

Environment Temperature Fluctuations as a Source of Energy Generation

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Abstract

This article examines the potential of environment-temperature variability as a source of usable energy for free. For example, on the Moon, the diurnal temperature swing reaches 300 K (approximately 100 K to 400 K), enabling a heat engine to operate with a Carnot efficiency of about 75%. On Earth, the most favorable conditions occur in the Taklamakan Desert, where a diurnal variation of 35 K (from roughly 255 K to 290 K) corresponds to a Carnot efficiency of 12.1%. The analysis employs the classical Carnot efficiency for systems with two heat reservoirs of constant temperature and introduces the concept of exergy efficiency for configurations in which only one reservoir maintains a constant temperature. Opportunities for practical implementation are discussed for selected locations on Earth and within the Solar System. Both substance working fluids and radiation working media are considered. For context, the study also compares these results with the exergy efficiency of natural solid fuels, which can exceed 100%.

Keywords

Environment Temperature Fluctuation, Radiation as Working Medium, Carnot Efficiency, Exergy Efficiency

1. Introduction

Energy of matter depends only on the thermodynamic parameters of that matter, for any arbitrarily chosen reference state adopted for calculations. However, the beauty of the concept of the exergy of that energy, although it also depends on these thermodynamic parameters, lies in the fact that the reference state for exergy calculations is not arbitrary and is determined by the thermodynamic parameters of the environment in which the matter is considered [1]. For humans, this environment

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naturally defines the reference state primarily through its chemical composition and temperature. Following the environment temperature as the defining reference, the exergetic line of inquiry in the search for energy sources leads to considerations of the possibility of exploiting natural fluctuations of that temperature.

Historically, the first monograph on exergy [2] presents the exergy balance equation for a system subjected to a fluctuating environmental temperature. This equation closes only after introducing an additional term, ΔB_{en} , corresponding to the variability of the environment temperature, and the value of this additional term can be determined directly from the balance equation:

$$\int_0^t B_{\text{in}}(t) dt = \int_0^t B_{\text{out}}(t) dt + (B_t - B_0) + \int_0^t \Delta B_{\text{ir}}(t) dt + \Delta B_{\text{en}} \quad (\text{a})$$

Equation (a) is considered over the time interval from $t = 0$ to $t = t$. In this equation, B_{in} is the exergy of the streams supplied to the system, B_{out} is the exergy of the streams removed, ΔB_{ir} is the instantaneous exergy destruction due to irreversibility, and $(B_t - B_0)$ denotes the difference in the system's exergy between the initial state (at $t = 0$) and the final state (at $t = t$). Equation (a) shows that a process may be organized in time such that a change in environment temperature leads to the creation of exergy ($\Delta B_{\text{en}} > 0$).

A simple example of such a process is the following: at $t = 0$, a portion of air is taken from the instantaneous environment and placed into a perfectly insulated vessel, where it remains until time t , when the environment temperature has changed. During this interval, no streams enter or leave the vessel ($B_{\text{in}} = 0$, $B_{\text{out}} = 0$), and no irreversible processes occur ($\Delta B_{\text{ir}} = 0$). From equation (a) it follows that, solely due to the change in environment temperature, exergy has been created (or destroyed) in the amount

$$\Delta B_{\text{en}} = B_t - B_0. \quad (\text{b})$$

This reasoning therefore draws attention to the possibility of generating energy by exploiting fluctuations of environment temperature. The effect of environment-temperature change on the value of ΔB_{en} in the example of a sphere heated by radiation is discussed in more detail in §6.9 of [3].

In general, exergy consists of several components; however, since the present discussion concerns temperature, only one component is considered here: physical exergy, that is, the part that results mainly from the temperature level, while pressure plays only a secondary role. In any case, no other exergy components are examined here, and in particular the chemical component—arising from differences between the chemical composition of the working substance and that of the environment—is omitted. The temperature of the environment T_0 at a given location is considered, varying in time, with its maximum value denoted as T_{H} and its minimum as T_{L} . The use of slow changes in environmental temperature is very old and much older than any attempts to generate electrical energy [4]. As early as around 500 BCE, the Persians used daily temperature fluctuations and thermal radiation to the sky to produce ice in a desert climate. At night, water froze due to radiative heat loss, despite positive daytime temperatures. In India, shallow water

basins were used, which cooled during the night and produced ice. Natural night cooling was employed in Roman frigidaria. In the Middle Ages, European ice houses stored winter ice, which, thanks to slow temperature variations and insulation, could survive until summer. In Iran and Arabia, wind towers were used to direct cool night air into interior spaces. Psychrometric desert cooling was also known, relying on differences in temperature and humidity between day and night. These were all uses of daily fluctuations to regulate the microclimate.

The nineteenth century brought the first heat engines operating on small temperature differences (the Stirling engine). This was the first step toward “energy harvesting” from slow temperature variations [5] [6]. In the twentieth century, the first practical devices appeared that were powered solely by slow daily and seasonal changes in environmental temperature. The concept of phase-change materials emerged, intended for storing heat and releasing it slowly. Materials capable of generating electricity from temperature differences (thermoelectrics) also began to be used, although the daily ΔT is usually too small to produce significant power. “Thermal clocks” were developed as devices driven by slow temperature changes; for example, the Atmos clock by Jaeger-LeCoultre (1928), which operated thanks to the thermal expansion of a gas.

The twenty-first century is marked by modern concepts of “thermal harvesting”, that is, attempts to extract energy from very slow temperature variations. Examples include thermal resonators developed at the Massachusetts Institute of Technology (MIT), materials with high heat capacity and thermal conductivity that “resonate” with the daily temperature cycle and generate small amounts of electrical power, or Stirling engines driven by Earth’s thermal radiation, which use terrestrial infrared emission as a source of mechanical energy (American Association for the Advancement of Science, AAAS).

For clarification, one of the simplest and most durable methods of converting mechanical energy into electrical energy on the milliwatt scale is the use of a piezoelectric element [7]. This is a material or a small device that produces an electric voltage when compressed, bent, or deformed. It also works in reverse; when a voltage is applied, it deforms itself. Another method involves a small container in which, during the day, the gas warms up, pressure increases, and a membrane pushes a piston outward. The piston’s motion tensions a spring or deforms a piezoelectric element. At night, the gas cools, pressure drops, and the piston returns. The return stroke generates a pulse of electrical energy.

The natural phenomenon of a varying environmental temperature has also been considered many times as a potential energy source, but it has not yet become a practical energy technology. Research and conceptual proposals exist, yet their applicability is constrained by the fundamental laws of thermodynamics. To produce energy, at least two heat sources are required. Typically, one heat source is, for example, the hot exhaust gases from fuel combustion, while the second heat source is the environment. However, in some cases, two heat sources can be identified when the environmental temperature changes. Such heat sources do not oc-

cur simultaneously, and therefore, to generate energy, one would need to accumulate the thermal effect of the environment at one moment in order to use the stored heat at another moment, when the environmental temperature has changed due to natural causes. An example of such a method of obtaining useful energetic effects is the long-known practice of collecting ice blocks in winter, storing them in insulated spaces, and using this ice for cooling purposes later in the summer.

The phenomenon of daily and seasonal environmental temperature fluctuations has long appeared in the literature as a potential energy source, yet it has not led to the development of a mature energy technology. Classical thermodynamic analyses emphasize that the available exergy at small temperature amplitudes is inherently very limited, which follows directly from the dependence of ideal efficiency on the temperature difference in the Carnot cycle [5] [8] [9]. Under typical terrestrial conditions, where daily temperature variations are on the order of 5 - 20 K, the maximum theoretical efficiency is negligible, and the actual efficiency, after accounting for thermal and mechanical losses, usually falls below 1% [8] [10]. Consequently, most of the concepts considered remain at the level of laboratory demonstrators or niche applications with very low power output.

The most frequently analysed class of devices consists of heat engines operating at very small temperature differences, in particular low-temperature-differential (LTD) variants of the Stirling engine. The literature describes both theoretical models and prototypes capable of operating at ΔT values of only a few tens of kelvins, powered for example by geothermal, solar or waste heat sources. Analyses by Senft and other authors, however, indicate strict geometric and thermodynamic constraints that prevent achieving high specific power at such small temperature differences [11] [12]. In practice, LTD engines reach power levels on the order of watts or tens of watts, which is sufficient to drive small generators but does not constitute competition for conventional energy sources [11]-[13].

A second widely studied group of solutions consists of systems employing phase-change materials (PCM). These materials allow heat to be stored within a narrow temperature range, which makes them attractive for solar-energy buffering or for building-temperature stabilization [14] [15]. However, PCM do not themselves generate mechanical or electrical energy; they serve only as a storage medium that can operate in conjunction with another energy converter, such as a heat engine or a thermoelectric module [14]. In the context of exploiting environmental temperature fluctuations, this means that PCM can smooth the temperature profile and extend the duration over which a useful temperature difference ΔT is available, but they do not resolve the fundamental limitation of low exergy in the source.

A third class consists of thermoelectric devices based on the Seebeck effect. Thermoelectric modules are capable of operating at small temperature differences, which makes them natural candidates for converting energy from daily temperature fluctuations [6] [16] [17]. Their efficiency, however, is limited both by the fundamental laws of thermodynamics and by the finite value of the material

quality factor (ZT), which for most commercial semiconductors remains moderate [16]. Numerous environmental “energy harvesting” demonstrators have been described in the literature—installed on heating pipes, building surfaces or infrastructure elements—but the power obtained is typically in the milliwatt to single-watt range per module, restricting applications to powering sensors and low-power electronics [6] [17].

It is also worth mentioning the concepts of so-called “thermal clocks” and micro-devices driven by cyclic expansion and contraction of materials. In micro-mechanics and micro-electro mechanical systems (MEMS) research, systems have been proposed in which environmental temperature changes induce periodic deformations of bimetals, polymers or elastic structures, generating small amounts of mechanical work [18] [19]. The power of such devices is inherently very low (in the milliwatt range or below), and their applications are limited to niche solutions such as autonomous triggers, indicators or clocks with extremely low energy consumption [18]. From the perspective of system-scale energy engineering, they do not constitute a meaningful power source but rather an engineering curiosity.

Analyses of the exergy available from environmental temperature fluctuations consistently show that the main barrier is the small temperature amplitude and the difficulty of maintaining a temperature difference for the time required to perform work [1]-[3]. For a typical daily $\Delta T \approx 10$ K at an environmental temperature of about 300 K, the ideal Carnot efficiency is only around 3.3%, and after accounting for thermal irreversibility and conduction losses, the actual conversion efficiency falls below 1% [8] [10]. Moreover, achieving noticeable power output would require processing very large heat fluxes, which entails substantial heat-exchanger size, integration challenges and high capital costs. As a result, the energy-economic balance of such systems is unfavourable compared with classical renewable technologies such as photovoltaics or wind power [9] [10].

An interesting direction, appearing with increasing frequency in the literature, concerns planetary environments with extreme temperature amplitudes. On the Moon, Mercury or other bodies lacking an atmosphere, daily surface-temperature variations can reach several hundred kelvins, which radically increases the exergy potential available from cyclic temperature changes [20]. Proposed concepts include cyclic heat engines coupled with massive thermal stores that accumulate energy during the day and release it at night, generating mechanical work or electrical power [21]. It was demonstrated that radiative cooling—including nocturnal cooling—can significantly increase the effective temperature difference in solar-thermal systems [22]. Although these concepts remain at the stage of feasibility studies and numerical analyses, they demonstrate that in extraterrestrial conditions the limitations known from Earth may be partially alleviated.

In summary, the literature review indicates that the energetic use of environmental temperature fluctuations has been analysed many times at various scales—from MEMS micro-devices, through thermoelectric modules and LTD Stirling engines, to concepts of thermal stores and hybrid systems. The common conclusion

of all these studies is that on Earth the available exergy is too small to justify the construction of large, stand-alone energy installations based solely on daily temperature variations [5] [6] [8]-[10] [16] [17]. These technologies find niche applications in the field of energy harvesting for low-power electronics and in thermal-storage systems, while their role in the overall energy balance remains marginal. In planetary environments with extreme temperature amplitudes, however, there emerges a realistic opportunity to use this phenomenon as one component of power-supply systems, which represents an interesting direction for further theoretical and design research [20]-[22].

The novelty of the present work lies in the discussion of the possibilities of producing energy from environmental temperature fluctuations on the basis of the Carnot efficiency and the so-called exergy efficiency. Both efficiencies are analysed as functions of the maximum difference ΔT in the varying environmental temperature, as well as of the temperature level (T_L), at which this difference occurs. These efficiencies are presented in diagrams, which allows for a convenient discussion of their values over a wide range of conditions, encompassing both those on Earth and in the Solar System. The use of substances (understood as gases, liquids, or solids) and of radiation ("photon gas") as working media in devices exploiting environmental temperature fluctuations is evaluated. Radiation as a working medium is particularly important in processes occurring in vacuum. For comparison, natural fuels are briefly discussed as examples of natural environmental resources for which the exergy efficiency exceeds 100%.

2. Fluctuation of Environment Temperature

A temperature difference is required to produce energy, that is, two distinct heat sources at different temperatures. A heat source is understood as a medium capable of supplying or absorbing infinitely large amounts of heat without undergoing a change in its own temperature. Let us look more closely at the temperature of the human environment. We observe its fluctuations over time: hourly, daily, and yearly. These fluctuations occur in our vicinity, in a country, in a region of the world, on the planet, and beyond the planet Earth. They may be small or large, but they all share one essential feature: the temperature difference that could potentially be used for energy production does not occur at the same time. For example, on Earth the daily variation of the environment temperature may reach 20 degrees, while the annual variation may reach even 50 degrees. On the Moon, the daily temperature change is approximately from -173°C to 127°C , that is, about 300 degrees [23], with the lunar day lasting 29.53 Earth days. This leads to the conclusion that one should nevertheless consider the possibility of using the environment at its minimum and maximum temperatures as the two heat sources required for energy generation. For an energy-producing process of significant power, on the order of megawatts, two possibilities emerge.

One possibility is to select, for heat storage (first period), a substance that would, during the second period, exchange the stored heat at one extreme envi-

environment temperature with a second heat source also at a constant extreme environment temperature. Theoretically, a variation of this case could involve a device producing energy that is extended in space in such a way that it would simultaneously be in contact with locations having extreme environment temperatures.

The second possibility would rely on the appropriate use of insulation to preserve a substantial portion of the environmental effect captured during one extreme temperature period, so that it could be used during the opposite extreme temperature period. The weakness of this process is that the substance, once isolated, becomes a heat source whose temperature changes as the process proceeds.

The economic viability of energy generation in both cases increases with the amplitude of the environment temperature fluctuations, that is, the peak-to-peak value ($T_H - T_L$), and also depends on the values of the extreme temperatures themselves—for example, on the lower extreme temperature T_L ; the lower it is, the higher the efficiency. Naturally, when determining economic feasibility—an issue not considered in this work—many additional factors would have to be considered, such as the time scale of the environment temperature variations.

3. Use of Environmental Temperature Fluctuations

For energy generation, the ideal situation would be that locally extreme differences in environmental temperature occurred within a very short time and preferably were available simultaneously. Since this is impossible, only the two possibilities described in Section 2 are considered.

In the first case, one would need to ensure constant values of the extreme temperatures for the energy-generation process, for example for the cycle of a heat engine. This could be achieved as follows:

a) Ideally, one would thermally insulate a working substance after it has been heated by the environment at the high extreme temperature T_H . This substance could, for instance, be saturated vapor at temperature T_H , which would then release its condensation heat isothermally to the engine cycle at the same temperature T_H . The second heat source required for the process could be another suitably insulated working substance that evaporates at low extreme temperature T_L , removing heat isothermally from the cycle at constant temperature T_L , and then undergoes isothermal condensation as it is cooled by the environment at temperature T_L . These would be evaporation/condensation processes.

b) An analogous process could be implemented using a substance undergoing melting/freezing, thereby creating the two required heat sources at constant temperature for the operation of a heat engine.

c) One could also consider a sublimation/resublimation process.

d) Another possibility would be a substance undergoing chemical reactions at constant temperature; this would involve exothermic/endothermic processes.

In the above cases, the magnitude of the latent heat of phase change (a, b, c) or the reaction heat (d) plays a major role. The larger this value, the smaller the required amount of working substance. For phase changes, the heat of fusion of

metals is often moderate (100 - 300 kJ/kg), the heat of sublimation of metals is enormous (several to several tens of MJ/kg), the heat of vaporization of water is only about 2257 kJ/kg, the heat of vaporization of pentane is about 360 kJ/kg, and the heat of vaporization of ammonia is about 1370 kJ/kg [24]. For typical thermal-storage materials, the reaction heat—depending on the specific system, for example for salt hydrates (dehydration/hydration reactions)—is on the order of 200 - 800 kJ/kg [25]. The heat of sorption reactions (e.g., zeolites, silica gel + water) is on the order of 500 - 2000 kJ/kg [26]. Some high-temperature chemical reactions (e.g., oxides, carbonates) have reaction heats of about 1000 - 3000 kJ/kg [27].

Thus, the heat of vaporization of water is relatively large, but chemical reactions in thermal-storage substances can yield similar or even greater heat values per kilogram. Sublimation of metals (especially high-melting ones) may have a transformation heat larger than typical thermal-storage reactions but is completely impractical technically.

All the above cases are characterized by isothermal heat-exchange processes, which affects the efficiency of using the temperature difference $T_H - T_L$. Cases a) through d) should therefore be analyzed on the basis of the Carnot efficiency.

A less favorable, though perhaps easier to implement, possibility is:

e) simply storing a substance at the extreme temperature T_H or T_L and using it in the next period, either during cooling to T_L in a forward heat-engine cycle, or during heating to T_H in a reverse cycle.

In case e), the temperature of the substance is not constant and changes during heat exchange. Instead of the Carnot efficiency, it is more appropriate to use another efficiency measure that is less strict and more realistic. It is therefore proposed to use, in this case, the exergy efficiency discussed later.

The thermodynamic assessment of the feasibility of using environmental temperature fluctuations is carried out by comparing the process with the corresponding theoretical maximum efficiency, which cannot be exceeded in practice. The following sections therefore discuss the values of Carnot efficiency or exergy efficiency for the considered cases. The values of both efficiencies depend not only on the peak-to-peak difference ($T_H - T_L$), but also on one of the temperatures, T_L or T_H , which determines the temperature level of that difference.

4. Theoretical Assessment of the Temperature Difference ($T_H - T_L$) for Constant Temperatures of Both Heat Sources

4.1. Carnot Cycle

In this case, the estimation of variations in the temperature of the environment can be based on the Carnot efficiency. The concept of this efficiency arises from analysing the thermodynamic cycle of a heat engine [5]. Such an engine operates by being supplied with heat from a hot heat source at a constant temperature T_H , while simultaneously being able to reject heat to a second heat source at a lower temperature, which may be regarded as equal to the constant environmental tem-

perature T_0 . The source at temperature T_0 is available at no cost, whereas the hot source at temperature T must be created and maintained at some expense. The thermodynamic cycle under consideration, known as the Carnot cycle, is a theoretical model used to analyse the process of energy conversion in real heat-engine systems. The Carnot cycle proceeds in a thermodynamically reversible manner, that is, without friction, and with heat transfer occurring under infinitesimally small temperature differences. For the Carnot cycle, the thermal efficiency has been derived and because all processes are reversible, this efficiency represents the maximum theoretical efficiency attainable when two heat sources are available. The efficiency is defined as the ratio of the work obtained to the amount of heat supplied from the hotter source at temperature T . It therefore represents the maximum possible efficiency achievable when two heat sources at temperatures T and T_0 are available. When considering fluctuations of the environmental temperature, one interprets $T = T_H$ and $T_0 = T_L$, and the Carnot efficiency is then given by:

$$\eta_c = 1 - \frac{T_L}{T_H} \quad (1)$$

Equation (1) may be transformed by introducing the temperature difference $\Delta T = T_H - T_L$:

$$\eta_c = \frac{1}{1 + \frac{T_L}{\Delta T}} \quad (2)$$

One may calculate the ratio of the partial derivative of the Carnot efficiency with respect to the temperature T_L to the partial derivative with respect to the temperature difference ΔT :

$$\left(\frac{\partial \eta_c}{\partial T_L} \right) \cdot \left(\frac{\partial \eta_c}{\partial \Delta T} \right)^{-1} = - \frac{\Delta T}{T_L} \quad (3)$$

The minus sign in Equation (3) indicates that the quantities ΔT and T_L influence the value of the Carnot efficiency in opposite directions. When $\Delta T = T_L$, their influence is equal; however, for $\Delta T > T_L$ the effect of T_L dominates, whereas for $\Delta T < T_L$ the influence of the temperature difference ΔT prevails.

4.2. Extraterrestrial Possibilities

The diagram of relation (2), presented in **Figure 1**, makes it possible to determine the Carnot efficiency η_c for situations in which both the environmental temperature T_L and the temperature difference ΔT are known. The data from **Table 1** were used to indicate on this diagram the characteristic values of η_c corresponding to the conditions prevailing on selected bodies of the Solar System.

In general [28], the largest diurnal temperature variations in the Solar System occur on the Moon and on Mercury, exceeding 300 K, whereas on planets with atmospheres these variations are much smaller. The absence of an atmosphere means the absence of thermal insulation, and the surface heats and cools almost exclusively through radiative processes. The largest peak-to-peak environmental

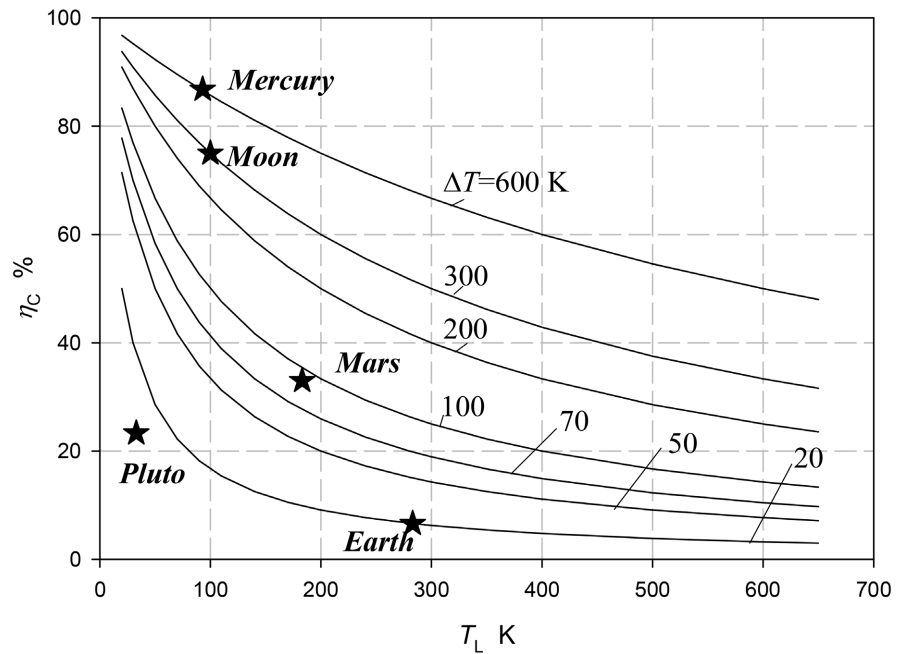


Figure 1. Carnot efficiency η_c as a function of the temperature T_L and the temperature difference $\Delta T = T_H - T_L$.

Table 1. Approximate data on the diurnal fluctuation of the environmental temperature for selected bodies of the Solar System [29], together with the calculated efficiencies of utilizing environmental temperature fluctuations.

Object	Day temperature T_H K	Night temperature T_L K	Peak-to-peak Difference ΔT K	Atmosphere	Carnot efficiency η_c %	Exergy efficiency η_E %
Moon	400	100	300	none	75	53.8
Mercury	703	93	610	none	86.8	69.2
Venus	733	733	~0	very dense	0	0
Earth	303	283	20	moderate	6.6	3.38
Mars	273	183	90	thin	33.0	18.7
Jupiter	No solid surface		small	very dense	-	-
Pluto	43	33	10	very thin	23.3	12.7

temperature variation (approximately 610 K) occurs on Mercury. The second-largest variation is found on the Moon, with a range of about 300 K. The corresponding maximum Carnot efficiencies—Moon: 75%, Mercury: 86.8%—indicate the possibility of obtaining energy from environmental temperature fluctuations with potentially high real efficiencies. Venus possesses a dense atmosphere that produces a strong greenhouse effect, under which the environmental temperature variations are below $\Delta T \approx 5$ K. On Earth, the presence of the atmosphere and oceans stabilizes the climate, and temperature variations are moderate, resulting in a low Carnot efficiency of about 6.6%. The thin atmosphere on Mars corresponds to a Carnot efficiency of 33%. Pluto, with its very slow rotation and extremely tenuous atmosphere, exhibits relatively large environmental tempera-

ture variations, although these are poorly characterized. The Carnot efficiency for Pluto is estimated at 23.3%. The gas giants—Jupiter, Saturn, Uranus, and Neptune—lack a solid surface, and therefore classical “diurnal” ground-temperature variations do not occur.

The actual efficiency of utilizing environmental temperature fluctuations is significantly lower than the theoretical value η_c . If, for example, one assumes that a theoretical efficiency of 10% is the threshold of practical usefulness, then on the diagram (**Figure 1**) the line of constant efficiency $\eta_c = 10\%$ defines the region below this line as corresponding to pairs of values of the environmental temperature T_L and the temperature difference ΔT for which the fluctuation should rather be excluded from consideration.

4.3. Earth-Based Possibilities

As shown in **Table 1**, the diurnal temperature variations on Earth are relatively small, although there are exceptional locations. The largest peak-to-peak temperature differences occur where land is far from the oceans (no moderating effect), where dry air masses heat up and cool down rapidly, where the terrain is flat or elevated, which promotes strong radiative heat loss in winter, or where the latitude is high (long winter nights, short summer nights).

Based on data [30], **Table 2** presents the top 20 cities with the largest diurnal temperature ranges. The cities are listed in descending order of the Carnot efficiency, calculated here to characterize the potential for generating energy from ambient temperature fluctuations.

Table 2. Top 20 cities with the largest diurnal temperatures ranges.

City, Country	Lowest daily temperature, T_L K	Peak-to-peak temperature difference, ΔT K	Carnot efficiency, η_c %	Exergy efficiency, η_e %	Location notes
Yarkand, China	255	35	12.1	6.3	Taklamakan Desert
Kashgar, China	258	33	11.3	5.9	Continental basin, very dry
Turpan, China	260	32	11.0	5.7	Deep depression, extreme dryness
Urumqi, China	255	30	10.5	5.5	Far continental climate
Lhasa, China	250	28	10.1	5.2	Tibetan Plateau
Elko, USA	255	27	9.6	4.9	Great Basin Desert
San Pedro de Atacama, Chile	270	28	9.4	4.9	One of the driest places on Earth
Flagstaff, USA	258	26	9.2	4.7	High elevation, clear skies
Alice Springs, Australia	275	25	8.3	4.3	Central Australian desert
Tucson, USA	283	25	8.1	4.2	Desert basin
Phoenix, USA	285	25	8.0	4.1	Sonoran Desert
Riyadh, Saudi Arabia	290	24	7.6	3.9	Arabian Desert interior
Isfahan, Iran	285	23	7.5	3.8	Iranian Plateau

Continued

<u>Ulaanbaatar, Mongolia</u>	245	20	7.5	3.9	High continentality
Baghdad, Iraq	288	23	7.4	3.8	Continental desert
Windhoek, Namibia	280	22	7.3	3.7	Semi-arid plateau
Lima, Peru	285	22	7.2	3.7	Coastal desert, Humboldt Current
Yakutsk, Russia	235	18	7.1	3.6	Very cold, very dry
Gaborone, Botswana	282	21	7.0	3.5	Kalahari region
Death Valley, USA	290	22	7.0	3.6	Extreme radiative cooling

Table 2 shows that China contains regions with the highest potential for obtaining energy from diurnal fluctuations of the environmental temperature, where the corresponding Carnot efficiency reaches approximately 12 percent.

To determine the annual fluctuation of environmental temperature on Earth, ten locations with the largest annual temperature range [31] were selected, and **Table 3** lists the Carnot efficiencies η_C and the exergy efficiencies η_E calculated here. A comparison of the efficiencies in **Table 2** and **Table 3** illustrates the increased possibilities of energy generation based on annual and diurnal temperature fluctuations.

Table 3. Top 10 places on Earth with the largest annual temperature range.

Place	Lowest temperature T_L K	Annual temperature range ΔT K	Carnot efficiency, η_C %	Exergy efficiency, η_E %	Location notes
Oymyakon, Russia	205.5	105	33.8	19.2	Cold pole of the Northern Hemisphere; deep continental basin.
Verkhoyansk, Russia	205.4	103	33.4	18.9	One of the two “cold poles”; extreme continentality.
Yakutsk, Russia	209.2	100	32.3	18.3	Largest city on continuous permafrost.
Ulaanbaatar, Mongolia	231.2	70	23.2	12.6	High-altitude continental basin; severe winters.
Astana, Kazakhstan	222.1	65	22.6	12.3	Flat steppe; strong Siberian winter influence.
Winnipeg, Canada	228.2	60	20.8	11.2	Deep continental interior of North America.
Harbin, China	233.2	60	20.5	11.0	Northeastern China; long, harsh winters.
Fairbanks, Alaska, USA	233.7	58	19.9	10.7	Interior Alaska; strong winter inversions.
Hothot, China	236.2	55	18.9	10.1	Inner Mongolia plateau; dry continental climate.
Bismarck, North Dakota, USA	238.2	55	18.8	10.0	Northern Great Plains; large winter-summer contrast.

5. Theoretical Assessment of the Temperature Difference ($T_H - T_L$) for a Variable Temperature T_H of the Hotter Heat Source

5.1. Exergy Cycle

The simplest way to utilize fluctuations of the environmental temperature appears to be to capture and thermally insulate a certain amount of a substance that is not

subjected to phase changes or chemical reactions, and, for example, during the period of maximum environmental temperature T_H , to heat this substance to that temperature, and then to extract this heat during the period of minimum environmental temperature T_L . The substance releases heat while its temperature decreases, theoretically from T_H down to T_L , and the assessment of such a fluctuation-based process should not be carried out by comparison with the Carnot cycle, in which T_H is constant. In the case considered here, a different, appropriate theoretical reference cycle must therefore be defined. This problem of utilizing a moderately hot substance could be approached similarly to the utilization of waste gases whose temperature is of a comparable order.

For the analysis of heat recovery from waste gas, such a theoretical model of the thermodynamic power cycle was introduced [32]. This cycle was proposed to be called the “recovery cycle”; however, in the present work, this cycle using a substance heated by the environment, may be referred to more generally as the “exergy cycle”. Like the Carnot cycle, the exergy cycle consists only of ideal, reversible processes. This means that all heat transfer occurs at an infinitesimally small temperature difference, and the compression and expansion of the working fluid occur without friction. The processes of the exergy cycle are shown on the temperature-entropy (T, S) diagram in **Figure 2**. The curve L-H corresponds to the heat input to the cycle, and this process occurs while the temperature of the substance heated by the environment decreases from T_H to the current minimum environmental temperature T_L . Heat rejection from the cycle at constant temperature T_L and isothermal compression is represented by the line E-L. The cycle is closed by the line H-E, representing isentropic expansion.

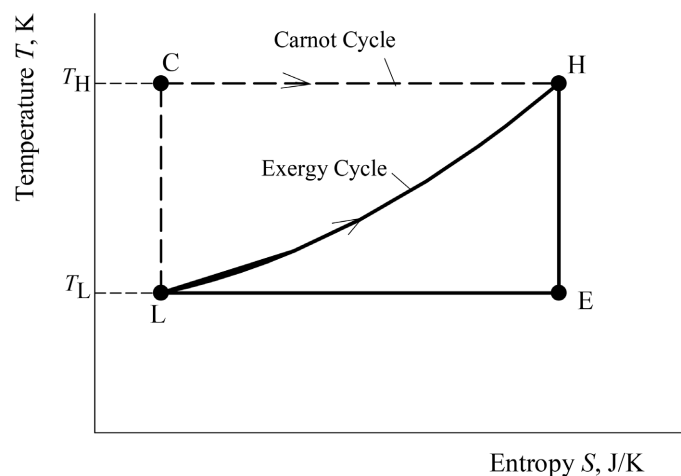


Figure 2. Comparison of the Exergy Cycle (L-H-E-L) to the Carnot Cycle (L-C-H-E-L).

Figure 2 also shows a comparison of the exergy cycle with the corresponding Carnot cycle (dotted line). The Carnot cycle consists of four processes: heat addition to the cycle (C-H), expansion (H-E), heat rejection from the cycle (E-L), and compression (L-C). It may also be added that the difference between the exergy cycle and the well-known Rankine cycle lies in the fact that the compression pro-

cess in the Rankine cycle is isentropic, whereas in the exergy cycle it is isothermal.

Corresponding to the Carnot efficiency defined by Equation (1), the exergy efficiency η_E is introduced, defined as the ratio of the work obtained from the cycle to the energy supplied to the cycle. The supplied energy is therefore equal to the heat delivered at temperature T_H , which is equal to the enthalpy of the heated substance ($h_H - h_L$) during the period of temperature T_H , while the work obtained—maximum and theoretical—is equal to the exergy b_H of this heated substance.

$$\eta_E = \frac{b_H}{h_H - h_L} \quad (4)$$

where h —specific enthalpy of the heat-storage substance, corresponding to the temperature T_H or T_L , kJ/kg;

b_H —specific exergy of this substance at temperature T_H , kJ/kg.

The specific physical exergy b_H of the heat-storage substance [1] [10] can be interpreted as follows:

$$b_H = h_H - h_L - T_L (s_H - s_L) \quad (5)$$

where h , s —specific enthalpy and specific entropy of the substance, respectively, at the temperatures T_H and T_L , kJ/kg, kJ/(kg·K).

Let us consider the case in which the heat-storage substance is an ideal gas, a liquid, or a solid for which a constant, temperature-independent specific heat may be assumed. For a process at constant pressure:

$$s_H - s_L = c_p \ln \frac{T_H}{T_L} \quad (6)$$

where c_p —the specific heat of the gas, or $c_p = c$ for a liquid or a solid.

Considering $h = c_p T$, and substituting formulas (5), and (6) into (4):

$$\eta_E = \frac{c_p T_H - c_p T_L - T_L c_p \ln \frac{T_H}{T_L}}{c_p T_H - c_p T_L} = 1 - \frac{T_L}{\Delta T} \ln \left(1 + \frac{\Delta T}{T_L} \right) \quad (7)$$

where $\Delta T = T_H - T_L$.

One can calculate the ratio of the partial derivative of the exergy efficiency η_E with respect to the temperature T_L to the partial derivative with respect to the temperature difference ΔT :

$$\left(\frac{\partial \eta_E}{\partial T_L} \right) \cdot \left(\frac{\partial \eta_E}{\partial \Delta T} \right)^{-1} = - \frac{\Delta T}{T_L} \quad (8)$$

The same result as that given by equation (3) was obtained. Thus, the minus sign in equation (8) indicates that the quantities ΔT and T_L influence the value of the Carnot efficiency in opposite directions. When $\Delta T = T_L$, their influence is equal; however, for $\Delta T > T_L$ the effect of T_L dominates, whereas for $\Delta T < T_L$ the influence of the temperature difference ΔT prevails.

5.2. Assessment of Possibilities Using Exergy Efficiency

Analogously to **Figure 1**, Equation (7) allows one to plot in **Figure 3** the exergy

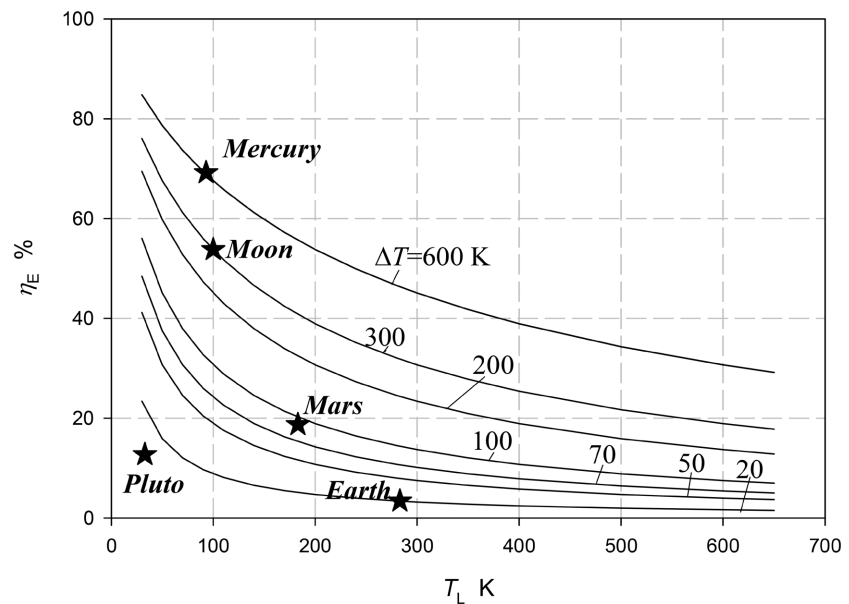


Figure 3. Exergy efficiency η_E as a function of the temperature T_L and the temperature difference $\Delta T = T_H - T_L$.

efficiency η_E as a function of the temperature difference ΔT and the temperature T_L . The values of η_E are much smaller than those of η_C . For example, for $T_L = 200$ K and $\Delta T = 100$ K, one obtains $\eta_C \approx 35\%$, whereas $\eta_E \approx 20\%$.

Exergy efficiencies η_E calculated from Equation (7) for conditions prevailing on the surfaces of selected Solar System bodies are presented in **Table 1** for comparison with the corresponding Carnot efficiencies. The exergy efficiencies for these bodies are also shown in the plot in **Figure 3**.

A comparison of **Figure 1** and **Figure 3** illustrates how much larger the Carnot efficiency is than the exergy efficiency. This relationship for Earth conditions is likewise shown in **Table 2**, where the exergy efficiencies were computed using Equation (7).

The actual efficiency of utilizing environmental temperature fluctuations is much smaller than the theoretical value η_E . As in the case of the Carnot efficiency, if one assumes, for example, that a theoretical efficiency of 10% is the threshold of practical usefulness, then on the plot (**Figure 3**) the line of constant efficiency $\eta_E = 10\%$ defines the region below this line as corresponding to pairs of values of the temperature T_L and the temperature difference ΔT for which the fluctuation should rather be excluded from consideration.

6. Remarks on the Possibility of Obtaining Energy Resulting from the Variable Temperature of Environmental Radiation

6.1. The Case of Constant Temperatures T_H and T_L

The problem of utilizing radiation whose environmental temperature varies arises mainly when the heat source at temperature T_H cannot transfer heat by direct con-

tact, in which convection and conduction would occur. This means that a vacuum exists between the heat source and the energy-generating device. Heat transfer to the device therefore takes place through absorption of the radiation emitted by the source at temperature T_H .

The processes of emission and absorption of radiation are irreversible and involve exergy losses. The loss associated with absorption may be attributed to imperfections of the device when evaluating its performance, whereas the loss associated with emission is not caused by the device itself.

Consequently, the input to the device must be taken as the exergy b_r of the radiation emitted from a surface at temperature T_H , expressed for a black surface by the formula given in [3]:

$$b_r = \frac{\sigma}{3} (3T_H^4 + T_L^4 - 4T_L T_H^3) \quad (9)$$

where $\sigma = 5.6693 \cdot 10^{-8} \text{ W}/(\text{m}^2 \text{ K}^4)$ —Boltzmann constant for black radiation.

The exergy b_r , due to the irreversibility of emission, is smaller than the exergy b_q of the heat leaving the source. The heat q is defined as the difference between the emissions of black surfaces at temperatures T_H and T_L , and according to the Stefan-Boltzmann law:

$$q = \sigma T_H^4 - \sigma T_L^4 \quad (10)$$

Multiplying the heat q by the Carnot efficiency:

$$b_q = \sigma (T_H^4 - T_L^4) \left(1 - \frac{T_L}{T_H} \right) \quad (11)$$

For example, for the Moon ($T_H = 400 \text{ K}$ and $T_L = 100 \text{ K}$ – **Table 1**), using equations (9) and (11), one can calculate the ratio $b_r/b_q = 0.894$. It follows that a device utilizing environment-temperature fluctuations receives $1 - 0.894 = 0.106 \approx 10.6\%$ less exergy via radiation compared with the exergy delivered to the device through direct contact with a heat source at temperature T_H . In the case of radiation, instead of the Carnot efficiency $\eta_C = (1 - T_L/T_H)$, it is therefore more appropriate to use, for example, the modified Carnot efficiency:

$$\eta_{C,r} = \frac{b_r}{q} \quad (12)$$

Considering the values of b_r and q , obtained respectively from Equations (9) and (10), one obtains for the Moon an efficiency of $\eta_{C,r} = 67.06\%$, which is lower than the Carnot efficiency in **Table 1** ($\eta_C = 75\%$). Both efficiencies, η_C and $\eta_{C,r}$, would apply in the case of radiation emitted by bodies undergoing a phase change at a constant temperature T_H .

6.2. Case of Variable Temperature T_H

The working medium in this case is thermal radiation in vacuum (for example, in the absence of an atmosphere), which could be stored during the period when the temperature T_H prevails and then used to generate energy during the period when

the temperature T_L prevails. Radiation exhibits pressure dependent on temperature. One could therefore consider using radiation to perform work by means of a cylinder initially filled with radiation at temperature T_H . The stored radiation could be insulated by mirrorlike internal walls of the cylinder and of the piston face. The piston rod would serve to extract the mechanical work.

During the period of temperature T_H , a body with constant temperature T_H is briefly introduced into the cylinder in order to fill it with the radiation emitted by that body. The cylinder is therefore initially filled with radiation at pressure p_H , resulting from formula [3]:

$$p_H = \frac{a}{3} T_H^4 \quad (13)$$

During the period when the temperature T_L prevails, the environment is filled with radiation at temperature T_L , and therefore the radiation pressure of the environment is $p_L = aT_L^4$. The pressure difference $p_H - p_L$ initiates the expansion of the radiation inside the cylinder until the final pressure p_L is reached. In an ideal reversible process, the work performed is equal to the exergy $b_{u,H}$ of the initial radiation [3]:

$$b_{u,H} = \frac{a}{3} (3T_H^4 + T_L^4 - 4T_L T_H^3) \quad (14)$$

where $a = 7.564 \cdot 10^{-16} \text{ J}/(\text{m}^3 \text{ K}^4)$ —is a universal constant. The input to the process of utilizing the energy of radiation at temperature T_H is equal to the internal energy u_H of the radiation at the beginning of the process [3]:

$$u_H = aT_H^4 \quad (15)$$

and now, using Equations (14) and (15), the process can be evaluated by means of the following exergy efficiency:

$$\eta_E \equiv \frac{b_{u,H}}{u_H} = 1 + \frac{1}{3} \left(\frac{T_L}{T_H} \right)^4 - \frac{4}{3} \frac{T_L}{T_H} \quad (16)$$

And for example, for radiation on the Moon ($T_H = 400 \text{ K}$, $T_L = 100 \text{ K}$), $\eta_E = 66.8\%$. In the literature, the coefficient ψ is often used; it is calculated from Equation (16) and represents precisely the exergy efficiency [3]. The use of radiation concerns small, milliwatt-level powers. For example, 1 m^3 of radiation at temperature $T_H = 400 \text{ K}$ on the Moon, at a momentary environment temperature $T_L = 100 \text{ K}$, represents only the exergy $b_u = 0.0129 \text{ mJ}/\text{m}^3$. In general, one can observe that radiation is energy of rather high quality, measured by the radiation temperature, but it is very dilute. Therefore, the utilization of radiation is usually associated with its concentration [33]. The dependence of η_E on T_L and on $\Delta T = T_H - T_L$, based on Equation (16), is shown in **Figure 4**.

For comparison with some bodies of the Solar System, **Figure 4** also shows the exergy efficiency $\eta_E = 2.7\%$ for Yarkand on Earth, which appears in first place in **Table 2** for the top 20 cities with the largest diurnal temperature ranges. The plot in **Figure 3** refers to the case in which the working medium in the process of utilizing environmental temperature fluctuations is a substance, whereas in **Figure 4**

the working medium is radiation. A comparison of these figures shows that higher values of the exergy efficiency η_E for radiation are obtained for $\Delta T > \sim 70$ K, while below this temperature difference the efficiency η_E becomes higher for substances. This may result from the fact that the thermodynamic parameters of radiation depend on temperature to the fourth power. For example, as given in **Table 4**, for Mercury the efficiency for radiation is 82.4%, while for a substance it is 69.2% (**Table 2**), whereas for Earth the corresponding values are 0.83% for radiation and 3.38% for a substance. This issue is discussed in more detail in Section 7. **Table 4**

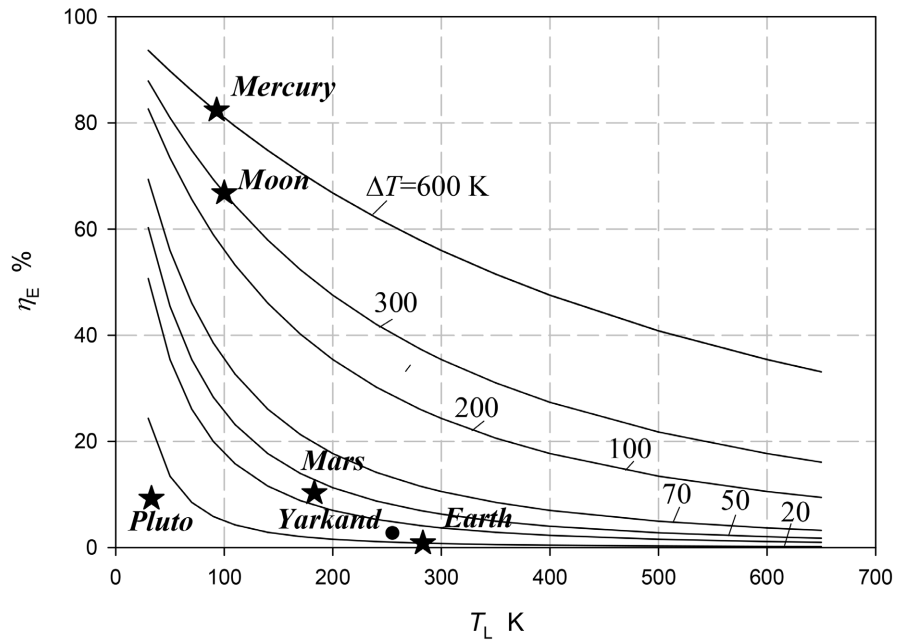


Figure 4. Exergy efficiency η_E of radiation as a function of the environment temperature T_L and the temperature difference $\Delta T = T_H - T_L$.

Table 4. Approximate data on diurnal fluctuations of the environment temperature for selected bodies of the Solar System [29] and for Earth, and the calculated exergy efficiencies of radiation obtained from environmental temperature fluctuations.

Object	Day temperature T_H K	Night temperature T_L K	Peak-to-peak Difference ΔT K	Exergy efficiency $\eta_{E,r}$ % Working medium: radiation	Exergy efficiency η_E % Working medium: substance (for comparison to Table 1 and Table 2)
Moon	400	100	300	66.8	53.8
Mercury	703	93	610	82.4	69.2
Earth	303	283	20	0.8	3.38
Mars	273	183	90	10.3	18.7
Pluto	43	33	10	9.2	12.7
Yarkand	290	255	35	2.7	6.3
Lhasa	278	250	28	1.9	5.2
Yakutsk	253	235	18	1.0	3.6

also includes data for three selected locations on Earth (Yarkand, Lhasa, and Yakutsk), for which the corresponding exergy efficiencies are lower than the efficiencies listed in **Table 2**.

7. Comparison of Efficiencies

Three efficiencies have been discussed. The first one, when the working fluid is a substance and both heat sources have constant temperature, can be considered as the Carnot efficiency defined by Equation (2):

$$\eta_C = \frac{1}{1 + \frac{T_L}{\Delta T}}$$

The second case, when the working fluid is a substance and only one heat source has a constant temperature, allows one to consider the exergy efficiency defined by Equation (7):

$$\eta_E = 1 - \frac{T_L}{\Delta T} \ln \left(1 + \frac{\Delta T}{T_L} \right)$$

The third case, when the working fluid is radiation, which serves as a heat source with a variable temperature while the second source has a constant temperature, allows one to consider the exergy efficiency $\eta_{E,r}$ defined by Equation (16) in the form:

$$\eta_{E,r} = 1 + \frac{1}{3} \left(\frac{T_L}{T_L + \Delta T} \right)^4 - \frac{4}{3} \frac{T_L}{T_L + \Delta T}$$

The characteristic variability of these three efficiencies is illustrated by the plot in **Figure 5**.

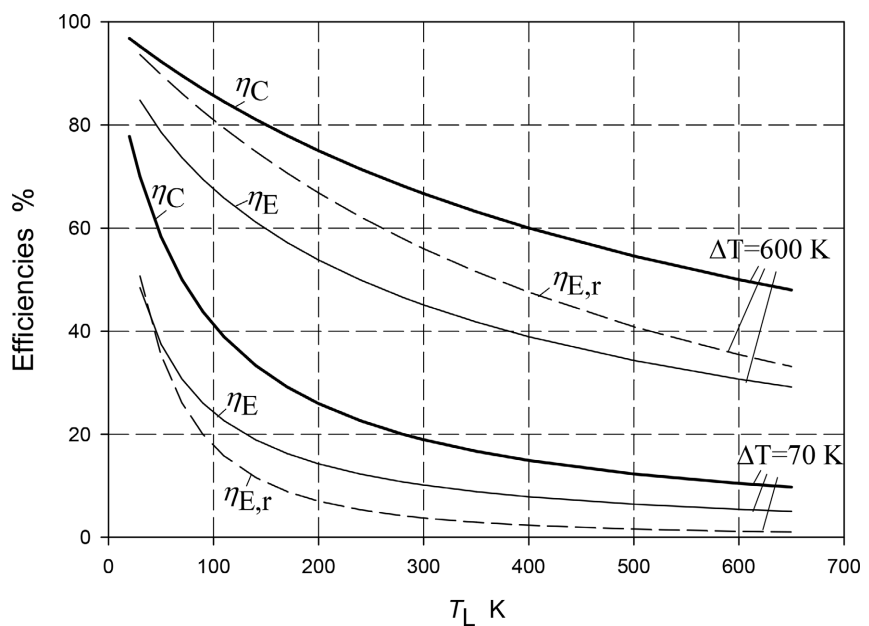


Figure 5. Comparison of the efficiencies η_C , η_E and $\eta_{E,r}$.

For relatively large values of ΔT , one can observe that $\eta_C > \eta_{E,r} > \eta_E$, whereas for small values of ΔT the relation becomes $\eta_C > \eta_E > \eta_{E,r}$. In **Figure 6**, example points are shown at which $\eta_E = \eta_{E,r}$.

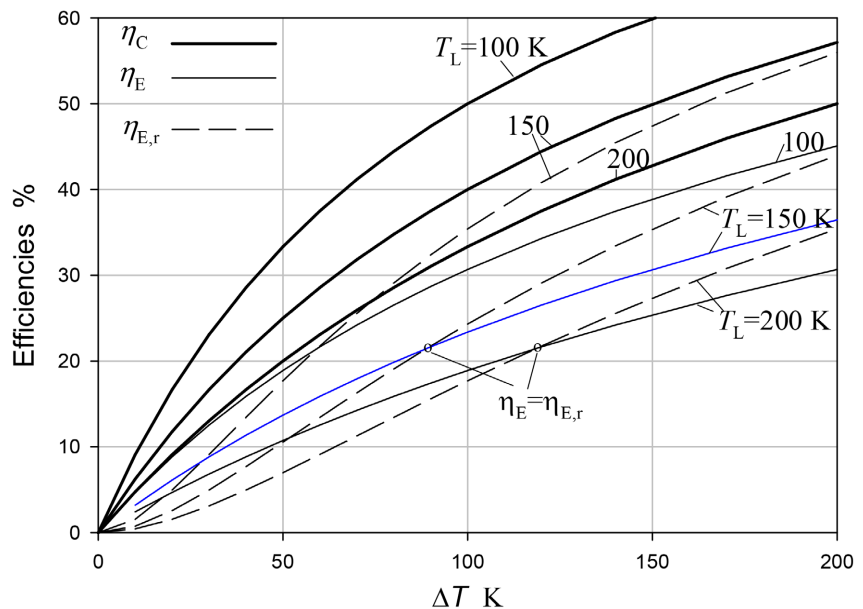


Figure 6. Two example points, at which $\eta_E = \eta_{E,r}$.

8. Natural Fuels

In general, depending on the problem considered, the exergy of a substance may consist of physical, chemical, kinetic, potential, and also other components in special cases. Up to this point, in discussing the exergy efficiency of a substance, only the physical exergy has been considered, because the focus was on the temperature of the environment. However, for completeness and comparison, another component of the substance's exergy is considered here: only the chemical exergy, assuming that the substance has the constant temperature (and pressure) of the environment. Chemical exergy arises from the difference between the chemical composition of the substance under consideration and the common constituents of the environment [2].

As an example, natural fuels from the geological sequence wood-peat-lignite-coal-anthracite are examined. It turns out that while the efficiency of physical exergy cannot exceed 100%, the efficiency of chemical exergy may be greater than 100%, which is the case, for example, for natural fuels. Such fuels are regarded as a natural asset.

The chemical exergy efficiency of a fuel $\eta_{E,ch}$ is understood as the ratio of the chemical exergy b_{ch} of the fuel to the input to the process of complete combustion of that fuel, in which the full energetic value of the fuel is realized, that is, the net calorific value V_N of the fuel:

$$\eta_{E,ch} = \frac{b_{ch}}{V_N} \quad (17)$$

Based on the statistical method [34], the values of $\eta_{E, ch}$ for fuels were determined. A formula was derived which, after simplification by omitting—because of their relatively small significance—the mineral matter, moisture, sulfur, and nitrogen in the fuel, takes the form:

$$\frac{b_{ch}}{V_N} = 1.0438 + 0.1882 \frac{H}{C} + 0.0610 \frac{O}{C} \quad (18)$$

and the net calorific value was determined using the formula [35]:

$$V_N = 8100C + 29000 \left(H - \frac{O}{8} \right) \quad (19)$$

where H , C , O —gram fraction of hydrogen, carbon and oxygen, respectively, in the fuel.

Based on formulas (18) and (19), **Figure 7** presents a plot of the approximate dependence of the efficiency $\eta_{E, ch}$ on the volatile-matter content VM for natural solid fuels [36]. The VM content represents the geological age of the fuel: the higher the content, the geologically younger the fuel. It follows that the carbonization of natural fuels over time causes a degradation of the value defined by exergy, which shows wood as the most valuable substance in the sequence of natural fuels. The younger the fuel, the more chemically complex the substance is, and the more valuable it becomes as a feedstock for chemical processing.

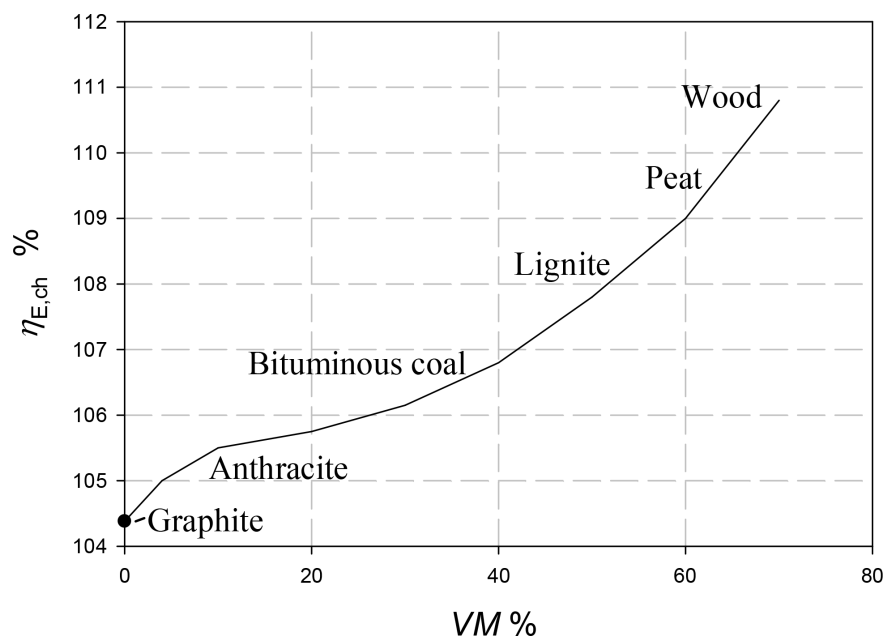


Figure 7. Exergy efficiency of chemical exergy $\eta_{E, ch}$ of natural solid fuels as a function of the volatile-matter content VM .

An exergy efficiency greater than 100% may indicate that the utilization of natural fuels through the energetic process of combustion is unjustified, because such a process can at most yield the calorific value at 100% efficiency. This therefore suggests using natural fuels by means of some process other than combustion—

namely, a process or processes that would theoretically allow the full exergy efficiency to be achieved. One such solution is the appropriate chemical processing of fuels (for example, by devolatilization), as a result of which substances with already lower exergy efficiencies are obtained. Only the utilization of such products of chemical processing, with efficiencies below 100%, could then be considered as fuels for combustion.

A strong conclusion therefore follows it is justified to burn only the products of chemical processing of natural fuels whose exergy efficiency is less than 100%.

9. Conclusions

In every newly arising situation in which two heat sources are available, the possibility of obtaining energy is examined primarily on the basis of the theoretical efficiency appropriate to that situation. If both sources have constant but different temperatures, the Carnot efficiency is used. If one of the sources changes its temperature as the process proceeds, then exergy efficiency may be applied. The use of both efficiencies has been discussed in the present work.

If the value of the theoretical efficiency is considered sufficiently high, and thus one may expect that the lower real efficiency will still remain acceptable, then one can proceed to consider and select the process and the device by which energy will be produced. It should be emphasized that even the best device, with the highest possible efficiency and quality, cannot exceed the theoretical efficiency applied.

It is assumed that the aim of the present work is to analyse the situation for a specified value of the environmental temperature. The climatological data for this temperature were taken from the sources cited in the present work. However, it may occur that the value of the environmental temperature is not unambiguous, since the very notion of the environment is not straightforward to define. The method of determining this environmental temperature in such particular specific cases—including considerations involving substances or radiative media—constitutes a broad issue that warrants a separate study, and it may be necessary to introduce a suitable concept of an effective environmental temperature.

The short description of the process that exploits environmental temperature differences, together with its evaluation using the efficiencies applied in this work, is provided in the paper. For the detailed theoretical assumptions, the reader is referred to the literature—A. Bejan for the Carnot efficiency and R. Petela (Florence) for the exergy efficiency.

Using theoretical efficiencies, the possibilities of exploiting environmental temperature fluctuations on Earth and in the Solar System have been evaluated. Conditions on the Moon allow a Carnot efficiency of 75%, and on Mercury even 86.8%. On Earth, daily environmental temperature fluctuations allow only 12.1%, although annual environmental temperature fluctuations on Earth may be used at a Carnot efficiency of 33.8%.

An interesting observation is that when radiation is used as the working medium, the exergy efficiency—compared with the exergy efficiency in the case of

using a substance—is higher for large temperature differences ΔT and lower for small ΔT . For example, for Mercury, $\eta_e = 69.2\%$ for a substance and $\eta_e = 82.4\%$ for radiation; whereas, conversely, the corresponding efficiencies for Lhasa are 5.2% and 1.9%. However, obtaining significant power would require handling large volumes of radiation, considering that, for example, 1 m³ of radiation at a temperature of 100 K possesses a relatively small exergy of 0.0129 mJ/m³.

For comparative purposes, it has been shown that exergy efficiency can serve as a tool for identifying natural resources in the environment, taking values greater than 100%, as is the case for natural solid fuels in the sequence wood-peat-lignite-coal-anthracite-graphite.

The issue of the scale of energy production under a given pattern of environmental temperature fluctuations is not included within the scope of the present work. This scale may depend on the quality of the device used or, for example, on the local level of energy demand, especially under unusual or exceptional circumstances. In general, however, the scale of energy generation is in the milliwatt range when efficiencies are low, and it increases to multi-watt levels as the achievable efficiency rises.

The considerations in this work concern locations on Earth and beyond. The work may be of particular relevance for Earth at present, because it discusses one of the possible energy sources that are highly sought after as non-polluting to the environment. The work carries an element of inspiration.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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