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Emergy and Life Cycle-Based Analyses of Energy Production Systems: Preliminary Study of a Biogas Power Plant

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ABSTRACT

Biogas power plants (BPPs) have been rapidly developing in Italy in the latest years, thanks also to major government subsidies, especially in Northern Italy where numerous agriculture and zoo technical Companies are located. In this paper, conventional Emergy Analysis (EMA) and Life Cycle Assessment (LCA) methods are used to study the sustainability conditions for a BPP. A real power plant located in Northern Italy and operating since 2012 is taken as case study. The quantification, in emergy terms, of natural resources used to build and operate the plant and the possible environmental impacts of materials and energy flows require a detailed analysis of several subsystems in the BPP. In this work, preliminary results are presented pointing out differences and complementarity of the used methodologies, with the aim of setting the basis for an emergy evaluation of the whole BPP and biomass production phases at the technosphere level of detail provided by the Life Cycle Inventory (LCI), using the emergy calculation software SCALEM®.

INTRODUCTION

Emergy accounting (EMA) is suitable for analyzing bio-geosphere systems (e.g., ecosystems) and technosphere systems in which human activities is well embedded in the context of the contribution of natural capital, such as agricultural processes, wetland areas, cities and their support areas, and so on. Temporal and spatial scales may be comparable to those of resource (re)generation, such for example the case of agricultural system, in which the crop rotation cycles have a time span of several months. However, when EMA is applied to industrial human activities, given the complexity of their production chain, the quantification in emergy terms of human-made product or services used up by the activity may typically suffer from a low level of accuracy. On the other hand, approaches such as Life Cycle Assessment (LCA), which use very detailed information about productive processes (the so-called "technosphere"), have been developed to evaluate the possible impact of these processes on both environment and human beings. The possibility and the benefits of integrating EMA and LCA has been long discussed in the literature by Raugei et al. (2014), Rugani and Benetto (2012), Arbault et al. (2014). However, a prominent hurdle persists: how to achieve an accurate representation of the studied industrial system as well as all the background systems supporting it, so to perform a relevant emergy accounting? This is a quite relevant question, considering that the emergy of a product depends on the path followed from the emergy sources to the delivery of that product. Therefore, the accuracy with which the entire system is described can have significant impact on the results obtained. The software SCALEM®, recently developed, allows the calculation of the emergy of a chosen product, applying the emergy algebra rules, benefitting of the accurate representation of the entire system (foreground and background processes) that is provided by Life Cycle Inventory (LCI) databases normally used in LCA, of which Ecoinvent (Wernet, 2016) is nowadays the most popular.

THE CASE STUDY

This work is a first step of a more general study that will take into account several methods, in order to evaluate the actual sustainability of renewable power plants. Among these, the Emergy Synthesis method is the first to be applied at a biogas power plant, also addressing possible different emergy calculations. First results of the conventional emergy analysis are presented here, and a description of the subsequent steps of the study is then briefly reported. The 625 kW biogas power plant chosen is fed with wheat and corn cultivated in a 165 ha field owned by the same Company, added with liquid cattle manure coming from a livestock 2 km far from the power plant. As shown in Figure 1, the agricultural silage, stocked in silos, is loaded in the first fermenter by a pump system and mixed with the liquid manure coming from the liquid digestate tank. Here the process of fermentation takes place, and the biogas starts to be produced. The digested biomass is then transferred to the second fermenter where continues the fermentation process. Part of the digestate biomass is extracted from the fermenters and carried to the separator tank where it is divided in solid and liquid fraction: the liquid part can be either recirculated in the fermenters or used as fertilizer for the cultivation of the biomass. The biogas produced in the fermenters is collected on the top of the gasometric domes and carried to the Cogenerator unit where it is burned producing electricity and heat. The heat is used inside the plant to heat up the fermenters. The electricity so produced is then taken to the medium voltage by a transformer station and injected into the national grid. Part of the electricity production is self-consumed for the power supply of electric devices in the plant, while, when the plant is under maintenance, it is powered by the national grid.

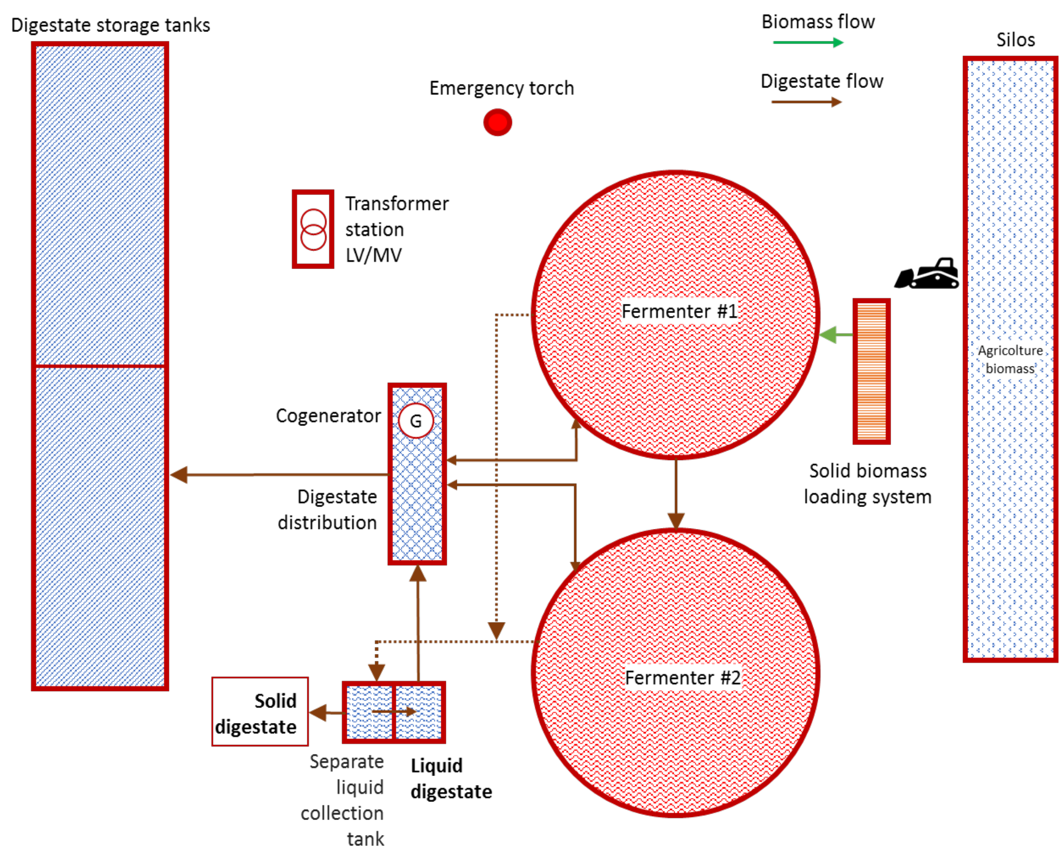

Figure 1. *Schematic description of the biogas power plant analyzed with biomass and digestate flows.*

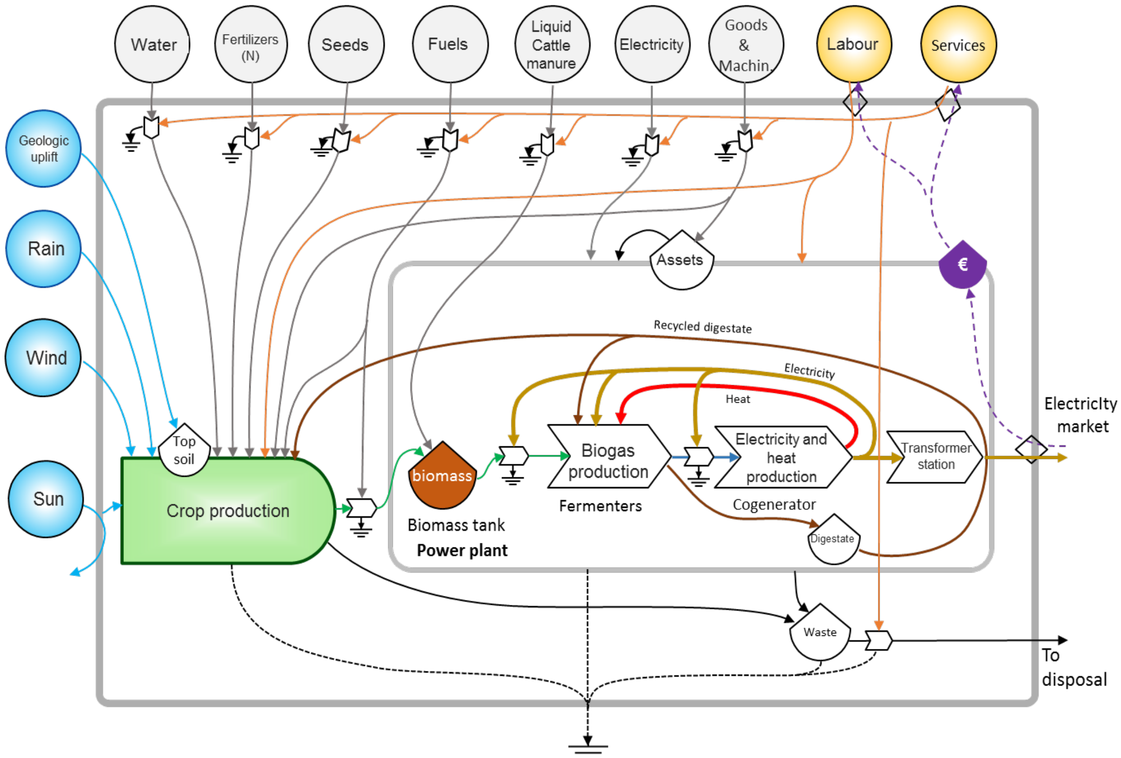

Figure 2. *Energy system diagram of the biogas power plant, including the biomass cultivation.*

THE ANALYSIS

Emergy analysis (Odum, 1996) was applied to the power plant, including the agricultural fields owned by the Company itself. During the inventory phase, local data were collected from the agricultural holding and the building Company, referred to one year of operation (2017 data). Materials, goods and machinery data have been divided by their lifetime.

The energy system diagram (Figure 2) shows all the flows of energy and matter inputs to the system as well as the energy and matter, recycled inside, necessary to produce the electricity. All the conversions of the energy and matter inputs in emergy flows have been done using UEVs updated to the GEB_{2016} of 12.0E+24 seJ/yr (Brown et al., 2016). The emergy table results, not reported here, address a system much dependent on imported resources, mostly necessary for the agricultural production. The electricity production UEV results of 9.15E04 sej/yr with labor and services and 2.67E04 without labor and services.

In order to study a possible refinement of the emergy analysis, the software SCALEM® has been recently developed (Marvuglia et al., 2013), and will be used in a further forthcoming paper to calculate the UEV of the electricity produced by this power plant. As this software uses the LCI matrix to calculate the emergy flow of processes or services, it will be necessary to build the process with an LCA software (see flowchart in Figure 3) like SimaPro (https://simapro.com) or OpenLCA (http://www.openlca.org/) using the database ecoinvent (Wernet et al., 2016). SCALEM® will read the project exported as a matrix in .csv extension. As explained in Marvuglia et al. (2013), this matrix needs to be re-allocated in order to calculate emergy flows according to the rules of emergy algebra, and currently the software contains a tool to perform this re-allocation.

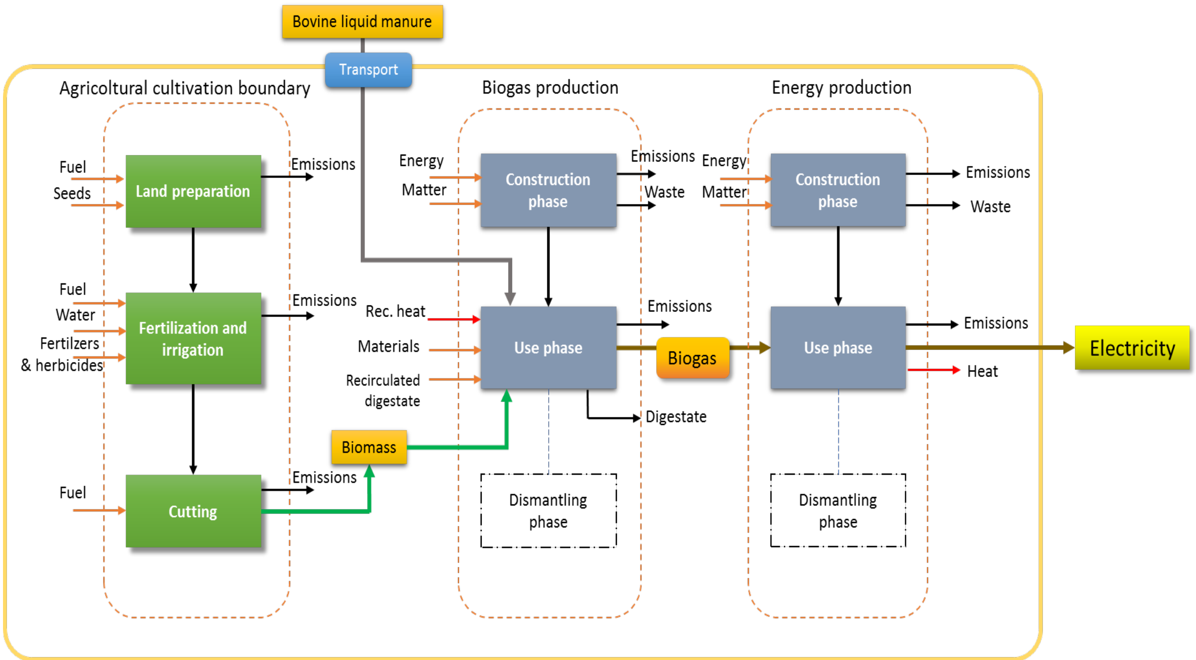

Figure 3. *Life cycle flowchart for the biogas power plant.*

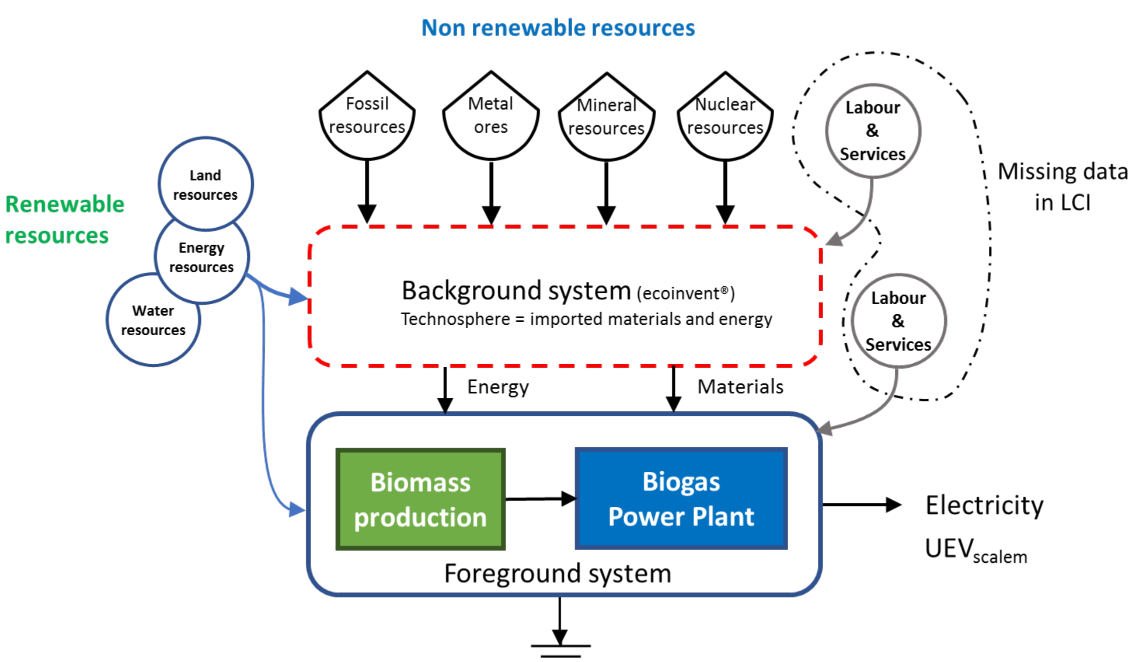

Figure 4. *Graphical representation of SCALEM® emergy evaluation.*

Looking at the general system diagram of Figure 4, it is clear that the emergy calculation performed by SCALEM® follows a different architecture than the classical one. By creating the project using a LCA software (SimaPro or OpenLCA are supported in the latest version of SCALEM®), it is possible to identify two main systems, background and foreground. The first includes the processes not directly assessed by the user. They comprise all the processes delivering products or services used by the process under study (e.g. electricity or transport). The foreground system is instead the process directly studied by the user. SCALEM® is able to account separately for the emergy flows of renewable and non-renewable resources (if present in the ecoinvent description) used up by the background and by the foreground process (local resources), and to calculate the emergy performance indicators accordingly. The issue of Labor and Services quantification remains still to be addressed by SCALEM®, since these flows are missing in the LCA databases. One of the next steps of development of SCALEM® will be the inclusion of these flows by creating an appropriate process of "production" of a unit of work following the approach by Rugani et al. (2012).

Figure 5 describes schematically the steps performed when using SCALEM®. Once the project created in a LCA software (using the "re-allocated" version of the LCI database, as explained in Marvuglia et al., 2013) is exported in .csv format, it can be imported in SCALEM®. When the user choses the functional unit (the process under study, for which one wants to calculate the final EUV) the matrix inversion calculations and the conversion of elementary flows from nature (i.e. natural resources consumed) into emergy are performed. The conversion in into emergy is done using a list of UEVs of natural resources that is already contained in SCALEM®. Obviously, the list can be updated as long as newly updated UEVs are available in the scientific community. The last step consists in the implementation of the *depth first search (DFS)* algorithm on the emergy-based LCI matrix and the summation of the emergy flows that reach the functional unit, thus yielding the UEV of this latter.

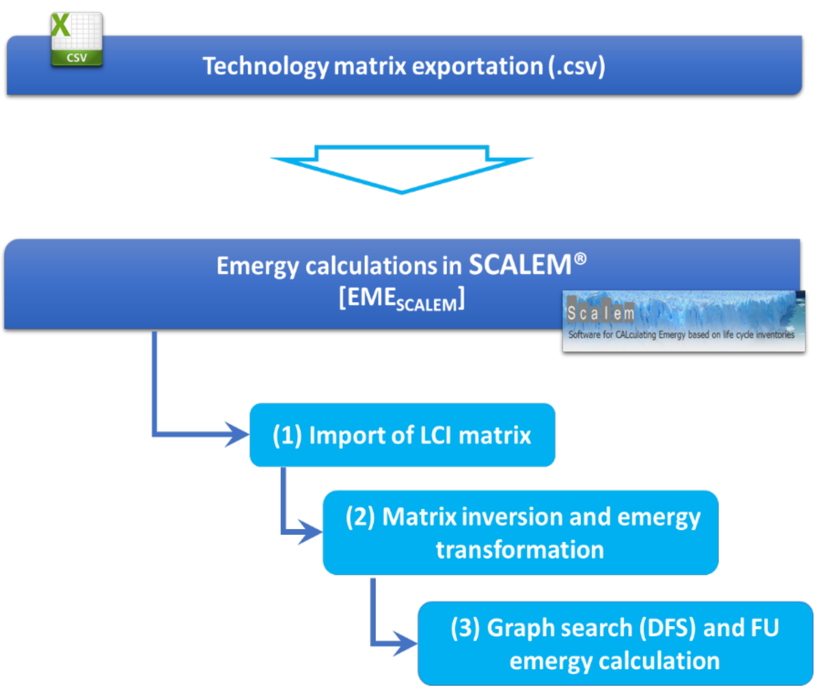

Figure 5. *Schematic procedure of calculation made by the software SCALEM®.*

CONCLUSIONS

Emergy analysis following the SCALEM® approach may actually represent an affective step forward towards a more accurate accounting, at least for systems in which the human activity plays a major role. In particular, it has been shown how further work has to be done to better understand the operational differences in the procedures, in order to obtain reliable, shared and standardized calculation protocols. The reported case study is actually a first step towards a complete analysis of the potential of the SCALEM® approach that should possibly refine the classical emergy analysis complying with the fundamental conceptual and operational aspects of the Emergy theory. This was actually the main purpose of this preliminary study. As far as the results are concerned, the UEV value for the electricity production of the studied power plant (9.15E04 sej/yr with labor and services and 2.67E04 without labor and services) is similar to other values reported in the literature (Brown and Ulgiati, 2012). On the other hand, the system is clearly operated mainly on non-renewable resources and services, but this is not surprising, since the use of large territories intensively cultivated to provide the necessary biomass, shifts the equilibrium of the used resources, making the environmental sustainability of this kind of plants at least questionable. A comparative quantitative approach following the SCALEM® methodology is still to be completed, and has not been reported in this preliminary presentation. Nevertheless, the enhancement process the SCALEM® software is currently going through is likely to render possible in a medium term future the emergy accounting of a number of products produced by all industrial activities. This would allow the compilation of a comprehensive inventory of UEVs of products (as well as services and any process described in LCIs) that could be then used by emergy analysts to compare the sustainability of different processes and perform emergy analysis of large (industrial) systems.

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DOI 10.1007/s11367-012-0403-1