



## Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering

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### ABSTRACT

*Energy, entropy and exergy concepts come from thermodynamics and are applicable to all fields of science and engineering. Therefore, this article intends to provide background for better understanding of these concepts and their differences among various classes of life support systems with a diverse coverage. It also covers the basic principles, general definitions and practical applications and implications. Some illustrative examples are presented to highlight the importance of the aspects of energy, entropy and exergy and their roles in thermal engineering.*

**Keywords :** Energy, entropy, environment, exergy, thermodynamics

### 1. Introduction

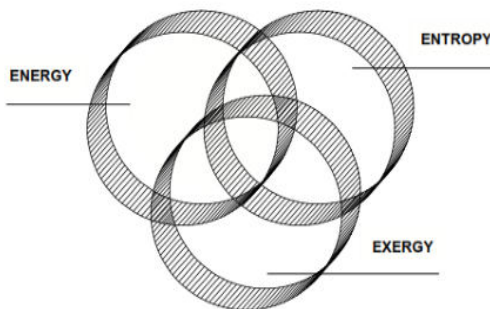
Thermodynamics is broadly viewed as the science of energy, and thermal engineering is concerned with making the best use of available energy resources. The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamics* (force), which is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power production, refrigeration, and relationships among the properties of matter.

The science of thermodynamics is built primarily on two fundamental natural laws, known as the first and the second laws. The first law of thermodynamics is simply an expression of the conservation of energy principle. It asserts that *energy*

is a thermodynamic property, and that during an interaction, energy can change from one form to another but the total amount of energy remains constant. The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. The high-temperature thermal energy is degraded as it is transferred to a lower temperature body. The attempts to quantify the quality or “work potential” of energy in the light of the second law of thermodynamics has resulted in the definition of the properties entropy and exergy.

The scope of this article is partly illustrated in Fig. 1, where the domains of energy, entropy and exergy are shown. This paper focuses on the portion of the field of thermodynamics that intersects with the energy, entropy and exergy

fields, and particularly emphasizes the intersection of all three domains. Note that entropy and exergy are also used in other fields (such as statistics and information theory), and therefore they are not subsets of energy. Also, some forms of energy (such as shaft work) are entropy-free, and thus entropy subtends only part of the energy field. Likewise, exergy subtends only part of the energy field as well since some systems (such as air at atmospheric conditions) possess energy but no exergy. Most thermodynamic systems (such as steam in a power plant) possess energy, entropy, and exergy, and thus appear at the intersection of these three fields.



**Figure 1.** Interactions between the domains of energy, entropy and exergy.

## 2. Energy

### 2.1 Introduction

Thermodynamics plays a key role in the analysis of systems and devices in which energy transfer and energy transformation take place. Thermodynamics' implications are far-reaching, and its applications span the whole range of the human enterprise. All along our technological history, the development of sciences has enhanced our ability to harness energy and use it for society's needs. The industrial revolution is a result of the discovery of how to exploit energy and how to convert heat into work. Nature allows the conversion of work completely into heat, but heat is taxed when converted into work. For this

reason, the return on our investment of heat transfer is compared with the output work transfer and attempts are made to maximize this return.

Most of our daily activities involve energy transfer and energy change. The human body is a familiar example of a biological system in which the chemical energy of the food or body fat is transformed into other forms of energy such as heat transfer and work transfer. Our encounter with the environment also reveals a wide area of engineering applications. These include power plants to generate electricity, engines to run automobiles and aircraft, refrigeration and air conditioning systems.[4]

In the hydroelectric power system the potential energy of the water is converted into mechanical energy through the use of a hydraulic turbine. The mechanical energy is then converted into electric energy by an electric generator coupled to the shaft of the turbine. In a steam power generating plant, chemical or nuclear energy is converted into thermal energy in a boiler or a reactor. The energy is imparted to water, which vaporizes into steam. The energy of the steam is used to drive a steam turbine, and the resulting mechanical energy is used to operate a generator to produce electric power. The steam leaving the turbine is then condensed, and the condensate is pumped back to the boiler to complete the cycle.[3]

Gas turbine engines, commonly used for aircraft propulsion, convert the chemical energy of the fuel into thermal energy that is used to run a gas turbine. The turbine is directly coupled to a compressor that supplies the air required for combustion. The exhaust gases, upon expanding in a nozzle, create the necessary thrust. For power generation,

the turbine is coupled to an electric generator and drives both the compressor and the generator.[2]

## 2.2 Concept of Energy

The concept of energy was first introduced in mechanics by Newton when he hypothesized about kinetic and potential energies. The concept of energy is so familiar to us today that it is intuitively obvious, yet we have difficulty in defining it exactly. Energy is a scalar quantity that can not be observed directly but can be recorded and evaluated by indirect measurements.[1] The absolute value of energy of system is difficult to measure, whereas its energy change is rather easy to calculate. In our life the examples for energy are endless. The sun is the major source of the earth's energy. It emits a spectrum of energy that travels across space as electromagnetic radiation. Energy is also associated with the structure of matter and can be released by chemical and atomic reactions.

## 2.3 Forms of Energy

In thermodynamic analysis, the forms of energy can be classified into two groups:

The **macroscopic forms of energy** are those where a system possesses as a whole with respect to some outside reference frame such as kinetic and potential energies. For example, the macroscopic energy of an upmoving object changes with velocity and elevation. The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity and surface tension. The energy that a system possesses as a result of its motion relative to some reference frame is called *kinetic energy*. The energy that a system has as a result of its elevation in a gravitational field is called *potential energy*. Kinetic energy refers to the energy possessed by

the system because of its overall motion, either translational or rotational. The word "overall" is italicized because the kinetic energy to which we refer is the kinetic energy of the entire system, not the kinetic energy of the molecules in the system. If the system is a gas, the kinetic energy is the energy due to the macroscopic flow of the gas, not the motion of individual molecules. The potential energy of a system is the sum of the gravitational, centrifugal, electrical, and magnetic potential energies.[1]

The **microscopic forms of energy** are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the *internal energy* of a system. The internal energy of a system depends on the inherent qualities, or properties, of the materials in the system, such as composition and physical form, as well as the environmental variables (temperature, pressure, electric field, magnetic field, etc.). Internal energy can have many forms, including, sensible and latent (i.e., thermal), chemical, nuclear, electrical, mechanical, magnetic, and surface energy. For example, a spring that is compressed has a higher internal energy (mechanical energy) than a spring that is not compressed, because the compressed spring can do some work on changing (expanding) to the uncompressed state.[1]

## 2.4 The First law of Thermodynamics (FLT)

The FLT stands for the *first law of the conservation of energy*. This is stated as energy can be neither created nor destroyed; it just changes form. The FLT defines internal energy as a state function and provides a formal statement of the conservation of energy. However, it provides no information about the

direction in which processes can spontaneously occur, that is, the reversibility aspects of thermodynamic processes. For example, it cannot say how cells can perform work while existing in an isothermal environment. It gives no information about the inability of any thermodynamic process to convert heat into mechanical work with full efficiency, or any insight into why mixtures cannot spontaneously separate or unmix themselves.

**2.5 FLT vs Energy**

The total energy *E* represents the sum of all forms of energy a system possesses, and the change in the energy content of a system during a process is expressed as  $\Delta E_{System}$ . In the absence of electrical, magnetic, surface, etc effects, the total energy in that case can be expressed as the sum of the internal, kinetic, and potential energies as

$$E = U + KE + PE \quad \text{and}$$

$$\Delta E_{system} = \Delta U + \Delta KE + \Delta PE \quad \text{---- (1)}$$

Energy can be transferred to or from a system in three forms: *heat Q*, *work W*, and *mass flow m*. Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process. Then the FLT or energy balance for any system undergoing any kind of process can be expressed as

$$E_{in} - E_{out} = \Delta E_{system} \quad \text{-----(2)}$$

Net energy transfer by heat, work and mass	change in internal, kinetic, potential, etc energies.
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That is, *the net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy*

*entering and the total energy leaving the system during that process.* This relation can also be expressed per unit mass, differential, and rate forms as[1]

$$e_{in} - e_{out} = \Delta e_{system} \quad \text{-----(3)}$$

$$\delta E_{in} - \delta E_{out} = de_{system} \quad \text{or}$$

$$\delta e_{in} - \delta e_{out} = de_{system} \quad \text{-----(4)}$$

$$E_{in} - E_{out} = \Delta E_{system} \quad \text{-----(5)}$$

Rate of net energy transfer by heat, work and mass.	Rate of change in internal, kinetic, potential etc energies.
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The only two forms of energy interactions associated with a fixed mass or closed system are *heat transfer* and *work*. For a closed system undergoing a *cycle*, the initial and final states are identical & thus  $\Delta E_{system} = E_2 - E_1 = 0$ . Then the energy balance for a cycle simplifies to  $E_{in} - E_{out} = 0$  or  $E_{in} = E_{out}$ . Noting that a closed system does not involve any mass flow across its boundaries, the energy balance for a cycle can be expressed in terms of heat and work interactions as

$$W_{net,out} = W_{net,in}$$

That is, the net work output during a cycle is equal to net heat input for a cycle.[1]

For a control volume that involves a fluid stream at pressure *P*, the fluid upstream acts like a piston, doing boundary work *Pv* per unit mass of fluid to maintain flow. For convenience, the flow work and internal energy are combined into enthalpy,  $h = u + Pv$ , which represents the microscopic forms of energy for a flowing fluid (as opposed to non-fluid in a container). Then the energy transfer by mass flowing into or out of a

system per unit mass of the fluid stream can be expressed as[1]

$$h_{tot} = h + ke + pe$$

Energy balance for an adiabatic steam turbine with negligible kinetic and potential energies, for example, can be expressed as  $mh_1 = W_{out} + mh_2$  is the mass flow rate, and where 1 is the inlet state of steam, 2 is the exit state, m is the mass flow rate,  $W_{out}$  is the power output.

### 3. Entropy

#### 3.1 Introduction

Within the past 50 years our view of Nature has changed drastically. Classical science emphasized equilibrium and stability. Now we see fluctuations, instability, evolutionary processes on all levels from chemistry and biology to cosmology. Everywhere we observe irreversible processes in which time symmetry is broken. The distinction between reversible and irreversible processes was first introduced in thermodynamics through the concept of "entropy".[1]

In the modern context, the formulation of entropy is fundamental for understanding thermodynamic aspects of self-organization, evolution of order and life that we see in Nature. When a system is isolated, energy increase will be zero. In this case the entropy of the system will continue to increase due to irreversible processes and reach the maximum possible value, which is the state of thermodynamic equilibrium. In the state of equilibrium, all irreversible processes cease. When a system begins to exchange entropy with the exterior then, in general, it is driven away from equilibrium, and the entropy producing irreversible processes begins to operate. The exchange of entropy is due to exchange of heat and matter. The entropy flowing

out of an adiabatic system is always larger than the entropy flowing into the system, the difference arising due to entropy produced by irreversible processes within the system. As we shall see in the following chapters, systems that exchange entropy with their exterior do not simply increase the entropy of the exterior, but may undergo dramatic spontaneous transformations to "self-organization." The irreversible processes that produce entropy create these organized states. Such self-organized states range from convection patterns in fluids to life. Irreversible processes are the driving forces that create this order.

Much of the internal energy of a substance is randomly distributed as kinetic energy at the molecular and sub molecular levels and as energy associated with attractive or repulsive forces between molecular and sub molecular entities, which are moving closer together or further apart in relation to their mean separation. This energy is sometimes described as being 'disordered' as it is not accessible as work at the macroscopic level in the same way as is the kinetic energy or gravitational potential energy that an entire system possesses owing to its velocity or position in the gravitational field. Although energy is the capacity to do work, it is not possible directly to access the minute quantities of disordered energy possessed at a given instant by the various modes of energy possession of the entities so as to yield mechanical shaft work on the macroscopic scale. The term 'disorder' refers to the lack of information about exactly how much energy is associated at any moment with each mode of energy possession of each molecular or sub molecular entity within the system.

Heat transfer to a system increases the disordered energy of the system. Heat

transfer from a system reduces the disordered energy. Reversible heat transfer is characterized by both the amount of energy transferred to or from the system and the temperature level at which this occurs. The property entropy, whose change between states is defined as the integral of the ratio of the reversible heat transfer to the absolute temperature, is a measure of the state of disorder of the system. This 'state of disorder' is characterized by the amount of disordered energy and its temperature level. When reversible heat transfer occurs from one system to another, both systems have the same temperature and the increase in the disorder of one is exactly matched by the decrease in disorder of the other. When reversible adiabatic work is done on or by a system its ordered energy increases or decreases by exactly the amount of the work and the temperature level changes in a way that depends on the substances involved. Reversible work is characterized by the amount of energy transferred to or from the system, irrespective of the temperature of the system. Irreversible work, such as stirring work or friction work, involves a change in the disorder of the system and, like heat transfer to a system, has the effect of increasing the entropy.[3]

### 3.2 Entropy Aspects

It is now important to introduce a new thermodynamic property, entropy, that is simply a measure of the amount of molecular disorder within a system. In this regard, a system possessing a high degree of molecular disorder (such as a high temperature gas) has a very high entropy value and vice versa. It is important to note that numerical values for specific entropy are commonly listed in thermodynamic tables along with values for specific volume, specific internal energy, and specific enthalpy.

Therefore, entropy is known as the core of the second law thermodynamics. Here, we have to highlight the following facts:

- The entropy of a system is a measure of the amount of molecular disorder within the system.
- A system can only generate, not destroy, entropy.
- The entropy of a system can be increased or decreased by energy transports across the system boundary.

In any transfer or conversion of energy within a closed system, the entropy of the system increases. The consequences of the second law can thus be stated positively as the spontaneous or natural direction of energy transfer or conversion is toward increasing entropy, or negatively as all energy transfers or conversions are irreversible. Or, in keeping with our paraphrasing of the FLT as "You can't get something for nothing," the SLT asserts: You can't even get all you pay for.

It is low-entropy energy sources that are being used up, and low-entropy energy is "useful" energy. The energy sources in the universe were rated on an entropy/usefulness scale from the zero entropy, highly useful mechanical forms such as gravitational potential energy, which are easily converted to work, to the high-entropy, unusable heat of our surroundings.[5]

In summary, this broader interpretation of the SLT suggests that real "energy conservation" should include the practice of thermodynamic economy. Each energy transfer or conversion, all else being equal, should be arranged so that the total change in entropy (entropy generation) is a minimum. This requires that energy sources be matched in entropy to energy end use.

### 3.3 Significance of Entropy

The "entropy" of the state of a system is a measure of the probability of its occurrence. States of low probability have low entropy; states of high probability have high entropy. With this definition we see, from the previous discussion and examples, that in any transfer or conversion of energy, because the spontaneous direction of the change of state of a closed system is from a less to a more probable state, the entropy of the system must increase. That is the broader statement we have been seeking for the second law, "In any energy transfer or conversion within an isolated closed system, the entropy of that system increases."

### 3.5 The Second Law of Thermodynamics (SLT)

Although a spontaneous process can proceed only in a definite direction, the FLT gives no information about direction; it merely states that when one form of energy is converted into another, identical quantities of energy are involved regardless of feasibility of the process. In this regard, events could be envisioned that would not violate the FLT, e.g., transfer of a certain quantity of heat from a low temperature body to a high-temperature body, without expenditure of work. However, the reality shows that this is impossible and FLT becomes inadequate in picturing the complete energy transfer. Furthermore, experiments indicated that when energy in the form of heat is transferred to a system, only a portion of heat can be converted into work.

The SLT establishes the difference in quality between different forms of energy and explains why some processes can spontaneously occur, whereas other can not. It indicated a trend of change and is

usually expressed as an inequality. The SLT has been confirmed by experimental evidences like other physical laws of nature.[1]

### 3.6 SLT Statements

Although there are various formulations of the SLT, two of them are better known such as the Clausius statement and the Kelvin-Planck statement.

- The **Clausius statement**. It is impossible for a system to transfer heat from a lower temperature reservoir to a higher temperature reservoir. Simply, heat transfer can only occur spontaneously in the direction of temperature decrease. For example, we can not construct a refrigerator that operates without any work input.[1]
- The **Kelvin-Planck statement**. It is impossible for a system to receive a given amount of heat from a high-temperature reservoir and provide an equal amount of work output. While a system converting work to an equivalent energy transfer as heat is possible, a device converting heat to an equivalent energy transfer as work is impossible. For example, we can not build a heat engine that has a thermal efficiency of 100%. [1]

## 4. Exergy

### 4.1 Introduction

A very important class of problems in engineering thermodynamics concerns systems or substances that can be modelled as being in equilibrium or stable equilibrium, but that are not in mutual stable equilibrium with the surroundings. For example, within the earth there are reserves of fuels that are not in mutual stable equilibrium with the atmosphere and the sea. The requirements of mutual chemical equilibrium are not met. Any system at a temperature above or below that of the environment is not in mutual stable equilibrium with the environment. In this case the

requirements of mutual thermal equilibrium are not met. It is found that any lack of mutual stable equilibrium between a system and the environment can be used to produce work. The SLT allows the maximum work that could be produced to be determined.

The exergy of a system is defined as the maximum shaft work that could be done by the composite of the system and a specified reference environment that is assumed to be infinite, in equilibrium, and ultimately to enclose all other systems. Typically, the environment is specified by stating its temperature, pressure and chemical composition. Exergy is not simply a thermodynamic property, but rather is a co-property of a system and the reference environment. The term exergy comes from the Greek words *ex* and *ergon*, meaning from and work: the exergy of a system can be increased if work is done on it. The following are some terms found in the literature that are equivalent to or nearly equivalent to exergy: available energy, essergy, utilizable energy, available work, availability.[4]

Exergy has the characteristic that it is conserved only when all processes of the system and the environment are reversible. Exergy is destroyed whenever an irreversible process occurs. When an exergy analysis is performed on a plant such as an entire power station, a chemical processing plant or a use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined.

- It is an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. It is a key component in obtaining sustainable development.

refrigeration plant, the thermodynamic imperfections can be quantified as exergy destruction, which is wasted work or wasted potential for the production of work. Like energy, exergy can be transferred or transported across the boundary of a system. For each type of energy transfer or transport there is a corresponding exergy transfer or transport. In particular, exergy analysis takes into account the different thermodynamic values of work and heat. The exergy transfer associated with shaft work is equal to the shaft work. The exergy transfer associated with heat transfer, however, depends on the temperature level at which it occurs in relation to the temperature of the environment.

Before getting into details of the linkages between energy and exergy, exergy and the environment, energy and sustainable development, we provide some key points to highlight the importance of the exergy and its utilization:

- It is a primary tool in best addressing the impact of energy resource utilization on the environment.
- It is an effective method using the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems.
- It is a suitable technique for furthering the goal of more efficient energy resource.

#### 4.2 Exergy Aspects

It is also important to illustrate some meanings of exergy by the following simple examples:

- A system in complete equilibrium with its environment does not have any exergy. No difference appears in temperature, pressure, or concentration etc. for running any processes.



- The more a system deviates from the environment, the more exergy it carries. Hot water has a higher content of exergy during the winter than it has on a hot summer day. A block of ice carries hardly any exergy in winter while it does in summer.[4]
- When the energy loses its quality, it results in exergy destroyed. The exergy is the part of the energy which is useful in the society and therefore has an economic value and is worth taking care of.
- Almost all energy, converted in the thin layer on the earth's surface, where life can be found, derives from the sun. Sunlight, rich in exergy, reaches the earth. A lot of it is reflected but the energy absorbed on the earth is converted and finally leaves the earth as heat radiation with no exergy relative to the earth. The net exergy absorbed by the earth is consequently gradually destroyed but during this destruction it manages to drive the water/wind system and the life on earth.
- The green plants absorb exergy from the sunlight and convert it via photosynthesis into chemical exergy. The chemical exergy then passes through different food chains in the ecosystems.[5]

### 4.3 Exergy vs Energy

The traditional method of assessing the energy disposition of an operation involving the physical or chemical processing of materials and products with accompanying transfer and/or transformation of energy is by the completion of an energy balance. This balance is apparently based on the FLT. In this balance, information on the system is employed to attempt to reduce heat losses or enhance heat recovery. However, from such a balance no information is available on the degradation of energy, occurring in the process and to quantify the usefulness or quality of the heat content in various streams leaving the process as products, wastes, or coolants.[4]

The exergy method of analysis overcomes the limitations of the FLT. The concept of exergy is based on both FLT and SLT. Exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation or technology. It can also quantify the quality of heat in a reject stream. So, the main aim of exergy analysis is to identify the causes and to calculate the true magnitudes of exergy losses. Table 1 presents a general comparison of both energy and exergy.[5]

**Table 1.** Comparison of energy and exergy.

ENERGY	EXERGY
<ul style="list-style-type: none"> <li>• is dependent on the parameters of matter or energy flow only, and independent of the environment parameters.</li> <li>• has the values different from zero (equal to <math>mc^2</math> upon Einstein's equation).</li> <li>• is governed by the FLT for all the processes.</li> <li>• is limited by the SLT for all processes (incl. reversible ones).</li> <li>• is motion or ability to produce motion.</li> <li>• is always conserved in a process, so can neither be destroyed or produced.</li> <li>• is a measure of quantity only.</li> </ul>	<ul style="list-style-type: none"> <li>• is dependent both on the parameters of matter or energy flow and on the environment parameters.</li> <li>• is equal to zero (in dead state by equilibrium with the environment).</li> <li>• is governed by the FLT for reversible processes only (in irreversible processes it is destroyed partly or completely).</li> <li>• is not limited for reversible processes due to the SLT.</li> <li>• is work or ability to produce work.</li> <li>• is always conserved in a reversible process, but is always consumed in an irreversible process.</li> <li>• is a measure of quantity and quality due to entropy.</li> </ul>

To begin with, we must distinguish between exergy and energy in order to avoid any confusion with the traditional energy-based methods of thermal system analysis and design. Energy flows into and out of a system via mass flow, heat transfer, and work (e.g., shafts, piston rods).

Energy is conserved, not destroyed: this is the statement made by the FLT. Exergy is an entirely different concept. It represents quantitatively the "useful" energy, or the ability to do work the work content-of the great variety of streams (mass, heat, work) that flow through the system.

The first attribute of the property "exergy" is that it makes it possible to compare on a common basis interactions (inputs, outputs) that are quite different in a physical sense. Another benefit is that by accounting for all the exergy streams of the system it is possible to determine

the extent to which the system destroys exergy. The destroyed exergy is proportional to the generated entropy. In actual systems, exergy is always destroyed, partially or totally: this is the statement made by the SLT. The destroyed exergy, or the generated entropy is responsible for the less-than-theoretical efficiency of the system.

An engineer designing a system is expected to aim for the highest possible technical efficiency at a minimum cost under the prevailing technical, economic and legal conditions, but also with regard to ethical, ecological and social consequences. Exergy is a concept that makes this work a great deal easier. Thus, exergetics offers a unique insight where losses and possible improvements can be determined, and Life Cycle Exergy Analysis (LCEA) is suggested as a method to better meet environmental conditions.[5]

## 5. Conclusions

In a broader perspective (except for the zeroth and third law of thermodynamics), we can define the thermodynamics as a science of energy, exergy, and entropy. Apparently, the FLT refers to the energy analysis which only identifies losses of work and potential improvements or the effective use of resources, e.g., in an adiabatic throttling process. However, the SLT, i.e., exergy analysis takes the entropy portion into consideration by including irreversibilities. During the past decade exergy related studies have received considerable attention from various disciplines ranging from chemical engineering to mechanical engineering, from environmental engineering to ecology and so on. As a consequence of this, recently, international exergy community has expanded greatly.

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