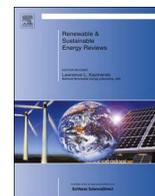




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Unavailability percentage as energy planning and economic choice parameter

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ABSTRACT

The unavailability percentage is suggested as an indicator of the level of the technological development in relation to the optimized use of energy. This quantity can be used in economic, and socio-political evaluations because it is related to the exergy lost during a process, and therefore it can provide information on the optimization level obtained through a technology or it can be useful to compare different technologies.

1. Introduction

One of the main problems of industrialized countries is the management of CO₂ emissions [1]. The Kyoto Protocol suggestion of CO₂ emissions reduction can be achieved through two primary actions:

1. Renewable energy sources.
2. CO₂ sequestration, with very high estimated investment costs, and difficult to be carried out due to this reason.
3. Promotion of existing high efficiency technologies, and adoption of advanced low-CO₂ emission energy systems. Indeed, CO₂ reduction is directly related to the thermodynamic efficiency of any plant. An energy policy to promote best existing technologies, and their adoption could be developed.

In order to reduce greenhouse gas (GHG) emissions, the Kyoto Protocol suggested three mechanisms:

1. The Clean Development Mechanism (CDM), a mechanism that enables the creation of credits (CERs, Certified Emissions Reductions) in developing countries to be generated by investment in carbon-reduction projects to offset emissions.
2. The Joint Implementation (JI), a similar mechanism but applicable to methane (CH₄), nitrous oxide (N₂O), carbon dioxide (CO₂) from deforestation, decay of biomass, change and forestry, fossil fuel use, perfluorocarbons, hydrofluorocarbons, etc.
3. The international emissions trading (AAUs trading).

Many factors can affect overall carbon dioxide emissions: economic growth levels, technological development, and production process selected for any particular production [2]. At the same time, the CO₂ emission problem could represent a real opportunity to promote high-efficiency design of conventional plants, and consequent dissemination of advanced technologies. Indeed, the European Union also designed the Strategic Energy Technology (SET) Plan, to develop researches on new technologies, with particular regard to those relevant in climate change [3]: measurement, tracking, and program evaluation are important to evaluate the impact of the sustainable policy, with particular regard to emissions reductions.

In the entire scientific history, scientists and engineers tried to obtain universal principles useful to the evaluation of the system's developments: examples being Fermat's principle in optics and Hamilton's principle in mechanics, Prigogine's least entropy production [4–8], in thermodynamics, in order to describe the dissipative systems, used in a several energy efficiency problems in design and optimization of thermal and power systems [9–11]. The entropy approach was first introduced in industrial ecology by Lowenthal and Kastenberg [12], whose results were to assign an entropy value, interpreted as a cost, to stages in a product's life cycle, but its use was also a thermodynamic measure for resource use, or waste generation [13].

In order to determine how far a process, or a system, is from its maximum thermodynamic performance, exergy can be introduced [14–16]; indeed, exergy losses and thermodynamic efficiencies are related to assess thermo-economic costs [17].

The aim of this paper is to develop the use of a new thermodynamic

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indicator, the unavailability percentage, named also exergy inefficiency, recently introduced [18], and based on the exergy analysis and fluxes, in order to evaluate, and improve the thermodynamic performance of industrial processes. In the whole paper product will mean “as a result of a production process”, or “service” if referred to an industry of services.

2. Indicators and sustainable development

Science and technology are considered fundamental to the growth and socio-economic development of countries; indeed, technological development has impact on income distribution, economic growth, employment, trade, environment and industrial structure [19,20]. The 1992 Earth Summit stipulated that countries at national level as well as governmental and non-governmental organizations at international level should develop indicators of sustainable development in order to support countries in making decisions on sustainable development [19].

At all levels, the role of science and technology is fundamental; scientific knowledge and technologies are the basis to challenge economic, social, and environmental problems, in order to avoid unsustainable conditions. The analysis of technological processes can be developed using a thermodynamic approach for the whole system and for all its interactions both internal to the process, and external to the environment and society. The results consist of a quantitative evaluation of the flows of matter and energy which occur in the system and of the consumption rate of the available resources. This information can represent a fundamental support to policy planning and resource management [21].

In order to evaluate the technological level, and the advanced level of industrial processes, some indicators must be considered. Every company applies different production processes, which cause different carbon emissions or environmental impact, therefore as regards the environmental effects, the process itself results more important than the product obtained. In order to analyze both the environmental impact and the technological level acquired by the countries several indicators can be introduced. These can be defined as [21] “an aggregate, a quantitative measure of the impact of a ‘community’ on its surroundings (environment)”. It implies that:

1. The ecological indicators must be applicable to any “community”.
2. They are aggregated because it cannot be limited to a single individual.
3. They consider only the effects produced on the environment that surrounds the community under examination.

From these definitions, it follows that the community and the environment must be considered as two separate, but interacting systems [21].

The consequent properties of the environmental indicators can be summarized as follows:

1. They must be evaluated using unambiguous and reproducible methods under a well defined set of fundamental assumptions.
2. They must be expressed by a numerical expression whose results can be ordered in an unambiguous way.
3. They must be calculated on the basis of intrinsic properties of the community and of the environment.
4. They must be normalized in order to compare different communities or environments.
5. They must be defined on the basis of the accepted laws of thermodynamics.

Sciubba analyzed in detailed a lot of indicators and pointed out their limits in Ref. [21]. Here his results are summarized according to the most used environmental indicators:

1. MTA (Material Throughput Analysis or Material Inventory Analysis): it is an indicator based on the assumption that the lifestyle of a community can be measured by the global equivalent material flow used to produce the commodities on which it thrives. The method involves highly disaggregated accounting of the material inputs/outputs and it requires detailed knowledge on production processes. Moreover, it does not use the second law of thermodynamics.
2. EEn (Embodied Energy): it is an indicator which obtains a direct measure of environmental impact. The amount of energy used to construct a product, in terms of resources and work done, is evaluated, but it does not include any measure of the quality of the energy flows considered.
3. The transformity: in the Emergy Analysis the energy accounting is considered, but the fundamental assumption is that the only input form of energy is the solar radiation. All other flows of matter and energy are related to equivalent solar energy necessary to obtain them. This evaluation is carried out using a proper set of coefficients, the transformities. It does not include any measure of the different quality of the energy flows.

All these indicators do not consider the quality of energy, but this property is fundamental in the analysis of the technological level involved in a process. In the early ‘80es Goran Wall and others scientists and engineers analyzed territorial systems using exergy flows, which involve the first and second law of thermodynamics [21]. This quantity considers the quality of the energy used, too. In relation to the aim of this paper, the exergy dissipated must be consider; indeed, it represents the available energy dissipated in the environment and the less is its value the higher is the technological level used in a process. This will be developed in the next section, starting from the laws of thermodynamics.

3. The thermodynamic approach to production (services included) systems

The best system, from an energy point of view, is the one which uses less energy to obtain the same useful output [22]. Consequently, the thermodynamic efficiency of a country is related to its technological and ecological development.

In order to evaluate the energy efficiency, two different thermodynamic approaches must be considered:

1. The first law analysis, known also as the net energy analysis: it allows tracing the energy flows useful to produce products or services. Its mathematical expression is the energy balance:

$$\sum_{in} G_{in}(h + e_k + e_p)_{in} - \sum_{out} G_{out}(h + e_k + e_p)_{out} + \sum_i Q_i - W = 0 \quad (1)$$

where G is the mass flow, h is the specific enthalpy, e_k and e_p are the kinetic and the potential specific energy, Q is the exchanged heat and W the work done. From this equation, a useful formulation of the first law efficiency was proposed [23] as:

$$\eta_l = \frac{H_{out}^{useful}}{H_{in}} \quad (2)$$

where H_{out}^{useful} represents the raw energy resource converted to useful energy, met downstream as final or end-use demand [24], while H_{in} is the input enthalpy.

2. The second law analysis, also known as the entropy or the exergy analysis: this law allows us to take into account the degradation of the energy due to irreversible processes. In relation to this analysis the exergy balance equation:

$$\sum_{in} G_{in} ex_{in} - \sum_{out} G_{out} ex_{out} + \sum_i (Ex_Q - Ex_W)_i - I = 0 \quad (3)$$

where G is the mass flow, ex is the specific exergy, Ex_Q is the exergy associated with the exchanged heat Q , Ex_W is the exergy associated with the work done W and $I = Ex_{in} - Ex_{out}$ is the exergy loss for irreversibility. From this equation a useful formulation of the second law efficiency was proposed [25] as:

$$\eta_{II} = \frac{Ex_{out}}{Ex_{in}} \quad (4)$$

First law analysis does not consider the energy quality, while the second law allows pointing out that not all the heat input can be converted into useful work, due to irreversibility. This law requires the definition of parameters that allow us to quantify the maximum amount of work achievable in a given system with different energy sources: this quantity is the exergy Ex defined as the available energy for conversion from a reservoir with a reference to the ambient environmental temperature [26]. So it represents the thermodynamic quality of the energy of a system [23].

The parameter useful to quantify the technological level of the process used is the unavailability percentage, or exergy inefficiency, defined as [18]:

$$E_{\lambda}^{\%} = \frac{Ex_{\lambda}}{Ex_{in}} \cdot 100\% \quad (5)$$

with Ex_{λ} unavailability, defined as:

$$Ex_{\lambda} = Ex_{\lambda}^{out} - Ex_{\lambda}^{in} = E_{in} - Ex_{out} = Ex_{in} - Ex_{out} - W \quad (6)$$

where E_{in} is the total energy input in the system, Ex_{out} is the total exergy coming out from the system. This factor explicitly takes into account the irreversibility in the process, and if the process is well optimized in relation to present technologies.

This quantity is interesting to evaluate the technological maturity of a production system, because it is useful to obtain information on the losses of processes, even if it cannot be considered an environmental indicator [21]. The less is the value of the unavailability percentage, the more the industrial process is efficient in terms of energy use.

4. Considerations

In this section some considerations on the quantity introduced will be developed in order to make clear on the results obtained in the applications, developed in the next section.

Technology is considered one of the fundamental driving force for the growth, and socio-economic development of contemporary countries, because technological development has impact on income distribution, economic growth, employment, trade, environment and industrial structure [21,27]. The analysis of technological processes can be developed using a thermodynamic approach for the whole system, based on the quantitative evaluation of the flows of matter and energy which occur in the system and of the consumption rate of the available resources. This information can represent a fundamental support to policy planning and resource management [21].

Exergy is a quantity that allows the engineers to design systems with the aim of obtain the highest efficiency at a least cost under the actual technological, economic and legal conditions, but also considering ethical, ecological and social consequences [18]; indeed,

1. It allows the evaluation of the impact of energy resource utilization on the environment.
2. It allows the evaluation of more efficient energy-resource use, and of

the locations, types, and magnitudes of wastes and losses.

3. It is an efficient technique to evaluate if it is possible to design more efficient energy systems by reducing the inefficiencies in existing technologies.

Now, we wish to highlight that any effect in Nature is always the result of the dynamic balances of the interactions between the open systems and their environment, and the exchange of energy drives some behaviour of natural systems, i.e. their evolution is driven by the decrease of their free energy in the least time [28–36]. Exergy is defined as the maximum amount of work obtainable by a system as it comes to equilibrium with its reference environment. So, it represents a measure of the ability of a system to cause changes, due to its non complete stable equilibrium, in relation to the reference environment. Consequently, we highlight that [28,36]:

1. The exergy of a system in complete equilibrium with its environment is null.
2. Exergy doesn't follow any conservation law.
3. A system carries exergy proportional to the level of disequilibrium with its environment.
4. Any loss of energy quality results in consumption of exergy.

Moreover, all the real systems operate on irreversible thermodynamic processes which take place in a finite proper time [33], its process lifetime. In the analysis of the thermodynamic behaviour of open systems, irreversible processes represent one of the fundamental topic of investigation in thermodynamics. Indeed, the studies on irreversibility are important in the design and development of the industrial devices [37]; indeed, they allow us to evaluate the dissipations by using entropy generation, and, consequently, to express the usual thermodynamic inequality by means of equations [37–43] of the irreversible and non-equilibrium thermodynamics. In thermodynamics, in 1824, Carnot [44] introduced an ideal engine operating on a reversible cycle without dissipation. This engine convert the absorbed heat in work and, apparently, it has no irreversibility. Carnot proved that [44,45]:

1. All ideal engines operating between the same two thermal baths (thermal reservoirs) of temperature T_1 and T_2 , with $T_1 > T_2$, has the same ideal efficiency $\eta_C = 1 - T_2/T_1$
2. Any other engine, operating between the same temperature, has an efficiency η such that it is always $\eta < \eta_C$

Carnot's conclusions represent the existence of a definite limit for any conversion of the heat into the kinetic energy and work [44,45].

Now, we must consider that energy is a thermodynamic property which characterizes any state of a thermodynamic system in relation to a reference state. It is a conserved quantity in relation to the universe (the system and its environment), and its total value is always constant [27]. So, its physical meaning is related to its variation, which is the value, and the cause of the useful work. Consequently, any change in a system is no more than a transition between two states.

On the other hand, the exergy of a system is the maximum shaft work obtainable by the system in relation to its specified reference environment, which is considered infinite, in equilibrium and it is specified by fixing its temperature, pressure and chemical composition [27]. In 1889, Gouy and, in 1905, Stodola, independently, proved that the lost exergy in a process is proportional to the entropy generation [16]. The Gouy's results were used in a great number of analysis of irreversibility [46–85]. The exergy flows, related to the increase of the entropy generation, are no more than the heat exchanged with the required second thermal reservoir of a Carnot engine. Consequently, the exergy flow, between the system and its environment, result a fundamental quantity for the analysis of the open systems, industrial and social sectors included. The fundamental role of fluxes in thermo-

dynamics has been highlighted in the constructal law, a recent and advanced thermodynamic theory [34].

5. Applicative examples

In this section some examples of application, of the previous theoretical results, will be developed.

The first example allows underlining the useful behaviour of the unavailability percentage in relation to different production sectors for Italy, using the data available in 1990. In order to evaluate unavailability, the first step is to develop the evaluation of the exergy. The general approach to exergy evaluation for National system has been developed [25]: the particular characteristics of each sector were weighted and associated to a parameter [23]. Exergy consumption calculation is well-established, and recently it has been expanded to include the impacts of material resources and water consumption in addition to energy use [21,26]. In order to develop an exergy analysis of a country, the country system is subdivided into the following sectors [86]:

1. Extraction, which includes mining and quarrying, oil and natural gas, refining and processing.
2. Conversion, which comprises heat and power plants.
3. Agriculture, forestry, fishery and related industries.
4. Industry, manufacturing industry except food industry and oil refineries.
5. Transportation services.
6. Tertiary sector, services other than transportation.
7. Domestic sector, households.

All fluxes between these sectors and between the surroundings and sectors within the system are being considered; each one of them is characterized as follows:

1. Resources: primary (fossil fuels, solar, wind, minerals, metals, geothermal, hydraulic) and secondary (products from petroleum refining, mineral and metal working) and electric energy.
2. Natural resources: agricultural products, wood, natural fibers, livestock, fish, game.
3. Products: products and services generated by industry, tertiary and transport sectors.
4. Trash fluxes: organic and inorganic waste materials, deposited in the environment.
5. Discharge: combustion gases, thermal discharge including radiated heat, heat and mass spread in the environment.
6. Human work.

An exergy value is assigned to all these fluxes, derived from the annual energy balances or energy accounting published by the national statistics agencies. The exergetic value of W -flux is obtained as:

$$Ex_W = \frac{n}{n_{tot}} Ex_{in} \quad (7)$$

where n is the flux of work-hours into a sector, n_{tot} is the total amount of work-hours, and Ex_{in} is the exergy influx to the society. Consequently, the following facts must be considered:

1. Fossil fuel and renewable energy: the exergy associated with energy carriers is taken to be the product of the gross heating value of the carrier and the quality factor.
2. Transportation: exergy associated is related to the primary energy carrier, which is petroleum based.
3. Fresh and saline water: the exergy reference state for water is assumed to be seawater, the chemical exergy for saline is defined to be zero, while the chemical exergy for freshwater is given as 50 MJ/m³ [87].

4. Food: the nutritional content of food or its ability to supply energy to people is represented in the caloric content of food, which is considered as the exergy content of food.
5. Construction materials, metals and plastic: exergy content of construction material and metals will be considered as the chemical exergy of the material [88] multiplied by the amount of the material consumed.
6. Paper and wood: the exergy of wood for energy is assumed to be 10.44 GJ/m³ [89], for construction is 8 GJ/m³ with a density of 450 kg/m³, while the exergy of paper is 17.00 GJ/t [90].

The analysis of the exergy balance for Italy has been developed by Wall et al. [91]. The reference year for the exergy analysis in Italy is 1990. The population of Italy was 57.66×10⁶ people. Wall et al. [92] analyzed:

1. The inflow of sunlight: the total inflow of sunlight over the area of Italy is about 1×10 PJ/y. The converted flow of solar heat supplies the heat for water heating, mainly in households. A solar panel could produce about 20 m³ of warm water (40 °C) per year and m².
2. The forestry and industrial based on forests: the exergy of wood is assumed to be 8 GJ/m³. The exergy content of wood is given by the total change of chemical (exergy stored in the material as lack of binding exergy between the atoms in a molecule) and structural (exergy stored in the structure of materials) exergy. Forest crops are used for construction and for paper production. The amount of timber cut in Italy was 0.53 GJ/capita for material use and 0.50 GJ/capita for use as firewood. Cutting for char-coal production was 0.01 GJ/capita. The result was 1.04 GJ/capita, while the imports add was 4.79 GJ/capita as wood, timber, pulp, and paper, and the total export of mainly paper amounts to 0.46 GJ/capita. Moreover, 5.33 GJ/capita of the forest crops (lignin), together with 0.89 GJ/capita from other fuels and 0.44 GJ/capita of electricity are transformed to 2.77 GJ/capita of products, heat, wood, and paper. The exergy dissipation is about 3.89 GJ/capita.
3. The agriculture and food production: the inputs in the agriculture and food industries are solar radiation and fertilizers, fuels, and electricity. Food consists partly of vegetable substances such as grains and greens, partly of animal substances such as meat, milk and fish. The extent of agricultural land in Italy was about 121,500 km², the 41% of the total land area. The exergy content of the total domestic crops is estimated at about 10 GJ/capita. In addition, there are residues estimated about the same exergy. The exergies from fossil fuels and electricity used in agriculture was 1.59 GJ/capita and in the food industry 0.74 GJ/capita. Imports of agricultural products were about 4 GJ/capita. Exports were estimated about 1 GJ/capita. The input exergy for the food-producing sector resulted to be about 20 GJ/capita. Food consumption, representing the outflow for food production, was estimated about 4 GJ/capita. Consequently the exergy dissipation can be estimated in 9.67 GJ/capita.
4. Electricity, hydroelectric power and thermal power: electricity is used in the forest industry, food production, lighting, heating, cooling, mechanical drives, electrochemical processes and other generic uses in households and in the commercial sector. About 1.73 GJ/capita were used in the mechanical and textile industries, 1.6 GJ/capita for metal production, 1.23 GJ/capita for chemicals, 0.38 GJ/capita in the transportation sector, 0.8 GJ/capita in the ceramic and other industries, and 5.82 GJ/capita in the household and commercial sectors. In 1990, the production of electricity was 2.58 GJ/capita as hydro-power, 1GJ/capita as geothermal energy, 11.15 GJ/capita as thermal power plants, 2.16 GJ/capita as importation: the total production of electricity was 15.71 GJ/capita, of which 2.32 GJ/capita was lost along the electric network.
5. Metals: the metal industry was completely composed by steel production. The use of scrap metal was about 3.85 GJ/capita. The

production of steel was 25.5 Mt and cast iron was 11.9 Mt, representing 4.47 GJ/capita, while the exergy obtained from other metals was 0.36 GJ/capita. The total metal production used 4.83 GJ/capita of which about 4.43 GJ/capita of coal for coke production and other fuels and 1.67 GJ/capita of electricity were needed;

6. Chemical fuels: the uses of natural gas amounted to 28.38 GJ/capita, of oil to 68.01 GJ/capita and of coal to 10.22 GJ/capita. In the chemical industry, fuels are also used as raw materials so a large fraction of the exergy remains in the products and the relative conversion losses are moderate. Moreover, 12.11 GJ/capita of chemical fuels were converted into asphalt, grease, lubricants, rubber, plastics, fertilizers, etc. The transportation system used about 25 GJ/capita of fuel. About 7.11 GJ/capita were used by the energy sector for oil refineries and 18.92 GJ/capita for direct conversion into heat in households, in the commercial sector, etc., while 27.74 GJ/capita were used for the production of electricity in thermal power plants, 6.33 GJ/capita mainly for heat production in the ceramic industry and 2.10 GJ/capita were used in the mechanical and textile industries.
7. The energy loss in the conversion into heat and cold: in space heating, the need of heating is entirely dependent on the ambient temperature; considering a constant indoor temperature of 20 °C, the exergy factor was about 0.03. Moreover, 3% was assumed to be the exergy percentage of the indoor energy during the heating and cooling seasons in Italy. Other losses such as exhaust gases are small in comparison with this loss. Exergy for space heating and air-conditioning is obtained by multiplying the supplied energy by the energy efficiency, which is assumed to be 0.7 with the exergy factor of 0.03, obtaining 0.02.

The result is that the inflow exergy of resources was 140 GJ/capita (1 GJ/capita=16.0175 TW h), while the output exergy was 25 GJ/capita and the electric work produced was 13.55 GJ/capita. The consequent unavailability, evaluated using the relation (6), results $Ex_{\lambda}=101.45$ GJ/capita=5.85 EJ and the unavailability percentage results of 72%, pointed out that in 1990 Italy did not efficiently use technologies, with the 1990 economic results. The evaluation of the unavailability percentage is represented in Fig. 1 in relation to the total inflow exergy and in Fig. 2 in relation to the total unavailability. Fig. 1 represents the unavailability percentage for Italy in relation to the total inflow exergy. Fig. 2 points out the distribution of the unavailability percentage for Italy in relation to the Italy total unavailability. These figures show how the unavailability percentage allows us to compare dissipation among different production sectors. This application points out that the unavailability percentage allows comparing the dissipation among different production sectors, which involve different processes and technologies.

This result must be confirmed by considering also other models. To do so, we introduce a second example of the use of the unavailability percentage (exergy inefficiency): the analysis of the district of Alessandria. In relation to the data available, related only to the year 2004, we can consider only the flows of exergy from energy resources,

neglect of the flows of products and services [18]. Alessandria is an Italian district of Piedmont region, which covers a surface of 3560 km², with a population of around 440,613 people, including 190 municipalities, among which the administrative centre: the municipality of Alessandria. We analyze just the municipality of Alessandria, which covers 204 km² with a population of 93,922 people. We consider the following exergy flows only related to the city management in order to obtain information from the energy management of the city administration [18]:

1. The exergy inflow from the tertiary sector: it is distinguishing trait mainly from consumption of building heatings, water systems and electrical appliances, from electricity you obtain low temperature heat, from fuels, which consists of Electricity 712 TJ (85% for low temperature heat) and Fuels 559 TJ, with a total amount of 1271 TJ.
2. The exergy outflow from the tertiary sector uses: Electricity 289 TJ (low temperature heat 182 TJ, other uses 107 TJ) and Fuels 148 TJ, with a total amount of 437 TJ.
3. The exergy inflow from the residential sector: the consumptions of this branch are mainly for residential use for residential lightening, heating, etc.: Electricity 309 TJ and Fuels 2825 TJ, with a total amount of 3134 TJ.
4. The exergy outflow from the residential sector uses: Electricity 125 TJ (low temperature heat 79 TJ, other uses 46 TJ), and Fuels 992 TJ, with a total amount of 1117 TJ.
5. The exergy inflow from the public transport: This sector receives in input fuel and in output mainly produces mechanical power: Electricity 14 TJ and Fuels 29 TJ, with a total amount of 43 TJ.
6. The exergy outflow from the public transport: Electricity 0 TJ, and Fuels 10 TJ, with a total amount of 10 TJ.
7. The exergy inflow from the private transport: This sector receives in input fuel and in output mainly produces mechanical power: Electricity 0 TJ and Fuels 2230 TJ, with a total amount of 2230 TJ.
8. The exergy outflow from the private transport: Electricity 0 TJ, and Fuels 652 TJ, with a total amount of 652 TJ.

with a total exergy inflow of 6678 TJ and exergy outflow 2216 TJ and an exergy lost of 4462 TJ. So, we can evaluate the unavailability percentage as 66.8%.

Now, we can consider possible policy decision of the city administration, as follows:

1. Introduce district heating: it would reduce
 - i. The exergy inflow for tertiary sector of electricity uses to 107 TJ for the electricity and to 0 TJ for the fuels.
 - ii. Of the 90% of fuels for the exergy inflow and outflow from the residential sector.
2. Improve the public transportation: it would:
 - i. Improve, for public sector, the exergy inflow to 100 TJ and the

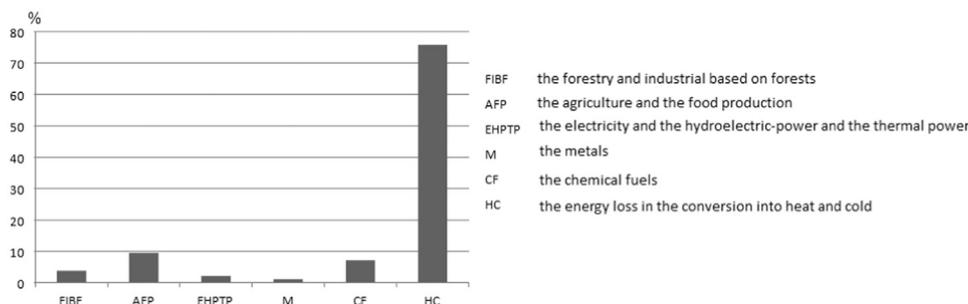


Fig. 1. Unavailability percentage evaluated on the inflow total exergy.

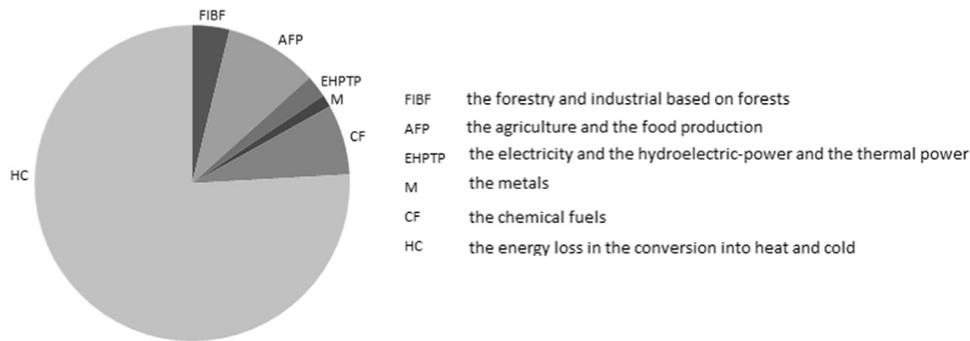


Fig. 2. Unavailability percentage evaluated on the total Unavailability.

Table 1

Unavailability percentage for two different technologies ((A, B, C) and D) and three different solutions for one technology (A, B, C).

	Input exergy [MW]	Unavailability [MW]	Unavailability percentage %
Case A	386.10	241.37	62.52
Case B	469.03	294.78	62.85
Case C	442.78	274.67	62.03
Case D	72.26	11.62	16.08

exergy outflow to 34 TJ.

- ii. Decrease, for private sector, the exergy inflow to 1400 TJ and the exergy outflow to 409 TJ.

The result of these two energy management decision is to reduce the unavailability percentage to 0.338, with a better energy management. We can also compare this result with an economic indicator, the equivalent primary resource value for the work-hour *EI*, defined as:

$$EI = \frac{Ex_{in}}{n_h n_w} \quad (8)$$

where n_h is the number of work hour and n_w the number of workers. This quantity indicates the exergetic cost necessary to support the workhours and to generate capital flows. For Alessandria city, the number of worker in 2004 was 21,289, while the work hours per worker were 1819, so the indicator *EI* results 172 MJ/workhour when the unavailability percentage is 66.8% and 52 MJ/workhour when the unavailability percentage is 33.8%. We can highlight how *EI* is reduced to one third by halving the unavailability percentage.

The third example is the power generation. Four cases will be considered. This example will underline as the unavailability percentage allows comparing the different technologies involved in industrial production. The first plant (Case A) is a power plant working at a conventional Rankine steam cycle with a power output of 232.6 MW, as analyzed by Verkhivevker and Kosoy [92]; the plant produces both electricity and heat without reheaters. The exergy analysis determined a value of exiting exergy of 144.73 MW (entering exergy 386.10 MW, generated electric power 88.70 MW) and that the exergy destruction was caused by the irreversibility associated with the combustion process, heating of the process fluid and the heat transfer to the heat exchangers [92]. A decrease in exergy destruction was obtained by.

1. Increasing the thermodynamic parameters of the working fluid supplied at the turbine and by reducing the temperature differences of the heaters (Case B): the exergy becomes 174.25 MW (entering exergy 469.03 MW, generated electric power 118.22 MW).
2. Inserting a reheater between the first and the second stage of the turbine and increasing the upper boiler pressure (Case C): the exergy becomes 168.11 MW (entering exergy 442.78 MW; generated electric power 112.08).

The second plant is a Rankine cycle operating in subcritical conditions (Case D), analyzed by Regulagadda et al. [93]. The generator power output is 32.00 MW. The boiler is a circulating fluidized bed combustion boiler with a capacity of 140 TPH of steam at 100% BMCR at the rated steam parameters. The power plant is designed to utilize an air cooled condenser to condense the exhaust steam. Coal is the supply fuel of the power plant, with the following components: moisture=25%, ash=0.88%, hydrogen=4.06%, nitrogen=1.10%, sulphur=0.075%, oxygen=7.94%, carbon=60.95%, GCV=21,981.75 kJ/kg. The input exergy is 72.26 MW, while the output exergy is 28.64 MW, $T_a=293$ K and $T_{Hl}=790$ K.

The evaluation of the unavailability percentage for these plants is summarized in Table 1. The result is that a great difference in the unavailability percentage exists only if there is a difference in technology. The value of similar technologies is comparable, even if little differences exist in relation to the optimization of the process, but the great difference can be obtained only with different technologies. The result is also represented in Fig. 3 from which it must be underlined that Case A, B and C are the optimization of the same technology, while Case D involves another technology. Fig. 3 shows this difference; indeed, even if the three Cases A, B and C are optimized in a different way, their fundamental technological level is similar, so their energy percentage is about equal, while case D assume a very different value because it involves a different technological level. We can highlight how the use of a technology involves the use of some physical and chemical processes and that these processes present an upper limit of conversion of energy. Consequently, the process of optimization is limited by the specific nature of the process involved.

Now, we consider a power production system with the use of solar energy, which consists of two subsystems [93]:

1. The collector–receiver circuit consists of a number of parabolic collectors, arranged in modules that operate in tracking mode so that

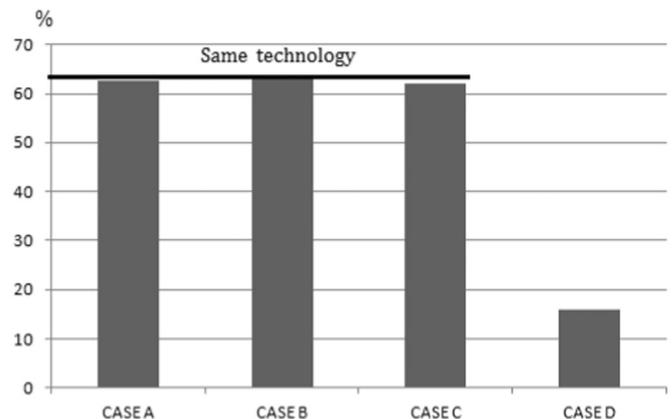


Fig. 3. Unavailability percentage for two different technologies ((A, B, C) and D) and three different solutions for one technology (A, B, C).

the working fluid goes through them.

- The heat engine circuit, which is a Rankine cycle, consists of a boiler heat exchanger, a two-stage turbine, a pump and a regenerator. The cold fluid enters the collector at a temperature of 230 °C and exits at a temperature of 288.5 °C. The hot fluid enters the boiler heat exchanger where it heats up the working fluid of the heat engine, in this case ammonia. Ammonia enters the exchanger at 185 °C and exits at 245 °C. The temperature of the condenser is 100 °C and the ambient temperature is 30 °C.

The unavailability percentage of this power system can be evaluated by the exergy analysis developed in Ref. [95] and results 74.5%. The unavailability percentage analysis of the plant highlights how this plant can be improved. Indeed, the unavailability percentage in the heat engine subsystem results 72.4%, greater than that unavailability percentage in the collector–receiver subsystem which results 56.30% [93]. The high unavailability percentage in the collector–receiver subsystem is the consequence of the great quality of lost energy in this subsystem, while in the heat engine subsystem the lost energy is of low quality. Consequently, the technological research must be developed in order to reduce the loss of the high quality energy.

6. Conclusions

The fundamentals of sustainable development can be related to economics, environment and society. Indeed, a sustainable system must [94]:

- Be able to produce goods and services, to maintain manageable levels of government and external debt and to avoid damages to agricultural or industrial production.
- Maintain a stable resource base, biodiversity, atmospheric stability.
- Achieve fairness in distribution, opportunity and adequate provision of social services.

These three topics of sustainability introduce a multidimensional approach based on the balance of different needs. Indeed, the economic sustainability requires that manufactured capital, natural capital, human capital and social capital must be maintained over the long term, the conservation of ecosystems and natural resources is essential for sustainable economic production and intergenerational equity and the social equity is the basic element of development and is interrelated with environmental sustainability [94].

All these considerations are related to the technological development and its evaluation in relation to the processes used in the production activities.

In this paper the unavailability percentage is suggested as an indicator of the level of technological development, in relation to the optimized use of energy. This quantity, which is not a universal indicator in relation to the environmental impact [26], can be used in economic and socio-political evaluation. Indeed, the unavailability percentage is related to the exergy lost during a process, so it can provide information on the optimization level obtained by a technology or it can be useful to compare different technologies. Some examples have been proposed:

- The comparison between different sectors of production in a Country (Italy).
- The improvement of the sustainable and economic condition of a municipality (Alessandria municipality).
- The comparison between two different technologies and different optimization levels in the power production.
- The analysis of the power generation by a sustainable source.

The results have been analyzed and summarized in Figs. 1–3. Fig. 1 represents the unavailability percentage for Italy in relation to the total

inflow exergy. Fig. 2 points out the distribution of the unavailability percentage for Italy in relation to the Italy total unavailability. They allow us to highlight how the unavailability percentage can be used to compare dissipation among different production sectors. Fig. 3 shows the use of the unavailability percentage in relation to the analysis of the present technologies. Indeed, the three cases A, B and C are the no more than three different ways of optimization of the same technology, the fundamental technological level results similar. Consequently, their energy percentage is about equal. The case D assumes a very different value because it is a completely different technological level. So, the result highlights how unavailability percentage can be useful to point out the difference in the technological levels.

Additional information

The authors declare no competing financial interests.

Author contribution statement

U.L. developed the modelling and the theoretical approach, designed and identified the applications. G.G. developed the numerical analysis of the cases.

References

- Massardo AF, Santarelli M, Borchiellini R. Carbon exergy tax (CET): its impact on conventional energy system design and its contribution to advanced systems utilisation. *Energy* 2003;28:607–25.
- Hoeller P, Coppel J. Energy taxation and price distortion in fossil fuel markets: some implications for climate change policy. OECD. Economic Department. Working paper n. 110, OECD/GD(92)70, Paris, 1992. (<http://78.41.128.130/dataoecd/62/62/35416758.pdf>). [accessed 12.09.13].
- Gros D, Egenhofer C. (in collaboratio with: N. Fujiwara, S. Sarisoy Guerin and A. Georgiev). Climate change and trade. taxin carbon at the border? Bruxelles: Centre for European Policy Studies; 2010.
- Onsager L. Reciprocal relations in irreversible processes I. *Phys Rev* 1931;37(4):405–26.
- Onsager L. Reciprocal relations in irreversible processes II. *Phys Rev* 1931;38(12):2265–79.
- Prigogine I. Étude thermodynamique des phénomènes irréversibles [Thermodynamic study of irreversible phenomena]. Paris: Dunod; 1947.
- Prigogine I. Introduction to thermodynamics of irreversible processes. Springfield: Charles C. Thomas; 1955.
- Prigogine I. Thermodynamics of irreversible processes. New York: Wiley; 1961.
- Bejan A. Entropy generation minimization: the method of thermodynamic optimization of finite-size systems and finite-time processes. New York: CRC Press; 1996.
- Bejan A. Models of power plants that generate minimum entropy production while operating at maximum power. *Am J Phys* 1996;64(8):1054–9.
- Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: John Wiley & Sons; 1996.
- Lowenthal MD, Kastenber WE. Industrial ecology and energy systems: a first step. *Resour Conserv Recycl* 1998;24(1):51–63.
- Zvolinchi A, Kjelstrup S. An indicator to evaluate the thermodynamic maturity of industrial process units in industrial ecology. *J Ind Ecol* 2008;12(2):159–72.
- Lucia U. Stationary open systems: a brief review on contemporary theories on irreversibility. *Physica A* 2013;392(5):1051–62.
- Lucia U. Maximum or minimum entropy generation for open systems?. *Physica A* 2012;391(12):3392–8.
- Lucia U. Entropy and exergy in irreversible renewable energy systems. *Renew Sustain Energy Rev* 2013;20(1):559–64.
- Sciubba E. From engineering economics to extended exergy accounting: a possible path from monetary to resource based costing. *J Ind Ecol* 2004;8(4):19–40.
- Lucia U. Econophysics and bio-chemical engineering thermodynamics: the exergetic analysis of a municipality. *Physica A* 2016;2016(462):421–30.
- Ahmed A, Stein JA. Science, technology and sustainable development: a world review. *World Rev Sci Technol Sustain Dev* 2004;1(1):5–24.
- Stoneman P. The economic analysis of technology policy. Oxford: Clarendon Press; 1987.
- Sciubba E. Exergy-based ecological indicators: a necessary tools for resource use assessment studies. *Termotechnica* 2009;2:11–25.
- Chicco G. Sustainability challenges for future energy systems. *J Sustain Energy* 2010;1(1):6–16.
- Hammond G, Stapleton AJ. Exergy analysis of the United Kingdom energy system. *Proc Inst Mech Eng Part A: J Power Energy* 2001;215(A2):141–62.
- Slesser M. Energy in the economy. London: Macmillan; 1978.
- Van Gool W. The value of energy carriers. *Energy* 1987;12(6):509–18.
- Sciubba E. Modelling the energetic and exergetic self-sustainability of societies with

- different structures. *Trans ASME: J Energy Resour Technol* 1995;177:75–86.
- [27] Dincer I, Cengel YA. Energy, entropy and exergy concepts and their roles in thermal engineering. *Entropy* 2001(3):116–49.
- [28] Denbigh KG. The many faces of irreversibility. *Br J Philos Sci* 1989;40:501–18.
- [29] Bertola V, Cafaro E. A critical analysis of minimum entropy production theorem and its application to heat and fluid flow. *Int J Heat Mass Transf* 2008;51:1907–12.
- [30] Lucia U. Irreversibility entropy variation and the problem of the trend to equilibrium. *Physica A* 2007;376:289–92.
- [31] Lucia U. Statistical approach of the irreversible entropy variation. *Physica A* 2008;387(14):3454–60.
- [32] Lucia U. Irreversibility, entropy and incomplete information. *Physica A* 2009;388:4025–33.
- [33] Lucia U. Thermodynamic paths and stochastic order in open systems. *Physica A* 2013;392(18):3912–9.
- [34] Lucia U. Exergy flows as bases of constructal law. *Physica A* 2013;392(24):6284–7.
- [35] Lucia U. The gouy-stodola theorem in bioenergetic analysis of living systems (irreversibility in bioenergetics of living systems). *Energies* 2014;7:5717–39.
- [36] Lucia U, Sciubba E. From Lotka to the entropy generation approach. *Physica A* 2013;392(17):3634–9.
- [37] Tolman RC, Fine PC. On the irreversible production of entropy. *Rev Mod Phys* 1948;20:51–77.
- [38] De Donder T, Van Rysselberghe P. *Affinity*. Menlo Park: Stanford University Press; 1936.
- [39] Weber HC. *Thermodynamics for chemical engineers*. New York: John Wiley & Sons; 1939.
- [40] Keenan JH. *Thermodynamics*. New York: John Wiley & Sons; 1941.
- [41] Eckart C. The thermodynamics of irreversible processes. I. The simple fluid. *Physica Rev* 1940;58:267–9.
- [42] Eckart C. The thermodynamics of irreversible processes. II. Fluid mixtures. *Physica Rev* 1940;58:269–75.
- [43] Bridgman PW. *The nature of thermodynamics*. Teddington: The Cambridge University Press; 1941.
- [44] Carnot S. *Réflexion sur la puissance motrice du feu sur la machine à développer cette puissance*. Paris: Bachelier Libraire; 1824.
- [45] Lucia U. Carnot efficiency: why?. *Physica A* 2013;392(17):3513–7.
- [46] Jouget E. Remarques sur la thermodynamique des machines motrices. *Rev Mecanique* 1906;19:41. [In French].
- [47] Jouget E. Le théoreme de M. Gouy et quelques-unes de ses applications. *Rev. Mecanique* 1907;20:213–38. [In French].
- [48] Jouget E. *Theorie des moteurs thermiques*. Paris: Gauthier-Villars; 1909. [In French].
- [49] Goodenough GA. *Principles of thermodynamics*. New York: H. Holt Pub; 1911.
- [50] De Baufre WL. Analysis of power-plant performance based on the second law of thermodynamics. *Mech Eng ASME* 1925;47:426–8.
- [51] Born M. Kritische betrachtungen zur traditionellen darstellung der thermodynamik. *Phys Z* 1921;22:218–24. [In German].
- [52] Born M. Betrachtungen zur traditionellen darstellung der thermodynamik. *Phys Z* 1921;22:249–54. [In German].
- [53] Born M. Kritische Betrachtungen zur traditionellen Darstellung der Thermodynamik. *Phys Z* 1921;22:282–6. [In German].
- [54] Darrieus G. Définition du rendement thermodynamique des turbines à vapeur. *Rev Gen l'Electr* 1930;27:963–8. [In French].
- [55] Darrieus G. L'évolution des centrales thermiques et la notation d'énergie utilisable. *Sci Ind* 1931;15:122–6. [In French].
- [56] G.V. Lerberghe P. Glansdorff Le rendement maximum des machines thermiques. *Publ Ass Ing Mines*. vol. 42; 1932. p. 365–418. [In French]
- [57] Maxwell JC. *Theory of heat*, 1st ed.. London: Longmans Green and Co; 1871.
- [58] Lorenz H. Beitrage zur Beurteilung von Kuhlmaschinen. *Zeitschr des V.D.I.*; 1894. vol. 38. p. 62–8. [In German]
- [59] Lorenz H. Beitrage zur Beurteilung von Kuhlmaschinen. *Zeitschr des V.D.I.*; 1894. vol. 38. p. 98–102. [In German]
- [60] Lorenz H. Beitrage zur Beurteilung von Kuhlmaschinen. *Zeitschr des V.D.I.*; 1894. vol. 38. p. 124–130. [In German]
- [61] Lorenz H. Die Beurteilung der Dampfkessel. *Zeitschr des V.D.I.*; 1894. vol. 38. p. 1450–52. [In German]
- [62] Keenan JH. A steam chart for second law analysis. *Mech Eng ASME* 1932;54:195–204.
- [63] Keenan JH, Shapiro AH. History and exposition of the laws of thermodynamics. *Mech Eng ASME* 1947;69:915–21.
- [64] Keenan JH. Availability and irreversibility in thermodynamics. *Br J Appl Phys* 1951;2:183–92.
- [65] Keenan JH, Hatsopoulos GN. *Principles of general thermodynamics*. New York: John Wiley & Sons; 1965.
- [66] Keenan JH, Gyftopoulos EP, Hatsopoulos GN. The fuel shortage and thermodynamics – the entropy crisis. In: Macrakis, M, editor. *Proceedings MIT energy conference*, February 1973, Cambridge, Mass.: the MIT Press; 1974.
- [67] Bosnjakovic EHF. Solar collectors as energy converters. In *Studies in Heat Transfer*. Washington: Hemisphere Publ. Corp.; 1979. p. 331–81
- [68] Emden R. Why do we have winter heating. *Nature* 1938:141.
- [69] Wall G. The exergy conversion in the society of Ghana. In: *Proceedings of the 1st international conference on energy and community development*. Athens; 10–15 July 1978.
- [70] Wall G. The use of natural resources – a physical approach report, SMR51-24. In: *Proceedings of the international centre for theoretical physics (ICTP)*, Trieste, Italy; 1978.
- [71] Wall G. Exergy – a useful concept [Ph.D. thesis]. Physical Resource Theory Group. Chalmers University of Technology. S-412 96 Göteborg, Sweden; 1986.
- [72] Wall G. Thermoeconomic optimization of a heat pump system. *Energy* 1986;11:957–67.
- [73] Wall G. Exergy conversion in the Swedish Society. *Resour Energy* 1987;9:55–73.
- [74] Wall G. Exergy flows in a pulp and paper mill, in a steel plant and rolling mill. In: *Proceedings IV international symposium on second law analysis of thermal systems*, Rome; 25–29 May 1987. p. 131–40.
- [75] Wall G. Thermoeconomic optimization of a single stage heat pump system. In: *Proceedings IV international symposium on second law analysis of thermal systems*, Rome; 25–29 May 1987. p. 89–95.
- [76] Wall G. Exergy flows in industrial processes. *Energy* 1988;13:197–208.
- [77] Wall G. Exergy conversion in the Japanese Society. *Energy* 1990;15:435–44.
- [78] Wall G. Exergy needs to maintain real systems near ambient conditions. In: Stecco SS, Moran MJ, editors. *Proceedings of the florence world energy research symposium*, 28 May–1 June 1990, Florence, Italy. A Future for Energy, New York: Pergamon; 1990. p. 261–70.
- [79] Wall G. On the Optimization of refrigeration machinery. *Int J Refrig* 1991;14:336–40.
- [80] Wall G. Energy, society and morals. *J Hum Values* 1997;3:193–206.
- [81] Sciubba E. Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems. *Exergy* 2001;1:68–84.
- [82] Sciubba E. Artificial intelligence applications to the synthesis of thermal processes. In: *Proceedings conference on 2-nd law analysis of energy systems*, Roma; 1995.
- [83] Sciubba E. Beyond thermoeconomics? The concept of Extended-Exergy Accounting and its application to the analysis and design of thermal systems. *Exergy Int J* 2000;1:68–84.
- [84] Sciubba E. Exergo-economics: thermodynamic foundation for a more rational resource use. *Int J Energy Res* 2005;29:613–36.
- [85] Sciubba E. Exergy as a direct measure of environmental impact. In: Aceves SM, Garimella S, Peterson R, editors. *Proc. ASME-AES*; 1999. vol. 39. p. 573–81
- [86] Ertesvåg IS. Energy, exergy, and extended-exergy analysis of the Norwegian society 2000. *Energy*; 2005. vol. 30. p. 649–75
- [87] Szargut J, Morris DR, Steward FR. *Exergy analysis of thermal chemical and metallurgical process*. New York: Hemisphere Publishing Corp. and Springer-Verlag; 1988.
- [88] Wall G. Exergetics. (<http://www.exergy.se/ftp/exergetics.pdf>); 2009 [accessed 11.08.15].
- [89] Wall G Exergy use in the Swedish society 1994. In: *Proceedings of the international conference of thermodynamics analysis and improvement of energy systems*, TAIES'97; 1997, p. 403–13. (<http://exergy.se/ftp/sweden94.pdf>) [accessed 11.08.15].
- [90] Ertesvåg IS, Mielnik M. Exergy analysis of the Norwegian society. *Energy* 2000;25(10):957–73.
- [91] Wall G, Sciubba E, Naso V. Exergy use in the Italian society. *Energy* 1994;19(12):1267–74.
- [92] Verkhivevker GP, Kosoy BV. On the exergy analysis of power plants. *Energy Convers Manag* 2001;42:2053–9.
- [93] Regulagadda P, Dincer I, Naterer GF. Exergy analysis of a thermal power plant with measured boiler and turbine losses. *Appl Therm Eng* 2010;30:970–6.
- [94] Harris JM, Wise TA, Gallagher KP, Goodwin NR, editors. *A survey of sustainable development: social and economic dimensions*. Washington, D.C.: Island Press; 2001.