italy	%	4.03%	

[a] Cialani et al. (2005).
[§] Data from Table 2.

renewable emergy alternative), we generate an aggregated "sustainability" index, i.e., a measure of the potential contribution to the larger system (EYR) per unit of loading imposed on the local system (ELR). This indicator, called emergy index of sustainability (EIS), is usefully applicable to measure changes in openness and loading occurring over time in both technological processes and economies.

Finally, the empower density, ED, measures the amount of emergy invested on one unit of land area in one unit of time (s, hour, year). ED may suggest land be a limiting factor for a development or process or, in other words, may suggest the need for a given amount of support land around the system, for it to be sustainable. Higher ED's characterize city centers, information centers such as governmental buildings, universities and research institutions, power plants, industrial clusters, while lower ED's are calculated for rural areas and natural environments (Odum et al., 1995; Huang et al., 2001).

2.5. Sensitivity analysis

As pointed out previously, our results were obtained by implementing a calculation procedure on an excel platform. This also allowed us to perform a sensitivity analysis, by gradually assuming a variation of the main inflows by ±10%, ±20%, . . ., ±50%, and assessing to what extent such a variation affected the final results (i.e., the emergy-based indicators: total emergy, emergy/GDP, emergy/person, among others). The variation can be independently applied to the raw amount of each input flow or to its transformity or both, in so accounting for the uncertainty of estimates and possible errors. We applied the procedure to selected individual flows larger than 5% of total emergy use (gasoline, diesel, electricity, steel, textiles, etc.).

3. Case study. The city of Rome

Rome, one of the largest European cities, is characterized by a very high landscape complexity, due to the presence of 7000 ha with buildings and ruins of historical interest, intertwined with 35,650 densely urbanized hectares with more or less modern buildings, 41,000 ha of environmentally protected areas, 41,000 ha of agricultural land, 4400 ha of industrial areas and 19.3 km of coastline. The original landscape was a hilly area with wetlands, crossed by the Tiber river, which affected and still affects urban development and physical features.

The official surface area of the city of Rome changed several times in the last 150 years. From a surface of 214,000 ha in the year 1871 the city faced a gradual decrease in favor of other nearby administrative townships, down to the present surface of about 130,000 ha (Comune Roma, 2003a). Instead, the population of Rome increased steadily from the 210,000 units in the year 1870 up to 2.8 million people in the year 1972. Then, due to the splitting of the administrative townships of Fiumicino (the Rome Airport area) to form a new town, population decreased down to 2.5 million units in the year 2002 (Comune Roma, 2003a). As a consequence of surface decrease and population increase, population density increased from a low 0.89 persons/ha in the year 1860 up to 19.4 persons/ha in the year 2002. Complexity of city management and growth also increased significantly by the fact that Rome is the capital of Italy. Rome's city administration has to contend also with the presence of the Vatican State as an additional attractor for religious events and pilgrims, as well as by the huge artistic patrimony. This cultural complexity attracts tourists but requires significant investments for maintenance. The diagram also shows physical components and economic sectors as well as their interactions (pathways of matter and energy flows exchanged), providing a preliminary picture of internal complexity and dynamics. A pictorial representation of input flows (Fig. 1) was used to identify and list items to be used in calculation tables. Input resource flows support the development and dynamics of the system as a whole, as well as its component sectors. Resources drive the urban complexity and build a network of interacting production and consumption parts:

(a) Physical components: downtown and residential areas, natural parks and public gardens, agricultural areas, laboratories for small industrial activities, resources storages (water reservoirs, standing tree biomass, built environment).
(b) Functional components: primary production, manufacture and service sectors.
(c) Population: demographic aspects, social status (residents, commuters, immigrants), income and other economic aspects.
(d) Matter, energy and information flows: energy infrastructure, commodity and people transportation patterns, information networks (TV, telephones, schools and universities, etc.), economic flows.

In the present paper we focus on the total emergy demand of the city, based on city level databases (e.g., total gasoline consumption, total natural gas, total amount of construction materials, total amount of food used, total water, fertilizers, etc.). Such an evaluation of the system as a whole provides a reference picture for detailed investigation of specific production and consumption sectors as well as urban zones. Complementing such a preliminary global evaluation, Cherubini et al. (2008) performed a material and emergy evaluation of the waste management sector in Rome, while Giannantoni et al. (2009) investigated energy and emergy options of the transportation sector.

4. Results

The amount of each input flow is shown in Table 2, the last column of which also shows their related emergy, while aggregated flows are listed in Table 3. It clearly appears that local flows (be they renewable or not) are negligible (less than 2%) compared to imported emergy flows (98%). Surprising it may appear, Rome is also supported by wave and tidal emergies, due to its relatively long shoreline. Topsoil erosion indicates the annual degradation of fertile land due to intensive agricultural exploitation of the land available within the administrative boundaries of the city. The largest input category is represented by the flow of imported goods and commodities (42%, out of which construction material was 75%), followed by imported fuels and electricity (21%). Water and food items account for about 13.6% of total emergy use. Services associated to imports account for about 22.5%, most of which supported by non-renewable emergy flows (i.e., nonrenewable flows driving the economies of Italy and other countries from which services were purchased). The emergy provided by the Governmental support is about 7% of the total, while the emergy provided by the tourist sector (i.e., the emergy-equivalent of the money that tourists carry in) is about 13.3%. Emergy is associated to the latter sectors under different points of view: governmental funds (salaries of teachers, investments for public functions and buildings, etc.) are supported by emergy flows driving the economy of Italy, while tourists are supported by the emergy driving their countries and generating their GDP's. Tourists use money to purchase goods and services (hotel, restaurants, souvenirs, clothes, museums access). Finally, Rome uses this money to purchase emergy resources from outside. Therefore, these two flows of money from national Government and tourists translate into purchased emergy flows supporting the economy of Rome.

Table 4
Comparison of emergy flows and performance parameters of selected international cities.

	Units	Macao (China)	Taipei (Taiwan)	San Juan (Porto Rico)	Rome (Italy)
Population	People	4.48E+05	6.53E+06	1.71E+06	2.54E+06
Surface	m^2	2.73E+07	2.33E+09	5.37E+08	1.29E+09
GDP	US$/year	7.90E+09	1.19E+11	2.29E+10	6.90E+10
Total Emergy used	seJ/year	2.20E+22	1.24E+23	3.76E+22	1.38E+23
Emergy per capita	seJ/pc/year	4.90E+16	1.90E+16	2.20E+16	5.45E+16
Emergy density	seJ/(m^2 year)	8.04E+14	5.32E+13	7.00E+13	1.07E+14
Emergy/$	seJ/$	2.78E+12	1.04E+12	1.64E+12	2.01E+12

Source of data: San Juan: Odum et al. (1995); Taipei: Huang (1998); Macao: Lei et al., 2008; Rome: this study.

Table 3 also shows the emergy-based performance indicators of Rome compared to the same indicators for Italy in the same year 2002 (Cialani et al., 2005). According to the study, the emergy used in Rome is about 4% of the total emergy supporting Italy.

Finally, Table 4 compares the performance parameters of Rome to the same parameters of selected international cities, from literature.

Results of the sensitivity analysis point out the importance of flows simultaneously characterized by large amounts and large transformities, so that even a small change of input flow translates into relatively high changes of the related emergy content and calculated indicators. As an example, variations from +20% to +50% to the transformity of electricity translate into a variation from 1.3% up to 3.2% of the parameter emergy/person. Variations up to +50% of both electricity amount and transformity end up with a total 8.5% variation of the emergy/person indicator. The same procedure applied to smaller inflows does not yield significant changes of final results. Given the large number and diversity of input flows, an even large uncertainty on flows characterized by an emergy content smaller than 5% of total emergy use translates into negligible changes of the final calculated performance indicators. Instead, uncertainty, variations over time or data errors on a small number of flows (namely fuels, electricity, construction materials and selected food items) either supplied in large amount or characterized by high transformities are likely to affect the actual value or the reliability of calculated indicators. These flows must be monitored very carefully and their transformities double-checked by independent researchers.

5. Discussion

Most of the input flows investigated at city level could easily be assigned to well identified production, consumption and service patterns (transportation, space heating, road and building construction, agriculture and gardening, among others). However, for the purpose of the present work, we preferred to keep our focus on the system as a whole, leaving to a future paper both the details about allocation of emergy flows to each activity sector (domestic, commercial, transportation, health services, education, business, among others) as well as to specific districts of the city (downtown, business, residential, green areas, etc.). The reason of such a choice relies in what Odum used to call the “macroscope”, i.e., in the fact that the local scale can be better understood from the point of view of the next larger scale (i.e., the national scale helps understanding the regional, the regional clarifies the urban, and the urban illuminates the disaggregated sectors).

Table 3 provides an aggregated list of categories of input flows. As already pointed out, Rome is mainly supported by imports of non-renewable resources. This simply suggests that the local carrying capacity would be much smaller than the present developed carrying capacity based on imports. Such a result cannot be obtained only by comparing the actual energy locally available (solar radiation, wind and wood) to the total energy used (mainly fossil fuels), because in so doing several kinds of input resources are disregarded (minerals, ecosystem services such as rain, labor, information). Results underline the large fraction of goods and commodities (most of which construction materials) that annually supports the assets of the city, for both new constructions and maintenance. The emergy associated to fuels and electricity (for transportation and domestic sectors) is also a large share of the total. Reliance on such a large basis of imported resources is impressive even when compared to Italy as a whole, which is in turn a country 77% dependent on outside emergy sources (Cialani et al., 2005, p. 408).

Services, a money-based measure of indirect labor supplied and related information and know-how, indicate a category of emergy flows which is not directly linked to technology and raw resources. While it is very likely that mining technologies, agricultural technologies, industrial technologies, etc., are all the same worldwide, specially in times of globalization of markets, the same does not apply to services, the amount of which can be largely different depending on the country’s welfare and economic structure.

The comparison of emergy-based indicators (emergy/GDP, emergy/person, EYR, ELR, empower density, ESI) for Rome and Italy shown in Table 3 is also very telling. It is not difficult to recognize that the concentration of people and resources within the city makes it much more heavily dependent on outside support. The economy of Italy as well as the economy of Rome is both largely dependent on outside as well as non-renewable resources. Imported resources supported their welfare during times of cheap oil and small competition for food and minerals, while making them economically and environmentally fragile and unsustainable in the present times of shrinking resource base and higher international demand. In particular, the small value of the EYR of Rome (1.02) shows that the city is simply a consumer system, without any possibility of relying on local resources, while the Italian system as a whole (1.29) relies much more on local resources (agriculture, minerals, hydroelectricity, etc.). The environmental loading ratio of Rome is four times higher than that of Italy, indicating that the urban system is very far from being in equilibrium with the surrounding environment. Such a result is not unexpected, but is also an alarming signal of fragility in times of declining resources and this calls for policies that decrease the dependence on non-renewable and imported resources.

Fig. 2 shows a bar diagram (so-called “emergy signature”) in which all input emergy flows are compared. Again, the dominance of human-controlled input flows (fuel, goods, labor and services) from outside the system is impressive, compared to locally available free renewable and non-renewable resources. Although such a result was already suggested by the previously cited studies on energy and material consumption in urban systems, the conversion of input resources into emergy units allows a much more telling comparison among flows of different environmental quality and,

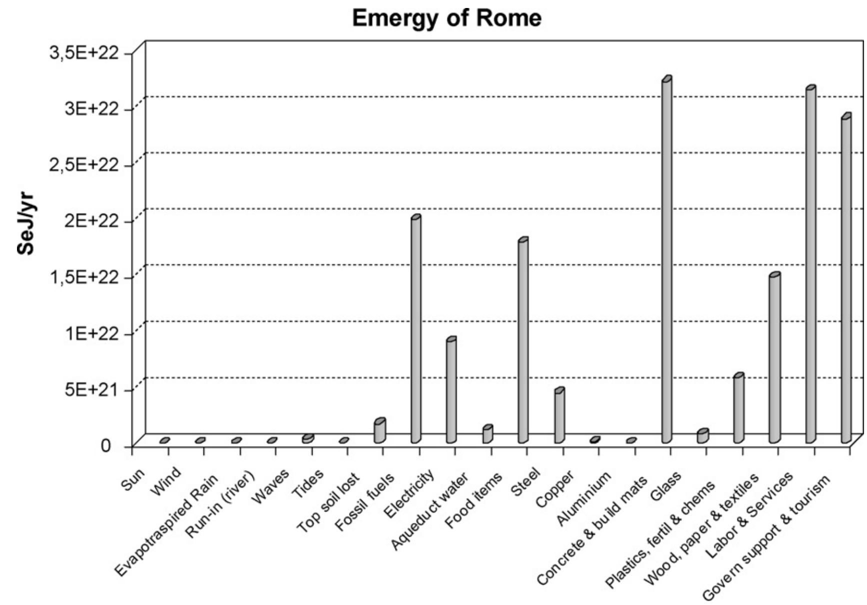

Fig. 2. Direct and indirect environmental flows supporting the city of Rome in the year 2002 (expressed in emergy units, seJ/year).

most of all, modifies the relative importance of these flows compared to each other. The demand for environmental support to the supply of food, building materials, labor and services is comparable or even larger than for direct fuel and electricity use, when calculated in emergy terms. In fact, traditional embodied energy or exergy methods indicate very well when the use of fossil fuels is inefficient or unnecessary, but they hardly identify the natural capital and the environmental services directly utilized by an urban system or embodied in low energy carriers (e.g. labor, services, information).

How could these results be used for policy making? First of all, it would be very useful to identify those flows that rely more on imported non-renewable emergy. The fact that a resource is imported suggests an economic unsustainability in that resources must be paid for and also in that it makes the country dependent on outside sources that may be constrained by geo-political events, competition, and adverse strategies. Moreover, the fact that a resource is non-renewable also suggests a future shortage which depends on actual resource availability on earth. Concerned policy makers should address this problem in order to replace or decrease the use of this kind of resources by means, for example, of increased energy efficiency and renewable energy devices. Furthermore, the structure of the economy and the structure of the service sector could be modified (e.g., by decreasing the use of individual cars in favor of mass transportation; more online shopping and less related traffic, etc.) by means of suitable policies; long lasting and low emergy intensive materials could be selected (materials contribute to the largest emergy inflow to Rome); policies to decrease consumerist habits might be implemented and enforced; finally, recognizing the strict correlation between empower density and population density might suggest policies aimed at decreasing urban population and increasing green areas, for better equilibrium of society and nature. All of the above solutions would require being tested against the same kind of emergy assessment, in order to make sure that they meet the promised expectations. Much work needs to be done in this regard, although several emergy-based LCA studies on alternative choices were recently performed by the authors of the present paper as well as by other researchers in order to check their feasibility and sustainability (biofuels: Ulgiati, 2001; transportation: Federici et al., 2005; photovoltaics: Raugei et al., 2007; fuel cells: Bargigli et al., 2007; waste management: Cherubini et al., 2008; hydrogen: Giannantoni et al., 2009, among others).

5.1. Comparison with other studies

A detailed overview of published studies about urban environment and structures is provided in the Introduction. Based on such a literature and the results of our investigation, an emergy-based comparison can be drawn among the cities of San Juan (Odum et al., 1995), Taipei (Huang, 1998), Macao (Lei et al., 2008), and Rome (this work). This would have the effect of decreasing the gap between renewable carrying capacity and the present developed carrying capacity based on non-renewable resources. Since these studies refer to different years and typology of urban systems, extensive parameters such as population, surface, GDP and total emergy used are not very telling. In fact, they linearly reflect the differences of physical size and economic activity without being sensitive to the actual system's performance in resource use. For this reason, we found much more useful to compare their emergy intensity indicators (emergy per capita, empower density, emergy/GDP ratio) in so making results independent of the "size" of the system. Table 4 shows population, GDP and area of the four cities in the year in which the study was performed. In absolute terms, Taipei shows by far the largest GDP, area and population, also due to the special feature of Taiwan (a relatively small island – 1/9 of Italian surface, 1/3 of the Italian population – with the majority of the people concentrated in very few urban areas). Taipei city has a population of about 3 million people, but its urban sprawl has expanded over Taipei county, so that the population of Greater Taipei reaches approximately 6 million. Macao shows, instead, the smallest GDP, area and population, due to the fact that it has been a small Portuguese colony surrounded and constrained by the sea and by the Chinese territories until 1999, when its reunification to China took place. Rome ranks second in all of these extensive parameters, while San Juan ranks always third.

Table 4 also shows the total emergy used by the investigated cities in the referred years. In spite of its smaller population, Rome shows the largest emergy use. Taipei ranks second, followed by

San Juan and Macao. The resource flow to Macao is very low, compared to the other cities, not only due to its smaller population, but also due to its economy being mainly based on tourism (including transportation and service sectors), a relatively low-intensity sector. The importance of Macao's economy declined in the last century and its biggest attractions remained the gambling industry and casinos. Macao is in fact located in a favorable position for tourism, and attracts international travelers and businessmen from mainland China and from nearby rich Hong-Kong city. As already pointed out, absolute emergy-based values are not very telling for a comparison. Composite emergy indicators such as emergy intensities in Table 4, dependent on both emergy used and actual measures of system's size (population, area, GDP), require a detailed analysis of trends of their component factors in order to be fully understood (Lomas et al., 2006).

It is not surprising that Macao shows the highest value of the empower density (more than 7.00E+14 seJ m^{-2} $year^{-1}$). This figure mainly depends on the small available land area where emergy is concentrated and used up with no supporting land around. Instead, larger land areas are available around Rome, Taipei and San Juan, capable to dilute the intensity of emergy use, to allow a larger carrying capacity for development (defined according to Brown and Ulgiati, 2001) and to lower the empower density, in spite of the very intense tourism and service sectors in Rome and the large demand for housing and industrial activities in Taipei.

Emergy per capita is much larger for Macao and Rome than for San Juan and metropolitan Taipei. In the case of Taipei, the low value is determined by its large population, while instead it is the relatively low emergy use that determines the low per capita intensity in San Juan. Since emergy use per capita suggests wealth potential (Brown and Ulgiati, 2004a), by indicating actual or possible access to resources and driving forces, the meaning of such values in Table 4 is that people in Macao and Rome have access to larger amounts of emergy per person than people in Taipei and San Juan. Wealth potential does not, however, only have an economic meaning, but globally refers to possibility of exploitation of direct and indirect environmental services which do not necessarily translate into higher GDP's.

Finally, Table 4 also shows the efficiency of the conversion of resources into an economic product (emergy/GDP). Apparently, it takes more emergy to generate one unit of GDP in Macao and Rome than in Taipei. This means that the productive sectors that contribute to Taipei's economy are more efficient in the conversion of resources into economic wealth. Such efficiency may depend on how each given sector is operated, but also on the "mix" of sectors that compose the local economy. Policy makers will therefore have to ascertain carefully the efficiency and inefficiency sources and act accordingly. As always with composite indicators, changes of the emergy/GDP ratio depend on both changes of emergy inflows and changes of monetary circulation, which in turn may depend on increased economic activity or increased inflation. In order to fully understand the real meaning of emergy-based indicators, it is always useful to focus on the time evolution of the specific components of these ratios as suggested by Lomas et al. (2006).

6. Conclusion

An emergy synthesis of the urban system of Rome was performed, generating indicators of demand for environmental support to city dynamics and economic performance. Rome data referring to the year 2002 were collected and processed, yielding a clear picture of the mix of resources supporting the city (mainly non-renewable inputs) and providing a clear quantification of their importance within the total emergy "budget". The latter information could be used for environmentally sound policy making, in order to replace non-renewable or scarce materials with less emergy-intensive ones or in order to use matter and energy flows more effectively as well as to increase reuse and recycling. Comparison of calculated emergy intensity indicators of Rome with those published by other authors for international cities provided a picture of their environmental and economic performances of the investigated cities, although a full understanding would also require an investigation over time and a careful decomposition of composite indicators. Emergy intensity indicators and performance ratios for Rome and Italy were also compared, confirming Rome to be a special resource attractor, but also confirming its fragility and unsustainability, due to the excess reliance on non-renewable and outside resources.

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Appendix A. References of transformities used in Table 2 (values published prior to the year 2000 were updated according to the new biosphere emergy baseline, Odum, 2000)

[a] After Odum, 1996; [b] Odum, 2000; Odum et al., 2000; [c] Brown and Ulgiati, 2004a; [d] Brown and Arding, 1991; [e] after Ulgiati et al., 1994; [f] after Bargigli and Ulgiati, 2003; [g] Bargigli, 2004; [h] Haukoos, 1995; [i] Cialani et al., 2005; [l] Weighed average of emergy/money ratios of countries which tourist come from (online database for selected national economies, http://sahel.ees.ufl.edu:80/database_resources.php).

References of data used in Table 2

Area of Rome: 128530.6 ha = 1.29E+09 m^2 [Comune Roma, 2003a]

1. *Solar radiation*: Solar energy received = (average yearly insolation) (area) (4186 J/kcal). Insolation (average) = 1737.4 kWh/m^2/year [ENEA, 2002] = 6.25E+09J/m^2/year. Urban area = 1.29E+09 m^2. Total solar energy received = 8.04E+18 J/year.
2. *Wind* (*kinetic energy of wind used at the surface*): Wind energy = (density) (drag coefficient) (geostrophic wind velocity)^3(area) (s/year). Air density = 1.3 kg/m^3. Wind speed (average 2002) = 2.175 m/s [Comune Roma, 2004a]. Geostrophic wind = 5.2 m/s. Drag coefficient = 3.00E−03. Area = 1.29E+09 m^2; s/year = 3.15E+07 s/year. Total wind energy = 2.22E+16 J/year.
3. *Evapotranspired rain* (*chemical potential energy*): Gibbs free energy of evapotranspired water, i.e. work potential of water used by plants. Evapotranspiration energy: (land used) (evapotranspiration rate) (density) (Gibbs free energy per gram).

(A) Land covered by forest = 9726 ha; land used for wood farm = 112.8 ha; land used for fruit production = 1798.1 ha. Total area covered by trees (forest + wood farm + fruit trees) = 11636.9 ha = 1.16E+08 m^2 [Comune Roma, 2003a]. Transpired water = 0.559 m/year [calculated after Ulgiati et al., 1994]. Density water = 1.00E+06 g/m^3. Gibbs energy of rain water relative to sea water = 4.94 J/g. Total evapotranspiration energy (chemical potential energy) = 3.08E+14 J/year.

(B) Land covered by pasture = 5227.9 ha = 5.23E + 07 m^2 [Comune Roma, 2003a]. Transpired water = 0.728 m/year [calculated after Odum, 1996]. Density water = 1.00E+06 g/m^3.

Gibbs energy of rain water relative to sea water = 4.74 J/g. Total evapotranspiration energy (chemical potential energy) = 1.81E+14 J/year.

(C) Land covered by crops = 30016.2 ha = 3.00E + 08 m^2 [Comune Roma, 2003a]. Transpired water = 0.694 m/year [calculated after Odum, 1996]. Density water = 1.00E+06 g/m^3. Gibbs energy of rain water relative to sea water = 4.74 J/g. Total evapotranspiration energy (chemical potential energy) = 1.48E+15 J/year.

Total evapotranspiration energy (A + B + C) = 1.97E+15 J/year.

4. *Run-in, river geopotential energy*: Geopotential energy received (relative to sea level) = (flow vol.)(density) (height at entry) (gravity).

   Volume flow = 230 m^3/s [Autorià di Bacino del Fiume Tevere (Tiber Watershed Authority), Presidenza del Consiglio dei Ministri, http://www.abtevere.it/] = 7.25E+09 m^3/year. Density water = 1.00E+03 kg/m^3. Height at entry = 30 m (our estimate). Gravity = 9.81 m/s^2. Total geopotential energy received (relative to sea level) = 2.13E+15 J/year.
5. *Waves* (*energy delivered on shore*): Wave energy = (parallel component of shore length) (front wave energy) (time in s/year). Coast length = 1.93E+04 m [http://www.osservatoriomare.lazio.it/]. Component of length parallel to front wave = 11001 m (our estimate). Average front wave power = 2.20E+04 W/m [Couper, 1990]. Time = 3.15E+07 s/year. Total wave energy delivered = 7.62E+15 J/year.
6. *Tidal energy* (*half of tidal energy is supposed to be absorbed at the shelf*): Tidal energy = (shelf) (0.5) (tides/year) (mean tidal range)^2(density of seawater) (gravity).

   Coastal length of Rome = 1.93E+4 m [http://www.osservatoriomare.lazio.it/]. Continental shelf area of Rome = 3.86E+06 m^2 [IIM, 1992]. Average tide range = 0.30 m [IIM, 1992]. Density of sea water in the area = 1.03E+03 kg/m^3 [Couper, 1990]. Tides/year = 7.30E+02 (2 tides/day in 365 days). Total tidal energy = 1.27E+12 J/year.
7. *Topsoil loss* (*erosion, weathering; areas with mature untouched vegetation are assumed to have little net gain or loss of topsoil*): Energy of net loss = (net loss) (% organic in soil) (5.0 kcal/g) (4186 J/kcal). Farmed area subject to erosion = 4.10E+08 m^2 [http://www.urbanistica.comune.roma.it/attachment/516171D1.pdf]. Erosion rate of farmed area = 1.50E+03 g/m^2/year [http://www.urbanistica.comune.roma.it/attachment/516171D1.pdf]. Fraction of organic matter in soil = 3.00% [Odum, 1996]. Energy content per gram organic = 5.00 kcal/g [Odum, 1996]. Net loss = (farmed area) (erosion rate) = 6.15E+11 g/year. Total energy of net loss = 3.86E+14 J/year (energy content of degraded organic matter in soil).
8. *Gasoline*: Gasoline used = 1.33E+00 Mton/year = 1.33E+06 ton/year = 1.33E+12 g/year [ENEA, 2002]. HHV (higher heating value) = 44 MJ/kg = 44000 J/g. Total gasoline energy = 5.87E+16 J/year. Gasoline unit price (yearly average) = 1.047 €/L [Unione Petrolifera, 2003]. Gasoline density = 750 kg/m^3 = 750 g/L. Total gasoline cost = 1.86E+09 €/year.
9. *Diesel*: Total diesel used = 1.63E+00 Mton/year = 1.63E+06 ton/year = 1.63E+12 g/year. HHV = 43 MJ/kg = 4.30E+04 J/g. Total diesel energy = 7.02E+16 J/year [ENEA, 2002]. Diesel unit price = 0.856 €/L [Unione Petrolifera, 2003]. Diesel density = 832.5 kg/m^3 = 832.5 g/L. Total diesel cost = 1.68E+09 €/year.
10. *LPG*: Total LPG used = 1.92E−01 Mton/year = 1.92E+05 ton/year = 1.92E+11 g/year. HHV = 19800 Btu/lb = 46376 J/g [ENEA, 2002]. Total LPG energy = 8.92E+15 J/year. LPG unit price = 0.52 €/L [Unione Petrolifera, 2003]. LPG density = 505 kg/m^3 = 505 g/L. Total LPG cost = 1.98E+08 €/year.
11. *Heavy oil for domestic heating*: Total used = 1.27E+11 g/year [Unione Petrolifera, 2003]. HHV of Heavy Oil = 4.26E+04 J/g. Total energy = 5.42E+15 J/year. Unit price = 0.834 €/L [Unione Petrolifera, 2003]. Density = 830 kg/m^3 = 830 g/L. Total cost for heavy oil = 1.28E+08 €/year.
12. *Natural gas*: [Comune Roma, 2003a]. Volumes used: Total natural gas used = 1.22E+09 m^3/year (of which, for domestic use = 1.10E+08 m^3/year; used for building heating = 4.47E+08 m^3/year; for other uses = 6.65E+08 m^3/year). Density of natural gas = 7.89E+02 g/m^3 Total mass of natural gas used = 9.64E+11 g/year (of which, for domestic use = 8.69E+10 g/year; for building heating = 3.52E+11 g/year; for other uses = 5.25E+11 g/year). Conversion to energy units: HHV = 2.13E+04 Btu/lb = 4.99E+04 J/g. Total energy in natural gas = 4.81E+16 J/year (of which, for domestic use = 4.34E+15 J/year; for building heating = 1.76E+16 J/year; for other uses = 2.62E+16 J/year). Unit price of natural gas = 0.4 €/m^3. Total cost of natural gas = 4.89E+08 €/year (of which, for domestic use = 4.41E+07 €/year; for building heating = 1.79E+08 €/year; for other costs = 2.66E+08 €/year).
13. *Electricity*: Total used = 8.09E+03 GWh/year = 8.09E+06 MWh/year = 8.09E+09 kWh/year = 2.91E+16 J/year [Comune Roma, 2003a]. Unit price = 0.093€/kWh. Total electricity cost = 7.52E+08 €/year.
14. *Water* (*from aqueduct*): Total water used = 3.28E+08 m^3 [Comune Roma, 2004a]. Water density = 1.00E+00 kg/L = 1.00E+03 kg/m^3 = 1.00E+06 g/m^3. Mass of water used = 3.28E+14 g/year. Unit price = 1.39 €/m^3. Total water cost = 4.56E+08 €/year.
15. *Main food items* (*all data from* [ISMEA, 2005] *unless specified*):
    a. *Fish*: Total fish used = 1.80E+10 g/year. Total cost = 1.56E+08 €/year.
    b. *Meat*: Total meat used = 6.83E+10 g/year. Total cost = 4.76E+08 €/year.
    c. *Fruits and Vegetables*: Total fruits and vegetables used = 2.43E+11 g/year. Total cost = 3.33E+08 €/year.
    d. *Milk, cheese and other dairy products*: Total milk, cheese and other dairy products used = 1.49E+11 g/year. Total cost = 3.77E+08 €/year.
    e. *Cereals and derivatives*: Total cereals and derivatives used = 1.33E+11 g/year. Total cost = 3.15E+08 €/year.
    f. *Wine and alcoholics*: Total wine and alcoholics used = 3.83E+10 g/year. Total cost = 7.29E+07 €/year.
    g. *Olive and seed oils*: Total oils and seed oils used = 1.95E+10 g/year. Total cost = 6.59E+07 €/year.
16. *Steel and iron*: Total used = 1.42E+12 g/year [Provincia Savona, 2002]. Total cost = 7.52E+08 €/year [CCIAA Roma, 2003]
17. *Copper*: Total used = 4.98E+10 g/year [ASSOMET, 2002]. Total cost = 1.38E+08 €/year [CCIAA Roma, 2003]
18. *Aluminium*: Total used = 6.71E+10 g/year [ASSOMET, 2002]. Total cost = 1.30E+08 €/year [CCIAA Roma, 2003]
19. *Cement* (*Portland*): Total used = 1.83E+12 g/year [AITEC, 2003]. Total cost = 1.43E+08 €/year [CCIAA Roma, 2003]
20. *Sand and Gravel*: Total used = 1.35E+13 g/year [ISTAT, 2002]. Total cost = 1.98E+09 €/year [ISTAT, 2002]
21. *Rocks*: Total used = 3.00E+12 g/year [ISTAT, 2002]. Total cost = 8.66E+07 €/year [ISTAT, 2002]
22. *Glass*: Total used = 2.35E+11 g/year [Assovetro, 2003]. Total cost = 1.28E+08 €/year [CCIAA Roma, 2003]
23. *Plastics*: Total used = 5.60E+11 g/year [ISTAT, 2002]. Total cost = 9.48E+08 €/year [ISTAT, 2002]
24. *Asphalt*: Total used = 1.46E+11 g/year [ISTAT, 2002]. Total cost = 6.19E+06 €/year [ISTAT, 2002]
25. *Chemicals*: Total used = 5.17E+11 g/year [ISTAT, 2002]. Total cost = 5.96E+08 €/year [ISTAT, 2002]

26. *Wood*: Total used = 5.94E+11 g/year [ISTAT, 2002]. Total cost = 1.60E+08 €/year [ISTAT, 2002]
27. *Textiles*: Total used = 8.32E+10 g/year [ISTAT, 2002]. Total cost = 7.31E+08 €/year [ISTAT, 2002]
28. *Paper and derivatives*: Total used = 4.88E+11 g/year [Inceneritorizero, 2002]. Total cost = 4.10E+08 €/year [CCIAA Roma, 2003].
29. *Fertilizers*: Total used = 7.67E+09 g/year [CCIAA Roma, 2003]. Unit price = 0.21 €/kg [CCIAA Roma, 2003]. Total cost = 1.63E+06 €/year. *Price*: Average value from: http://www.tv.camcom.it/docs/Bisogni/di-Indici-/download-p/2002
30. *Imported labor* (*Commuters*): Daily commuters from nearby villages and countryside deliver work in support to city dynamics and economy. This work is at least partially supported by additional emergy flows outside the city. Number of workers = 2.54E+05 people/year (Our estimate based on the assumption that daily commuters are about 10% of total Rome's population)
31. *Services*: Services is a measure of indirect labor performed outside of the system in order to make and deliver imported goods and commodities. Services are expressed in money terms (€, $) and calculated as the total cost of imports. Services are converted into emergy (seJ) by multiplying by the emergy-to-money ratio (seJ/€) of the country in the year under investigation. Total value of services = 1.36E+10 €/year [Sum of costs of Items from 8 to 29]
32. *Governmental support* (*salaries, health services, schools, etc.*): Governmental money for salaries = 5.05E+09 €/year [ISTAT, 2006]. Governmental funding for public services = 1.14E+09 €/year [Comune Roma, 2003b]. Total money from Government = 6.19E+09 €/year.
33. *Tourism* (*from Italy and abroad*) Number of tourists = 1.91E+07 units/year [Comune Roma, 2004b]. Permanence days (average) per person = 2.69 days [Comune Roma, 2004b]. Exchange ratio $/€ 2002 = 0.945385 $/€ [X-rates, 2002: http://www.x-rates.com/d/USD/EUR/hist2002.html]. Daily expenses per person (average) = 95.48 $/day [DOXA, 2003]. Total money from tourists = 4.91E+09 $/year.

Output: Population supported for one year (people year^{-1}) and yearly GDP assumed as products of city dynamics in the investigated year 2002.

Population of Rome **=** 2,540,829 Units/year [CCIAA Roma, 2004].

GDP of Rome **=** 5.75E+10 €/year (Our calculation based on a VAT – value added tax percentage value equal to 0.07) [CCIAA Roma, 2004 and Comune Roma, 2005]

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