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Research Thesis

EMERGY-BASED SUSTAINABILITY ASSESSMENT OF RENEWABLE ENERGY SYSTEMS AT DIFFERENT SCALES

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Index

Index of figures

Objective of the research

The purpose of my research is to apply Emergy Analysis to different energy production systems based on renewable sources, with the aim at assessing their integrated sustainability and study the effect of the boundary selection on the calculated emergy indicators of sustainability.

Thesis outline

The first chapter introduces the global situation of energy consumption and production, the sustainability concept and an overview on the main methods used for the sustainable assessment; the method Emergy Analysis (EA) is also extensively explained. In the second chapter the application of EA on an Italian biogas power plant is reported while in the third chapter the EA of photovoltaic systems is explored, and the existing studies present in literature are analysed. A general discussion and conclusions close the thesis.

Introduction

Sustainability, sustainable development and renewable energies are often used as equivalent concepts. Sustainability has not a univocal meaning, and since its first “political” definition in the Brundtland Report (WCED, 1987) its purpose shifted from guaranteeing the well-being of future generations to provide a sustainable “growth”, reaching a compromise between the three “pillars”: society, economy and environment. Many other definitions have been proposed (Kuhlman and Farrington, 2010), and scientists keep on debating its biophysical definition, necessary for its correct assessment. When dealing with the energy transition, *sustainability* and *renewable* energy production are called into play. The problem is also in the very definition of “renewability”: its meaning has changed over time, also accordingly to policy changes. For example, in Italy the energy produced by incineration of wastes is considered renewable, and so it can get subsidies as well as energy produced by other renewable sources. Herendeen (2019) reported the case of the “100% renewable energy” city of Burlington (USA), where the renewable electricity energy is essentially produced very far from the city, leading to "unsustainable" environmental burdens ranging from the location of energy transmission lines to the transportation of biomass. It is relevant the case of bioenergies (agriculture and forestry residues, energy crops, zootechnical and food industry residues, etc.) that are considered renewable because derived from plants, while many studies have proven that they are not really “clean” and viable from an economic, energy and emergy point of view (Jacobson, 2019; Tomei and Helliwell, 2016; Ulgiati, 2001). It is, therefore, necessary to analyse complex systems like energy production ones from a systemic point of view, considering different spatial and time scales. In this perspect, Emergy Analysis permits to assess the real sustainability of systems, understood as to promote, design, and develop human-built and social systems that are structurally coupled with feedbacks that maintain themselves and contributes to their contextual environment. This research studies the implications of the boundary selection in the assessment of the sustainability of two types of energy production: biogas power plants and photovoltaics.

Chapter 1. Overview of the energy sector

1.1. Introduction

In the last decades, energy has assumed a pivotal role in any debate concerning sustainability and sustainable development. Energy enters as a major aspect all the main global problems we are facing: environment degradation, poverty, migration, underdevelopment, conflicts, climate change and inequalities are all issues that depend on or are strictly related to the energy, in terms of its availability, sustainability, consumption and safeness, involving political, social, economic and ethical issues. Energy efficiency is also often addressed as the mandatory starting point for a global strategy of sustainability, but it does not necessarily reduce the consumption, due to the possible associated increase of the energy demand (Sorrell, 2009). The development of specific narratives, aimed at creating a specific consensus, has been a common strategy throughout history. Socio-economic mainstream requires – and allows at the same time – a complex and articulated narrative to support the adoption of factual policies, and the case of energy is becoming more and more sensitive to this attitude. The objectives of the energy policies are rarely explicitly addressed, and suitable indicators for the effectiveness of the actions and measures are almost always lacking in the corresponding narrative. Renewable energy sources are often seen as part of the future solution to the problem of keeping the energy business as usual, while realizing the mandatory transition from the fossil fuels imposed mostly by the climate change issues. Be this technology optimism justified or not, the compatibility of a global economic growth with a liveable geobiosphere for the future generations is questioned, in particular considering the systemic approach that is mandatory to handle the issue.

1.2. Global energy production

The gross electricity production in the world has grown continuously since 1974 to 2017, with an average annual growth rate of 3.3%[1], reaching the amount of 25.721 TWh in

[1] including pumped hydro.

2017 (IEA, 2019). Considering the evolution of energy production in OECD and non-OECD countries (Fig. 1.1), it can be observed a divergence around the year 2000: the average growth rate of non-OECD countries from 2000 to 2017 is 6.4%, while, in the same period, in the OECD countries the growth rate decreased to 1.1%. In 2010 the non-OECD gross energy production overcame that of the OECD for the first time and continued to grow since then.

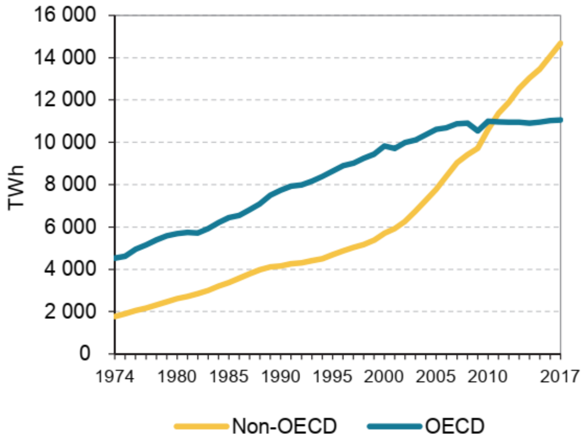

Fig. 1.1. Total gross electricity production from 1974 to 2017 in OECD and non-OECD countries.

In 2017 fossil fuels accounted for 64.5% of total world gross electricity production (GEP) (Fig. 1.2), of which the main contribution was that of coal (≈ 38%), followed by natural gas (≈ 23%), nuclear (≈ 10%) and oil (≈ 3%). Among the renewable sources of energy, hydro provided the greatest contribution to the GEP (≈16%), followed by wind, biofuels, waste, solar, geothermal, tidal, and other sources, that together accounted for 9% of the total GEP.

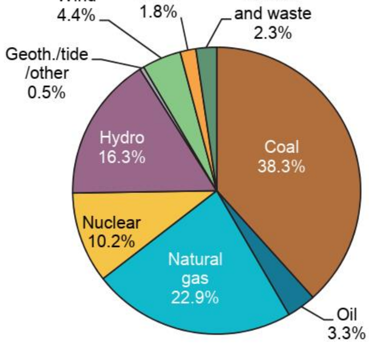

Fig. 1.2. World gross electricity production by sources in 2017 (IEA, 2019).

Comparing the evolution of electricity production by sources in the OECD and non-OECD countries (Fig. 1.3), it is evident the increasing role played by coal in the non-OECD countries, while in the OECD countries there is an increase in the electricity production from natural gas and renewables.

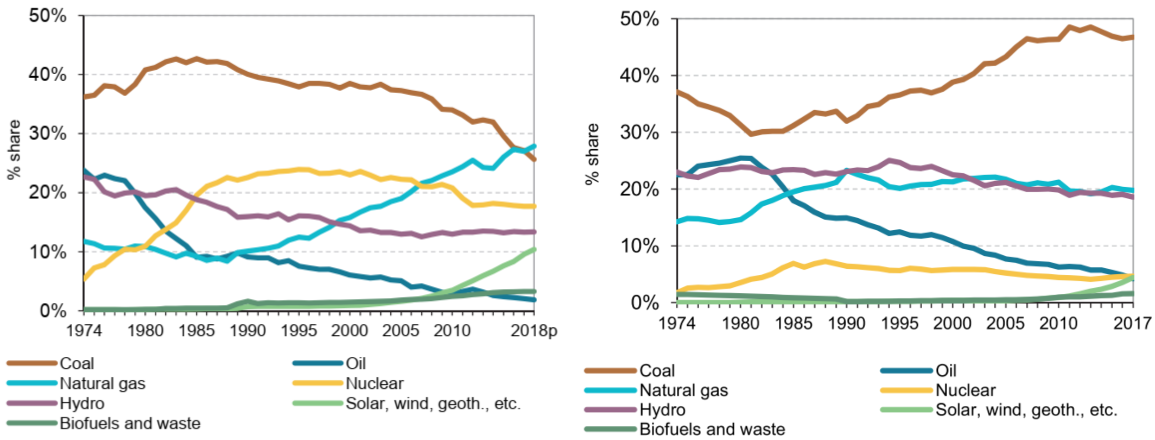

Fig. 1.3 Share of gross electricity production in OECD (left) and non-OECD (right) countries, by sources.

In the OECD countries, electricity production from renewables in 2017 (Fig. 1.4) was mainly driven by hydroelectric power plants, followed by wind and solar photovoltaics (PV). Energy production from PV technology grew much faster than energy produced from other renewable technologies (IEA, 2018a).

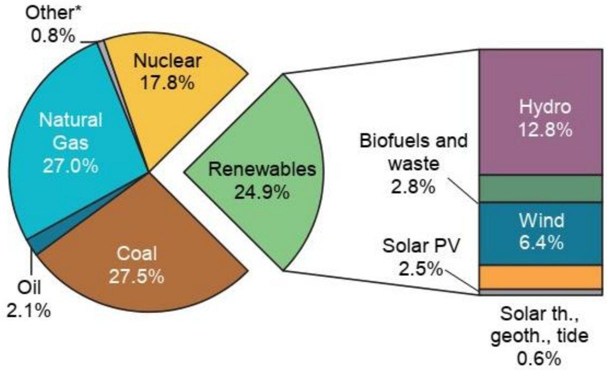

Fig. 1.4. Renewable shares in OECD electricity production in 2017. Other includes non-renewable wastes and other sources not included elsewhere* (IEA, 2018a).

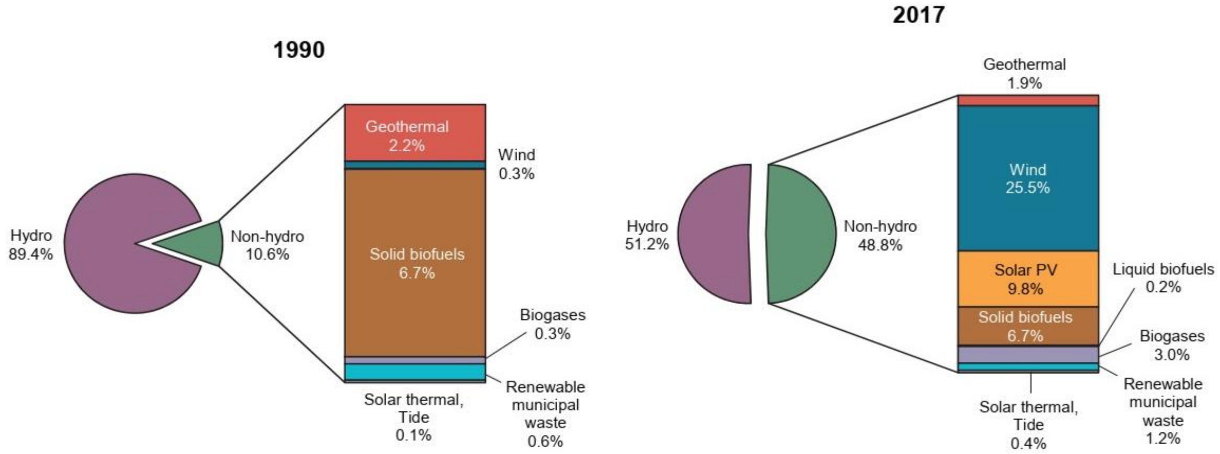

Fig. 1.5. Changing shares of OECD renewable electricity production from 1990 to 2017. (IEA, 2018a)

The global population reached 7.7 billion in mid-2019, and since 2015 it is growing at a rate of about 1.1% (United Nations, 2019). Considering the UN projections, the global population is expected to reach 8.5 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100 (Fig. 1.6). Population growth and related economic development are increasing the use and competition of non-renewable resources while intensifying the consumption of biotic resources, the production of harmful emissions and waste, and the destruction of natural habitats (UNFPA, 2012). Environmental damage may become particularly significant in sub-Saharan Africa and parts of south-east Asia, where high population growth rates coincide with a direct dependency on natural capital – forests, fisheries, freshwater, etc. (IOM, 2009; OECD, 2018).

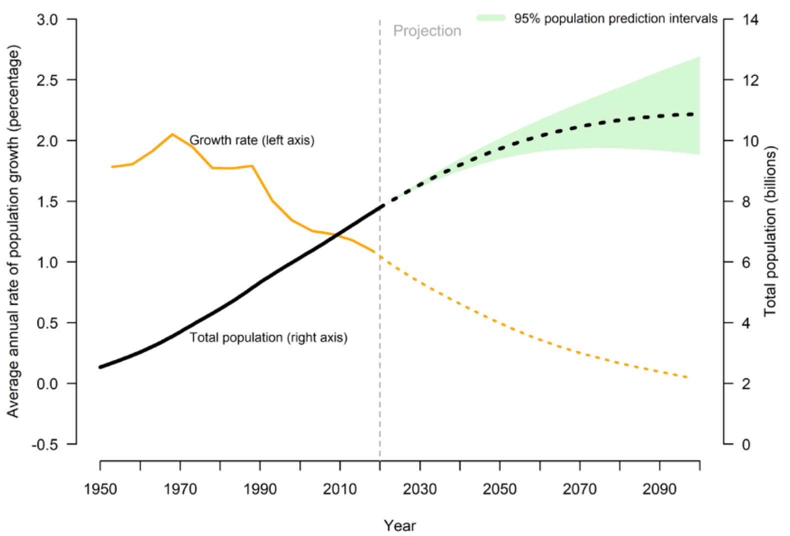

Fig. 1.6. Population size and annual growth rate for the world. (United Nations, 2019).

The linkages between energy systems and environment are at multiple levels and scales – from local to global: locally, the resource extraction, their processing, and the energy conversion can affect negatively ecosystems and human health (Watts et al., 2017); globally, the pressure of humans on Earth systems is carrying to an irreversible change in the global equilibrium (IPCC, 2014). The global anthropogenic GHG emissions from electricity production accounted in 2015 for over 2/3 (Fig. 1.7), and for more than 80% of the global CO_2 emissions. 60% of the global CO_2 emissions from electricity and heat production comes from Asia (Fig. 1.8).

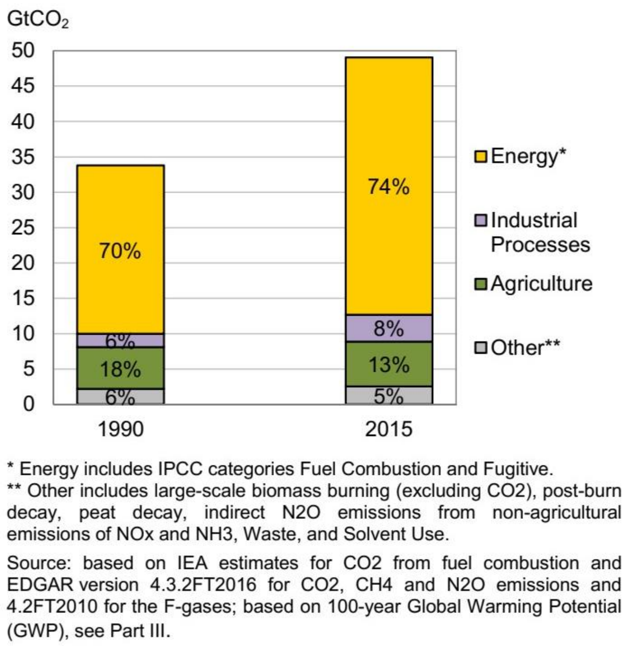

Fig. 1.7. Global anthropogenic GHG emissions change from 1990 to 2015. (IEA, 2018b).

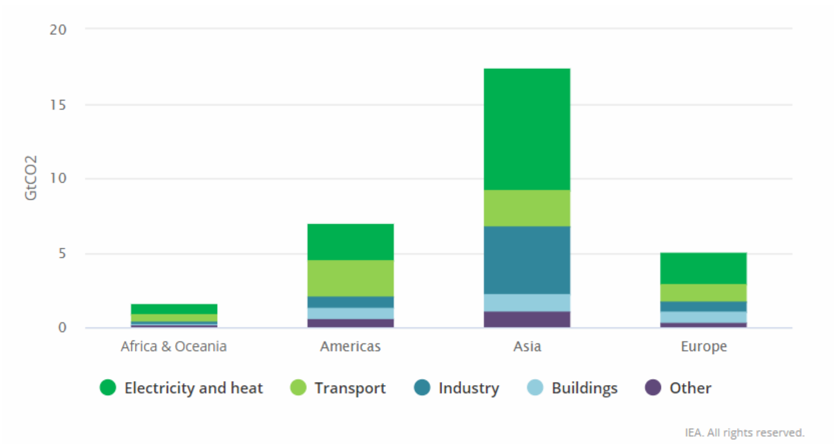

Fig. 1.8. CO_2 emissions by sector for selected regions (2016)

The amount of emissions grew up continuously since 1971 (IEA, 2018b), and this trend (Fig. 1.10) is expected to be the same in the following years, warning that the current efforts to reduce the climate change could be not sufficient to meet the objectives of the Paris Agreement (Fig. 1.11 and Fig. 1.12). The growing up of energy emissions in recent years (since 2000) is mostly due to non-Annex I countries, which almost doubled the energy-related emissions from 1990 to 2015, while in the Annex I[2] countries the emissions lowered by 10% in the same period. The shift towards a low-carbon world requires mitigation efforts that must occur across all countries and must involve both energy supply and demand.

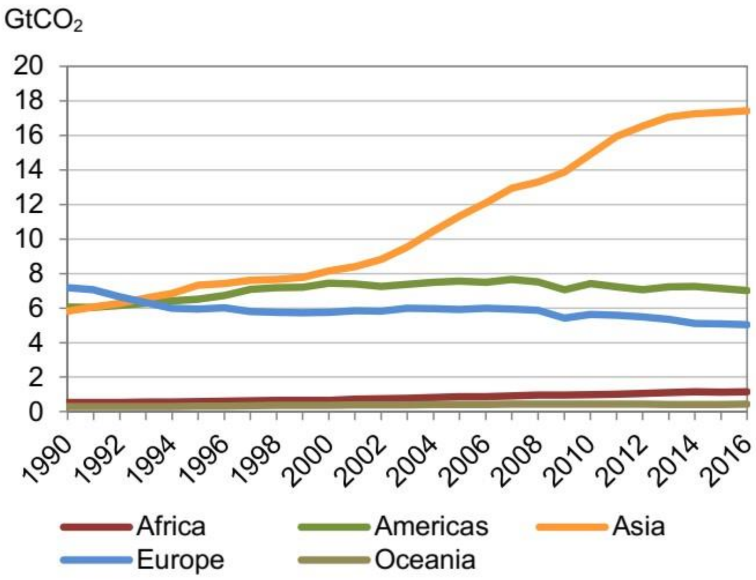

Fig. 1.9. Regional CO_2 emissions from fuel combustion.

[2] Annex I countries: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein (not available in this analysis), Lithuania, Luxembourg, Malta, Monaco (included with France), the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, the United Kingdom and the United States.

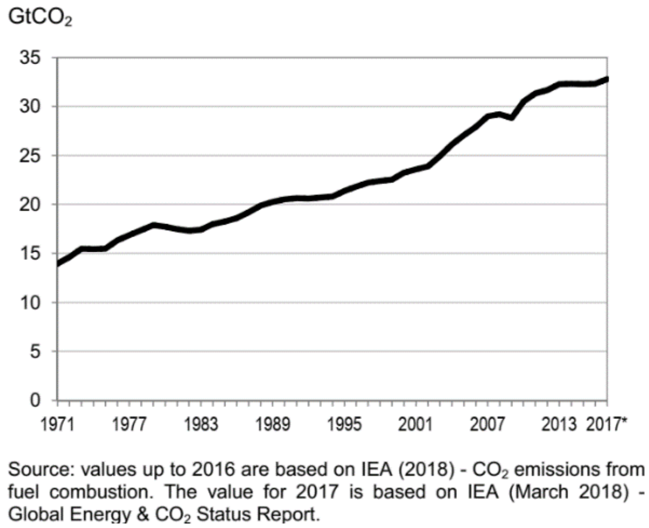

Fig. 1.10. Global evolution of CO_2 emissions from fuel combustion (IEA, 2018b).

The Paris Agreement[3], adopted in December 2015, reports the GHG mitigation obligations for all developed and non-developed countries. The ambitious targets set the limit of the temperature rise below 1.5°C, in so achieving a "balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century", presuming to obtain net-zero emissions by this time. The Paris Agreement is founded on Nationally Determined Contributions (NDCs) made by countries, which include the quantitative emissions reduction targets for the period from 2020 to 2030 or 2025.

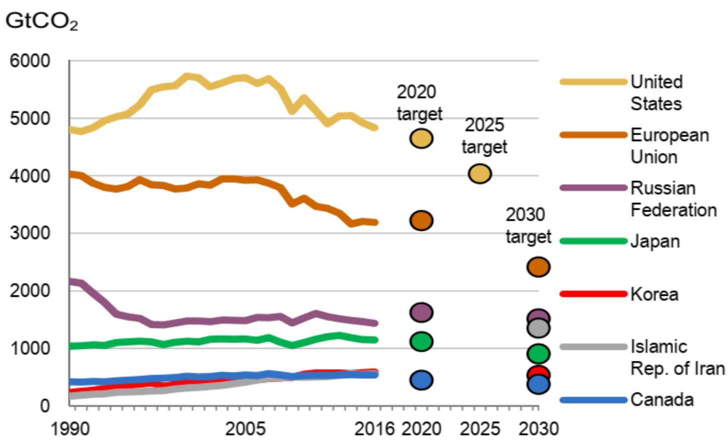

Fig. 1.11. Historical trend of CO_2 emissions and emissions reductions targets established by the Paris Agreement, for the first ten emitting Parties (excluding China and India) (IEA, 2018b).

[3] ratified by 185 parties, August 2019

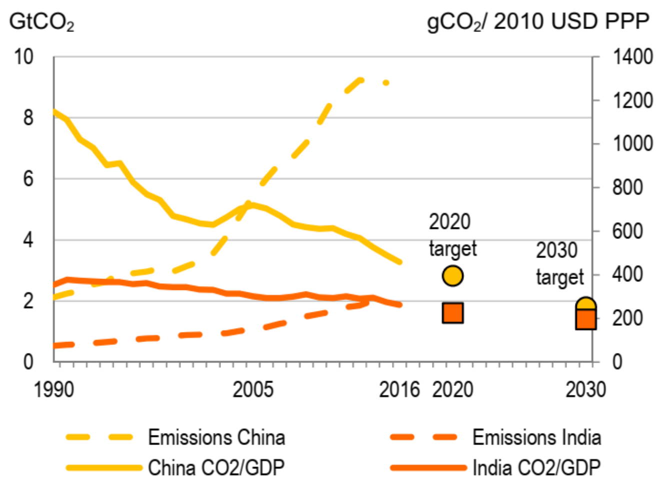

Fig. 1.12. Historical trend of CO_2 emissions and emissions reductions targets established by the Paris Agreement, for the China and India (IEA, 2018b).

1.2.1. The energy transition from fossil fuels to renewables

The growth of the population together with the increased consumption of resources due to the actual business-as-usual production and consumption styles is generating an unsustainable load on the environment. The increasing demand for energy, yet mostly dependent on non-renewable resources (e.g., fossil fuels) and the damage due to their extraction, processing and combustion (e.g. land transformation, climate change, health and environmental issues...) call for an urgent global transition to a sustainable energy system. In the Energy Union Package the European Commission (2015a), states:

"...our vision is of the Energy Union as a sustainable, low-carbon and climate-friendly economy that is designed to last; [...]we have to move away from an economy driven by fossil fuels, an economy where energy is based on a centralised, supply-side approach and which relies on old technologies and outdated business models."

The tools adopted by the EU (European Commission, 2017) to monitor the progress toward a transition to a sustainable energy system are a set of indicators (in total 24) derived by statistics data on energy consumption and production, energy import, prices, investments, Green House Gases emissions (GHG), land use and land-use changes and forestry (LULUCF), and energy consumption from renewables (Table 1). Regarding the latter, the main goal is to achieve at least 27% of the consumption from renewable energy in 2030.

Table 1. Objective of European Union (European Commission, 2017)

Objectives	Area
Monitoring the relative dependency of the Member States and the EU as a whole on net imports of main energy carriers and on specific trade partners, and the overall reliability of the energy system (i.e. its overall ability to supply energy without interruption)	Energy security
Monitoring progress towards an EU internal energy market in terms of competition, cross-border trade and consumer empowerment	Internal energy market
Monitoring progress on the 2020 and 2030 targets for moderating primary and final energy demand and in terms of energy savings and energy intensities in various sectors, including transport	Energy efficiency
Monitoring progress on the 2020 and 2030 targets on greenhouse gas (GHG) emission reductions, renewable energy share in gross final energy consumption and changes in GHG intensity	Decarbonisation
Monitoring research, innovation and development activities relating to the European Strategic Energy Technology Plan (SET-Plan)[4] and Energy Union priorities; monitoring energy prices and cost differentials between the EU and its major trading partners.	Research, innovation and competitiveness

The International Renewable Energy Agency, regarding the energy transition, predicts that the future energy system will be characterized by "a vast expansion of low-cost renewables, smarter and much more flexible electricity grid, and considerable increases in the numbers of vehicles and other products and processes that run on electricity. Digitalisation, decentralisation and electrification, supported by

4 https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan

innovative policy frameworks and market instruments, are poised to create new business models, change consumer behaviour and radically transform established systems" (IRENA, 2019). Predictions made IRENA and IEA seems to disregard the limited reserves on which energy production relies on and considers technology and energy efficiency as the solution of the global energy system problems, on which it must be invested more (IEA, 2018c). The role of technology in energy transition and global problems was extensively analysed and discussed by Gonella et al. (2019a), where the Authors state that "As long as global and local energy systems are run by corporations, any attempt to change things at specific levels by technology will fail, since the system will rearrange itself to maintain the profit, which is the real systemic purpose".

1.3. The sustainability assessment of energy systems

1.3.1. The sustainability concept

The concept of sustainability has not a univocal definition, and at present, the debate on a globally accepted definition of sustainability is yet actual (Purvis et al., 2018). In the first formalization of this concept, the Brundtland Commission in the document "Our Common Future" (WCED, 1987) stated:

Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

In this document, the Commission admits the unsustainability of the present economy, but on the other hand, calls for its further expansion without considering the limitation of the global resources. In fact, the first conceptualization of sustainability was represented as an intersection of the three individual and separated areas: *economy*, *society* and *environment* seen as individual areas not interconnected one with the other (Fig. 1.13).

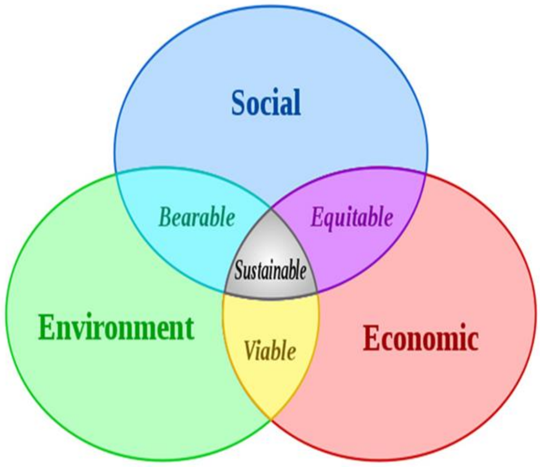

Fig. 1.13. The three pillars of sustainable development.

This interpretation was criticized by the American ecological economist Herman Daly, father of the steady-state theory, who considered the economy as a subsystem of the biosphere, dominated by transformations of matter and energy, that aim to serve the humans needs (Fig. 1.14). For Daly (1991):

...a sustainable economy is one whose depletion is within regeneration rates and whose pollutions within absorptive capacities of the containing biosphere.

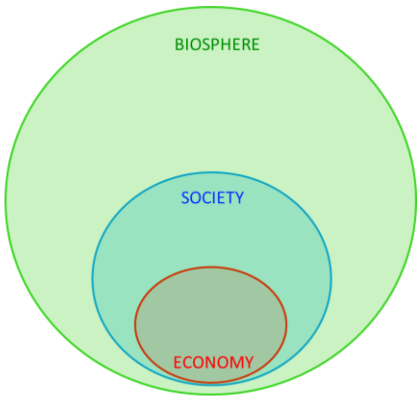

Fig. 1.14. The real relation between economy, society and biosphere.

This idea can be represented as a stock-flows diagram (Fig. 1.15), in which the condition of sustainability is reached when the rate of harvesting is the same of the regeneration rate of the resources, and the rate of production of pollutants is the same of their absorption or degradation rate. If the rate of change of these stocks exceeds the ability of the system to respond, it loses its sustainability and viability.

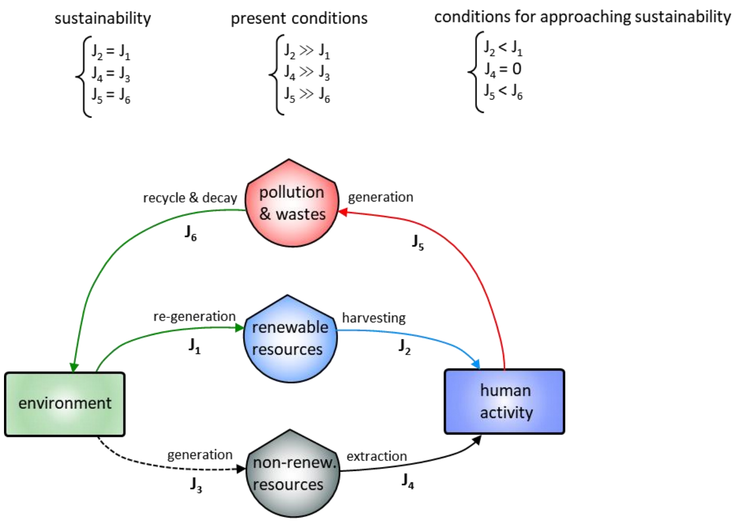

Fig. 1.15. The conditions for sustainability (from Daly, 1991).

Goodman and Daly (1996) defined sustainability also as the "maintenance of different types of essential capital" that can be divided into natural and human capitals. Therefore, sustainable development should have the goal to guarantee the equitable use of all these forms of capitals.

Considering the different vision of economics, sustainability can be classified as *weak* and *strong*. The *weak* sustainability approach (based on neoclassical economics) considers the natural capital as replaceable with technological capital. This approach does not take into account the scarcity of resources and the irreplaceable function that certain natural resources have. This is the case of the exploitation of soil for agriculture and the maintenance of its productivity by means of strong fertilization, irrigation and mechanization practices. The *strong* sustainability, on the other hand, is "the maintaining intact of natural capital and man-made capital" (Costanza and Daly, 1992), as not all functions of natural capital are replaceable and there are some critical levels above which is not possible to compensate the damages made to ecosystems (e.g. the maximum level of global temperature increase to avoid climate change threshold effects). Due to the objective difficulty of calculating the threshold levels for substitutability, some people claim that the best approach should be that of maintaining intact all the natural, economic, social, institutional and technological capitals independently, and the functionality of ecosystems (Holling, 1973). Being this approach rather radical, the compromise should be to limit the human activities within the carrying capacity of the remaining natural capital. Therefore, there is a need for indicators to understand where we are with respect to the goal of sustainability.

1.3.2. Methods for sustainability assessment

The sustainability assessment of energy systems needs integrated approaches, in order to involve in the analysis all the previously cited aspects of sustainability. No simple approach seems to be able to deal with this complexity and several indicators have been developed for this scope, providing information from a different point of view. Sustainability indicators and methods can be classified in different ways. Some classifications are reported hereunder:

- *Linear, Systemic*;
- *Static, Dynamic*;
- *Integrated, Isolated;*
  - *user*, *donor* side;
  - *environmental, economic, social, technological, ethics*;
  - *single score, grouped, composite*;
    - *descriptive* (e.g., % of energy produced per fuel type);
    - *basic normalized* (e.g., energy consumption or use per GDP or per capita);
    - *comparative*;
    - *structural indicators* capturing the economic structure and its distribution to measure energy system performance;
    - *intensity* (energy performance of an activity or a system);
    - *decomposition* (disaggregate the influences of different factors into sub-components);
    - *causal* (linking influencing causes to energy use);
    - *consequential factors* (measure the human factors and energy use link); and
    - *physical* (use physical outputs or inputs to measure performance, like exergy).

Some examples of methods classified by using these classifications are:

Static and linear methods based on integrated evaluations of environmental, social and economic aspects from a user side point of view:

- LCA – Life Cycle Assessment, for the evaluation of the possible impacts of services or processes on environment and humans along their lifespan; standardised method (EC-JRC, 2010; ISO, 2006);
- sLCA — Social Life Cycle Assessment, for the evaluation of the possible positive or negative impacts on society of services or processes along their lifespan (UNEP/SETAC, 2009);
- LCCA – Life Cycle Cost Analysis, that evaluate the total cost of services or processes, along all their life cycle (Estevan et al., 2018);
- ELCA - Exergetic Life Cycle Analysis: is used to account the exergy input required by the system, considering the renewable and non-renewable sources (Cornelissen and Hirs, 2002).

Static and linear method based on isolated evaluation of technology or environmental aspects from a user side point of view:

- EROEI - Energy Return On Energy Invested, rate of usable energy produced by a certain energy system to the amount of energy used to produce the usable energy.
- Water footprint: quantifies the potential environmental impact on water of a product, process or organization during its lifespan (ISO, 2014);
- Carbon footprint: total GHGs emissions in CO_2 equivalents directly or indirectly produced by a product, service or organisation (ISO, 2018).

Static and linear method based on integrated evaluation of environmental aspects from a user side point of view:

- Ecological footprint: it calculates the necessary land area for the production and maintenance of goods and services consumed by a community (Wachernagel and Rees, 1996).

Static and linear method for the calculation of composite index from a user side point of view:

- ESI - Environmental Sustainability Index: it is a composite index that integrates 76 variables, tracking natural resources, past and present pollution levels, environmental management efforts, and the capacity of a society to improve its environmental performance. These variables are condensed into 21 indicators which fall into the following categories: environmental systems, reducing environmental stresses, reducing human vulnerability to environmental stresses, societal and institutional capacity to respond to environmental challenges, and global stewardship (Esty et al., 2005).

- MCI – Material Circularity Indicator: an indicator of the "circularity" of a process, based on the amount of virgin/recycled material, durability, destination after use and efficiency of recycling: it was developed on a product and company level. Other optional indicators can be used to assess risk (business-related), toxicity, material price variation, energy usage and CO_2 emissions (Ellen MacArthur Foundation and Granta Design, 2015).

Systemic methods for the integrated evaluation of environmental, social, economic sustainability from a donor side point of view:

- EA - Emergy Analysis: quantifies the work made directly and indirectly by the geobiosphere to produce a certain product or service, in the common unit of Emergy (Odum, 1996a); it includes the quantification of natural resources, human labour, money and information in a given period of time and the calculation of indicators of sustainability;
    - Dynamic EA: simulation of the emergy flow variation along time; based on the principle of Maximum Empower. Environmental management that maximises emergy production and use (''maximum empower'') develops more real wealth in the combined humans and environmental systems (Odum and Odum, 2000b);
- ECEC – Ecological Cumulative Exergy Consumption (Hau and Bakshi, 2004): considers the ecological processes that transform the global exergy inputs into ecological goods and services processed by industrial processes. It is similar to EA and they are equivalent if the following are identical: (I) analysis boundary, (II) allocation method, and (III) approach for combining global energy inputs;

- EEA – Extended Exergy Accounting (Sciubba, 2001): it unifies the Cumulative Exergy Consumption (CEC) and Thermoeconomic methods, including the exergy, flows of Capital, Labour and Environmental Remediation Production Factors. The CEC of a product is the sum of the raw exergy of the original constituents that form the input to the production process and the weighted sum of all the exergetic inputs into the process itself.

Certainly not thorough, this list shows the variety of tools that can be adopted to evaluate the sustainability of processes, services, communities, nations, and many others are continuously proposed by the scientific community (Agostinho et al., 2019; Cîrstea et al., 2018; Coss et al., 2017; García-álvarez et al., 2016; Ghenai et al., 2020; Giannetti et al., 2019; Hadian and Madani, 2015; Liu et al., 2017; Marvuglia et al., 2018; Sala et al., 2015; Viglia et al., 2018).

By considering a systemic vision, the primary challenge for sustainability should be to promote, design, and develop human-built and social systems that are structurally coupled with feedback that maintains themselves and contributes to their contextual environment. The System Thinking approach on sustainability assessment was applied on several energy systems: wind (Tejeda and Ferreira, 2014), bioenergy (Kaggwa, 2013), energy transition (Sgouridis and Csala, 2014). The theory of Daly, together with the systems thinking theory of D. Meadows (2009), has recently been applied on the energy field by Gladkykh et al. (2018), with the aim of analysing the sustainability of different energy policies. They verified that energy policies always need to be explored as "part of the broader causality structure into which they are embedded", if not they could carry to undesirable side effects. In this framework Emergy Analysis provides a contribution to the understanding of the systemic viability and sustainability of energy production processes.

1.4. The Emergy Analysis

In this chapter the theory of Emergy Analysis is reported, together with the phases of the Emergy evaluation and the description of the main emergy indicators.

1.4.1. Theoretical framework[5]

Emergy analysis is an environmental accounting method which aims at quantifying the geobiosphere support to processes and the sustainable patterns for integrated human and ecological systems. Its theoretical framework was developed by H.T. Odum (1988, 1996, 2007) and is based on studying how complex systems utilise and organise the resources needed for pursuing their systemic purpose, in so addressing the upstream investment of resources as a quantification of the "real" value of a product or a service. A perspective shift from the user-side to the donor-side is therefore realised, allowing to determine the burden of geobiosphere in contributing to some human activity and thus, implicitly, its sustainability. The quantity introduced for accounting all resource contributions (including human labour and services) under the same unit is Emergy, defined as the total available energy (exergy), used up directly and indirectly to produce a specific form of energy (a product or a service, in mass or energy unit), and expressed in term of solar equivalent. The emergy value of something includes the contributions of both the geobiosphere and the human activities – and so the economy – related to the work necessary for the creation. The unit of emergy is called emjoule. Since solar energy is the energy form typically used as a reference, it is called solar emjoules (sej). The emergy flows considered in the emergy accounting procedure, take also into account quantities not computable as money or energy in classical economic or energetic analyses, and so usually neglected. It is worth stressing that emergy analysis is however set up to address several issues related to the sustainability of a system, including environmental and economic aspects and the upstream impact on the geobiosphere,

[5] Chapter based on: S. Spagnolo, G. Chinellato, S. Cristiano, F. Gonella, A. Zucaro (2019) Integrated indicators of sustainability for the assessment of renewable energy sources and networks on different scales (under review in the Journal of Cleaner Production).

measured in terms of emergy (Brown and Ulgiati, 2004; Buonocore et al., 2014; Cristiano and Gonella, 2019)

The emergy algebra is widely described in Odum (1996) and can be summarised into the general rules which state that: (1) all emergy sources to a process are assigned to the output. From this one other two rules are derived, considering different types of outputs: (2) when dealing with *co-products*, the total emergy input to the system must be assigned to each of them; (3) in the case of *splits* the total emergy input must be assigned to each pathway according to the percent of energy of each of them. A fourth rule completes the framework: (4) energy flows cannot be counted twice within a system. This means that feedbacks cannot be double-counted and when co-products reunite, emergy cannot be added up, but only the largest one must be considered.

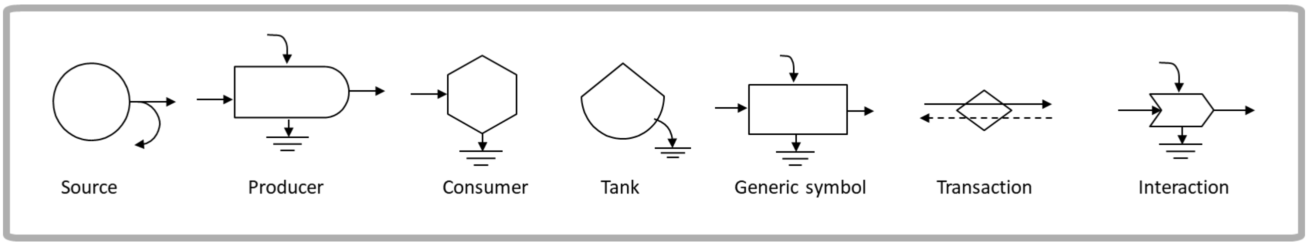

Fig. 1.16. Graphic elements of the emergy diagrams.

1.4.2. Phases of Emergy Assessment

The development of emergy accounting of a system, as set by Odum (1996) is made basically of three steps:

1. preparation of the emergy diagram;
2. preparation of the inventory table for the flows, their respective emergy values;
3. determination and interpretation of emergy indicators suitable for the analysis purpose.

The system boundary is the virtual boundary that defines inflows, outflows, and internal flows, while a temporal boundary is set for the time scale of the analysis. The main graphic elements of the emergy diagrams are shown in Fig. 1.16. They come from the symbolic language of the energy networks. The diagram can be set up at different levels, including sub-systems and processes depending on their relevance for the study. The focus of the study can be therefore addressed either to a local system or considering it together with its support system, which in turn will exchange resources with further external environments. In this way, the analysis can highlight the hierarchy of the energy flow networks, showing how some sustainability indicators may change when calculated at a different systemic level.

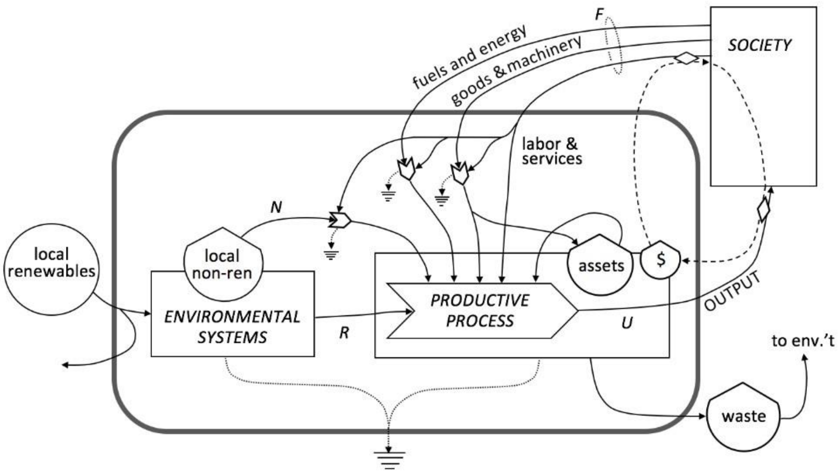

Fig. 1.17. Emergy diagram of a generic productive process.

Fig. 1.17 shows the emergy diagram of a generic production system, with flows grouped depending on their origin. The environment provides renewable and non-renewable resources, named R and N (local) or F (imported). Inputs from main economy are the necessary purchased resources and services, usually put in the non-renewable set. $U=R+N+F$ is the total emergy yield of the system. Labour and services enter in the main process(es) and in the activation of external resource flowing. The money flow (dashed lines) has a circular pattern and is necessary to pay the labour and the services. Energy

Once the emergy diagram is set up, the flows must be expressed in emergy units. For each quantity, a *Unit Emergy Value* (UEV) is used, representing the emergy necessary for generating one unit of output (mass, energy, labour, money, etc.). Fundamental UEVs are those related to energy and matter. The *Transformity* (sej/J) is the emergy input per unit of available energy output, thus the transformity of a product is the sum of all the inflows emergy divided by the available energy of the output.

When comparing same-product systems, lower transformity indicates a low need of resources per unit of product, a kind of efficiency that is not related to the economic one ("parallel-quality", see Paoli et al., 2008). By definition, solar radiation transformity is 1. The *Specific emergy* (sej/g) is the emergy per unit mass of output, that should consider also the energy required to concentrate a material spatially and chemically. Also, money and labour may be expressed in emergy units: *Emergy per unit money* is the emergy used in the creation of an economic unit, expressed in the money currency, depending on the purchasing power of a currency. It is given by the ratio of the annual total amount of emergy used by a Nation and its Gross Domestic Product (GDP). In multi-product systems, a *joint transformity* (J_{tr}) may be also calculated to evaluate its overall efficiency, by dividing the total emergy input to the system to the total available energy of the outputs (Bastianoni and Marchettini, 2000). *Emergy cost of labour* is the emergy supporting a unit of labour to a process, evaluated by computing the money necessary for labour or service provision in terms of money earned by the worker, in sej/€. This definition may appear questionable, but as a matter of fact, it is an actual averaged measure of the information carried into the system by a worker, paid proportionally to his/her professional skills and competences. Anyway, this average information has been demonstrated to be reliable in the analysis of most systems (Ulgiati, 2014).

The emergy inventory table reports all the input flows to the system (in their original unit) as well as, for each of them, the UEVs (sej/unit), the references for such UEVs, and the corresponding emergy flow for each item that is therefore calculated by multiplying input flows and related UEVs (in sej, sej/year, etc.).

1.4.3. Emergy indicators

A set of emergetic indicators is defined in the literature, allow to understand the systemic performance of the case analysed. With reference to Fig. 1.17 a selected shortlist of emergy indicators is here reported.

Emergy Yield Ratio, EYR=U/F

The total emergy output *U=(R+N+F)* is compared to that purchased from economy (*F*). It measures how well the system exploits the environmental resources locally available (R and N), without distinguishing between renewables and non-renewables, and so evaluating the net benefit that is provided to the society. Fossil fuels extraction is a typical process with a high EYR, since it exploits large amount of local non-renewable resources emergy (namely, the emergy of the fuel in the ground, which accounts for the work made in the past to synthesise and concentrate hydrocarbons), without needing relevant economic support (it must be stressed that as the natural reserves of fuels will decrease, this index will decrease in turn; Brown et al., 2011).

Environmental Loading Ratio, ELR=(F+N)/R

The ratio between the non-renewable fraction of resources used up by the system (goods and human services), and that coming from local renewable resources. It distinguishes between the non-renewable and the renewable fraction of the resources exploited by the system and measures the environmental stress

Emergy Sustainability Index, ESI=EYR/ELR

It is an integrated evaluation of the economic and environmental dimensions, expressing the contribution to a super-system per unit load of the subsystem. In fact, it encompasses two indices sensitive to local/non-local (EYR) and to renewable/non-renewable (ELR), respectively. In this sense, it gives a measure of long-term sustainability.

Areal empower intensity, AEI=U/A

The ratio between the total emergy output *U=(R+N+F)* and the area *A* necessary to the process (invested emergy per unit of land).

Recycle Benefit Ratio, RBR

The ratio between the emergy used in providing material from raw resources to the emergy used in the recycling process.

Recycle Yield Ratio, RYR

The ratio of emergy in recycled material to the emergy used for recycling. RYR evaluates the benefits that society receives by recycling materials than using the raw resource from nature.

Indicators represent powerful tools in decision-making processes, since they may address different technological or socio-economical solutions. On the other hand, the reliability of the obtained indicators requires a correct interpretation of their meaning and the evaluation of data sensitivity and uncertainty, which are critical points for such a complex approach, as discussed later.

Chapter 2. Emergy Analysis of biogas power production: An Italian case study[6]

2.1. Introduction

Energy demand is a crucial topic at a worldwide level, with an expected growing global economy still mostly depending on non-renewable fossil-based products also in the next decades (IEA, 2018d). Issues arise since (1) non-renewable sources are limited by definition – and there is a clear limit to economic and population growth on a finite planet (first pointed out by Meadows et al., 1972) – and (2) the scientific evidence addresses human activity as major responsible of global climate change, being tightly related to the fossil fuel consumption driving our economies since the beginning of the current industrial era (see for example the most recent IPCC report by Masson-Delmotte et al., 2018). It is in this critical framework that the development of environmentally friendly supply chains from renewable feedstocks has started drawing increased attention in the last decade. Among the renewable sources of energy, biomass is expected to cover part of the energy need of urban areas in different sector: solid biomass for heating and cogeneration units, biofuels for transport, and biogas and syngas for power generation, transport and injection into the gas grid (IEA, 2017; Scarlat and Dallemand, 2018), so providing suitable alternatives to the use of fossil fuels. Increased bio-based strategies, entailing both reduced dependence upon imported fossil fuels and reduced greenhouse gas (GHGs) emissions, have been inspired economy adjustments at a worldwide level, (Aquilani et al., 2018; Bennich et al., 2018; Imbert et al., 2019; Ingrao et al., 2018; Laibach et al., 2019; Zabaniotou, 2018). The Europe 2020 strategy for smart, sustainable and inclusive growth (COM, 2010) sets several targets for climate change and energy sustainability. Among these goals are the nationally binding targets of 20% reduction of the greenhouse gas emissions in the Union (with respect to 1990 levels) and the 20% increase in the Gross Final

[6] This chapter is based on the following paper submitted to the Journal of Cleaner Production:
S. Spagnolo, G. Chinellato, S. Cristiano, F. Gonella, A. Zucaro (2019) Integrated indicators of sustainability for the assessment of renewable energy sources and networks on different scales.

Consumption (GFC) of energy from renewable sources ("The climate and energy package": EC, 2009a, 2009b). The Directive 2009/28/EC (EC, 2009a) sets the specific national targets for each Member State of the European Union: the goal for Italy is to cover the 17.0% of the GFC with renewables by 2020. This goal was exceeded in 2017 when the 18.3% of the GEC was reached. The next non-binding target set by the Italian National Renewable Energy Action Plan (MISE, 2010) is to reach 26.4% of the GFC with renewables by 2020. The Italian DM 23/06/2016 (MISE, 2016) promotes the production of energy from renewable sources (excluded photovoltaics) by establishing a premium tariff for the energy sold to the National Energy Services Manager (Gestore Servizi Elettrici, GSE).

At the end of 2017, the number of biogas power plants (BPPs) installed in Italy was 2,116 (GSE, 2018), with a gross electrical capacity of 1,444 MW, and gross electricity production (GEP) of 8,299 GWh, equal to 8% of the total electrical production from renewables. BPPs can be fed on different types of biomass: Organic Fraction of Municipal Solid Wastes (OFMSW), sewage sludge, livestock effluents, products from agriculture and forestry activities. The latter is the most widespread typology in Italy, representing 67% of the total GEP from biogas. It must be emphasised that BPPs can be fed on different mixtures of biomass, which are not differentiated in the National statistics. From 2009 to 2012 there was a continuous growth in the electricity production from biogas, that passed from 1,665 GWh to 8,299 GWh. This growth is linked to the national public subsidies that favoured the increase of the BPPs sized between 200 kW and 1 MW (about 65% of the total BPPs).

The energy production activity studied in this work is a BPP fed on agriculture and zootechnical biomass, a policy option about which there is a significant debate, since it represents a food vs. energy competition (Gamborg et al., 2012; Hira, 2018; Smyth and Lubieniechi, 2018; P. Thompson, 2012; P. B. Thompson, 2012; Tomei and Helliwell, 2016). This BPP is related to several sectors, since it directly involves agricultural, industrial, and tertiary sector activities, drawing the attention of policy planning also in the framework of Circular Economy (CE) (Kalmykova et al., 2018). The complex interaction of the involved subsystems and the exchange of resource flows require powerful integrated analyses as well as the definition of reliable performance indicators. In this sense, partial, biased, or mono-dimensional indicators are intrinsically weak in their ability to capture the feedback-based circular nature of complex production systems (Ghisellini et al., 2016; Iacovidou et al., 2017). Indeed, emergy analysis has been addressed as specifically useful to integrate the upstream and the downstream aspects along with the potential circularity of resource flows, providing a quantitative estimation of the sustainability performance of the systems.

Emergy analysis applied to BPPs has been drawing increasing attention in the last years, as demonstrated by published research on biogas power systems and biogas digesters, fed on different types of organic biomass, like swine (Wang et al., 2014) and cow manure (Ghisellini et al., 2014a), organic waste from planting, aquaculture, and breeding (Chen and Chen, 2014), crops and food residues and cheese whey (Merlin and Boileau, 2017). These analyses set various different system boundaries, ranging from a single BPP (Ciotola et al., 2011) or a joint farm-BPP system (Zhang and Chen, 2016) to a whole village (Kursun et al., 2015). In some of these systems, digestate is used as organic fertiliser (Ghisellini et al., 2014a) or fish food (Chen and Chen, 2014), while in smaller systems its recycle is not considered (Ciotola et al., 2011). On the other hand, only a few EMA of energy production from biogas including other subsystems, like breeding or agricultural cultivations, are present in literature (da Silva et al., 2013; Ghisellini et al., 2014b). EMA was performed for systems aimed at producing biogas for cooking and lighting purposes (Chen and Chen, 2012; Wu et al., 2015) or are focused on the recycling of the biogas residue in agricultural systems (Wang et al., 2017). This short overview makes clear how EMA can be used to analyse the same product (in this case, electricity produced from biogas) on different scales, so providing different perspectives and information on the performance of the system at issue. On the other hand, it points out that the real definition of “local renewable” source is still debated, possibly leading to questionable results and so invalidating a comparison procedure between different systems.

In this chapter, the environmental sustainability of the energy generation from biogas produced by fermenting wheat and crop silage is assessed. The issue of emergy allocation of manure in the development of emergy analysis is also addressed, since the choice of the system boundary may lead to different accountings and affect the determination of emergy indicators. The case study, which includes the biogas power plant construction and operation and the cultivation of maize and wheat, was performed at two scales: (i) the one encompassing the whole company property, that comprehends both the BPP and the cultivated fields (Reference System), and (ii) that also including the breeding company that provides liquid manure to the plant, in order to consider the whole agroecosystem in which nutrients circulate and are recycled, and to assess the role of BPPs in the sustainability practice of agriculture (Expanded System).

2.2. Description of the case study

The system at issue is a biogas power plant linked to the biomass cultivations located in Mantua province (Fig. 2.1), Northern Italy, for the operations during the year 2017. It is in the middle of a flat area, south of the Mincio river and the Mantua Lakes, whose economy is strongly dependent on agriculture-based activities. The overall area in which biomass is cultivated, close to the BPP, is 160 hectares wide: 100 hectares are dedicated only to spring maize, while the rest to crops rotation in which winter wheat follows summer maize.

Fig. 2.1. The geographical location of the case study.

The Biogas Power Plant (Fig. 2.2, Fig. 2.3), with a 625 kW_{el} Cogeneration Heat and Power unit (CHP), produces electricity, which is sold to the market, and heat reused for the plant needs. It is made up of two fermenters, fed on wheat and maize shredder specifically cultivated for the purpose in fields owned by the company, as well as on liquid cattle manure coming from a breeding near the plant. The agricultural silage, stocked in horizontal prefabricated silos, is loaded in the first fermenter by an automatic system, and mixed with the liquid manure, temporarily stored in a liquid digestate tank. The process of Anaerobic Digestion (AD) takes place in this fermenter, owing to the action of anaerobic microorganisms that decompose the organic matter into methane, carbon dioxide and digestate (the nutrient-rich residue of AD). The digestate is then transferred into a second fermenter where the AD keeps taking place. This configuration is called "two-phase CSTR (Continuous Stirred Tank Reactor)" and permits the continuous recirculation of digestate from the second to the first fermenter. The total Hydraulic Retention Time (HRT) of the biomass in the two fermenters is about 60 days.

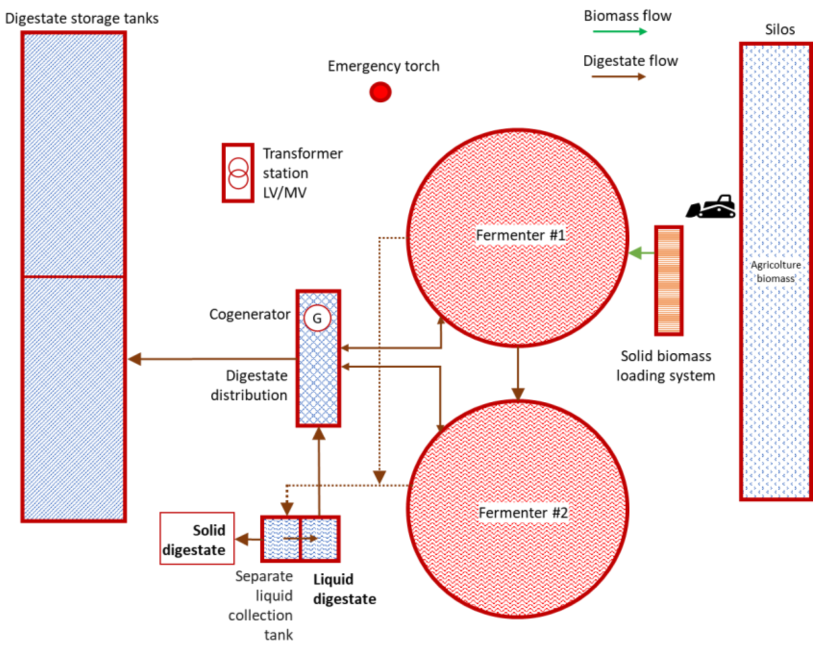

Fig. 2.2. Biomass and digestate flows inside the biogas power plant.

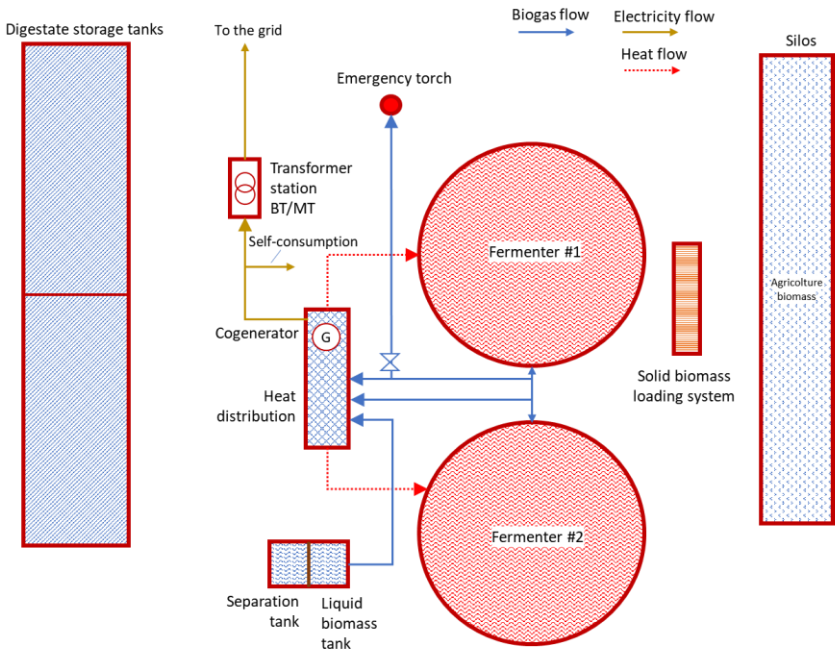

Fig. 2.3. Energy, heat and biogas flows inside the biogas power plant.

The digestate, mainly composed of water, nutrients, and lignin (see Table 2), is continuously extracted from the fermenters and carried to a mechanical separator where it is divided in its solid and liquid fractions, both of which are used as fertilisers or soil improver for the biomass cultivations. A fraction of the liquid digestate is also recirculated in the first fermenter to support the digestion of biomass.

Table 2. Digestate relevant constituents, in percentage of volume.

Constituents	Volume %
Dry matter	5.36%
Total N	0.40%
$N\text{-}NH_4$	0.20%
P	0.08%
K	0.31%

The biogas produced by the fermenters (see Table 3) is collected on the top of their gasometric domes and carried to the CHP unit for the production of energy. Before the combustion, the water vapour contained in the biogas is removed by condensation, and the condensate is collected and recirculated in the fermenters. The CHP unit is located in an insulated container where, in separated rooms, heat and digestate dispensers are installed for the automatic recirculation of digestate and heat recovering within the plant. Electricity, generated at a voltage of 400 V (AC), is increased to the medium voltage by a transformer station (property of the National Agency for Electricity) and injected into the national grid. Part of the electricity production is self-consumed to support the energy needs of the plant, while heat is used to maintain the mesophilic conditions inside the fermenters. When the plant is under maintenance, it is powered by the national grid. Material inputs to the BPP and productivity for the year 2017 are reported in Table 4.

Table 3. Average composition of biogas (values are in volume % of biogas).

Constituents of biogas	Amount
Methane (CH_4)	49-55%
Carbon dioxide (CO_2)	44-50%
Oxygen (O_2)	0.1-0.4%
Nitrogen (N_2)	0.5-2%
Water (H_2O)	0.8-7%
Hydrogen sulphide (H_2S)	100 ppm
Calorific value	1.8E+07 J/Nm^3 *

* Nm^3=normal m^3

Table 4. Annual energy and material inventory for the biogas power plant (2017).

Inputs	Amount	Unit
Wheat silage	2,000,000	kg
Maize silage	7,700,000	kg
Liquid cattle manure	7,300	m^3
Liquid digestate (recirculated)	7,300	m^3
Electricity self-consumed (8% of production)	435,940	kWh
Electricity from the grid (stopped machinery)	525	kWh
Lubricant, reducing, hydraulic oil (loading system)	240	kg
Lubricant oil (motor)	1,620	kg
Outputs		
Electricity production	54,500,000	kWh
Liquid fraction of digestate (to field fertilisation)	7,200	m^3
Solid fraction of digestate (to soil improvement)	4,000	m^3
Digestate (exchanged with bovine slurry)	3,650	m^3
Total waste to disposal	1,000	kg
Exhausted oil (loading system + motor)	1,860	kg

2.2.1. The agricultural phase

The cultivation of maize and wheat is carried out by the company, adopting processing soil techniques that aim at minimizing the soil erosion as well as the emissions of ammonia and bad smell from the spreading of digestate and inorganic fertilisers. Inventory data for the agricultural phase was collected directly from the company, apart from the number of herbicides that was taken from the inventory of three annual energy crops in Northern Italy, reported in González-García et al. (2013).

The temporal sequence of the cultivations is shown in Fig. 2.4.

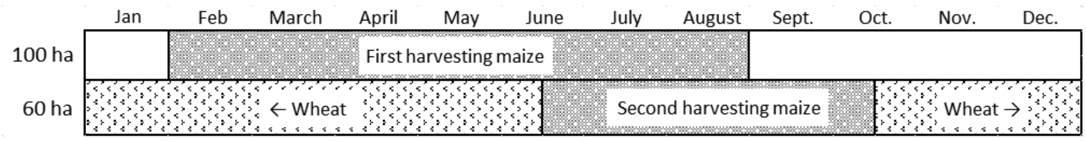

Fig. 2.4. Cultivations temporal scheme.

The cultivation of spring maize (Table 5) starts in February, with the organic fertilisation of the soil. In a fraction of the cultivated land of about 80 hectares, the solid digestate coming from the power plant is spread with a manure spreader and buried with a disc arrow. In the rest of the land (20 hectares), the liquid fraction of digestate is spread with a liquid manure/slurry injector. This machinery is connected, through a hose reel, to an umbilical system of underground pipes that permits the transportation of liquid digestate along the borders of the fields without using barrel trucks. By this technique, the soil is not compacted and the digestate is buried at a 10 cm depth, where the roots can absorb it rapidly so preventing relevant emissions of ammonia from the soil as well as the washing out of the latter.

In April, after the preparation of soil with a combined decompactor subsoiler, the sowing of maize seeds is carried out using a pneumatic precision seeds drill. The weeding takes place, only if necessary, by using a spraying machine. The irrigation occurs as well through hose reel irrigators connected to the umbilical system that spreads water in the whole area. It takes place once a week from June to August. In mid-July, the liquid fertiliser Urea Ammonium Nitrate 30.0.0 (UAN, 30% of nitrogen, 0% of phosphorous and potassium) is spread together with water. The harvesting occurs in August, using a mower-shredder-loader machine which picks up and cuts up the maize at the same time, with average productivity of 50 tonnes of maize per hectare.

Table 5. Material inputs for spring maize cultivation.

Operation	Month	Machinery	Input	Amount per 1 ha	Unit	Amount per 100 ha
Organic fertilisation (on 80 ha)	February	Manure spreader	Solid digestate	40,000	kg	3,200,000
Solid digestate incorporation	February	Disc arrow	-		-	-
Organic fertilisation (on 20 ha)	February	Ripper liquid manure/slurry injector	Liquid digestate	60,000	kg	1,200,000
Soil preparation	April	Combined decompactor subsoiler	-			
Sowing	April	Pneumatic precision seeds drill	700 class maize seeds	20	kg	1,969
Post-emergency weeding	May (one time)	Spraying machine	Amide herbicide	4	kg	200
Sprinkler irrigation	June - August (once a week)	Hose reel irrigator	Water	350	m^3	420,000
Inorganic fertilisation	Mid-July	Hose reel irrigator	Liquid fertiliser 30.0.0 (30% N)	0.3	m^3	30
			Output			
Harvesting	August	Mower-shredder-loader machine	Maize silage	50,000	kg	5,000,000

The cultivation operations for summer maize (Table 6) are quite different than those for the spring maize. The cultivation starts with the soil preparation by the combined decompactor subsoiler in June; afterwards, the organic fertilisation of soil takes place with solid (on 20 hectares) and liquid (on 40 hectares) digestate. Also, in this case, the weeding occurs only if necessary, and the irrigation is made by the combination of the umbilical system and the hose reel irrigators once a week from June to September. In the inorganic fertilisation, UAN 30.0.0 is spread together with water in July. The harvesting occurs in October with average productivity of 45 tonnes of maize per hectare.

Table 6. Material inputs for summer maize cultivation.

Operation	Month	Machinery	Input	Unit	Amount per 1 ha	Amount per 60 ha
Soil preparation	June	Combined decompactor subsoiler	-	-	-	
Organic fertilisation (on 20 ha)	June	Manure spreader	Solid digestate	kg	40,000	800,000
Solid digestate incorporation	February	Disc arrow	-	-		-
Organic fertilisation (on 40 ha)	June	Ripper liquid manure/slurry injector	Liquid digestate	kg	60,000	2,400,000
Sowing	June	Pneumatic precision seeds drill	600 class maize seeds	kg	20	1,181
Post-emergency weeding	If necessary	Spraying machine	Amide herbicide	kg	1	30
Sprinkler irrigation	June-Sept (once a week)	Hose reel irrigator	Water	m^3	350	336,000
Inorganic fertilisation	July	Hose reel irrigator	Liquid fertiliser 30.0.0 (30% N)	m^3	0.3	18
			Output			
Harvesting	October	Mower-shredder-loader machine	Maize silage	kg	45,000	2,700,000

After the harvesting of summer maize, in October the cultivation of durum wheat starts, which is characterised by less agricultural operations than maize (Table 7). The combined decompactor subsoiler is used to prepare the soil, and the ripper liquid manure/slurry injector connected to the umbilical system is used to spread the liquid digestate. In November, seeds are sowed using a mechanical seeds drill while the harvesting occurs in June, with a productivity of 33 tonnes per hectare.

Table 7. Material inputs of durum wheat cultivation.

Operation	Month	Machinery	Input	Unit	Amount per 1 ha	Amount per 60 ha
Soil preparation	October	Combined de-compactor subsoiler	-	-	-	
Organic fertilisation	October	Ripper liquid manure/slurry injector	Liquid digestate	kg	60,000	3,600,000
Sowing	November	Mechanical seeds drill for cereals	Wheat seeds	kg	220	13,200
			Output			
Harvesting	June	Mower-shredder-loader machine	Wheat silage	kg	33,000	2,000,000

To perform the EMA at the ES scale, the cattle breeding was modelled by using the inventory data of Ghisellini et al. (2014a), suitably updated to the GEB_{2016}.

2.3. Two-scale application of Emergy Analysis

2.3.1. The Reference System

Fig. 2.5 represents the general system diagram of the rotational crops linked to the biogas and energy production, which is the "reference system" of this analysis. The elements of this complex system are those within the virtual box containing the crop and plant areas, the troposphere (10 m high), and the rhizosphere (0.50 m deep). All the local and imported forms of energy and information that enter this system have been identified and drawn: on the left side of the diagram the local renewable sources, and on the top the imported non-renewable ones (usually coming from the economy). Inside the diagram are two local non-renewable sources directly used by the cultivated plants: one is the stock of topsoil organic matter (OM), which can be depleted by water erosion driven by precipitations (wind erosion was estimated negligible), in a rate dependent on both the weather condition and the soil processing techniques; the other one is the stock of soil nutrients containing nitrogen (N), potassium (K) and phosphorus (P). All these stocks, that in nature are maintained by plant and animal recycled matter that return to the soil and are decomposed by microorganisms, in lands cultivated with conventional techniques are depleted and need to be restored by organic and/or inorganic fertilisers. In this system, organic carbon and nutrients are provided by liquid and solid digestate, as well as by inorganic nitrogen fertilisers. The cultivation process is bullet-shaped, as is typical for primary production processes. On the upper left of the diagram are the sources of labour and services: "labour" represents the work people usually do inside the system, which can be directly influenced by the system itself, while "services" account for the work that is made outside the system to provide the purchased inputs from economy or the disposal services. Inside the system, the production of electricity is represented as a sequence of sub-processes, namely, the biogas production, fed on the biomass silage, and the combined heat and power generation. It is worth noticing the feedbacks driven by electricity, heat and digestate, that come back along the energy production processes and the cultivations of biomass, therefore, contributing to the system maintenance. On the right side are located the outputs of the system: electricity sold to the market, part of the liquid digestate given to the breeding farm and the waste to be disposed of.

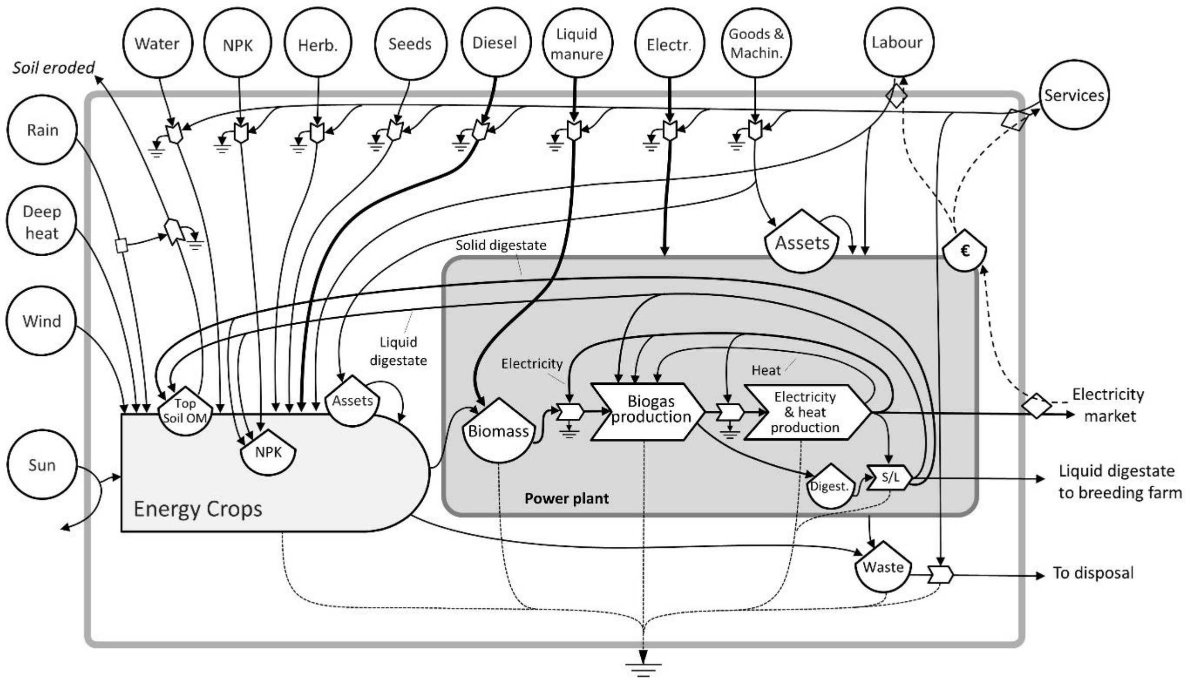

Fig. 2.5. General system diagram of electricity production from biogas (S/L=solid/liquid separator) including the biomass cultivation (Reference System).

To perform the emergy analysis of this system, data about energy, material, labour and services necessary to support the power plant operations and the cultivation of biomass were collected from the owner of the power plant and the building company (primary data set). Data about renewable energy sources locally available were provided by the regional environmental agency or meteorological websites (ENEA; Regione Lombardia). Where existing, the used UEVs were taken from literature, updated to the Geobiosphere Emergy Baseline GEB_{2016} of 12.0E+24 sej/yr (Brown et al., 2016). The working hours were assumed from the working hours per hectares reported in Ribaudo (2017). Regarding the UEVs of fertilisers, two values can be found in literature, from the works of Odum and Odum (1983) and Brandt-Williams (2002), calculated from a simplified EMA of the production of ammonia (NH_3) and the production of Diammonium Phosphate (DAP), respectively. The nitrogen fertiliser used in the cultivation of biomass is Urea Ammonium Nitrate (UAN), which derives from production routes different than those for the production of DAP and ammonia. New calculations have been therefore carried out for this work, by considering the main contributions (in emergy terms) of raw materials and energy consumptions (Giannetti et al., 2015; Spagnolo et al., 2018) used up in the industrial production processes of UAN (EFMA, 2000). The UEV of manure was calculated considering the simplified diagram of the cattle breeding system analysed in Ghisellini et al. (2014a) and reported in Fig. 2.6. As shown in this diagram, the products of this system are three: milk and meat, sold to the market, and manure, which is usually used as fertiliser in agriculture or, as in our case study, as feeding for biogas production.

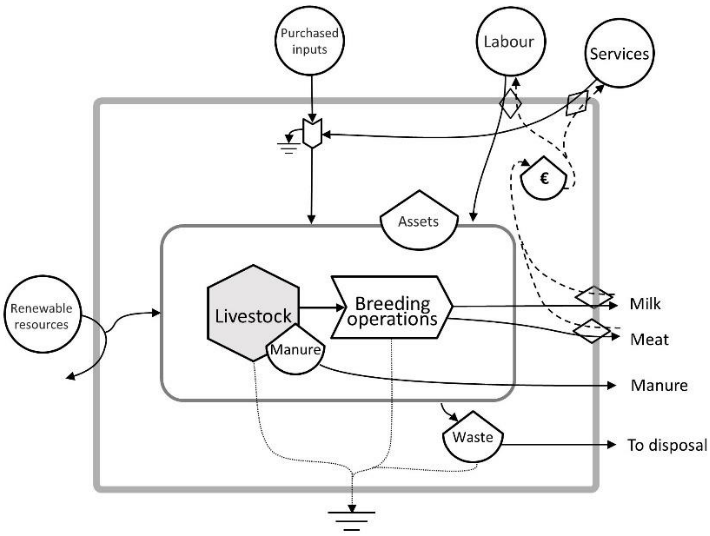

Fig. 2.6. Simplified general system diagram of a cattle breeding.

The calculation was made by following the 4th rule of emergy algebra, thus allocating all emergy inputs to the system to each output, leading to a transformity of manure (without Labour and Service, L&S) equals to 5.9E+05 sej/J (adopted in the emergy evaluation of the RS). In Table 8, the emergy accounting of RS is reported.

Table 8. Emergy accounting for the Reference System. All data refers to annual consumption and production for the year 2017.

#	Item	Amount	Unit	UEVs (sej/unit)	Ref.	Solar Emergy (sej/yr)	% Tot emergy w/o L&S
Primary renewable sources							
1	Sun	6.9E+15	J	1	By definition	7.0E+15	
2	Deep Heat	1.9E+11	J	4900	Brown and Ulgiati (2016)	9.5E+14	

Secondary renewable sources							
3	Wind (kinetic energy)	4.0E+12	J	800	Brown and Ulgiati (2016)	3.2E+15	
4	Rain (chemical potential)	2.3E+12	J	7000	Brown and Ulgiati (2016)	1.6E+16	
Total renewable input (largest of renewables)						2.4E+16	0.4%
Local non-renewable sources							
5	Topsoil organic matter (lost by water erosion)	5.1E+11	J	1.9E+03	after De Vilbiss and Brown (2015)	9.9E+14	0%
Imported inputs							
6	Water, river/stream (irrigation)	7.6E+11	g	1.0E+05	after De Vilbiss and Brown (2015)	7.6E+16	1.2%
7	Seeds	1.4E+07	$g_{d.w.}$	2.3E+09	Fahd et al. (2012)	3.3E+16	0.5%
8	Urea Ammonium Nitrate (N 30%)	4.8E+07	g	6.4E+09	This work	3.1E+17	4.7%
9	Herbicides	2.3E+05	g	1.1E+10	(Brown and Arding, 1991)	2.6E+15	0.0%
10	Diesel	7.2E+07	g	6.4E+09	Brown et al. (2011)	4.6E+17	7.2%
11	Liquid cattle manure (as coproduct)	9.0E+12	J	5.9E+05	our calculation based on Ghisellini et al. (2014)	5.3E+18	82.7%
12	Electricity (from the grid)	1.9E+09	J	4.0E+05	Brown et al. (2012)	7.6E+14	0.0%
13	Lubricant oil	8.2E+10	J	1.4E+05	Brown et al. (2011)	1.1E+16	0.2%
14	Agricultural machineries:						
	steel and iron	5.4E+07	g	2.4E+09	Bargigli and Ulgiati (2003)	1.3E+17	2.0%

	aluminium	2.4E+05	g	1.6E+10	Buranakarn (1998)	3.8E+15	0.1%
	rubber and plastic materials	1.7E+04	g	6.7E+09	Buranakarn (1998)	1.1E+14	0.0%
	copper	5.1E+04	g	2.9E+08	after De Vilbiss and Brown (2015)	1.5E+13	0.0%
15	Steel (reinforcing bar for concrete, devices, containers)	5.3E+06	g	2.4E+09	Bargigli and Ulgiati (2003)	1.3E+16	0.2%
16	Copper (CHP 625kW)	2.5E+04	g	2.9E+08	after De Vilbiss and Brown (2015)	7.3E+12	0.0%
17	Polyethylene (pipes, gasometric domes, coverage tissue)	5.7E+05	g	6.7E+09	Buranakarn (1998)	3.8E+15	0.1%
18	Concrete (structure)	2.7E+07	g	1.8E+09	Buranakarn (1998)	5.0E+16	0.7%
19	Wood (structure)	2.7E+06	g	1.1E+01	Buranakarn (1998)	2.9E+07	0.0%
20	Thermal insulation (extruded polystyrene panels, pipes rigid polyurethane foam)	1.2E+05	g	1.9E+09	Buonocore et al. (2015)	2.2E+14	0.0%
21	Water (for term convector fluid)	1.8E+05	g	1.0E+05	after De Vilbiss and Brown (2015)	1.8E+10	0.0%
22	Ethylenic glycol (for heat transfer fluid)	7.8E+04	g	6.1E+09	Sha et al. (2015)	4.8E+14	0.0%
23	Eccentric screw pump (digested extraction)	n.a.					

24	Copper (electric cables)	n.a.				
25	PVC (electric cables insulation)	n.a.				
Labour						
26	Workers	2.3E+03	h	1.4E+12	Kamp et al. (2016)	3.2E+15
Services						
Input related to service						
27	Wheat seeds	9.9E+03	$	2.4E+12	NEAD v.2.0	2.4E+16
28	Corn seeds	4.7E+04	$	2.4E+12	NEAD V2.0	1.1E+17
29	Water	8.8E+04	$	2.4E+12	NEAD V2.0	2.1E+17
30	Machineries:				NEAD V2.0	
	tractors	2.9E+04	$	2.4E+12	NEAD V2.0	6.9E+16
	wheel sprinklers	2.9E+04	$	2.4E+12	NEAD V2.0	6.9E+16
	irrigation water pumps	1.1E+04	$	2.4E+12	NEAD V2.0	2.5E+16
	other tools	8.2E+03	$	2.4E+12	NEAD V2.0	1.9E+16
31	Fertilisers	1.2E+04	$	2.4E+12	NEAD V2.0	2.8E+16
32	Weeding service	2.9E+04	$	2.4E+12	NEAD V2.0	6.9E+16
33	Irrigation flexible hose	4.7E+03	$	2.4E+12	NEAD V2.0	1.1E+16
34	Agricultural operations (external service)	2.1E+05	$	2.4E+12	NEAD V2.0	5.0E+17
35	Investment for power plant construction	2.2E+05	$	2.4E+12	NEAD V2.0	5.3E+17
36	Maintenance of power plant	1.9E+05	$	2.4E+12	NEAD V2.0	4.4E+17

37	Disposal of waste	2.3E+03	$	2.4E+12	NEAD V2.0	5.5E+15
Products						
	with labour and services					
38	Electricity	2.0E+13	J	4.4E+05	This work	8.6E+18
39	Electricity	5.5E+06	kWh	1.6E+12	This work	8.6E+18
40	Digestate	9.3E+12	J	9.2E+05	This work	8.6E+18
41	Digestate	1.1E+10	g	7.8E+08	This work	8.6E+18
	without labour and services					
42	Electricity	2.0E+13	J	3.3E+05	This work	6.4E+18
43	Electricity	5.5E+06	kWh	1.2E+12	This work	6.4E+18
44	Digestate	9.3E+12	J	7.0E+05	This work	6.4E+18
45	Digestate	1.1E+10	g	5.9E+08	This work	6.4E+18

2.3.2. The Expanded System

The *Expanded System* (ES) shows the link between the cultivation of biomass for biogas production, the power plant and the cattle breeding with the production of milk and meat. Fig. 2.7 describes this agroecosystem, showing the feedbacks between the sub-processes, represented by the return on the land of digestate nutrients.

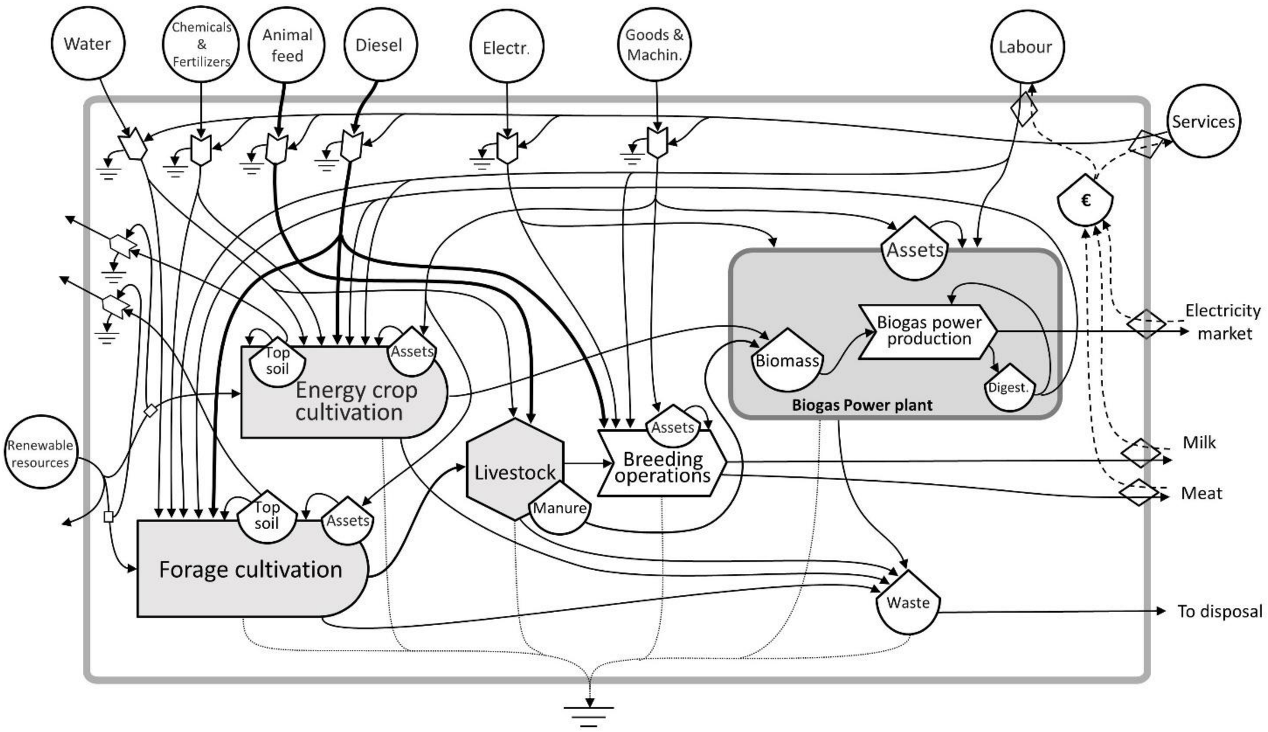

Fig. 2.7. Emergy system diagram of the ES. Thick lines represent the main contribution in terms of emergy flow.

In Table 9, the emergy accounting for the ES is reported, showing the main contributions, in terms of percentage of total emergy (without Labour and Services), of the flow inputs to the system. In Table 10, the main emergy indicators of sustainability are reported both for the RS and the ES. For the ES, also the *joint transformity* of the overall system was calculated and reported.

Table 9. Emergy accounting of ES. All data refer to annual consumption and production.

#	Item	Amount	Unit	UEV (sej/unit)	Ref.	Solar Emergy (sej/yr)	% Tot emergy w/o L&S
Primary renewable sources							
1	Sun	2.3E+16	J	1	By definition	2.3E+16	
2	Deep Heat	7.0E+12	J	4900	Brown and Ulgiati (2016)	3.4E+16	
Secondary renewable sources							
3	Wind (kinetic energy)	4.6E+13	J	800	Brown and Ulgiati (2016)	3.7E+16	

4	Rain (chemical potential)	1.2E+13	J	7000	Brown and Ulgiati (2016)	8.2E+16	
Total renewable input (largest of renewable sources)						1.4E+17	1.2%
Local non-renewable sources							
5	Topsoil organic matter (lost by water erosion)	6.0E+11	J	1.9E+03	after De Vilbiss and Brown (2015)	1.2E+15	0.0%
Purchased inputs							
6	Water, river/stream (irrigation)	9.0E+11	g	1.0E+05	after De Vilbiss and Brown (2015)	8.4E+13	0.0%
7	Seeds	1.5E+07	g	2.3E+09	Fahd et al. (2012)	3.5E+16	0.3%
8	Fertilisers:						0.0%
	N	1.3E+06	g	1.4E+10	This work	1.9E+16	0.2%
	Phosphorous (P_2O_5)	2.2E+06	g	5.0E+08	This work	1.1E+15	0.0%
	UAN	4.8E+07	g	6.4E+09	This work	3.1E+17	2.7%
9	Herbicides	3.8E+05	g	1.1E+10	Brown and Arding (1991)	4.3E+15	0.0%
10	Diesel	2.6E+08	g	6.4E+09	Brown et al. (2011)	1.6E+18	14.4%
11	Electricity (from the grid)	1.9E+12	J	4.0E+05	Brown et al. (2012)	1.3E+15	6.2%
12	Lubricant oil	9.4E+10	J	1.4E+05	Brown et al. (2011)	1.3E+16	0.1%
13	Animal bedding purchased	1.1E+09	g	7.96E+08	Fahd et al.(2012)	8.6E+17	7.5%
14	Animal feed purchased	5.5E+09	g	1.49E+09	Jaklič et al. (2014)	8.2E+18	71.8%
15	*Goods & Machineries:*						0.0%
16	Agricultural machinery (as steel)						0.0%
	steel and iron	5.9E+07	g	2.4E+09	Bargigli and Ulgiati (2003)	1.4E+17	1.2%
	aluminium	2.4E+05	g	1.6E+10	Buranakarn (1998)	3.8E+15	0.0%

	rubber and plastic materials	1.7E+04	g	6.7E+09	Buranakarn (1998)	1.1E+14	0.0%
	copper	5.1E+04	g	2.9E+08	after De Vilbiss and Brown (2015)	1.5E+13	0.0%
17	Steel (reinforcing bar for concrete, devices, containers)	5.3E+06	g	2.4E+09	Bargigli and Ulgiati (2003)	1.3E+16	0.1%
18	Copper (CHP 625kW)	2.5E+04	g	2.9E+08	after De Vilbiss and Brown (2015)	7.3E+12	0.0%
19	Polyethylene (pipes, gasometric domes, coverage tissue)	5.7E+05	g	6.7E+09	Buranakarn (1998)	3.8E+15	0.0%
20	Concrete (structure)	2.7E+07	g	1.8E+09	Buranakarn (1998)	5.0E+16	0.4%
21	Wood (structure)	2.7E+06	g	1.1E+01	Buranakarn (1998)	2.9E+07	0.0%
22	Thermal insulation (extruded polystyrene panels, pipes rigid polyurethane foam)	1.2E+05	g	1.9E+09	Buonocore et al. (2015)	2.2E+14	0.0%
23	Water (for term convector fluid)	1.8E+05	g	1.0E+05	after De Vilbiss and Brown (2015)	1.8E+10	0.0%
24	Ethylenic glycol (for heat transfer fluid)	7.8E+04	g	6.1E+09	Sha, S. et al. (2015)	4.8E+14	0.0%
25	Eccentric screw pump (digested extraction)	n.a.					
26	Copper (electric cables)	n.a.					
27	PVC (electric	n.a.					

	cables insulation)					
Labour						
28	Power Plant and Energy crop cultivation labour	2.3E+03	h	1.4E+12	Kamp et al. (2016)	3.2E+15
29	Breeding & forage cultivation labour	3.5E+05	$	2.4E+12	NEAD V2.0	8.3E+17
Services						
	Input related to service					
30	Biomass cultivation & power plant operation	8.9E+05	$	2.4E+12	NEAD V2.0	2.1E+18
31	Breeding & forage cultivation services	2.4E+06	$	2.4E+12	NEAD V2.0	5.6E+18
Products with L&S						
32	Electricity	5.4E+06	kWh	3.7E+12	This work	2.0E+19
33	Electricity	2.0E+13	J	1.0E+06	This work	2.0E+19
34	Raw milk (dry weight)	1.4E+09	$g_{d.w.}$	1.4E+10	This work	2.0E+19
35	Raw milk (energy)	3.0E+13	J	6.6E+05	This work	2.0E+19
36	Meat (dry weight)	6.9E+07	$g_{d.w.}$	2.9E+11	This work	2.0E+19
Products without L&S						
37	Electricity	5.4E+06	kWh	2.1E+12	This work	1.1E+19
38	Electricity	2.0E+13	J	5.8E+05	This work	1.1E+19
39	Raw milk[(a)] (dry weight)	1.4E+09	$g_{d.w.}$	8.1E+09	This work	1.1E+19
40	Raw milk (energy)	3.0E+13	J	3.8E+05	This work	1.1E+19
41	Meat[(a)] (dry weight)	6.9E+07	$g_{d.w.}$	1.7E+11	This work	1.1E+19
42	Meat (energy)	1.4E+12	J	8.1E+06	This work	1.1E+19

[(a)]Energy and water content from (CREA, 2019).

Table 10. Emergy sustainability indicators for the Reference System and the Expanded System.

			Reference System		Expanded system	
		Unit	Amount	% Solar emergy	Amount	% Solar emergy
R	Direct renewable input	sej/yr	2.4E+16	0.3%	1.4E+17	0.7%
N	Local non-renewable input	sej/yr	9.9E+14	0.01%	1.2E+15	0.01%
F	Purchased inputs	sej/yr	6.4E+18	75.0%	1.1E+19	56.6%
L	Labour	sej/yr	3.2E+15	0.04%	8.4E+17	4.2%
S	Services	sej/yr	2.1E+18	24.6%	7.7E+18	38.6%
U	Total emergy (with L&S) (R+N+F+L+S)	sej/yr	8.6E+18	100%	2.0E+19	100%
U'	Total emergy (without L&S) (R+N+F)	sej/yr	6.5E+18		1.1E+19	
Tr	of electricity (with L&S)	sej/J	4.4E+05		1.0E+06	
Tr'	of electricity (without L&S)	sej/J	3.3E+05		5.8E+05	
EYR	Emergy Yield Ratio (R+N+F+L+S)/(F+L+S)		1.00		1.01	
EYR '	Emergy Yield Ratio (R+N+F)/F		1.0		1.0	
ELR	Environmental Loading Ratio (N+F+L+S)/R		353		143	
ELR'	Environmental Loading Ratio (N+F)/R		265		81	
ESI	Emergy Sustainability index EYR/ELR		0.003		0.007	
ESI'	Emergy Sustainability Index EYR'/ELR'		0.004		0.01	
AEI	Areal Empower Intensity (with L&S) (U/Total area)	sej/m^2	5.3E+12		5.0E+12	
AEI'	Areal Empower Intensity (without L&S) (U'/Total area)	sej/m^2	4.0E+12		2.8E+12	

J_{tr}	Joint transformity (seJ/J) (with L&S)	sej/J	3.9E+05
J_{tr}'	Joint transformity (seJ/J) (without L&S)	sej/J	2.2E+05

2.4. Discussion

2.4.1. Energy Transformity

For the Reference System, the transformities of electricity are equal to 4.4E+05 sej/J with labour and services (L&S) and to 3.3E+05 sej/J without L&S. By comparing processes having the same product(s), the transformity provides a measure of the efficiency of the systems, as it shows how many resources are needed to produce one unit of available energy (e.g., exergy) of the output. The lower the transformity of the same product, the more efficient the system is. In particular, the value with L&S provides information about the dependency on the economic system, while without L&S information is provided about the technical performance of the process.

Considering previous EMA of BPPs, different transformities of electricity from biogas can be found, providing values quite different from those of this study (with L&S): 1.01E+06 sej/J from Ciotola et al., (2011); 1.6E+06 sej/J from Merlin and Boileau (2017); 2.63E+05 sej/J from Wang et al. (2014). The high transformities reported by the first two studies derive from the large amount of waste material fermented in the power plants, carrying high emergy contribution, whereas the lower value from Wang et al. is probably due to the larger scale of the system considered (700 m^3 of biogas daily production, versus 33.5 m^3 and 300 m^3 respectively, of the other works), which exploits the resources more efficiently than the smaller ones.

Regarding the Expanded System of our case study, the transformities of electricity are equal to 1.0E+06 sej/J with L&S and to 5.8E+05 sej/J without L&S. The difference from the RS values is justified by the inclusion of animal forage cultivation into the ES, which was not considered in the breeding system (BS) modelled for the calculation of the UEV of the manure (inasmuch as an imported input into the RS). In fact, in the latter BS part of the forage is purchased, and rely on production process other than the one considered in the ES. Cezar da Silva et al. (2013) performed the EMA of electricity production from cattle and pig breeding wastes, including the breeding into the system's boundary. The resulting transformities for the cattle waste-BPP are lower than the case study: 6.0E+04 sej/J for cattle system, while that for pig waste-BPP is quite similar and equal to 1.38E+05 sej/J.

In Fig. 2.8 the transformities of electricity from different energy sources are reported and compared to the one of the RS. It is interesting to observe that the obtained transformity from our RS results quite close to that of fossil-based energy production, most likely due to the dependence of the agricultural phase on fossil fuels. In fact, the renewable emergy fraction of resources exploited by the RS is lower than 0.3% of the total emergy input and for the ES is 0.7%, while the larger fraction of the total emergy input is covered by purchased resources and services.

It becomes clear that the sustainability of biogas production is questionable, much more than what is considered by public perception and confirms the necessity for a multi-scale analysis aimed at the correct assessment of energy production sustainability. In this respect, the difference between the obtained transformity values for RS and ES shows how the EMA procedure may point out very well the systemic role that a BPP can play in an energy supply network.

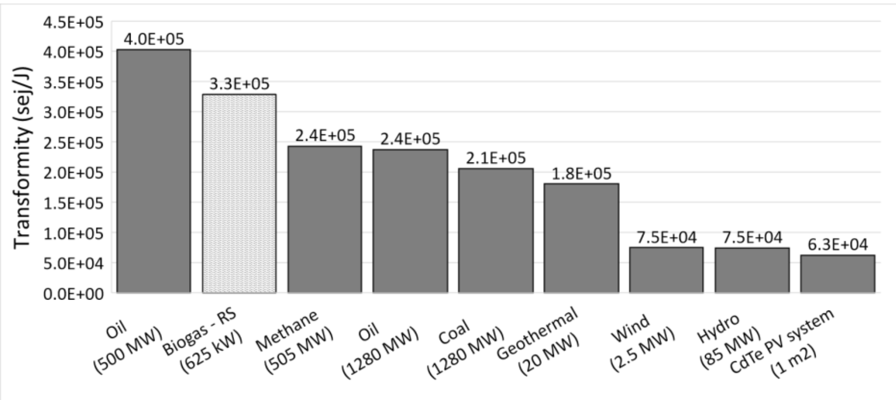

Fig. 2.8. Comparison among transformity values (without L&S) for different energy sources. References for the UEVs (all referred to the GEB_{2016}): (a) Brown et al. (2012); (b) this work; (c) Brown and Ulgiati (2002). Emergy contribution of "waste"

Delving into the reasons of the high transformity values of electricity found in this study, we can observe that the emergy flow associated with liquid cattle manure accounts for more than 70% of the total emergy investment of the RS (without L&S). Since manure is a co-product from another subsystem, some misinterpretation may arise when discussing the overall sustainability of the system. In fact, manure is generally considered as a waste that comes "for free" (economically speaking) and must be disposed of in some way. Typically, zootechnical companies spread it on cultivated lands but, if it is not possible, manure can be processed through anaerobic digestion, liquid/solid separation, composting, or urban wastewater treatment.

By adopting the emergy accounting method, and strictly following the emergy algebra rules, all the resources required to produce the main – marked related – products of the breeding system (BS), namely milk and meat, are completely allocated to manure. This, of course, affects the transformity value of electricity, which comes to be bigger than it would be obtained, for example, by substituting the liquid manure with an artificial mixture with similar nutrient content (by substituting the liquid manure with a mixture of N, P, and K, the transformity of electricity becomes 7.5E+04 sej/J without L&S, and 1.9E+05 sej/J with L&S), erroneously leading to think that the use of this waste makes the system less efficient. While, if we do not consider the emergy contribution of liquid manure at all, we can observe that the F fraction is still high, due to the diesel consumption of agricultural pieces of machinery. Since co-production systems may use more emergy than single-product processes, it seems that using waste materials co-produced upstream as inputs for a downstream system makes the systems integration unfavourable, which certainly sounds senseless. This kind of problem has been addressed by several authors, among whom Kamp and Østergård (2013) as well as Patrizi et al. (2018). They discussed cases in which a product (e.g., bio-energy), whose production depends on waste (e.g., manure) of another system, appears to be therefore less sustainable than the same product obtained from resources that do not share the energy investment of a co-production system. Also in Santagata et al. (2019), the electricity produced from animal by-products was evaluated by considering different allocation methods and waste treatment alternatives. The resulting transformity by considering the animal by-products as co-products was even higher than all the transformities calculated in this work (3.1E+07 sej/J, without L&S).

In order to rationalise the interpretation of emergy indicators in terms of sustainability, some distinction should be then addressed. For the case study at issue, a comprehensive analysis of the different allocation options is beyond the scope of the article but a question is anyway raised about whether the manure should be treated as a *co*-product, thus assigning to it all the emergy investment of the breeding operation, or as a *by*-product, defined in Brown (2015) as an "incidental or secondary product produced in a process in addition to the principal product", and so calculating its UEV as a split, specifically, allocating emergy in base of the exergy content. The expansion of the boundary allows to change the interpretation perspective: the ES – including both the Breeding plus Forage (BF) and BPP subsystems – has an overall output formed by the three co-products milk, meat, and electricity, while manure passes from BF to BBP internally to the ES. The boundary expansion allows to include all the breeding system resources into the resources quantification. The relatively high emergy investment appears therefore as a natural consequence of the energetic complexity of the outputs. Bastianoni and Marchettini (2000b) proposed the concept of *joint transformity*, defined as the ratio between the overall emergy input to a system producing more co-products and the sum of the available energy contents of the co-products. This definition may be seen as some sort of trade-off between the donor-side perspective of Odum's emergy framework and the user-side evaluation of the overall service provided by a system. A comparison of the joint transformity with the orthodox calculated transformity can be therefore useful to better clarify the general conceptualisation. Fig. 2.9 summarises the transformity of electricity calculated as co-product or allocating the emergy of liquid manure, for both the RS and the ES and the joint transformity of the ES.

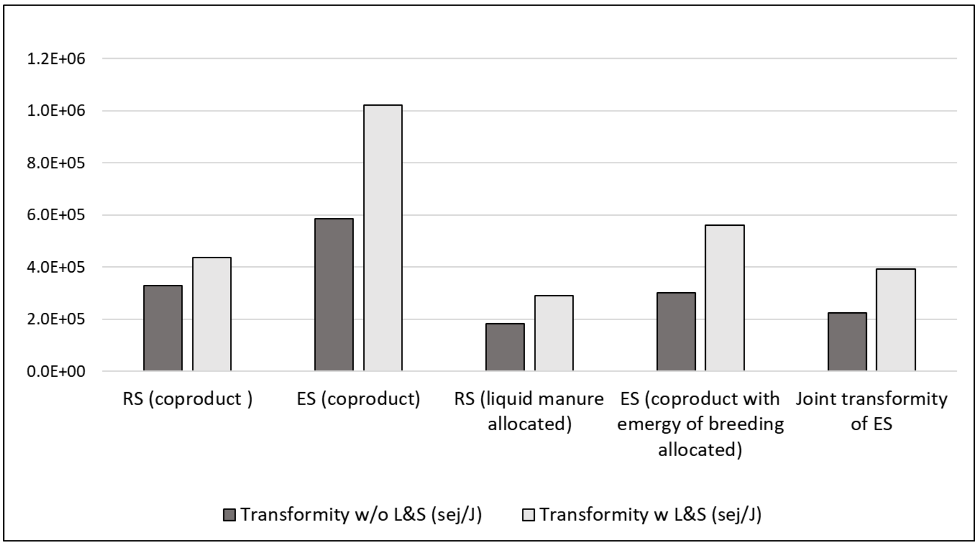

Fig. 2.9. Comparison between the transformities of electricity from biogas for the RS and the ES, considering different allocation methods. The joint transformity for the ES is also included.

The use of a waste for producing electricity can be more expensive (in terms of resources) than using artificial products, for example, synthetic fertilisers added to water to produce an "artificial liquid manure", since the emergy carried into the system by the real liquid manure brings the total emergy required for the breeding. But the idea of a process relying on co-products inputs, that for this reason may result much less sustainable (in emergy units) than similar ones using single-products that do not need to account for resources used in co-production, clashes against the intuitive idea that co-production, or – even better – the use of waste from some other process, should be certainly preferable as more "sustainable". This is a very important point. The fact is that the production of meat and milk is extremely resource expensive and may be considered as unsustainable. This means that all that is linked to it will carry the same donor-sided unsustainability. Indeed, all these considerations have to do with the very concept of emergy in its conceptual potential, that of determining an overall investment. In the original Odum's framework, each co-product branch carries the total emergy input to the process, as long as the branches are not reunited, and no emergy allocation is addressed. This is consistent with the very nature of Odum's conceptual framework, based on donor-side quality of products. In terms of investment needed, cattle manure is as much "expensive" as meat and milk, independently of their downstream use. If the integrated system were used by a culture that does not consume meat and milk, like in some Hindu communities, the user-side perspective on the co-products "value" might change radically, and this cannot affect the emergy accounting of the upstream system. The idea that liquid manure "is worth" much less than milk or meat relies only on our difficulty to overcome the user-side perspective instead of evaluating systems from the donor-side point of view, characteristic of the emergy analysis. As a matter of fact, EMA, looking at the work made by nature to produce something, does not distinguish between waste and resource, as everything inside a natural ecosystem is recycled, and its interpretation should always take into account the supporting system. Furthermore, EMA assigns to manure – and waste in general – an energy-quality value that is not provided by any other accounting methods. It is also worth mentioning that the trans-generational meaning of the very concept of sustainability (WCED, 1987) makes the use of integrated long-term indicators mandatory, and this is exactly the perspective of EMA even in treating the co-product issue.

2.4.2. Emergy indicators

In addition to transformity values, other emergy indicators can provide useful information about the integrated sustainability of the system at issue, inasmuch they aggregate yield, renewability, and load on the environment (Ulgiati et al., 1995). In Table 10 the main emergy indicators (EYR, ELR, ESI, %R) for the RS and the ES are reported and compared. The Emergy Yield Ratio is one of the most debated indicator (Brown et al., 2012a) as definitions and descriptions of EYR made in the past years has led to difficulties in its interpretation and consequently in the comparison among different systems.

As clearly reported in Brown and Ulgiati (1997), the EYR can be seen as:

$$EYR = \frac{U}{F} = \frac{F + R + N}{F} = 1 + \frac{R}{F} + \frac{N}{F}$$

expression that makes its interpretation easier. In our case study this index is 1 for both the RS and the ES, meaning that R and N are very low compared to F. In other words, none of the systems exploits local resources (neither renewable nor non-renewable) and are strongly dependent on economic resources. As reported in (Odum, 1996b), the EYR of fuels should be much higher than 1 as fuels are produced to sustain more than their own process (examples of EYR values for fossil fuels production in Campbell, 2015). In this case, biogas energy production uses almost the same amount of resources from the economy that it contributes.

The Emergy Loading ratio is a measure of stress on the environment due to the relatively low – or even null - exploitation of renewable sources.

$$ELR = \frac{F + N}{R}$$

The ELR with L&S of the RS is twice that of ES, meaning that larger amounts of non-renewable sources, both goods and human services, are used in the former system, compared to the latter. Considering the same indicator without L&S, the ELR of the ES decreases more than that of RS, suggesting that, in the latter system, the pressure on the local renewable resources due to the non-renewable fraction is higher than that of the ES. The ratio of EYR to ELR, that is the Emergy Sustainability Index ESI, measures the economic and environmental compatibility. The best option would be to have high EYR and low ELR, leading to high values of ESI. As shown in Brown and Ulgiati (1997), the ESI value (and thus the integrated sustainability of the system) can be increased not only by diminishing the feedbacks from outside the system, but also by increasing the number of renewable resources exploited compared to the feedback ones. In other words, if a system has large values of feedback inputs when they are used to exploit a large amount of renewables the system can still be sustainable. In both the systems at issue, this index is very low, indicating that, at present, the BPPs rely too much on external investments and too little on renewable sources. In other studies, different values for these indicators can be found, mainly due to the different classification of the fermented biomass, either as a renewable source or not, so misleading the interpretation and comparison among different studies and making it difficult to understand which is the most sustainable option. In fact, in some papers, fermented biomass is partially included in the local renewable fraction (Ciotola et al., 2011; Kursun et al., 2015; Wang et al., 2014), to which the renewable fraction of Labour is sometimes added. Obviously, this choice leads to very different indices values, inasmuch the emergy of manure is, as seen before, quite high. An additional calculation of the indices has been made, including the liquid manure as part of the renewable fraction of the emergy input to the system (Table 11).

Table 11. Emergy sustainability indices by considering liquid manure as a renewable input.

Index	Description	Amount
EYR	Emergy Yield Ratio with L&S (R+N+F+L+S)/(F+L+S)	2.7
EYR'	Emergy Yield Ratio w/o L&S (R+N+F)/F	5.9
ELR	Environmental Loading with L&S Ratio (N+F+L+S)/R	0.6
ELR'	Environmental Loading Ratio w/o L&S (N+F)/R	0.2
ESI	Emergy Sustainability Index with L&S EYR/ELR	4.5
ESI'	Emergy Sustainability Index w/o L&S EYR'/ELR'	29.2

Despite the "good" indices found by making this assumption, it must be stressed that liquid manure from conventional breeding cannot be considered as a renewable energy source like the sun, wind, rain, etc. as it is produced by using lots of non-renewable resources. The emergy indicators show that the biogas system cannot be strictly considered as an energy producer, as it acts more like as either a product consumer or a transformation process, and – at present – it cannot compete with richer energy sources that have higher yields (EYRs higher of 5 are from primary energy sources – Brown and Ulgiati (2002). It seems to be more correct to consider the biogas system as a "waste treatment" process, which should not be compared with other energy production systems, but rather with other alternatives for liquid manure and crop residues disposal, in order to understand which is the more performing and long-term sustainable option. Moreover, EMA can be applied to the economy at national or supranational scale to understand the systemic behaviour of the food for energy vs food for feed systems (Ghaley and Porter, 2013).

2.4.3. Sensitivity analysis

The problem of uncertainty calculation in emergy accounting has been faced by several authors (Hudson and Tilley, 2014; Ingwersen, 2010; Li et al., 2011; Reza et al., 2013; Yi and Braham, 2015) but, despite this, its estimation is currently not included in most EMA studies. Ingwersen (2010) suggests analytical and stochastic methods (the latter based on Monte Carlo simulations) to estimate the uncertainty of UEVs calculated from formula or table-form models. Li et al. (2011) provide two analytical methods to estimate the uncertainty in table-form models, while Reza et al. (2013) propose a fuzzy-based approach to emergy analysis, and Hudson and Tilley (2014) focus on the assessment of parameter uncertainty by using Monte Carlo simulations. Depending on the reliability of both available data and modelling, sensitivity analyses have been anyway performed by evaluating the variation of the emergy indicators values upon changing each of the most relevant emergy flows by a fixed quantity, typically between 10% and 20%. This variation in principle should account for both unreliable and partially unavailable data. It must be stressed that EMA not only provides an accounting in the form of numerical outcomes with their respective uncertainty values but also an insight about how the system is operated, by evaluating, through a comprehensive set of results and indicators, the overall system sustainability. While the analytical determination of the uncertainty on the results is anyway well beyond the scope of this paper, a sensitivity analysis was therefore performed to assess the reliability of the overall picture provided by the EMA. It was realised by varying by 20% the transformity of manure, whose emergy flow contributes for more than 80% of the total emergy yield. The corresponding variation of transformity, ELR, and EYR was then evaluated. It produces a transformity value (without L&S) varying from 3.8E+05 sej/J to 4.9E+05 sej/J (in the latter case, exceeding the transformity value of oil-fired power plant – see Fig. 2.8); the EYR remains almost the same, while ELR varies from 221 to 310. The EMA was also performed by deleting the emergy contribution of manure. The transformities of electricity become lower (1.6E+05 sej/J with L&S and 5.7E+04 sej/J without L&S), but the indicators remains almost the same: EYR equals to 1.01, ELR equals to 132 and ESI equals to 0.08. These considerations lead to confirm the intrinsic unsustainability of this system, despite the inclusion or not of manure in the emergy accounting. This is a consequence of the fact that the biogas production needs large amounts of goods and services, in particular for the biomass cultivation phase and, as a matter of fact, it does not exploit so much local renewable resources as a "renewable source of energy" should do.

Chapter 3. Emergy analysis applied to photovoltaics[7]

In this Chapter, recommendations on how to apply EA to photovoltaic energy production are given, and some literature studies are analysed and commented. The question of the scale of analysis is addressed and all the phases of construction of PV modules, energy production and recycling are considered.

3.1. Setting up the Emergy Analysis of photovoltaic systems

A systemic perspective helps to frame the different levels of analysis of an energy source sustainability. This is particularly important in the case of PV, for which various technological and managerial improvements are still expected in many aspects, from the materials to its use in hybrid energy production plants. Different systemic boundaries can be set in the analysis of PV-based energy systems, each one addressing a different level of analysis, namely that of PV materials, PV cells and modules, PV energy production, PV plant, household PV self-production, energy networks, energy policies, socio-economic policies. For any of these systems different analyses of sustainability can be set, pointing out the complexity of the evaluation. The choice of the level for the analysis will depend in turn on the policy-making framework, even if the information related to the sustainability at any level should be necessary for an overall assessment of the viability of a PV-based system. The inner levels are those of materials and of engineered solar PV modules and are of course a necessary starting point for evaluating the possible impacts on the environment, human health and resource depletion. This is important because – though the present PV technology is still largely based on the use of silicon –new materials such as perovskites are expected to be the basic constituents of the incoming generations of solar panels, even in the short-time period. The attention towards the sustainability of PV, as in the case of

[7] This chapter is based on the following publication: F. Gonella, S. Spagnolo (2019) On sustainable PV-solar exploitation: an emergy analysis, in Solar Cells and Light Management, F. Enrichi and G.M. Righini editors, Elsevier (in press).

many other sectors and technologies, was first drawn by the possible effects in terms of emissions and disposal of possible toxic materials (Parida et al., 2011). Even if PV technology does not release emissions during its operational life, the question of the disposal of solar cells at the end-of-life has attracted specific attention (Choi and Fthenakis, 2014; Corcelli et al., 2018; McDonald and Pearce, 2010). In fact, the European PV industry created an organization (http://www.pvcycle.org) for promoting the commitment in recycling programs of solar modules. In general, the analysis of possible impacts is currently framed in the Life Cycle Assessment (LCA) procedures, which provide a standardized operational framework for a quantitative evaluation of various impact categories (Curran, 2017). The link between the sustainability of solar technologies and the socio-political-economic planning emerged in recent years as mandatory for any decision-making process, given the importance of subsidies and incentive actions in the viability of the PV choice. It is interesting to note that PV electricity production is sometimes quantified in terms of "avoided emissions of CO_2". For example, the Federal Environmental Agency of Germany calculated a CO_2-eq avoidance factor for PV electricity production of 0.58 kg/kWh, giving rise to about 22 Mt of avoided CO_2 emission in 2016 (Fraunhofer ISE, 2016).

The necessity for more comprehensive and integrated tools able to frame the PV systems in larger and more complex systemic analyses has then become more and more evident in the latest years (Sundaram et al., 2016). Approaches like those of Ecological Economics (Spash, 2013; van den Bergh, 2001; Voinov, 2008), Blue Economy (Silver et al., 2015), Green Economy (Brand, 2012; UNDESA, 2012), Green Growth (Jänicke, 2012), Bioeconomy (Mills, 2015), Natural Capitalism (Hawken et al., 1999), Industrial Ecology (Ayres et al., 2015) and Regenerative Design (Lyle, 1996) all draw the attention to the need of integrating the "technical" sustainability of a single system within the more extended boundary of the socio-economy of which it is a part, and onto which it depends. Presently, the concept of Circular Economy (Ghisellini et al., 2016; Kalmykova et al., 2018; Korhonen et al., 2018) plays a privileged role in the global socio-economic debate. Circular Economy may be intended as a general framework for addressing the reduce, reusing and recycling activities in the production process as well as in the circulation and consumption of goods and services, aimed at replacing to some extent the traditional linear economy based on making, using and disposing. Many of the proposed approaches for dealing with integrated sustainability issues can be connected to the necessity of adopting a full systemic perspective, in particular, under the framework of what is usually referred to as Systems Thinking (Meadows, 2009; Monat and Gannon, 2015; Sterman, 2012). Within this framework, emergy analysis (EMA) has been developed as one of the most original and comprehensive approaches.

Emergy Analysis can be used to evaluate the sustainability of systems at different scales. To assess the real sustainability of photovoltaic systems, the analysis cannot be limited to the sole production of solar cells and panels, nor to their waste treatment, but it must be extended at a sufficiently wide scale to include all the significant aspects of the studied system, be them social, economic or environmental. When dealing with sustainability evaluation of complex systems, like an energy network, a set of indicators sufficiently descriptive of each subsystem should be used to assess their sustainability, but they should also provide information about the contribution of each subsystem to the viability of the whole system. Emergy analysis has the capacity of modelling and visualizing complex systems elements and interconnections and permits to quantify all the resources provided by nature and by economy under the same unit of measure. The real sustainability of systems (both ecological and anthropic) can be in this way evaluated and the leverage points critical for their viability identified. In this section some examples of how to draw an emergy system diagram considering different boundaries are reported, with the aim of accompanying the analyst who wanted to study this kind of system. The focus here will be set on power plants rather than domestic and diffused self-production. A comprehensive analysis can start from the relations between the photovoltaic power production, the production of solar cells, modules and panels and their end-of-life. The systemic boundary, in this case, includes all the processes between the transformation of raw materials, the power production and the final destination of plant components. Figure 4 shows these three main steps (box-shaped) referred to the silicon-based photovoltaics:

- the production of solar cells and panels from raw materials (quartz sand for Si);

- the electricity generation from a PV power plant;
- the processes of recycling and recovering for materials (Si, Al, Cu, etc.).

Some inputs of energy, materials and labour are necessary for all process operation. In system diagrams these sources are placed outside the boundary line, in an order established by the EMA rules: from left to right, they are placed in an increasing order of transformity values; renewable sources are placed on the left side, followed by other non-renewable inputs coming from economy, labour, services and money. In this system, sunlight can be identified as the crucial input of the photovoltaic power plant (B box in Fig. 3.1), where it is converted into electricity exchanged with money in the market. This generation can occur only thanks to the PV solar modules, correctly assembled and connected – and so needing human work – to form the assets of this process. The tank "assets" includes all that is further needed for the PV power production and commerce to take place. The industry of photovoltaics includes the production of solar cells, solar modules and their assembling in complete panels (A box in Fig. 3.1). The main input of this production chain is the quartz sand, that – like all purchased inputs – comes into the system thanks to "services". The corresponding emergy represents the memory of all the human work done in the past for extracting, processing and transporting it to the final user. If this amount is not known, emergy of services may be estimated from the cost of the input and the Emergy per unit money of the Nation in which the exchange takes place, as described above. Other purchased resources are reported outside the diagram and linked with arrows to the processes or storages. Labour differs from Services inasmuch it is directly done inside the system, but follows the same emergy conversion method of Services, therefore considering its cost. Being photovoltaics often strictly dependent on subsidies, this source of money is also separately reported and the corresponding emergy flow added to that coming from the sale of energy, all destined to pay for Labour and Services. When the PV panels finish their operation life, they can be processed in order to recover the most valuable materials, which can be re-sold to the market and enter again in the photovoltaic production chain (C box). Renewable flows, like rain and wind, can play fundamental services to provide the necessary dilution of pollutants emission. In the diagram of Fig.

3.1, wind is shown to support the dilution of pollutants produced by the PV industries: the quantification of its work is carried out by calculating the kinetic energy of the mass of air needed to take and dilute the pollutants in a larger area, and then converting it into emergy using the wind transformity, that gives the solar emjoules per joule of wind energy.

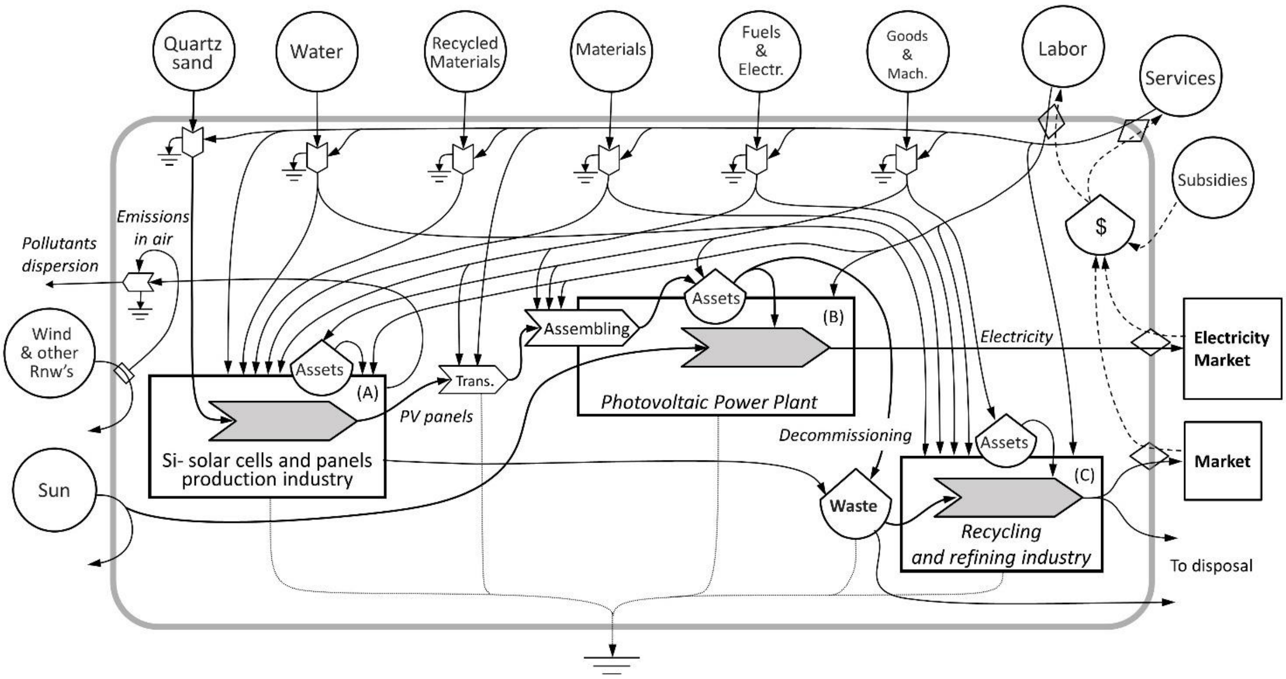

Fig. 3.1. Overall emergy system diagram of Si-based photovoltaic power production.

Expanding the A box of Fig. 3.1 provides an insight on how this subsystem works, allowing to analyse its strengths and weaknesses. The generic production process of silicon-based PV panels showed in Fig. 3.2, can be subdivided in four processes that take place either in the same factory or in different factories. The main input to be processed is the quartz sand, purchased and imported into the system and then transformed in consecutive processes. The symbol used for each step describes a process in which the main input in the left side is transformed thanks to the additional inputs from the top. In this diagram, a general source of "Renewable resources" is placed on the left side, but quite often all the relevant renewable sources are considered separately, any of which linked to the appropriate system processes. An analysis of this diagram makes possible to point out which specific process or stock is more emergy-intensive, and so which one could be improved to reduce its dependency on non-renewable resources, or to increase the exploitation of renewable local ones.

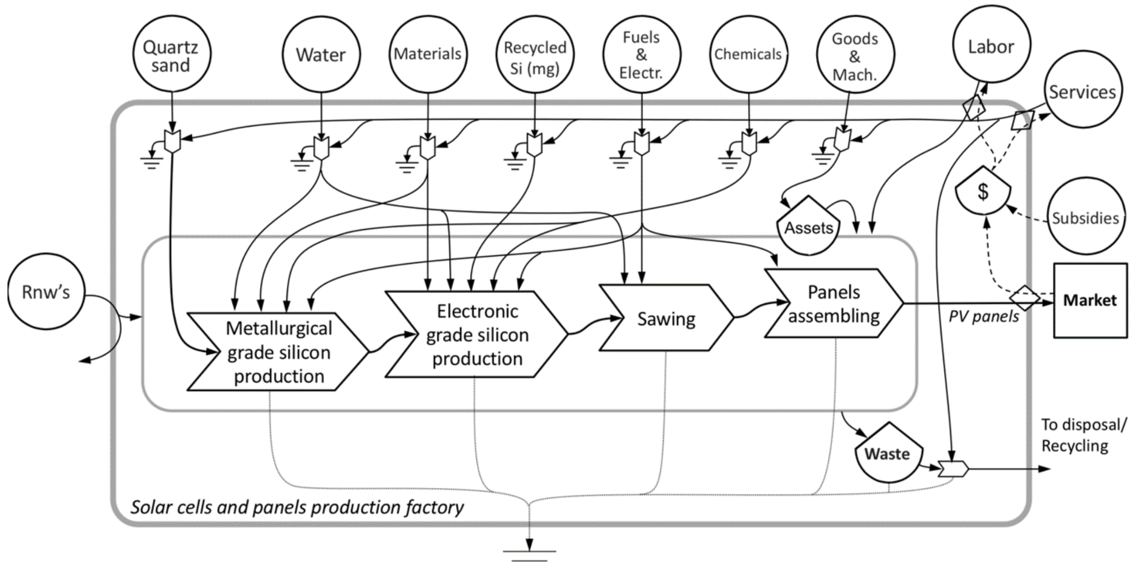

Fig. 3.2. Emergy diagram of solar cells and panels production factory.

Fig. 3.3 represents the processes included in the C box of Fig. 3.1, related to the end-of-life treatments of decommissioned silicon panels. In this diagram, a single general process shape (rectangle) is used for the main transformation processes of silicon panels, though they actually include further (not visualized) steps.

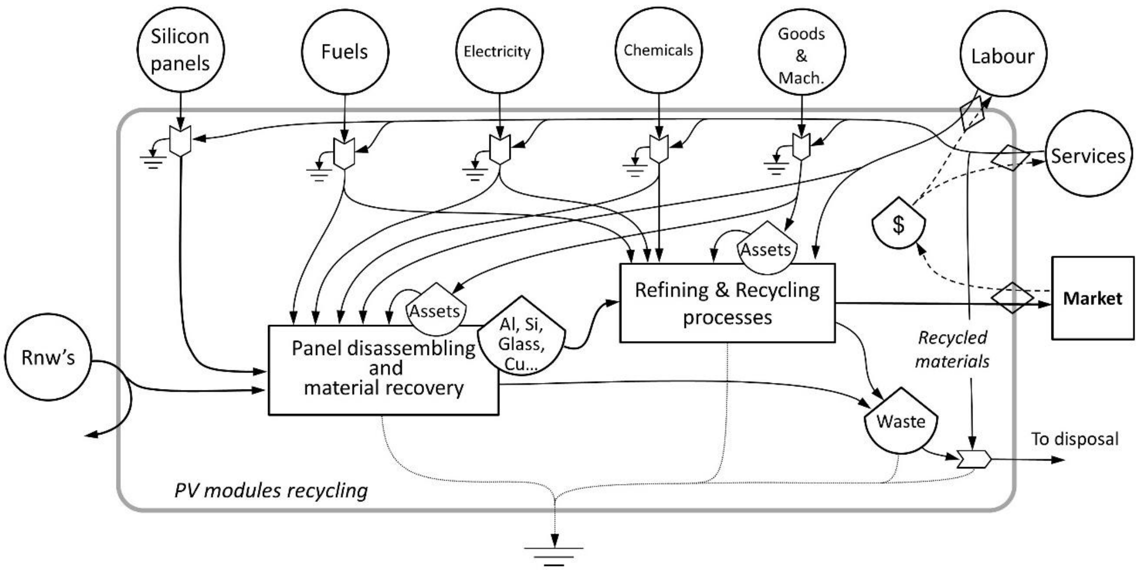

Fig. 3.3. Emergy diagram of PV recycling and recovering.

As described above, the construction of the emergy system diagram is followed by the collection of all the relevant resources inputs, gathered in renewable and non-renewable local resources, purchased resources, labour and services. From this quantification, it is possible to calculate the aforementioned indicators.

3.2. Emergy Analysis of PVs in literature

In the field of photovoltaics few EMA studies are reported in the literature. The first analysis of a PV energy network, located in Texas, is by H.T. Odum himself (Odum, 1996a), based on data of 1991 and scarcely comparable with more recent updated studies. Raugei et al. (2007) report the emergy analysis of a system including photovoltaic modules productions and plant installation, including also all the components and equipment of PV plant other than the PV panels (so called Balance of System – BOS). It considers the following solar cell types, namely, (i) poly-crystalline silicon (electronic grade), (ii) CIS (copper indium gallium selenide) thin films, and (iii) CdTe (cadmium telluride) thin films. The obtained transformity values for electricity from power plant ranged from 1.9E+05 to 2.3E+05 sej/J, whilst the usual emergy indicators were not considered because of their misleading interpretation when applied on plant scale systems (Raugei et al., 2005). The results also show how much the system depends on the emergy associated with Labour and Services (L&S). In fact, L&S for all the selected technologies range from 75% to 60% of total transformity of electricity including BOS, meaning that the entire PV industry heavily depends on L&S. A study where, in addition to the electricity generation, the production process of PV wafer is considered in detail is that of Paoli et al. (2008). They assessed a PV system made by monocrystalline solar cells which were compared to a solar thermal plant. For both solar technologies, the transformities were calculated together with common emergy indicators. It is worth noting how the Authors addressed the operational and conceptual meaning of transformity, explicitly named as both a “cross-quality” and “parallel quality” indicator. In the cross-quality perspective, transformity of systems with different products indicates higher capacity of energy concentration and high level in the hierarchy of energy. This means that several steps are required, in which more energy of low quality is used to maintain energy of higher quality potentially more useful for human activities. The heat produced by solar thermal plant was shown to have higher values of both ELR and EIR indicators with respect to PV electricity production. In fact, photovoltaic plant resulted more dependent on non-renewable resources than solar thermal plant, because of the complex process of PV panels production and the greater costs of their design and maintenance. It must be underlined that the Authors considered manpower as partially renewable, giving a relevant increase in the amount of renewable emergy in the EMA of the solar thermal plant. As concerns EIR compared values, PV is shown to be less efficient in exploiting local resources than a solar thermal plant, needing more imported resources than those locally available. When same-product systems are compared, one can refer to some "parallel quality", meaning that systems with lower transformities are more efficient in exploiting resources than alternatives with higher ones, and so they should be preferred in the policy-making procedures. The two further alternatives addressed to produce heat and electricity are based on fossil fuels, namely, methane for heat production and thermoelectricity. The comparison between the solar and fossil options shows that the solar ones use less resources (in emergy units) than the fossil alternatives to produce the same output. This result addresses quantitatively the need for the transition from fossil to renewable sources, but this time the attention is not drawn to the fuels progressive scarcity, nor to the environmental impacts, but rather to the long-term sustainability of the options.

Literature reports also an example (Brown et al., 2012b) of analysis for a CdTe-PV power system, compared to an oil-fired power plant. The Authors, in this case, adopted an approach derived from Life Cycle Assessment to classify resources in the foreground and background inputs. This was made in order to have a clearer conceptualization of the Environmental Yield Ratio (EYR) since it can assume different meanings depending on the chosen system boundary. On the basis of this classification of resources, a new definition of EYR is suggested and the calculation of this indicator and the transformity of electricity produced both by CdTe photovoltaic and the oil-fired power plants is presented considering all the production chain from the extraction of raw materials to the energy production. As observed by Raugei et al. (Raugei et al., 2007) and confirmed by this study, L&S in PV energy chain gives the highest contribution to the total emergy computation, and an EYR lower than that of the oil-fired power plant (2.2 versus 6.8), showing that PV energy is less efficient in exploiting purchased resources than the fossil alternative. The obtained transformity values, from a parallel-quality perspective, indicate in this case that PV uses more resources than the fossil alternative. The apparent contradiction with the results presented above is caused by the different choices of the system boundary – and consequently of the processes considered inside the system – in so further highlighting the importance of clarifying the assumptions of an EMA procedure.

In Kursun et al. (2015), several technologies to produce electricity in an Indian village are analysed and compared. Besides the solar PV technology, they considered the conventional and calcium looping, clean coal, biogas and biomass gasification. The analysis includes the phases from the metallurgical-grade silicon production to the installation and operation of the multi-crystalline silicon (mc-Si) based power plant. Data of energy and material inputs to the system came from the database ecoinvent while operational data were from the real PV plant installed in the village. In this paper, an example of how to use EMA into an integrated feasibility study of energy mix scenarios is reported, comparing the different alternatives from different points of view: environmental impacts, resources investment and costs. The most convenient solution for this village resulted to be the biogas power plant. It must be pointed out that different geographical locations affect the result of EMA, inasmuch as the availability of the resource can be strongly different also in the social and economic background, that affects the UEVs of money and labour.

The treatment of solar PV panels can lead to the emission of hazardous materials and gases, like chromium, lead and hydrofluoric acid. For this reason, sustainable solutions are required that take into account the environmental risks, along with suitable procedures for the recovery of useful materials like rare earths or metals. Despite the numerous processes existing to recycle the PV modules, at pilot or laboratory scale, nowadays it does not exist a completely automated process capable to treat different kinds of PV panels. Corcelli et al. (2017) report an EMA of the thermal treatment of a decommissioned Si-based PV panel and the recycling processes of aluminium, glass, silicon, metal electrodes and other inert material. The number of recovered materials was obtained from a previous analysis (Corcelli et al., 2018), while background data for the recycling processes were derived from the Ecoinvent database (Frischknecht and Rebitzer, 2005). The question of emergy accounting of waste flow is explicitly faced: contrary to the typical LCA approach, in which the production of waste to be treated does not carry any impact (the so-called "zero burden" approach), in emergy analysis it virtually carries as well the energy memory of its production. Actually, emergy analysts adopt different accounting methods when dealing with this kind of "product", depending on the context of the analysis. Corcelli et al. (2017) considered only the emergy required for the recycling process, assuming that if the material is recycled multiple times, the emergy of extraction and first treatment is "saved". Results from this paper show that the UEV for recycled silicon is a little lower than that of virgin silicon, because of the high emergy contribute of electricity and services needed to sustain this process. Other recovered materials have UEVs one order of magnitude lower than the virgin materials, showing that their recovery is more efficient.

3.3. Comments

Despite the dramatic increase of the interest towards both sustainability and energy transition issues, comprehensive integrated analyses that frame solar energy sustainability are still lacking. Emergy-based approaches are increasingly used for the analysis of several socio-economic and productive processes and appear particularly suitable for addressing the use of solar PV at different levels. First, the continuous development of new materials and configurations for PV, that makes it necessary to assess their sustainability also in a circular economy perspective, without limiting to address only their operation efficiency. Moreover, photovoltaics is not only an engineered technology but must be regarded also as an element of integrated energy production networks. In this sense, emergy analysis provides an effective tool to assess the PV sustainability both as a piece of technology throughout its lifetime and as a part of the more extended and complex system of energy provision and distribution.

Chapter 4. General discussion

A combination of anthropocentric and ecocentric epistemologies are the conceptual foundations – yet rarely explicated – of all sustainability narratives (Borland and Lindgreen, 2013). The ultimate dimension of sustainability is, of course, the ethical one, even for the energy technologies. The concept of "energy justice" nowadays has entered the debate on global energy systems, which should "fairly distributes both the benefits and burdens of energy services and contribute to more representative and inclusive energy decision-making" (Sovacool et al., 2017). Including the ethical dimension in the socio-economic and scientific arena of energy debate appears mandatory as far as the sustainability issue is a focal aspect, even in its "business as usual interpretation" (Mulvaney, 2013). On the other hand, putting together in some scientific fashion cost-benefit analyses, engineering aspects, political power drivers and social justice is certainly a hugely hard task. Do not exist simple solutions to complex problems. As far as the energy will have such a pivotal role in the definition of socio-economic scenarios at both local and global levels, systemic approaches able to encompass all the above-mentioned aspects will remain mandatory.

Emergy analysis is a conceptual tool that goes well beyond its operational use aimed at systemic accounting procedures. The epistemological aspects of emergy have been presented for example in the special issue of the "Ecological Modelling" Journal (Vol. 278, 2004), entitled "Philosophical overview of the contributions of H.T. Odum". From the scientific point of view, besides the very definition of emergy and the accounting method consequently developed, the most important conceptual contribution by Odum is embodied in the Maximum Empower Principle, that gained the theoretical status of Thermodynamic Principle and that is based on the idea of energy quality and hierarchical structure which characterizes the emergy picture (Brown and Ulgiati, 2004). Odum introduced the concept that in the competition among self-organizing processes, network designs that maximize empower (emergy flow) will prevail, by reinforcing resource intake as well as the operation at the optimum efficiency (Odum, 1996a). This collects all the elements virtually necessary to frame in a valid theory the description of how systems work. The principle has been addressed as the tool and the concept to describe and interpret the operation of virtually any system. In principle, an analytical simulation of a system, able to calculate the empower as a function of the state variables, will indicate the "natural", self-organizing evolution of the system given its systemic structure, pointing out the dynamic accessible patterns. In general, it may be said that the simulation of a system starting from his emergy diagram and inventory is potentially disrupting, as far as EMA could become a very powerful tool for decision-making processes (Odum and Odum, 2000a), even related to recently integrated perspectives like for example that of circular economy. As concerns the emergy method limitations, they have been analysed and discussed in several aspects since the Odum's foundational work, in particular, concerning its apparent lack of standardization in terms of UEVs and diagrams assessment, as well as for the difficulty in providing comprehensive uncertainty analyses. Most of all, EMA results difficult to be conceptually accepted by some scientific communities and by the policymakers (Sovacool et al., 2017), and the scientific community dealing with emergy is specifically working to address this crucial issue. The integrated biophysical perspective of the emergy synthesis, which addresses human activities and monetary flows but at the same time is definitely ecocentric, is a step forward in both the understanding and the managing of complex real systems. In fact, emergy analysis realizes one of the main aspects which the Systems Thinking is based on, that is, the idea of looking for the patterns, and not for local linear cause-effect chains, to describe and understand a system. The legacy of H.T. Odum, along with its assessments and developments, is still under-utilized and under-exploited, despite the increase of the literature dedicated to emergy-based analyses. Nevertheless, the more and more urgent necessity of holistic perspectives and approaches to face global threats makes emergy a conceptual and operational tool with a huge potential for use, being one of the few quantitative notions that intrinsically encompasses all the aspects required by a truly integrated analysis of the sustainability of any system.

The Emergy analysis of the BPP presented in this thesis describes a multi-faceted reality. The sustainability of the system, in particular, turns out to depend on the choice of the systemic boundary, and in general on the level of integration described by the analysis in terms of co-production of different outputs. As a matter of facts, a single scale analysis can provide misleading interpretation of the process sustainability, like the case of Burlington (Herendeen, 2019), due to the systemic archetype "shifting the burdens".

The presented study was made at two different scales, namely, the Reference System, including the rotational crops linked to the biogas and energy production, and the Expanded System, which adds also a cattle breeding, that produces milk and meat and at the same time provides the liquid manure used in the production process. The outcomes of the analysis may be then summarized as follows:

- The values of the electrical energy transformity resulted in 4.4E+05 sej/J with labour and services (L&S) and to 3.3E+05 sej/J without L&S, while for the ES they resulted 1.1E+06 sej/J and 5.8E+05 sej/J, respectively. These values are close to those obtained for the fossil-based energy production, due to the dependence of the agricultural phase on fossil fuels.
- The sustainability of biogas production results more questionable than it is perceived by public opinion, confirming the necessity for multi-scale analysis. In this respect, the obtained transformity values show how the EMA procedure is useful to point out the systemic role of a BPP within an energy supply network.
- Emergy Yield Ratio is close to 1 for both RS and ES, meaning that they do not provide a net contribution to the economy as they do not support more than their own systems.
- Environmental Loading Ratio of the RS is twice that of ES, meaning that the stress on the environment is greater for RS than for ES.
- The ratio of EYR to ELR, that is the Emergy Sustainability Index ESI, measures the economic and environmental compatibility. In both the systems at issue this index is very low, indicating that, at present, the BPP studied relies too much on external investments and too little on renewable sources.

- The emergy flow of liquid cattle manure accounts for a significant percentage of the total emergy investment of the RS. Since manure is a co-product from another subsystem, some misinterpretation may arise, since manure is generally considered as a "free" waste, addressing its use as "less efficient" and "less sustainable". This is actually true, in so far as it is the production of meat and milk associated with the co-product "manure", that carries the same donor-sided unsustainability of the cattle breeding. Of course, these considerations have to do with the meaning of the concept of emergy, aimed at determining an overall investment. If manure is considered as a renewable source, emergy indicators change significantly, but liquid manure from conventional breeding cannot be considered as a renewable energy source as it is not "free renewable emergy of environmental inputs from such as sun, wind, rain" (Odum, 1996).

The system efficiency, at both scales, results insufficient to make the BPPs competitive with the fossil fuel-based power generation. Results show that biogas power generation is not "green" enough, as the renewable fraction of the exploited resources locally available remains less than the non-renewable ones. In fact, more than the power plant itself, it is the agricultural phase that depletes most of the non-renewable resources (mainly in the form of diesel), affecting in this way also the sustainability of the livestock from which the liquid manure comes from. Anaerobic digestion is more suitable to be considered as a waste-treatment process that provides more benefits (electricity and fertiliser materials) than other alternatives of treatment, and thus its environmental performances should be compared with that of these kinds of processes.

Final comments

From the research presented in this thesis some general reflections are addressed:

- ❖ adopting integrated indicators based on a systemic approach is mandatory, especially for sustainability evaluation of energy alternatives in the policy guidelines;
- ❖ choosing an appropriate scale when assessing the sustainability of specific systems as agriculture-linked ones is mandatory as well. Otherwise, the risk of shifting the environmental burdens is significant;

- ❖ an analysis performed at different space- and time-scale setting is necessary for a reliable narrative of the real integrated sustainability of the system at issue;
- ❖ the use of global accepted UEVs for the calculation of emergy flows and indicators, together with an accepted calculation methodology, are necessary for the correct comparison of different alternatives.

The analysis of BPP, like many others, proved that energy crops are not a feasible substitute for fossil fuels-based energy production. Besides pollutions and competitions for food issues, not addressed here, it is a question of emergy/systemic efficiency, that tells us how much *resource* expensive are this type of processes. Emergy Analysis permits to define sustainability objectively: it is the work made by the geobiosphere and the network of energy transformations and feedbacks that tell us which systems will survive in the long run and which will not. No policy change could modify this interpretation of sustainability. Expanding the scale of analysis shows us which is the most resource-consuming subsystem linked to the one studied, indicating that the problems can originate at a larger scale (e.g. population increase -> meat request -> intensive farming -> intensive forage cultivations...). Also Herendeen (2019) showed how easy it is for politicians to talk about a 100% renewable city, just limiting the boundary of interest.

As already observed by Odum himself (1996): "....the emergy yield of economically intensive biomass plantations cannot alone substitute for fossil fuels and native woods until these two fuel sources are gone and the economy has been reorganized again to do less (less population, smaller cities, fewer autos...)". This means that results like those presented in this work further address the intrinsic difficulty of planning a suitable energy supply network, without considering the necessity of more radical changes in the entire economy. In this sense, the donor-side and systemic perspectives offered by EMA demonstrates again its potential in providing an effective quantitative tool to both scientist and economic analysts.

Appendix A Inventory

The following tables report the annual flows of material and energy used for the construction of the power plant (estimated from technical reports and projects), for the biomass cultivation and the energy production. Energy and fuels consumptions for the construction phase were not available. Flare and transformer station have not been included due to lack of information about their compositions.

Table A.1 - Material composition of the biogas power plant.

Item	Amount	Unit
Paved area	23,000	m^2
Loading system		
Steel (loading system 60 m^3)	13,000	kg
Polyethylene (anti-percolation floor)	300	kg
Fermenter (V = 2400 m^3)	*n° of fermenters*	*2*
Steel (mixer)	6,500	kg
Steel (gates)	130	kg
Steel (over-pression relief valves)	260	kg
Steel (railing)	500	kg
Steel (corrugated sheet)	3,000	kg
Steel (over ground pipes)	2,100	kg
Steel (underground, pre-insulated heating pipes)	70	kg
Steel (reinforcing bar for concrete)	27,340	kg
Concrete (walls and pillars)	179,000	kg
Concrete (foundations)	163,000	kg
Concrete (electric wells)	15,100	kg
Wood (roof boards)	6,000	kg
Wood (roof beams)	14,000	kg
Wood (coverage boards)	600	kg
Polyethylene (PEX) (Multilayer condensation pipes)	3	kg
Polyethylene (PEX) (Multilayer desulphurization pipes)	15	kg
Polyethylene (PEX) (Multilayer heating pipes)	450	kg

High density polyethylene (PE100) (coverage electro-weldable pipes)	7	kg
High density polyethylene (PE100) (background gas electro-weldable pipes)	410	kg
High density polyethylene (PE100) (corrugated tubes)	1,630	kg
Polypropylene (PP) (coverage tissue)	120	kg
Polyester fibres (gasometric dome)	460	kg
Extruded polystyrene foam (insulating panels)	1,130	kg
PVC un-plasticized (gas pipes)	100	kg
Rigid polyurethane foam (PUR) (insulation for underground, pre-insulated heating pipes)	17	kg
Electric cables	n.a.	
Water and glycol (30%) (Thermoconvector fluid)	1,300	L
Water	910	L
Ethylenic glycol	390	L
Eccentric screw pump (digested extraction)	n.a.	
Separation tank and liquid manure tank		
Steel (Agitator with submerged motor)	252	kg
Steel (Separator fan)	480	kg
Steel (reinforcing bar for concrete)	6,100	kg
Concrete (walls and foundations)	64,750	kg
Container All in One		
Steel (concrete reinforcing bar)	2,890	kg
Steel (insulated container)	12,000	kg
Concrete (foundation, pillars, slab)	43,560	kg
Insulation (container)	n.a.	
Steel (Cogenerator 625kW)	7,800	kg
Copper (Cogenerator 625kW)	200	kg

Table A.2 - Liquid cattle manure chemical composition

Substance	Average	Standard deviation
$N\text{-}NH_4^+$ (g/l)	1.1	0.2

N-TOT (g/l)	2.6	0.4
Volatile Fatty Acids (mg CH_3COOH/l)	5248	1653
Volatile Solids (% of Total Solids in dry matter)	82	3
Volatile Solids (% of TQ in dry matter)	6	1
Total solids (% of TQ in dry matter)	7	1

Table A.3 – Liquid digestate characterization.

Composition	% OS	% DM	kg/t_{OS}
Dry matter	5.61	-	
Organic dry matter	3.92	-	
Organic dry matter	-	69.90	
Nutrients			
Total magnesium (MgO)	0.05	0.91	
Total phosphorus (P_2O_5)	0.13	2.24	
Total calcium (CaO)	0.15	2.65	
Total potassium (K_2O)	0.40	7.20	
Total nitrogen (N_{TKN*})	0.50	8.92	5
Ammonia nitrogen (NH_4-N)	0.28	4.99	

*TKN = Total Kjeldahl Nitrogen.

Table A.4 - Solid digestate characterization.

Item	% OS	% DM	kg/t_{OS}
Dry matter	30.9	-	
Organic dry matter	25.9	-	
Organic dry matter	-	83.9	
Nutrients:			
Total Magnesium (MgO)	0.22	0.72	
Total Phosphorus (P_2O_5)	0.64	2.08	
Total Calcium (CaO)	0.74	2.41	

Total Potassium (K_2O)	2.33	7.54	
Total nitrogen (N_{TKN*})	0.81	2.62	8
Ammonia nitrogen (NH_4-N)	0.39	1.26	

*TKN = Total Kjeldahl Nitrogen

Table A.5 -Biogas composition (referred to 1 Nm^3)

Substance	Amount	Unit
Methane (CH_4)	49 – 55	%
Carbon dioxide (CO_2)	44 – 50	%
Oxygen (O_2)	0.1 - 0.4	%
Nitrogen (N_2)	0.5 – 2	%
Water	0.8 – 7	%
Hydrogen sulphide (H_2S)	100	ppm
Calorific value	2.16E+07	J/Nm^3

Appendix B Renewable energy flows

B.1. Solar energy

Area =	10,000	m^2	
Annual Solar radiation =	5.12E+09	J/m^2	(ENEA, 2019)
Albedo =	0.10		estimated, for cultivated area
Carnot efficiency =	0.93		
Solar energy =	(area) · (annual solar radiation) · (1–albedo) · (Carnot efficiency)		
=	4.29E+13	J/ha·yr	
UEV =	1.00	seJ/J	by definition

B.2. Wind energy

Area =	10,000	m^2	
Density of air =	1.23	kg/m^3	
Wind reference velocity =	1.70	m/s	annual average velocity in Mantova at 25 m overland (Regione Lombardia, 2019, data for year 2017)
α for land =	0.25		
Geostrophic wind velocity (land) =	(ref. velocity) · (height/reference height)$^{\alpha}$		
=	(1.70 m/s) · (1000 m/25 m)$^{0.25}$		
=	4.28	m/s	
Drag Coefficient for land =	0.00164		
Time =	3.15E+07	s/yr	
Available energy of wind dissipated on land =	1/2 · (air density) · (area) · (drag coefficient) · (geostrophic wind velocity) ^{3} · (time)		
=	0.5 · 1.23 (kg/m^3) · 1.00E+04 (m^2) · 0.00164 · (4.28 (m/s))^3 · 3.15E+07(s/yr)		
=	2.49E+10	J/ha·yr	
UEV =	800	sej/J	(Brown and Ulgiati, 2016)

B.3. Rain, chemical potential energy

Area =	10,000	m^2	
Annual precipitation on land =	0.404	m/yr	(Regione Lombardia, 2019) (Location: Mantova, year 2017)
Annual precipitation on land =	0.405	m/yr	
Evapotranspiration (average) =	75%		

Gibbs free energy of rain =	4,720	J/kg	
Density of water =	1,000	kg/m^3	
Available energy of rain =	(area) · (ann. prec.) · (% evapotr.) · (density of water) · (Gibbs free energy of rain)		
=	1,650,000 (m^2) · 0.405 (m/yr) · 0.75 · 1,000 (kg/m^3) · 4,720 (J/kg)		
=	1.43E+10	J/ha·yr	
UEV =	7,000	sej/J	(Brown and Ulgiati, 2016)

B.4. Geothermal energy

Area =	10,000	m^2	
Heat flow =	1.26E+06	J/m^2·yr	(Cataldi et al., 1995)
Carnot efficiency =	9.5%		= 1 – (287 K/ 317 K)
Available energy =	(area) · (heat flow) · (Carnot efficiency)		
=	1,650,000 (m^2) · 1.26E+06 · (J/m^2·yr) · 0.095		
=	1.20E+09	J/ha·yr	
UEV =	4,900	sej/J	(Brown and Ulgiati, 2016)

B.5. Topsoil erosion

Area =	1	ha	
Water soil erosion (for conservative agriculture) =	3,800	kg /(ha·yr)	(Regione Lombardia, 2013)
Soil eroded =	3,800	kg/yr	
Organic carbon content of soil =	2	%	(Regione Lombardia, 2013)
Total organic carbon(OC) lost =	76	kg	(Regione Lombardia, 2018)
Specific energy of OC =	10,000	kcal/kg	
Conversion factor =	4,187	J/kcal	
Available energy in OC lost by water erosion =	(area) · (water soil erosion) · (organic carbon content) · (specific energy of OC)		
	3.2E+09	J/ha·yr	
UEV =	1.24E+05	sej/J	(After Odum et al., 2000)

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