Multi-method and multi-scale analysis of energy and resource conversion and use.

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Abstract
Optimizing the performance of a given process requires that many different aspects are taken into account. Some of them, mostly of technical nature, relate to the local scale at which the process occurs. Other technological, economic and environmental aspects are likely to affect the dynamics of the larger space and time scales in which the process is embedded. These spatial and time scale effects require that a careful evaluation of the relation between the process and its 'surroundings' is performed, so that hidden consequences and possible sources of inefficiency and impact are clearly identified. In this work the authors summarise a number of studies in which they applied a multi-method and multi-scale approach in order to generate a comprehensive picture of the investigated systems/processes. The benefits of such an integrated investigation approach are discussed.

Keywords: Life Cycle Assessment, Integrated Evaluation, Emergy.

1. INTRODUCTION

Life Cycle Thinking (LCT) techniques are used worldwide to assess material and energy flows to and from a production process. LCT methodologies are aimed at assessing the environmental impacts of a product (or service) from 'cradle to grave' or better 'from cradle to cradle', including recycling and reclamation of degraded environmental resources. More than a specific methodology, LCT is a cooperative effort performed by many investigators throughout the world (many working in the industrial sectors) to follow the fate of resources from initial extraction and processing of raw materials to final disposal. This effort is converging towards standard procedures and common frameworks, in order to make results comparable and reliable. SETAC (the International Society for Environmental Toxicology and Chemistry) developed a "code of practice" to be adopted as a commonly agreed procedure for reliable LCAs (SETAC, 1993). The SETAC standardization has been followed by a robust effort of the International Organization for Standardization (ISO) to develop a very detailed investigation procedure for environmental management based on LCT, namely Life Cycle Assessment (International Standards ISO 14040/2006 – LCA Principles and framework and 14044/2006 - Requirements and guidelines, www.iso.org). The ISO documents suggest clear and standard procedures for the description of data categories, definitions of goals and scope, statements of functions and functional units, assessments of system boundaries, criteria for inclusions of inputs and outputs, data quality requirements, data collection, calculation procedures, validation of data, allocation of flows and releases,

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reuse and recycling, reporting of results. Nowhere in the ISO documents is preference given to a particular impact assessment method. In the opinion of the authors, LCA can be looked at as a standardized (and still to be improved) framework, where most of the methodologies already developed for technical and environmental investigations may be included and usefully contribute.
Finally, a European Platform on Life Cycle Assessment (http://lct.jrc.ec.europa.eu/eplca) has been established by the European Commission in support of the implementation of the EU Thematic Strategies on the Prevention and Recycling of Waste and on the Sustainable Use of Natural Resources, the Integrated Product Policy (IPP) Communication and Sustainable Consumption and Production (SCP) Action Plan. The purpose is to improve the credibility, acceptance and practice of Life Cycle Assessment (LCA) in business and public authorities, by providing reference data and recommended methods for LCA studies.

1.1 Factors of scale and system boundaries

It is self-evident that each evaluation can be performed at different space and time scales. Figure 1 shows the systems diagram of a generic thermal power plant, with fossil fuels used to produce electricity. The local scale only includes direct energy and mass inputs. The latter include plant components and buildings, discounted over the plant lifetime.

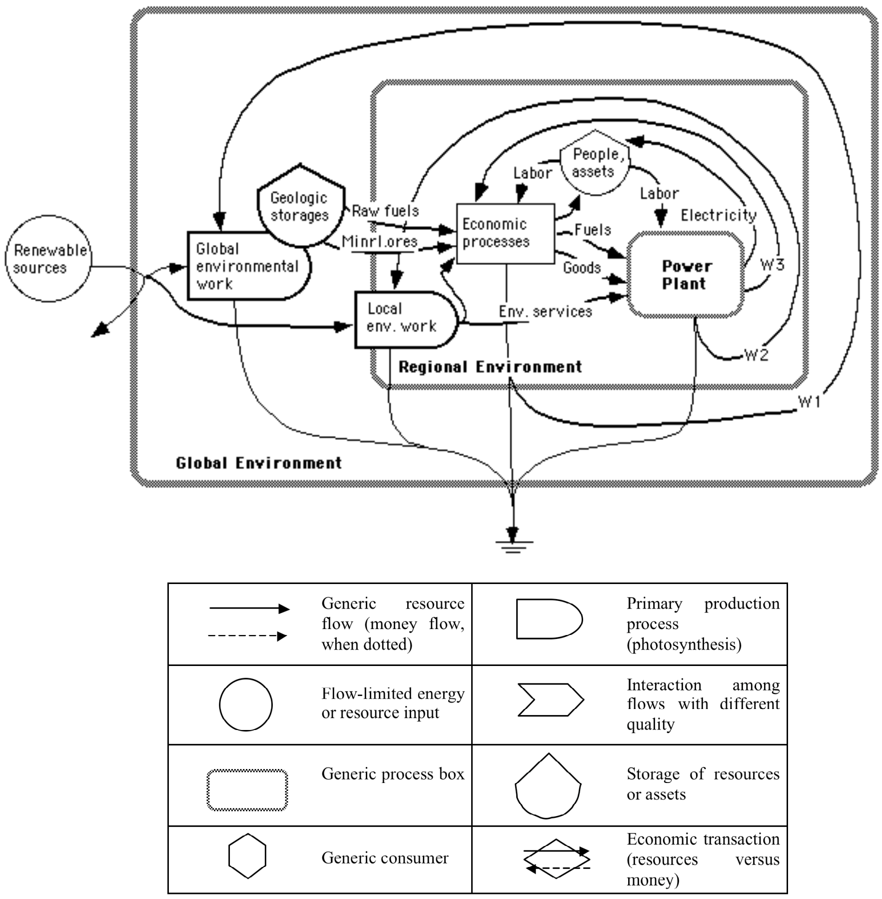

Figure 1. Systems diagram of a generic power plant, showing the convergence of matter and energy input flows from the larger to the local scale. Systems symbols are from Odum, 1996.

As the scale is expanded to the regional level [whatever the regional area is, it should include the production process for machinery components (boiler, turbine, insulating materials, etc.)

and plant building materials like concrete and steel], new mass and energy inputs must be accounted for. If the scale is further expanded, the mass of raw minerals that must be excavated to manufacture the pure metals for plant components also contribute to all of the calculated performance indicators. At this larger scale, raw oil used up in the extraction and refining of minerals and oil itself must also be accounted for. The evaluation may therefore be carried out at three different scales (local, regional and global), each one characterized by well-specified processes (respectively, resource final use, manufacturing and transport of components, resource extraction and refining), so that inefficiencies at each scale may be easily identified and dealt with.

The larger the spatial scale, the larger the cost in terms of material and energy flows, i.e. the worse the related conversion efficiency and other impact indicators. In fact, if a process evaluation is performed at a small scale, its performance may not be well understood and may be overestimated due to a lack of inclusion of some large scale impacts. Depending upon the goal of the investigation, a small-scale analysis may be sufficient to shed light on the process performance for technical or economic optimization purposes, while a large-scale overview is needed to investigate how the process interacts with other upstream and downstream processes as well as the biosphere as a whole. Defining the system boundary and clarifying at what time-scale an assessment is performed is therefore of paramount importance, even if the scale of the assessment is sometimes implicit in the context of the investigation. It is very important to be aware that a 'true' value of net energy return or other performance indicators does not exist. Each value of a given indicator is only 'true' at the scale at which it is calculated. When the same value is used at a different scale, it does not necessarily become false. It is, however, out of the right context, and therefore inapplicable and useless.

1.2 Accounting for time embodied in resources

Time is an important, but very often neglected, issue in any kind of evaluation. The simplest case is when we have inputs, whose lifetime exceeds the time frame of the analysis. It is easy to transform extended-lifetime inputs into annual flows by dividing by their lifetime (in years). Another and perhaps more important time scale is hidden in the resources used, i.e. the time nature takes to concentrate or produce a given resource (e.g., oil). A resource turnover time is often a good measure of its renewability. An effort to go beyond the concept of turnover time in resource evaluations is the introduction of emergy accounting procedures (Odum, 1988, 1996; Brown and Ulgiati, 2004), also included in the integrated approach discussed in the following of this paper.

2. TOWARDS AN INTEGRATED EVALUATION APPROACH

Environmental and socio-economic accounting procedures so far proposed by many authors were applied to different space-time windows of interest and were aimed at different investigations and policy goals (Szargut et al., 1988; Odum, 1996; Herendeen, 1998; Ayres and Masini, 1998; Giampietro et al., 1998; Lozano and Valero, 1993; Foran and Crane, 1998; Finnveden and Moberg, 2005, Ulgiati et al. 2006, Gasparatos et al. 2008). These Authors offered valuable insight towards understanding and describing important aspects of resource conversions and use. However, due to their different focus on specific scales, numeraires and questions, results from these methods are hardly comparable. Further effort is needed towards the development of LCA-like approaches that are capable to integrate different socio-economic and environmental points of view for a more comprehensive picture at different scales. The context and the goal of both the process and the investigation procedure are of paramount importance and likely to affect the results. For example, investigating only the behaviour of a single process and seeking maximization of one parameter (efficiency, production cost, jobs, etc.) is unlikely to provide sufficient insight for sustainable policy making. Instead, if suitable approaches are selected, applicable at different scales and designed in such a way as to complement each other, integration would be feasible. Each method may supply a piece of information about system performance at an appropriate scale, to which the others do not apply. Integration supplies an overall picture, characterized by an ’added value‘ that could not be achieved through each approach individually. The choice of the set of approaches is therefore of crucial importance. Moreover, if the integration is carried out properly, the same set in input data (similar to an LCA inventory, but complemented with other typologies of input, e.g. free environmental flows, environmental services, socio-economic data such as labor and economic services, etc.) may serve to expand the focus of the evaluation beyond the common accounting of energy costs and environmental impacts.

2.1 Accounting for matter flows

Quantifying input and output mass flows is a preliminary step. We need to assess not only the amount of input materials to the local process, but to the greatest possible extent the amount of outputs (products, co-products, and emissions) from the process. In addition, when we expand our scale of investigation, we realize that each flow of matter supplied to a process has been extracted and processed elsewhere. Additional matter is moved from place to place, processed and then disposed of to supply each input to the process. Sometimes a huge amount of rock must be excavated per unit of metal or other chemical actually delivered to the user. Most of this rock is then returned to the mine site and the site reclaimed, but its stability is lost and several chemical compounds become soluble with rainwater and may affect the environment in unexpected ways. Accounting for the materials directly and indirectly involved in the whole process chain has been suggested as a measure of environmental disturbance by the process itself (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998; Bargigli et al., 2005). A quantitative measure can be provided by means of Material Intensity Factors (MIPS, Material Input Per unit of Service) calculated for several categories of input matter, namely abiotic, biotic, water, and air (Ritthoff et al., 2003). The resulting MAterial Intensity Analysis (MAIA) method is aimed at evaluating the environmental disturbance associated with the withdrawal or divertion of material flows from their natural ecosystemic pathways. In this method, appropriate material intensity factors (g/unit) are multiplied by each input, respectively, accounting for the total amount of abiotic matter, water, air and biotic matter that is directly or indirectly required in order to provide that very same input to the system. The resulting material intensities (MIs) of the individual inputs are then separately summed together for each environmental compartment (again: abiotic matter, water, air and biotic matter), and assigned to the system’s output as a quantitative measure of its cumulative environmental burden from that compartment.

2.2 Accounting for heat flows

First-law heat accounting is very often believed to be a good measure of energy cost and system efficiency. The energy invested in the overall production process is no longer available to the user of the product. It has been used up and is not contained in the final product itself. The actual energy content (measured as combustion enthalpy, H.H.V.-Higher Heating Value, L.H.V.-Lower Heating Value) of the product differs from the total input energy because of conversion losses occurred in many steps leading to the final product. Energy analysts refer to the total energy required in the form of crude oil equivalent as to

"embodied energy". The Embodied Energy Analysis method (Slesser, 1974; Herendeen, 1998) deals with the gross (direct and indirect) energy requirement of the analysed system, and offers useful insight on the first-law energy efficiency of the analysed system on the global scale, taking into consideration all the employed commercial energy supplies. In this method, all the material and energy inputs to the analysed system are multiplied by appropriate oil equivalent factors (g/unit), and the cumulative embodied energy requirement of the system's output is then computed as the sum of the individual oil equivalents of the inputs, which can be converted to energy units by multiplying by the standard calorific value of 1 g of oil (41,860 J/g). The chosen cumulative indicator is the so-called "gross energy requirement" (GER), expressing the total commercial energy requirement of one unit of output in terms of equivalent Joules of oil.
Quantifying the total energy invested into a process allows an estimate of the total amount of primary energy invested and, as a consequence, the extent of the depletion of nonrenewable energy resources caused by the process. If the evaluation deals with an energy conversion process (e.g. conversion of oil to electricity or conversion of wind into electricity), the comparison of the energy output to the energy invested provides a measure of the performance named EROI (Energy Return on Investment): the higher the EROI the higher the energy benefit from the process.

2.3 Assessing user-side resource quality. The exergy approach.

Not all forms of energy are equivalent with respect to their ability to produce useful work. While heat is conserved, its ability to support a transformation process must decrease according to the second law of thermodynamics (increasing entropy). This is very often neglected when calculating efficiency based only on input and output heat flows (first-law efficiency) and leads to an avoidable waste of still usable energy and to erroneous efficiency estimates. The same need for quality assessment applies to every kind of resource supplied or released in a process. The ability of resources to supply useful work or to support a further transformation process must be taken into account and offers opportunities for inside-the-process optimization procedures, recycle of still usable flows, and downstream allocation of usable resource flows to another process.
The ability of driving a transformation process and, as a special case, producing mechanical work, may be quantified by means of the exergy concept. According to Szargut et al. (1988) exergy is "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature". Chemical exergy is the most significant free energy source in most processes. Szargut et al. (1988) calculated chemical exergy as the Gibbs free energy relative to average physical and chemical parameters of the environment.
By definition, the exergy (ability of doing reversible work) is not conserved in a process: the total exergy of inputs equals the total exergy of outputs (including waste products) plus all the exergy losses due to irreversibility. Quantifying the exergy losses due to irreversibility (which depends on deviations from an ideal, reversible case) for a process offers a way to calculate how much of the resource and economic cost of a product can be ascribed to the irreversibility affecting the specific technological device that is used as well as to figure out possible process improvements and optimization procedures aimed at decreasing exergy losses in the form of waste materials and heat. Exergy losses due to irreversibilities in a process are very often referred to as "destruction of exergy."
The exergy evaluation method is not routinely used in LCA assessments, where it could be instead adopted and implemented for the assessment of the second law efficiency of the

process, to be considered as another important LCA parameter. Each input to the process can be accounted for in terms of its exergy content. The ratio of the exergy content of the output to the sum of the input exergies is a measure of the maximum conversion efficiency attainable in theoretical reversible conditions. Exergy has also sometimes been suggested as an ecological metric to gauge ecosystem health and stability (Fath and Cabezas, 2004; Jørgensen, 2005), but the authors have made the choice to stick to a strictly thermodynamic evaluation of the systems under study, leaving the evaluation of direct and indirect ecosystem disturbance to the Emergy method, as well as to other "downstream" impact categories.

2.4 Assessing donor-side resource quality. The emergy approach.

The same product may be generated via different production pathways and with different resource demand, depending on the technology used and other factors, such as boundary conditions that may vary from case to case and process irreversibility. In its turn, a given resource may require a larger environmental work than others for its production from nature. As a development of these ideas, Odum (1988, 1996) introduced the concept of *emerg*y, 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". We may therefore have an oil emergy, a coal emergy, a solar emergy, etc. according to the specific goal and scale of the process. 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 exergy analysis and economic evaluation are "receiver systems of value", i.e. something has a value according to its usefulness to the end user. Solar emergy was 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 (like deep heat and gravitational potential) are expressed as solar equivalent energy by means of suitable transformation coefficients (Odum, 1996). The Emergy Accounting method focuses on the environmental performance of the system on the global scale, but this time also taking into account all the free environmental inputs such as sunlight, wind, rain, as well as the indirect environmental support embodied in human labour and services, which are not usually included in traditional embodied energy analyses. Moreover, the accounting is extended back in time to include the environmental work needed for resource formation.

The amount of input emergy dissipated per unit output exergy is called *solar transformity*. The latter can be considered a "quality" factor which functions as a measure of the intensity of biosphere support to the product under study. The total solar emergy of a given item may be calculated as: (solar emergy) = (exergy of the item) * (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. The specific emergy or transformity of a system's output is calculated as the sum of the total emergy embodied in the necessary inputs to the system, respectively, divided by the output mass or exergy. The total emergy requirement thus calculated can be interpreted as an indication of the total appropriation of environmental services by the analysed human activity. In particular, while the total *non-renewable* emergy input to the system under study provides a quantitative estimate of global non-renewable resource depletion, the total *renewable* emergy requirement is a measure of all the natural exchange-pool resources that

are diverted from their natural pathways, and that can therefore no longer provide their natural ecosystemic functions.
Values of transformities are available in the scientific literature on emergy. When a large set of transformities is available, other natural and economic processes can be evaluated by calculating input flows, throughput flows, storages within the system, and final products in emergy units. As a result of this procedure, a set of indices and ratios suitable for policymaking (Ulgiati et al., 1995; Ulgiati and Brown, 1998; Brown and Ulgiati, 1999) can be calculated. Such indicators expand the evaluation process to the larger space and time scales of the biosphere. While the emergy approach is unlikely to be of practical use in making decisions about the price of food at the grocery store or the way a process should be improved to maximize exergy efficiency at the local scale, its ability to link local processes to the global dynamics of the biosphere provides a valuable tool for adapting human driven processes to the oscillations and rates of natural processes, towards sustainable patterns of human economies. LCA procedures do not include the emergy method among the tools available to the analyst. Instead, emergy (a measure of the demand for environmental support by a process) could be easily included as an upstream, broad-focus, impact category, thus providing a comprehensive measure of cost at the scale of biosphere.

2.5 Accounting for airborne and waterborne emissions

Airborne and waterborne emissions are a crucial issue in the evaluation of a process impacts. They can be measured directly or estimated indirectly according to existing databases or stoichiometric parameters. In our investigations we used indirect emission factors from published databases (Corinair 2007, CML2 baseline 2000, among others) which calculate the potential environmental damage of airborne, liquid and solid emissions by means of appropriate equivalence factors to selected reference compounds for each impact category. The impact potential of the analysed system for each category is calculated by multiplying all emissions by their respective impact equivalence factors, and then summing the results. The CML2 method was preferred among other similar methods for its versatility and completeness. The impact categories analysed in the case studies are:
- *Global warming potential*, expressed in grams of CO_2 equivalent per gram of product;
- *Acidification potential*, expressed in grams of SO_2 equivalent per gram of product;
- *Eutrophication potential*, expressed in grams of $PO4^{3-}$ equivalent per gram of product;
- *Tropospheric ozone and photosmog formation potential*, in grams of ethene equivalent per gram of product;
- *Stratospheric ozone depletion potential*, in grams of CFC-11 equivalent per gram of product;
- *Ecotoxicity potential*, in grams of 1,4-dichlorobenzene equivalent per gram of product (this category is then sub-divided into freshwater, soil and sea water ecotoxicity potentials).

Within the framework of this downstream approach, the possibility for an update of the specific equivalence factors remains open for the future, as is usually the case for any equivalence factor. Similarly, the inclusion of further impact categories (e.g. radioactivity), in order to meet the specific requirements of the analysed case study, is also theoretically possible.

3. RESULTS FROM SELECTED CASE STUDIES

The case studies presented in this Section are the results of recent investigations performed by the authors by means of the multi-method and multi-scale approach described in the previous sections. Since results refer to the past years 2001-2009, some of them might be no longer representative of the technological progresses achieved by far, specially for those technologies that are undergoing a very fast development (e.g. photovoltaic and fuel cells). They are shown in order to support the understanding of the integrated evaluation approach discussed in this paper. The joint use of complementary methods, points of view and numeraires is the basis for an evaluation framework named SUMMA (Sustainability Multi-method Multi-scale Approach; Ulgiati et al., 2006) that allows the generation of a large set of performance indicators to be used for technological improvement, investment choices, resource and environmental policy. Figure 2 shows a schematic overview of how the framework is applied: The analysed system or process is treated as a 'black box', and a thorough inventory of all the input and output flows is firstly performed on its local scale. It is important to underline that this inventory forms the common basis for all subsequent impact assessments, which are carried out in parallel, thus ensuring the maximum consistency of the input data and inherent assumptions. Each individual assessment method is applied according to its own set of rules. The 'upstream' methods are concerned with the inputs, and account for the depletion of environmental resources, while the 'downstream' methods are applied to the outputs, and look at the environmental consequences of the emissions. The calculated impact indicators are then interpreted within a comparative framework, in which the results of each method are set up against each other and contribute to providing a comprehensive picture on which conclusions can be drawn. Results reflect the specific characteristics of each case study evaluated and do not claim to be generalisable. They are only presented here to illustrate what can be obtained by means of an integrated approach, not to support or counter the feasibility of a specific technology or process. For this to be done, the set of case studies should be increased, in order to rely on a representative sample of indicators.

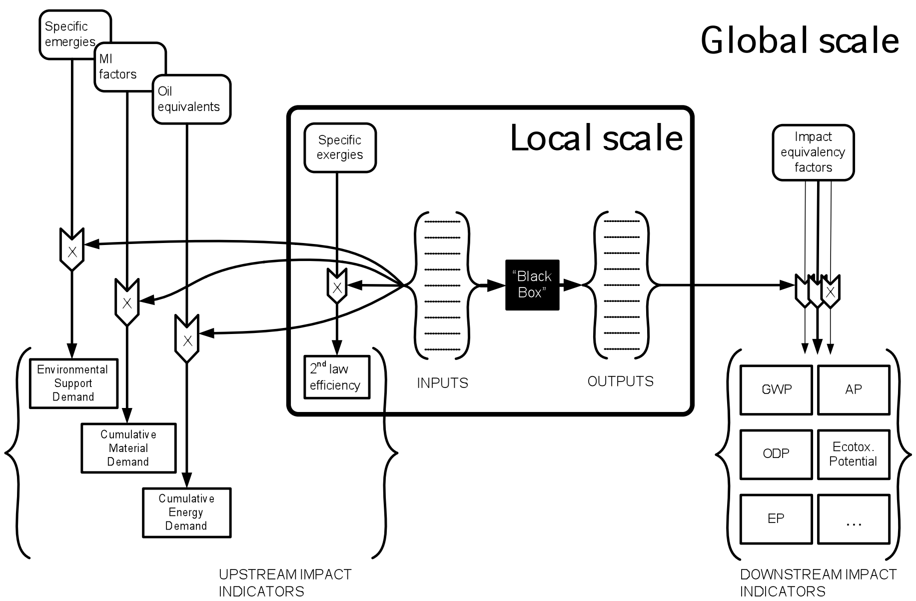

Figure 2. Flow diagram of the multimethod multiscale approach. The system is treated as a black box. Input and output flows are multiplied by specific exergy, energy, matter, emergy and emission factors to yield estimates of upstream and downstream impacts on resource and environmental dynamics. (diagram after Ulgiati et al., 2006, modif.)

3.1 Cogeneration of heat and electricity

Table 1 compares the results obtained from the application of the approach to a selection of different power plant for electricity and heat generation. The power plants investigated are all powered by natural gas, but differ by technology (internal combustion engine, gas turbine, steam turbine, combined cycle, fuel cells) and size, ranging from a power of 0.5 MWe (MCFC plant) to 1200 MWe (NGCC plant). Their technical characteristics and the full details of the evaluations performed are provided in Raugei et al. (2005), Bargigli et al. (2008), Bargigli et al. (2009). Comparison is made possible by the use of intensive indicators (i.e. indicators per unit of output or indicators of efficiency), that are not dependent on the size of the system.

Table 1. Performance indicators of selected Cogeneration electricity production processes

Process/product — Indicator	ICE (Internal Combustion Engine)	MCFC (*) (Molten Carbonate Fuel Cells)	Hybrid (*) (MCFC + GT100)	Gas turbine (TURBEC GT 600)	STGT (steam turbine + gas turbine)	NGCC (Natural Gas Combined Cycle)
Material resource depletion						
MI_{abiot} (g/kWhe)	1030	264	190	640	276	146
MI_{water} (g/kWhe)	3530	1144	870	1890	916	875
MI_{air} (g/kWhe)	=	878	=	=	5003	2655
Energy resource depletion and First Law efficiency						
GER of electricity (10^6J/kWhe)	9.00	10.30	7.83	11.78	13.80	7.35
Oil equiv of electricity (g/kWhe)	215.10	246.00	187.00	281.40	331.00	176.00
Electric Energy efficiency	0.40	0.35	0.46	0.20	0.26	0.49
Cogeneration energy efficiency	0.82	0.72	0.72	0.74	0.75	0.71
Exergy, Second Law Efficiency						
Cogeneration Exergy efficiency	0.66	0.61	0.62	0.55	0.45	0.60
Emergy, demand for environmental support						
Transformity (10^5seJ/J), with services	11.10	2.64	2.38	11.10	4.01	1.70
EYR	1.02	=	1.00	1.01	=	=
ELR	63	=	1896	73	=	=
Climate change						
GWP (CO_2-equiv, g/kWhe)	921	583	493	788	750	398
Acidification (SO_2-equiv, g/kWhe)	=	0.33	=	=	0.62	0.54

Source of data: Raugei et al., 2005; Bargigli et al., 2008, 2009.
(*) data for MCFC systems are from pilot scale production. As such, the corresponding results presented here should not be considered to be fully representative of the current state of the art.

A pictorial view of results if provided by Figure 3, where 5 different typologies of plants selected from Table 1 are compared according to the values of their contribution to selected impact categories or performance indicators. Absolute values are reported in Table 1, while instead the values in Figure 3 are adjusted and normalized for better visualization of results. It clearly appears that each plant shows a good performance concerning some impact categories, while ranks lower in other categories. In most cases, the higher the value of the indicator the worse is the performance. Since efficiencies have an opposite meaning (the higher the better), we reported their inverse values in the diagram. In so doing, the larger is the area identified by the indicators for each given plant on the radar diagram, the larger is the potential impact of that system in relative terms. According to the results shown in Figure 3, the best performance is shown by the cogeneration NGCC plant while ICE plant ranks lower (it should be acknowledged, however, that data for MCFC systems are from pilot scale production (first-of-a-kind). As such, the corresponding results presented here – although already satisfactory - should not be considered to be fully representative of the current state of the art, and they should not be included in the comparison if the emphasis is placed on identifying the most recommendable option for the near future).

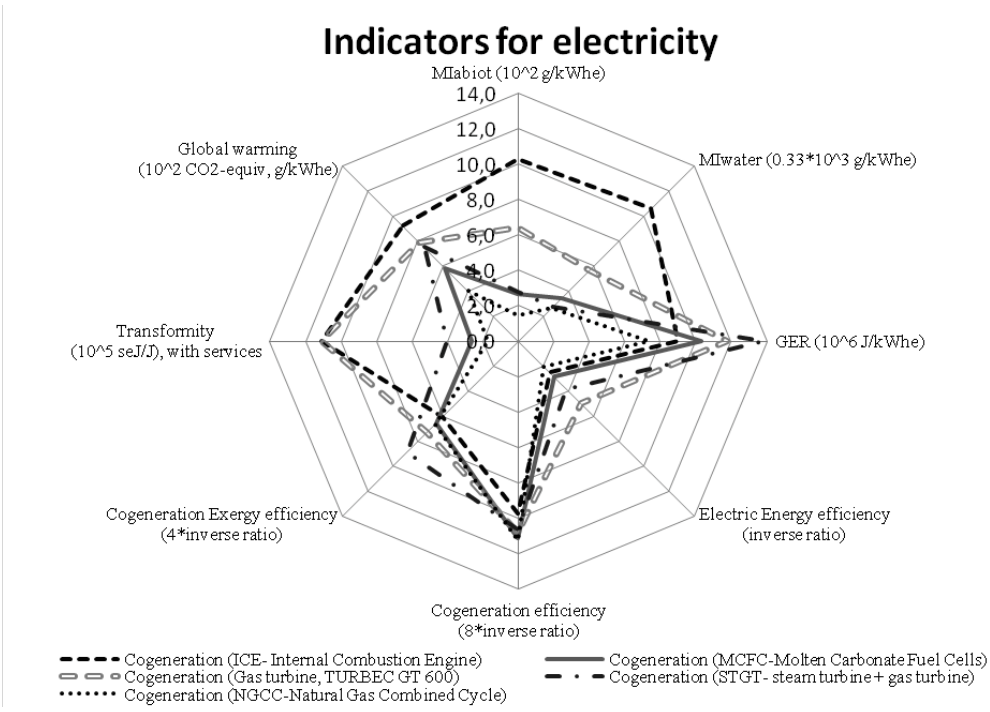

Figure 3. Radar diagram comparing the performance of selected typologies of cogeneration power plants, according to data from Table 1.

3.2 Photovoltaic electricity

Photovoltaic (PV) energy generation devices have experienced a sharp, almost 10-fold increase in production in less than a single decade (Jaeger-Waldau, 2008). Since the early 2000s, new PV technologies have begun to be employed commercially alongside the more traditional Si-based systems, among which in particular cadmium telluride (CdTe) PV, which now represents 5% of the global PV market (EPIA, 2008).

Three types of innovative PV modules were selected to be analysed in the original study performed by some of the authors (PVACCEPT, 2005; Raugei et al., 2007):

1. Micro-perforated, semi-transparent poly-crystalline silicon modules: in this technology the photoactive material is a layer of high-purity silicon, which is ’doped‘ on its opposite sides by introducing into its lattice structure a small number of atoms of the third and fifth chemical groups, respectively (e.g. boron and phosphorous). This procedure effectively turns the Si layer into an electrical P/N junction, characterised by a suitable bandgap energy. The single Si cells are then electrically connected in series and sandwiched between a transparent glass pane and a rear cover to form the finished module.
2. Cadmium Telluride (CdTe) thin film modules: in this technology the photoactive P/N junction is made up of two semiconductor compounds, CdTe and CdS, which are directly deposited in extremely thin layers on a treated transparent glass pane by means of a vapour transport deposition process. Series connection of adjacent P/N junctions is achieved by means of a repeated automated scribing process, and then a second protective glass pane is added on top to form the finished module.
3. Copper Indium diSelenide (CIS) thin film modules: this technology shares many similarities with the previous one (CdTe), the main difference between the two consisting of the chemical compound used for the P part of the heterojunction, i.e. $CuInSe_2$ instead of CdTe.

Resulting performance indicators from that original study are shown in Table 2 (absolute values) and diagrammed in Figure 4 (values adjusted for better visualization).
A sensitivity analysis allowed to identify the input flows that more likely affect the performance of each device and explore how suggested changes may translate into better performance. According to these results, CdTe modules could be identified as the ones that performed best.
It is however of paramount importance to underline that the results presented here only apply to the early pre-production (in the case of CIS) and pilot production (in the case of CdTe) modules available at the time when the original study was performed (2001 – 2004). Thin film PV technologies, and CdTe PV in particular, have since undergone staggeringly fast progress (e.g. CdTe module efficiency has increased from below 8% to almost 11%), and even comparatively more mature c-Si technologies have advanced considerably (e.g. c-Si wafer thickness has generally been reduced by almost 30%). As a consequence of such progress, recent studies have proven that, for instance, the Global Warming Potential of CdTe PV modules is now down to only slightly over 10 g CO_2-eq/kWhe (Fthenakis et al., 2009). Similar order-of-magnitude changes may be expected to have occurred in other impact indicators, too, thereby making the numerical results presented in Table 2 and Figure 4 *devoid of any practical relevance with respect to the actual environmental performance of current-production PV modules*.
The value of the comparison remains, though, *from a purely methodological point of view*, in that it illustrates the importance of going beyond the limited set of the most commonly employed indicators, and extending the analysis to also include non-conventional metrics of environmental impact.

Table 2. Performance indicators of selected thin-film photovoltaic modules

Indicator \ Process/product	**Poly-Si - Polycristalline Sylicon module**	**CdTe - Cadmium Telluride module (*)**	**CIS-Copper Indium Selenide module (*)**
Material resource depletion			
MI_{abiot} (g/kWhe)	140	70	150
MI_{water} (g/kWhe)	530	300	630
Energy resource depletion and First Law efficiency			
GER of electricity (10^6J/kWhe)	1.0	0.30	1.1
Oil equiv of electricity (g/kWhe)	23.9	7.2	26.3
Exergy, Second Law Efficiency			
Exergy efficiency	10.5%	6.0%	8.2%
Emergy, demand for environmental support			
Transformity (10^4seJ/J), without services	2.80	1.50	3.0
Climate change			
Global warming (CO_2-equiv, g/kWhe)	52	19	70
Acidification (SO_2-equiv, g/kWhe)	0.44	0.11	0.37

Source of data: PVACCEPT, 2005; Raugei et al., 2007. Assumptions for all systems: lifetime = 20 years; irradiation = 1,700 kWh/(m^2*yr); Performance Ratio = 75%; efficiencies = 14% (c-Si), 8% (CdTe), 11% (CIS).
(*) data for CdTe and CIS modules are from pilot scale production. PV systems, and those based on thin films in particular, have been proven to have improved considerably in the last few years; therefore, the corresponding results presented here should not be considered to be representative of the current state of the art, and are only presented for the purposes of illustrating the adopted methodology.

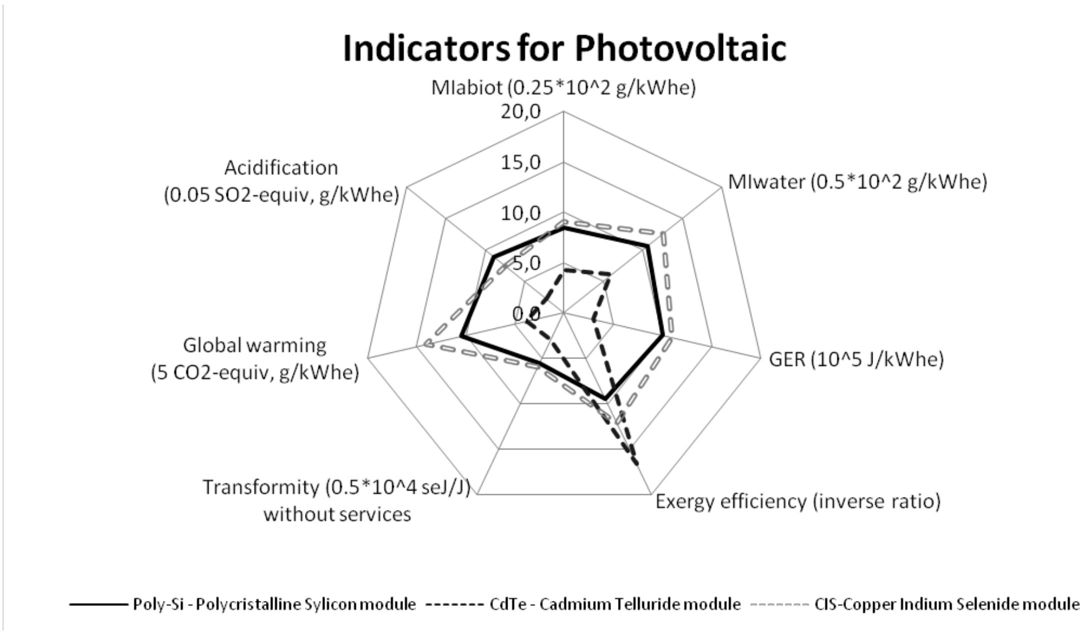

Figure 4. Radar diagram illustrating the relative performance of three typologies of photovoltaic devices, based on data from Table 2. Results for CdTe and CIS modules are from pilot scale production. PV systems, and those based on thin films in particular, have been proven to have improved considerably in the last few years; therefore, the corresponding results presented here should not be considered to be representative of the current state of the art, and are only presented for the purposes of illustrating the adopted methodology.

3.3 Alternative fuels and biofuels

Fuels and biofuels alternative to the commonly used fossil gasoline and diesel were explored and results presented in Table 3 (absolute values). A more detailed discussion of each process investigated (syngas, hydrogen, biofuels) as well as of the meaning of the results obtained is provided in Bargigli et al. (2004) and Giampietro and Ulgiati (2005).

Table 3. Performance indicators of selected fuels and biofuels

Process/ product — Indicator	Syngas (from coal gasification)	Hydrogen (from steam reforming of natural gas)	Hydrogen from water electrolysis (thermoelectricity)	Bioethanol (from corn)	Biodiesel (from sunflower)	Methanol (from wood)
Material resource depletion						
MI_{abiot} (g/g)	30.90	3.60	12.20	7.45	13.97	=
MI_{water} (g/g)	40.80	10.60	71.80	4811	2853	=
MI_{air} (g/g)	8.80	21.30	165.10	=	=	=
MI_{biot} (g/g)	=	=	=	0.35	0.79	=
Energy resource depletion and First Law efficiency						
GER (10^4J/g)	2.20	18.80	42.90	2.51	3.43	0.47
Oil equiv (g_{oil}/g)	0.48	4.48	10.20	0.60	0.82	0.11
Energy Return on Investment (EROI)	0.76	0.64	0.28	1.15	0.98	1.10
Exergy, Second Law Efficiency						

Exergy efficiency	0.75	0.71	0.27	=	=	=
Emergy, demand for environmental support						
Transformity (10^4seJ/J)	9.56	12.30	36.60	18.90	23.10	26.60
EYR	=	=	=	1.24	1.09	2.35
ELR	=	=	=	10.90	25.90	2.10
Climate change						
Global warming (CO_2-equiv, g/g)	5.20	9.50	33.70	2.02	3.21	1.54
Solid emissions (g/unit)	3.00	=	=	=	=	=

Source of data: Bargigli et al., 2004; Giampietro and Ulgiati, 2005.

Figure 5 shows the systems diagram of the industrial conversion of corn into ethanol (Sciubba and Ulgiati, 2005). The main process steps are indicated and the evaluation was performed step by step, in order to be able to identify the parts of the process that are crucial for the final performance. The diagram indicates the main input flows (matter, energy and labor) that support each step of the process; these flows are then listed in an inventory table and converted into embodied matter, embodied energy, exergy, emergy and emission flows according to the approach described in Section 2. Similarly, Figure 6A,B shows the systems diagram of two methods for hydrogen production (from steam reforming of natural gas and from water electrolysis powered by fossil generated electricity).

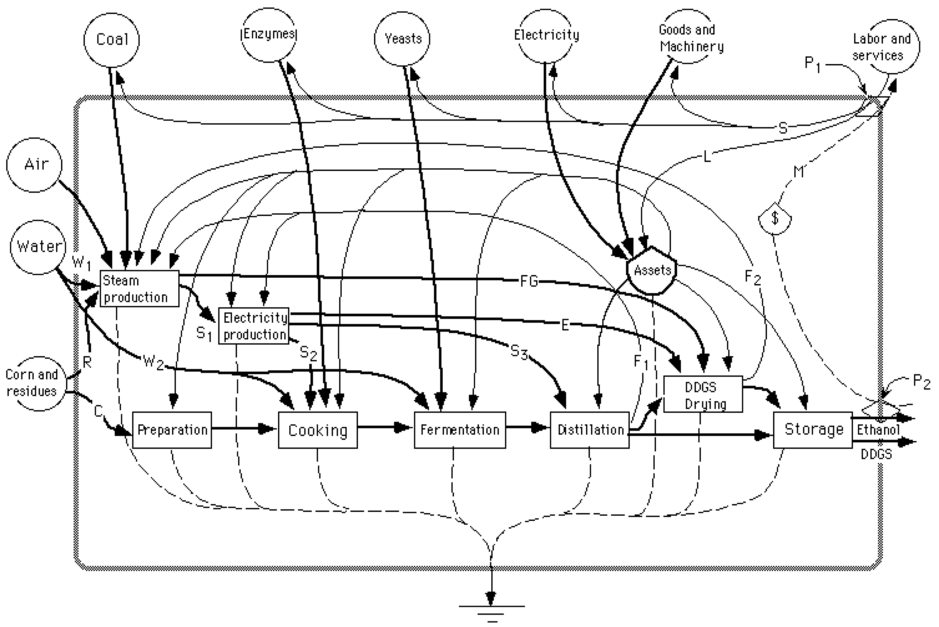

Figure 5. Energy systems diagram of industrial conversion of corn into bioethanol and animal feedstock (DDGS, Distilled Dry Grains with Solubles). The diagram shows the matter and energy input flows from outside to each step of the process as well as flows exchanged among system’s components (diagram from Sciubba and Ulgiati, 2005).

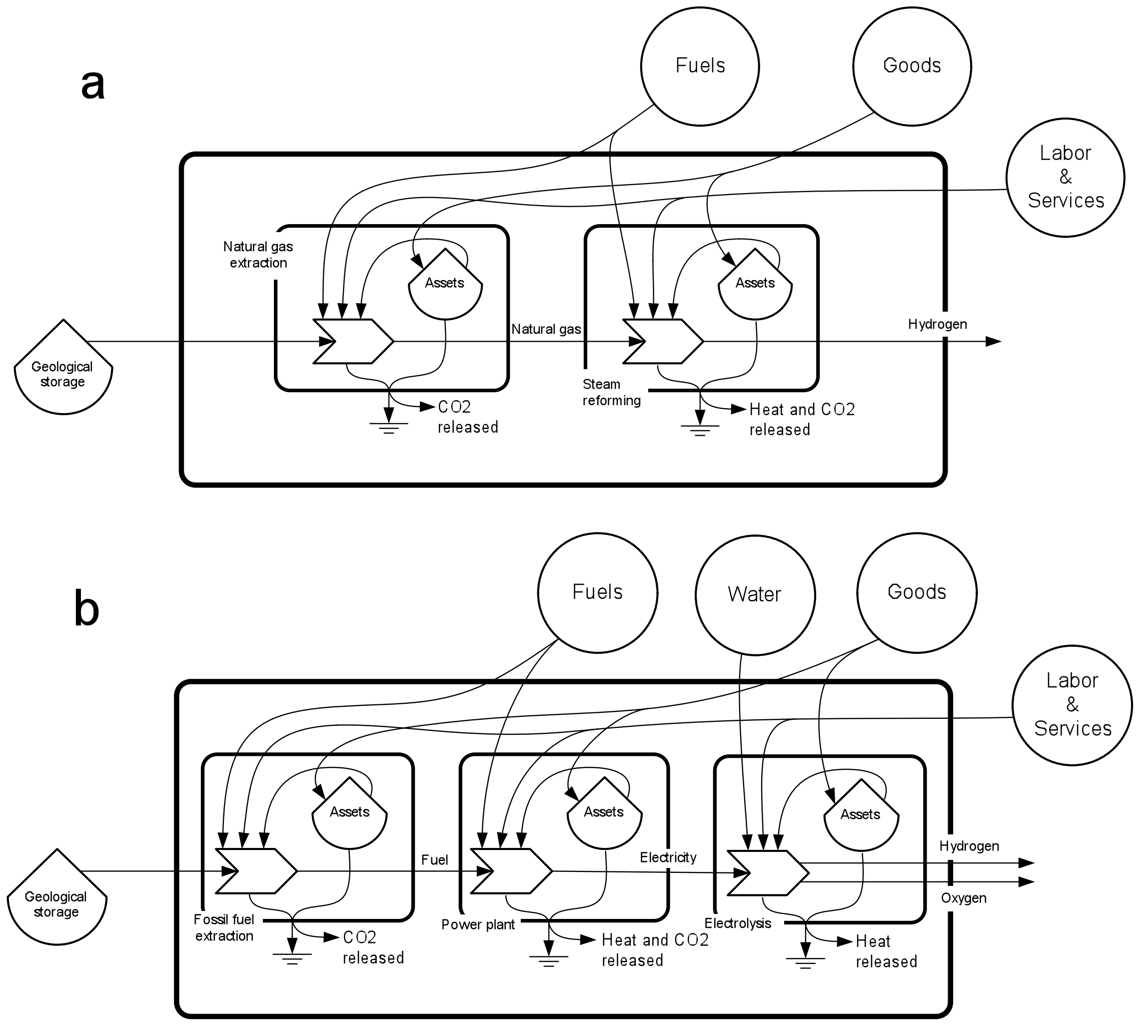

Figure 6a,b. Systems diagram of hydrogen production from natural gas via steam reforming (a) and via water electrolysis (b). (diagrams are from Brown and Ulgiati, 2004, modif.; systems symbols are described in Figure 1)

The final results for a selection of the investigated fuels are compared in the radar diagram in Figure 7. As with the previous radar diagrams, values are adjusted for better visualization and a larger area indicates a worse performance. i.e. identifies the system that is characterized by the largest potential impact. In the case of Figure 7, hydrogen from steam reforming shows the best relative performance. It should be noted here the large water demand related to the production of biodiesel from sunflower, mainly for the agricultural step. Such a result makes it apparent that even when most performance parameters are very good (e.g. EROI, GWP, etc), the global result may be easily worsened by one parameter only. However, this also provides a way to identify the process bottlenecks and try to remove them.

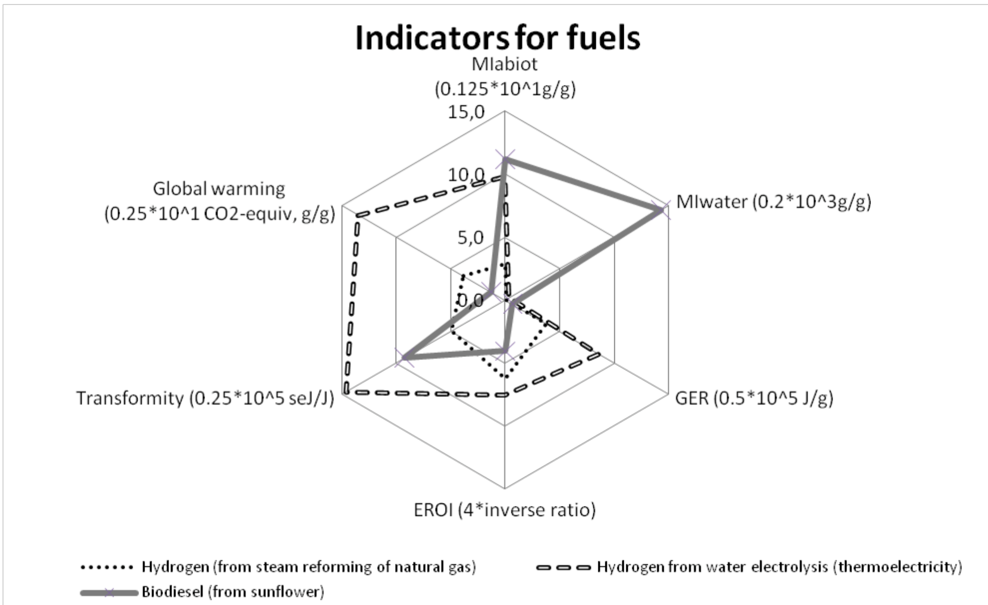

Figure 7. Radar diagram of three selected fuel production processes (data from Table 3) showing the relative global impact (depending on the selected set of performance indicators).

3.4 Transportation Systems

A selection of transportation modalities at local and national scales in Italy was investigated by Federici et al. (2003, 2008, 2009). These authors compared local transportation systems at urban level and national highway, railway and air systems, for passenger and commodity transport. A selection of their results is shown in Table 4 (absolute values), where values are, as always in this paper, presented as intensive indicators, per unit of service delivered (per passenger or ton transported per km, p-km and t-km), in order to allow a fair comparison. In particular, the Authors focus on two different typologies of railway transport (regular intercity trains and high speed trains). As a result of their study, the authors point out the huge importance of infrastructure (concrete and steel for viaducts and tunnels, road asphalt and other building materials, as well as special steel for machinery) and discuss how infrastructure, average occupancy and speed affect the final performance indicators. Figure 8 suggests that the railway passenger transport is characterized by the lowest relative impact.

Table 4. Performance indicators of selected transportation modalities

Process/ product Indicator	Highway passenger transportation by car (p-km)	Highway commodity transportation by truck (t-km)	Railway passenger transportation by intercity train (p-km)	High Speed Railway, passenger transportation by HS train (p-km)	Air passenger transportation by A320 aircraft (p-km)
Material resource depletion					
MI_{abiot} (g/unit)	530	600	770	1200	800
Energy resource depletion and First Law efficiency					
GER (MJ/unit)	1.87	1.25	0.69	1.23	2.20
Oil equiv (g_{oil}/unit)	44.70	29.90	16.50	29.40	52.60
Emergy, demand for environmental support					
Specific emergy (10^{11}seJ/unit)	1.74	1.08	1.10	1.41	1.28
Climate change					

Global warming (CO_2-equiv, g/unit)	134	90	49	88	158
Acidification (SO_2-equiv, g/unit)	1.69	0.80	0.39	1.53	n.a.

Source of data: Federici et al., 2003, 2008, 2009.

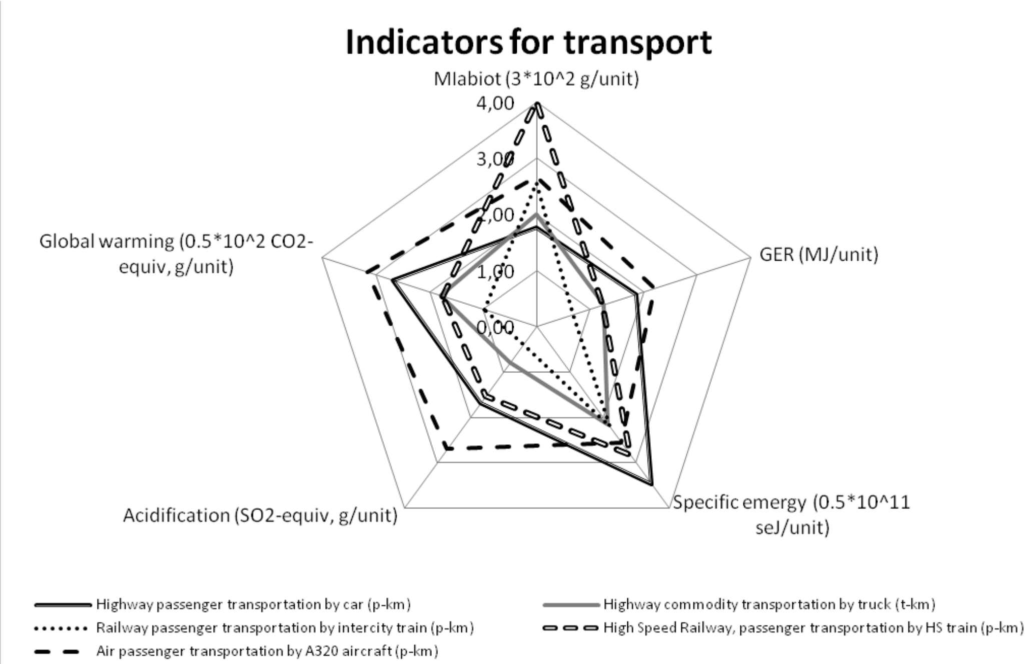

Figure 8. Radar diagram of selected transportation modalities (data from Table 4, normalised for comparison).

3.5 Waste Management

Four different urban waste management processes related to the city of Rome, Italy, were investigated by Cherubini et al. (2008, 2009). The study focused on (1) landfilling, (2) landfilling with biogas recovery, (3) conversion to biogas and Refuse Derived Fuel (RDF, for electricity production), and finally (4) direct incineration and electricity production. Calculated indicators are shown in Table 5. All steps were accounted for, including preliminary sorting of recoverable materials, collection and transport, landfilling of combustion ash and biogas digestion process. The energy generated from waste biomass was credited to the process, in so decreasing the global energy cost of management and the global emissions from the whole cycle. Performance indicators relative to the electricity generated are also shown in Table 5. In one case, (conversion to biogas and RDF) the process delivers a non-negligible amount of net energy, so that the net emissions (= actual process emissions minus avoided emissions due to the energy delivered) are negative.

Table 5. Performance indicators of urban waste management, Roma, Italy

Indicator	**Process/product**	**Landfilling**	**Landfilling with biogas recovery (*)**	**Sorting and conversion to biogas and RDF (*)**	**Direct incineration (*)**
Material resource depletion					

MI_{abiot} (g/ g_{waste})	0.24	0.24	0.30	0.36
MI_{abiot} (g/ kWhe)	=	1899	334	552
MI_{water} (g/unit)	0.03	0.02	2.09	1.04
MI_{abiot} (g/ kWhe)	=	0.82	2398	1578
Energy resource depletion and First Law efficiency				
GER (kJ/g_{waste})	0.05	2.15	9.71	9.52
GER (J/kWhe)	=	2.67E+07	1.38E+07	1.60E+07
$GER_{oil\ equiv}$ (g_{oil}/g_{waste})	0.001	0.05	0.23	0.23
$GER_{oil\ equiv}$ (g_{oil}/kWhe)	=	637.84	329.67	382.23
Energy efficiency	=	13%	52%	22%
Emergy, demand for environmental support				
Specific emergy (10^8 seJ/g_{waste})	1.58	1.54	1.22	1.83
Specific emergy (seJ/kWhe)	=	5.36E+05	2.28E+04	8.66E+04
Climate change				
Global warming (CO_2-equiv, g/g_{waste})	1.31	0.59	-0.23	0.15
Acidification, total emissions (SO_2-equiv, mg/ g_{waste})	0.37	0.13	-0.30	0.53

(*) followed by conversion to electricity. Source of data: Cherubini et al, 2008, 2009.

The radar diagram in Figure 9 allows a relative comparison of the three processes characterised by energy recovery, suggesting that landfilling with biogas recovery and direct incineration (the most commonly used technologies) are also the ones characterized by the higher global impact.

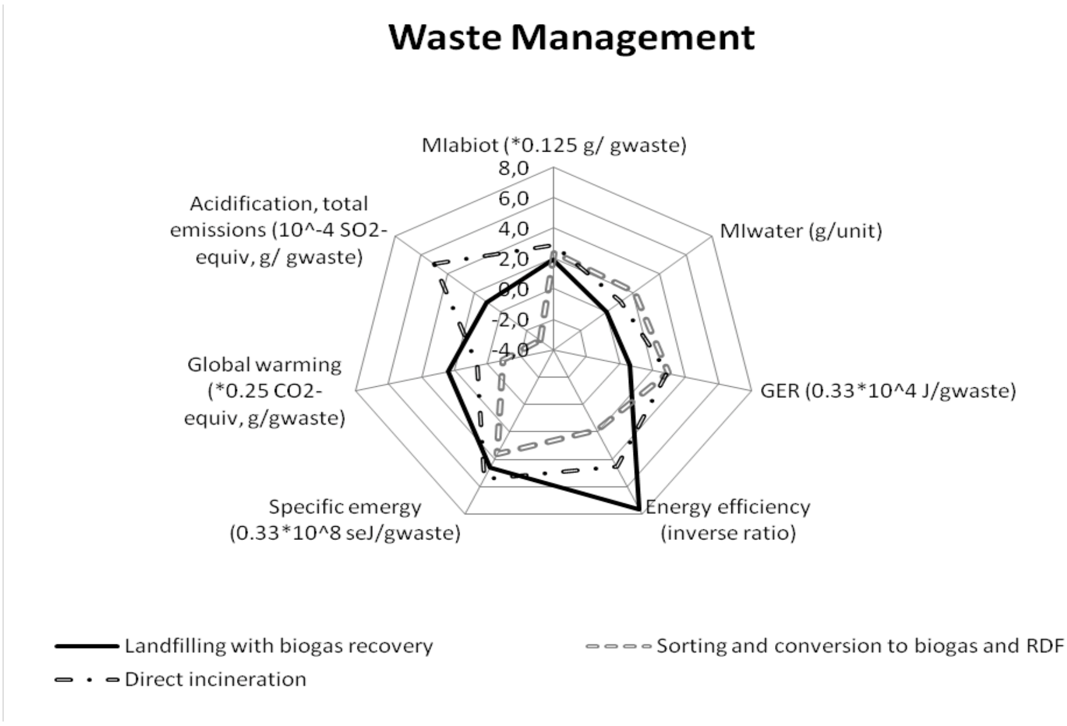

Figure 9. Radar diagram of three selected waste management options, based on data from Table 5. Landfilling option without biogas recovery was not included.

3.6 Urban systems

The metabolic patterns of an urban system (Rome, Italy) were investigated from 1962 to 2002 by Ascione et al. (2008, 2009). Figure 10 shows a systems diagram of the city and its surrounding environment (natural areas, agriculture) and infrastructure. The investigation took into account all the matter, energy, and emergy flows supporting the urban system over 40 years of growth and development, with the aim of ascertaining the total cost of supporting the urban system, its population, its economic activity and generation of GDP.

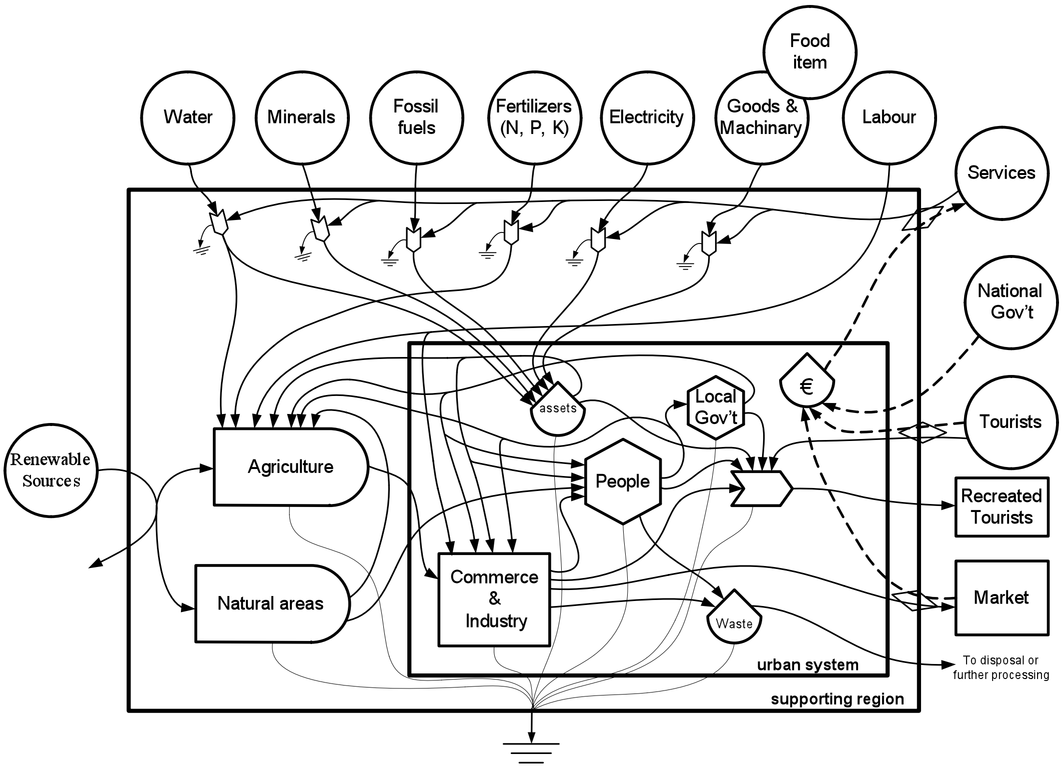

Figure 10. Systems diagram of an urban ecosystem surrounded by its supporting region. Systems symbols are described in Figure 1.

More than 20 indicators of performance and sustainability were calculated in this urban case study and their trends compared and discussed. The above waste management case study (section 3.5) was part of such an investigation effort, with focus on a specific sector (waste) that plays an important role in the whole urban metabolism. Results, shown in Table 6, point out a continuous growth of resource demand by the urban system. Unfortunately, such a demand was mainly demand for nonrenewable flows from outside the system, thus making it largely dependent on imports.

Table 6. Trend of urban metabolism, Roma, Italy (1962-2002).

Year / Indicator	1962	1972	1982	1992	2002
Material resource depletion					
MI_{abiot} (10^7g/person)	1.72	2.93	2.82	3.87	4.50
MI_{abiot} (10^3g/€)	82.70	40.60	5.98	2.30	1.99
MI_{water} (10^8g/person)	3.19	4.91	5.65	6.82	8.16
MI_{water} (10^4g/€)	154	68.20	12.00	4.05	3.61
Energy resource depletion and energy efficiency					
GER per person (10^{10}J/person)	6.34	11.40	14.80	19.70	27.30
GER per unit currency (10^7J/€)	30.50	15.80	3.14	1.17	1.21
Oil equiv (10^6g/person)	1.52	2.72	3.54	4.72	6.51
Oil equiv (10^2g/€)	73.00	37.80	7.51	2.80	2.88
Emergy, demand for environmental support					

Specific emergy (10^{16}seJ/person)	2.61	3.53	3.92	6.36	5.45
Specific emergy (10^{12}seJ/€)	126	49.10	8.33	3.78	2.41
EYR	1.05	1.03	1.02	1.01	1.02
ELR	40.85	61.94	52.38	94.73	64.47
Ecological footprint					
Area per person (ha/person)	2.13	2.12	2.81	2.84	3.60
Area per unit GDP (ha/€)	0.0103	0.0030	0.0006	0.0002	0.0002
Climate change					
Global warming (10^6CO_2-equiv, g/person)	4.62	8.42	11.00	14.40	20.00
Global warming (10^2CO_2-equiv, g/€)	223	117	23.40	8.57	8.83
Acidification (10^4SO_2-equiv, g/person)	1.30	2.54	3.08	4.00	5.67
Acidification (SO_2-equiv, g/€)	62.70	35.30	6.54	2.38	2.51

Source of data: Ascione et al., 2008, 2009.

The radar diagram in Figure 11 was drawn by normalising each performance index relative to the value of the same index in the year 1962. The Figure shows very clearly the impressive expansion of the urban system's impact over time, due to both increase of population and increase in demand for resources. The expansion seems to have been accelerating in the last decades.

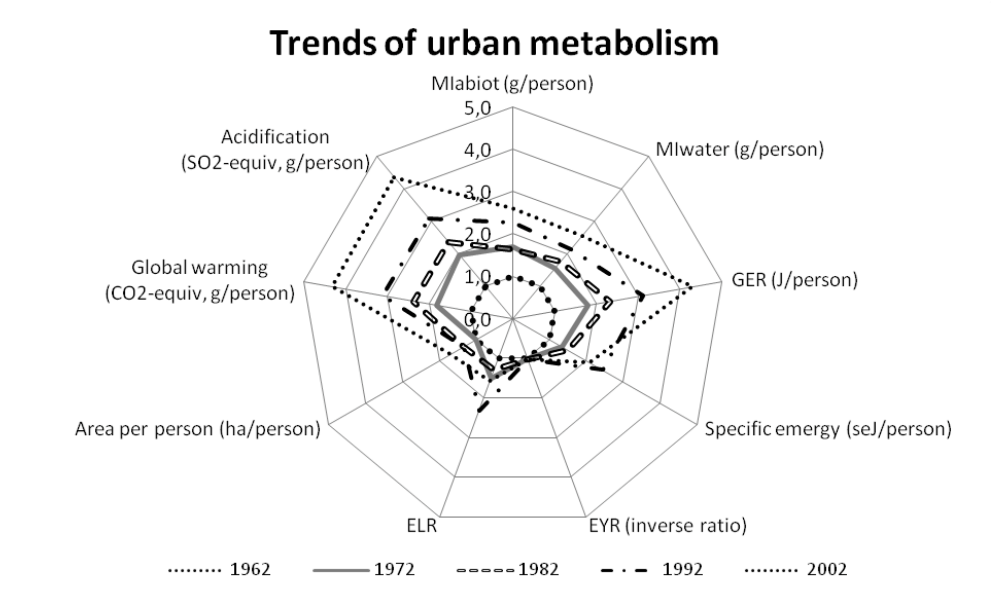

Figure 11. Radar diagram showing the trend over time of urban metabolism performance indicators. Values from Table 6 were normalised with reference to the year 1962.

3.7 Agriculture

A case study about the agricultural sector of Campania region in Southern Italy was performed and its performance assessed over a time span of 20 years (Ulgiati et al. 2008). As with the previous case studies, an inventory of the main input and output flows served as a basis for assessing the direct and cumulative support by the economic system as well as by the environment. The systems diagram of the process is shown in Figure 12, where all input flows from the environment and the economy are indicated together with system's components and internal exchanges of matter and energy.

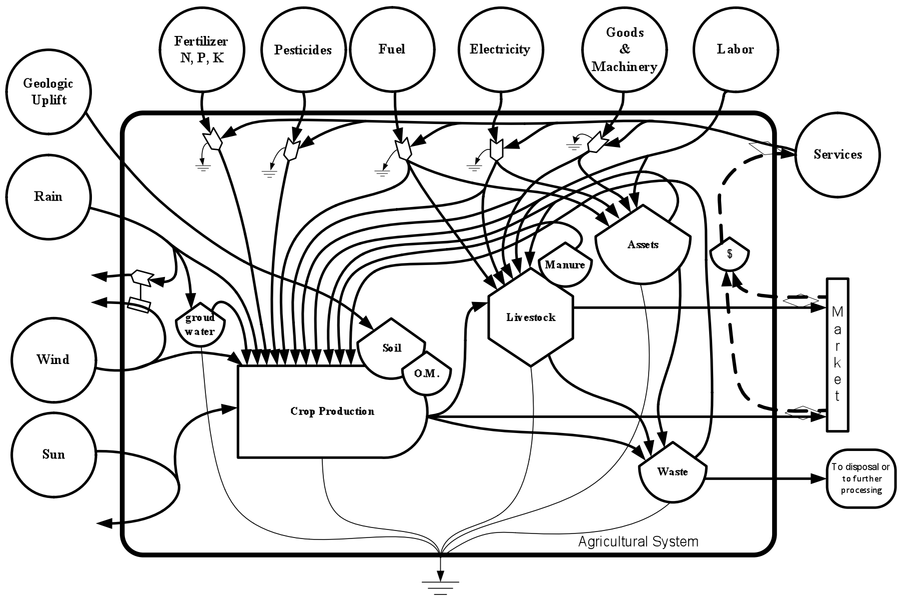

Figure 12. Systems diagram of a generic agricultural system, showing the main driving forces, system's components and internal interactions. Systems symbols are described in Figure 1.

The calculated performance indicators are listed in Table 7 and graphically shown in the radar diagram of Figure 13. The performances of the years 1993, 2002 and 2006 are referred to the year 1985, so that the expansion of the areas related to each investigated year suggests a higher relative impact over time. Such a trend is due, depending on the years, to: changed mix of crops, changed machinery use, changed climate conditions (mainly less rainfall), changed market value of products. It clearly appears that the agricultural system is increasingly impacting whatever is the performance indicator considered. The star-like shape is due to the fact that some composite indicators grow faster than others in the investigated years, which may depend on either numerator (energy used, amount of emissions, etc) or denominator (total product mass, product economic value, etc).

Table 7. Trend of the agricultural sector of Campania region, Italy (1985-2006).

Year / Indicator	1985	1993	2002	2006
Material resource depletion				
MI_{abiot} ($g/g_{d.m.}$)	0.33	0.27	0.76	0.98
MI_{abiot} ($10^3 g/€$)	2.59	2.06	1.64	2.24
MI_{water} ($g/g_{d.m.}$)	39.31	19.97	35.80	29.00
MI_{water} ($10^4 g/€$)	30.58	15.09	7.67	6.65
Energy resource depletion and energy efficiency				
GER per unit mass ($10^3 J/ g_{d.m.}$)	1.36	1.24	3.44	4.47
GER per unit currency ($10^6 J/ €$)	10.60	9.40	7.37	10.25
Oil equiv ($g/g_{d.m.}$)	0.03	0.03	0.08	0.11
Oil equiv ($10^2 g/ €$)	2.53	2.25	1.76	2.45
Energy efficiency	0.08	0.07	0.21	0.28
Emergy, demand for environmental support				
Specific emergy ($10^8 seJ/ g_{d.m.}$)	9.49	6.55	20.03	24.41
Specific emergy ($10^{12} seJ/€$)	3.70	2.48	2.15	2.80
EYR	0.81	0.80	0.87	0.89

ELR	1.69	2.06	2.78	4.25
Climate change				
Global warming (CO_2-equiv, g/g$_{d.m.}$)	0.10	0.09	0.26	0.34
Global warming (10^2CO_2-equiv, g/€)	8.04	7.03	5.53	7.71
Acidification (SO2-equiv, g/gd.m.)	1.40	1.19	0.94	1.33
Acidification (SO2-equiv, g/€)	0.0002	0.0002	0.0004	0.0006

Source of data: Ulgiati et al., 2008.

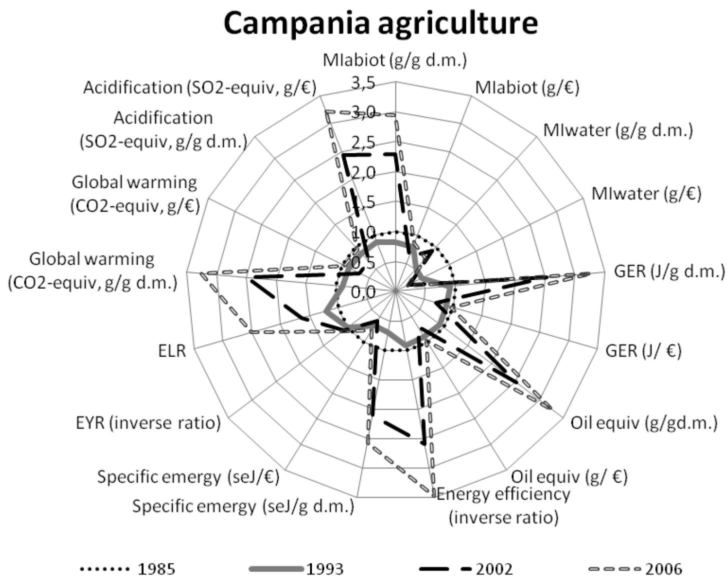

Figure 13. Radar diagram showing the trend over time of the performance of the agriculture of Campania region (Italy). Values from Table 7 are normalised with reference to the year 1985.

4. DISCUSSION

The discussion about each specific case study was already provided in the original studies referred to, published by the authors. Here we would like to point out the usefulness of an integrated approach as well as how it can be used for process improvement.

4.1 The 'added value'

Quantifying direct and indirect flows of matter and energy to and from a system permits the construction of a detailed picture of the process itself as well as of its relationship with the surrounding environment. Processing these data in order to calculate performance indicators and material and energetic intensities makes it possible to compare the process output to other products of competing processes. Results may differ depending on the goal, the boundaries, the time scale, and the technology and may suggest different optimization procedures. If the analyst is able to provide comprehensive results as well as to explain divergences at the appropriate scales of the investigation, a process can be more easily understood. Conclusions are also reinforced and are more likely to be acceptable for research, application and policy strategies.

Assessing a process performance on different scales offers an effective way to refine the analysis and improve the process. Results from the simultaneous application of a multiple set of methods yield consistent and comparable performance indicators and call for a two-fold optimization pattern:

a) Upstream: trying to decrease the use of or replace those input flows which affect the material, energy and environmental support demands more heavily;
b) Downstream: trying to decrease the use or avoid misuse of the investigated product, in order to negatively affect the input demand by controlling the end of the life cycle chain.

As already pointed out in the introduction, it was the authors' explicit choice not to provide a means of combining the results from the different upstream and downstream methods into one single "super-indicator", since this is contrary to the fundamental idea that separate indicators provide a much more comprehensive environmental profile, the interpretation of which should be left to the analyst. The latter should in fact clarify to the maximum possible extent the meaning and all the possible implications of the single results, highlighting the often inevitable trade-offs that all strategic choices entail, rather than simply attach to them one numerical tag, which would inevitably conceal much of the valuable detail of the study.

Last but not least, since the approach is based on a single common inventory of all the system's inputs and outputs, a systematic sensitivity analysis can simultaneously be performed on all calculated data and indicators, simply by allowing for variable cells for all input quantities as well as for the associated impact coefficients in the spreadsheet-based calculation procedures. Such an analysis is invaluable in order to estimate the actual reliability of the impact assessment itself, accounting for the inevitable uncertainties and variability in the input data and/or impact coefficients, as well as to single out which are the most critical key points of the analysed process in the light of the different assessment methods.

4.2 Weighting factors

Tables 1 to 7 list a selection of the calculated performance indicators. In general, many more indicators are generated by an integrated approach, but listing all of them is not necessary for the purpose of the present paper. If the focus is on the specific behaviour of the system from a single point of view (e.g. energy consumption), the analyst can refer to the calculation procedure that leads to that specific indicator and look carefully at the options available to minimize such an impact. Each choice can be tested in the calculation procedure (either implemented within an excel platform or a commercial software) and its consequences can be simulated, being aware that the improvement of the value of one indicator may lead to the worsening of another one. Since inventory data are linked to all the calculation procedure of all the indicators, this is a relatively easy task.

If the goal is providing a global picture of a process impact, then a selection of many indicators is needed in order to have a comprehensive evaluation across space and time scales. Since many indicators are generated by the same calculation procedure (e.g. Gross Energy Requirement, energy efficiency, EROI; or EYR, ELR, transformity) the analyst might select them according to his/her experience or according to the specific target of the investigation (e.g. assessing the environmental sustainability of the process). Once indicators are chosen, they can be normalized and diagrammed in such a way (histograms, radar, lines) that their values can be compared to a reference value or year, or simply looked at together, in order to provide a global picture of the impact. This is the case, for example, of Figures 3, 4, 7, 8 and 9, where several systems are compared each other and the normalization is performed in such a way that the area within each curve indicates a measure of the impact relative to the other processes investigated for comparison. Instead, Figures 11 and 13 show the behaviour of an urban system and an agricultural sector over time, by referring to the global performance in a given year. In this case, the larger the area the larger the variation of the impact over time, i.e. the diagram assesses how fast is the change for each individual impact and globally.

All the radar diagrams put a selection of indicators on each axis. Such a choice might lead to the erroneous assumption that their impacts are the same. This is not true, of course. Each indicator refers to a specific impact category in LCA as well as other evaluation methods (e.g. contribution to global warming, demand for environmental support, water footprint). Assigning weighting factors to the whole assessment is not easy nor there is any agreement in the scientific community in this regard, so that such a step is not mandatory in the ISO norms (ISO 14040/2006; ISO 14044/2006) that codify the LCA approach. In fact, weighting and grouping is explicitly discouraged by ISO 14044/2006 for all studies intended for public disclosure. Our choice of putting all the indicators on the same importance basis does not affect the final understanding of the impact, because assigning a different weighting factor to any indicator in Figures 3, 4, 7, 8 and 9 would change the values of all the investigated processes, but would leave the ranking unchanged. Same would happen with Figures 11 and 13. The shapes and areas in the diagram would be affected by choosing weighting factors, but relative ranking would not and therefore the same relative impacts would be suggested by the diagram. Some evaluation methods suggest weighting factors and scores (Eco-Indicator 1999), but the debate about the opportunity of such a choice is still open. The way data and indicators are used in the approach presented in the present paper does not require weighting factors to be applied.

4.3 Optimization procedures

The ultimate goal of any investigation about a process is to generate a clear picture of the crucial steps as well as crucial input and output flows, i.e. those steps and those flows that affect more heavily the process performance. In so doing it is possible to focus on these steps and flows, to understand how important are they in the global economy of the investigate process, and to suggest changes capable to lead to an improved performance. Some steps may be replaced by alternative patterns, some flows may be decreased by means of more efficient machinery or sub-processes, and finally some flows may simply be avoided without any important consequence for the final product. Suggesting an optimization procedure is not an easy task. Indicators are the result of a calculation procedure where the inventory data are multiplied by intensity factors specific of each given method (e.g. oil equivalent factors, transformity, global warming potential, etc). Therefore, when a performance indicator (e.g., the Acidification Potential for a coal powered plant) is not satisfactory, the analyst goes back to the calculation procedure in order to identify the input items that are responsible of the largest contributions to that impact category and may suggest to decrease their amount by applying technological changes to the process (e.g., use of de-sulphurized fuel). After the suggested changes have been implemented (or their adoption has been simulated) in the process, the analyst will recalculate the indicator under consideration and will assess the extent of the performance improvement. However, it is very likely that the suggested change affects other impact categories and, due to the reliance on the same set of input data, the improvement in one category might translate into a worse performance in another category (e.g. fuel de-sulphurization requires an additional technological process and increased energy input and generates additional waste to dispose of).

5. CONCLUSION

Investigating a system performance is by itself a very difficult task, due to the complexity of the problems that are always involved. When a simplified model is adopted, this is certainly a way to address part of the problem at the cost of leaving unsolved another part of it. Depending upon the goal of the investigation, this is sometimes a useful procedure. However, investigators very often run the risk of neglecting the complexity of the problem and taking

their model as reality. As a consequence, they assign a value to a process product according to the results of their simplified investigation. The outcome of this evaluation process is then used in other subsequent evaluations and translated into economic and policy actions. In so doing, the complexity is lost: reality does not fit the model and the planned policy fails or is inadequate.
An integrated approach is therefore suggested, to overcome the limits of individual methods and generate the added value of a comprehensive picture for the process steps, the process as a whole, the local scale and global scale environmental interactions, as well as the thermodynamic process performance. Evaluating comparable alternatives, when specific answers regarding different possible uses of resources in the space-time frame of interest are sought, necessarily requires the adoption of a multi-criteria approach. It must be realised that in virtually all cases there is no single 'optimal' solution to all problems. Only an analysis based on several complementary approaches can highlight the inevitable trade-offs that reside in alternative scenarios, and thus enable a wiser selection of the option embodying the best compromise in the light of the existing economic, technological and environmental conditions.

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