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Application of Exergy: A Low-Exergy Solution to Building Heating and Cooling

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Abstract

Considering heat a form of energy, the mechanical theory of heat (MTH), in making this historic advance of heat's ontological-category, made a relational-category error. The resulting energetic viewpoint of MTH sees all changes in nature as energy conversions and the problem of building heating and cooling as, quantitatively, energy-demand-and-supply problem. The IEA-ECBCS-programme introduced a correction to this energetic bias with the principle of "matching the quality levels between the energy supply and demand," which is known as LowEx approach. A recently formulated theory of heat, the predicative entropic theory of heat (PETH), is based on the cornerstone of correct categories of heat ontologically as well as predicatively (relationally). In the new theory, heat extraction plays a central role and, therefore, changes in nature are seen in terms of spontaneous entropy growth and heat extraction as powered by entropy growth potentials (EGPs). An alternative to the IEA-ECBCS's LowEx approach is suggested here based on heat extraction. Instead of matching of quality levels, LowEx can also be achieved by the management of natural EGPs: the *combined solar and heat pump systems* (S+HPs) can be transformed into LowEx S+HPs, a pure heat extraction system, by "eliminating" the energy conversion process of auxiliary heating.

Keywords: heat's categories, energy conversion, condensing boilers, IEA-ECBCS programme, low exergy approaches, reduction in exergy input to buildings, entropy growth potential, heat extraction, combined solar and heat pump systems (S+HPs), LowEx S+HPs

1. Introduction

The idea of *energy transformation* is central to the discussion of energy, energy efficiency, and the notion of sustainability. A suggestion is made that our misunderstanding of this critical

concept hinders our ability to find the best solutions to building heating problem—and, in the long term, to have a clear vision in our pathway to sustainability.

The energy problem is really an exergy problem. One cannot address energy issues intelligently without the concept of exergy. In fact, the term energy is often used to mean high-exergy energy, not energy in the general sense as a term in physics. Recall energy is, standardly, defined as the capacity for doing work. This definition works only if it is applied to *high-exergy energy* or even *pure-exergy energy* (see Section 2), not energy in general. For instance, with a part of ocean as the heat reservoir, the vast energy of ocean's other parts, unless the temperature of these other parts is distinctively different from the one part, has no capacity for doing work.

This chapter considers the problem of building energy, especially buildings' energy need for their heating and cooling. That is, buildings' need of low-temperature heat during heating sessions and the removal of low-temperature heat during cooling sessions. The application of low-temperature heat differentiates discussion on exergy in this chapter from exergy considerations that deal with high-temperature heat applications. Ever since Kelvin, exergetic/entropic considerations for high-temperature heat applications are encapsulated, in large part, in terms of the Carnot-Kelvin formula. Kelvin himself never used the term of entropy in his writing; even so, entropic/exergetic consideration is partially captured by the formula without explicitly referring to entropy and/or exergy so long as one is dealing with high-temperature heat problems.

This is the reason why the Carnot-Kelvin formula (Carnot efficiency) occupies the central significance in thermodynamics treating high-temperature heat problems [1, 2]. For a heat source at a constant temperature, the formula is all one needs for defining the "perfection" of using the heat source. For other heat sources or other energy sources in which the temperatures do not remain constant, the formula is only an approximation. But, engineering practice guided by the formula is still approximately valid as a first step, and the exergy analysis yields the refinement over the first step. But, one would not suggest an unrefined engineering analysis without explicit exergetic content to be invalid.

Low-temperature heat problems for building heating are different matter. While the application of the corresponding formula for heat pump application to cooling is a part of the standard thermodynamics, no such formula is available in the usual treatment of building heating problems, which are usually handled in terms of the first law of thermodynamics alone. That better understanding of fuel's theoretical potential for building heating by explicitly making use of the formula has been suggested for the first time in [3].

In other words, whereas for high-temperature heat problems either the Carnot-Kelvin formula is the proxy for their entropic treatment or the full entropic/exergetic treatment is made available in the textbooks or the literature, the usual literature on building heating is deficient in being entirely based on the first law absent of the second law content. That deficiency has been pointed out by an International Energy Agency (IEA) group, energy conservation in buildings and community systems (ECBCS) programme. In an ECBCS programme research project, ECBCS Annex 49 [4], the case was made that exergetic analysis should be applied for

high performance buildings and communities. This recommendation and conclusion deserve to be vigorously supported. It may be noted that this conclusion was consistent with what an earlier study by Ayres and Warr [5] suggested (see Section 4).

It is further noted that the theory of exergy is an integral part of the mechanical theory of heat (MTH) or classical thermodynamics, which is beset with inconsistencies (see [6]). In [6], Haddad wrote, "In fact, no other discipline in mathematical science is riddled with so many logical and mathematical inconsistencies, differences in definitions, and ill-defined notation as classical thermodynamics." The author shared with Haddad as well as many who commented on the matter before; it may even be suggested that MTH was a provisional theory, the logical conclusion of which is a new theory of heat, the predicative entropic theory of heat (PETH), [7] which was proposed in 2017 by the author (see Section 3).

The intent of this chapter is twofold: to support the LowEx approach initiated by IEA-ECBCS programme *and*, in this support, to formulate the LowEx approach with a different focus in terms of the PETH interpretation of the LowEx system approach—away from the IEA-ECBCS's focus of "matching the quality levels between the energy supply and demand" [4]. Our goal is the facilitation in the success of the LowEx approach with a specific proposed technology, LowEx combined solar and heat pump system (LowEx S+HP). Combined solar and heat pump (S+HP) systems was another IEA initiative (see below). LowEx S+HP represents a fundamental refinement of S+HP by cleansing MTH of its baggage of seeing all processes to be energy transformation processes: LowEx S+HP represents the idea of *electrification of heating with no energy transformation*.

2. Theory of exergy and universal energy transformation

As Ghoniem noted in the 2007 AIP-MIT Conference, "As we contemplate the impact of the inefficiencies associate with energy conversion…we realize that it is the quality of energy that matters and not the quantity, and that with each conversion step we lose, it is really Murphy's Law impersonated. In fact, some of us have come to conclude that we don't have an energy challenge, we have an entropy challenge" [8]. That is, the energy challenge cannot be dealt successfully with the first law reasoning alone. We must apply the second law as well.

This entropy challenge is best handled with the introduction of exergy in the analysis of energy, that is, exergy analysis. In introducing exergy analysis, Bejan et al. [9] explained the necessity of doing so as follows:

> *Exergy analysis also provides insights that elude a purely first law approach. Thus, from an energy perspective, the expansion of a gas (or liquid) across a valve without heat transfer (throttling process) occurs without loss. That such an expansion is a site of thermodynamic inefficiency is well known, however, and this can be readily quantified by exergy analysis. From an energy perspective, energy transfers to the environment appear to be the only possible sources of power plant inefficiency. On the basis of first law reasoning alone, for example, the condenser of a power plant may be mistakenly identified as the component primarily responsible*

for the plant's seemingly low overall efficiency. An exergy analysis correctly reveals not only that the steam generator is the principal site of thermodynamic inefficiency owing to irreversibilities within it, but also the condenser [loss] is relatively unimportant [9].

In the literature, the introduction of exergy concept was often attributed to Josiah Willard Gibbs in an 1873 publication. The concept was then, in the 1940s and 1950s, extended by Joseph Keenan for engineering applications, adapting it for the practical analysis of thermodynamic cycles. Gibbs' insight, however, is traced by Daub, as he noted in a historical study on Entropy and Dissipation, to Kelvin, "Although Gibbs never once mentioned Thomson in his work, he was indebted, I believe, to Thomson's concept of dissipation of energy via the good offices of Maxwell and his *Theory of Heat*" ([10], 351). Indeed, Maxwell wrote in a review of Tait's "*Thermodynamics,*" [11] "Thomson, the last but not the least of the three great founders [Clausius, Rankine, and Thomson], does not even consecrate a symbol to denote the entropy, but he was the first to clearly define the intrinsic energy of a body, and to him alone are due the ideas and definitions of the available energy and the dissipation of energy." This bit of history has an important consequence on our understanding of MTH as well as what the role the theory of exergy has occupied (see below) in MTH.

2.1. Exergy

First, the development of research on exergy analysis after Keenan led to the modern definition: *The exergy of a thermodynamic system S in a certain state S_A is the maximum theoretical useful work obtained if S is brought into thermodynamic equilibrium with the environment by means of ideal processes in which the system interacts only with this environment* [12].

Another influential definition was formulated by Rant [13] and Baehr [14]: *Exergy is the portion of energy that is entirely convertible into all other forms of energy; the remainder is anergy.* That is,

$$\text{energy} = \text{exergy} + \text{anergy} \tag{1}$$

We shall refer to them as the first exergy definition and the second exergy definition.

While one defines exergy in terms of "the portion of energy…," and considers the application of exergy analysis as well as speaks about exergy components, exergy balance, exergy transfer, etc. (see [9], chapter 3) as one does about energy analysis, energy components, energy balance and energy transfer, one fundamental difference of exergy from a property such as energy, which is defined for a system, is that exergy in general can only be defined for a system *and* the environment (heat reservoir) the system interacts with. This point is explicitly made in the first exergy definition. In the second exergy definition, the point is not explicit, but implicit because the determination of the portion of energy in a thermal energy system that is entirely convertible requires the specification of a heat reservoir (see below, but, of course, that determination for pure exergy energies does not have this requirement).

According to Bejan et al. [9] the total exergy of a system E can be divided into four components: physical exergy E^{PH}, kinetic exergy E^{KN}, potential exergy E^{PT}, and chemical exergy E^{CH},

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \tag{2}$$

Chemical exergy will not be discussed here for brevity. The kinetic and potential energies are in principle fully convertible to work as the system is brought to rest or to its reference level, respectively. Accordingly, for a system of mass m,

$$E^{KN} = KE = \frac{1}{2}mv^2 \tag{3}$$

$$E^{PT} = PE = mgz \tag{4}$$

where v and z denote velocity and elevation relative to the reference level. The physical exergy of a closed system at a specified state is given by the expression,

$$E^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{5}$$

where U, V, and S denote, respectively, the internal energy, volume, and entropy of the system at the specified state, and U_0, V_0, and S_0 are the values of the same properties when the system is at the *restricted dead state* (see [9] for detailed definition), that is, the state of thermodynamic equilibrium with the reference environment of the first exergy definition. For details of the derivation of Eq. (5), see reference [9].

Clearly, Eq. (5) is based on the first exergy definition and a system's physical exergy is defined in terms of the system *and* its environment the system interacts with. With the first exergy definition, the value of physical exergy is not subjected explicitly to the notion that it is a portion of energy as the second exergy definition declares. In the latter case, as Eq. (1) implies, *exergy ≤ energy* (in other words, all three quantities [*energy*, *exergy*, and *anergy*] are positive-definite and a negative *anergy* will be senseless). Yet, there are systems and their environments for which *anergy*s are found to be negative and, for these instances, the second exergy definition is problematic. However, the "problematic" second exergy definition is necessary for the concepts of kinetic exergy and potential energy as shown in Eqs. (3) and (4); it captures importantly that kinetic and potential exergies—as examples of *pure exergy energies*–can be completely converted into other forms of pure exergy energy such as electrical energy. Nonetheless, while both definitions are necessary, there is a conflict between the two definitions in that the first exergy definition allows the possibility of *exergy ≥ energy*, whereas the second exergy definition implies that *exergy*, as a portion of *energy*, is always smaller than *energy*.

Pure exergy energies and physical exergy are core parts of the theory of exergy, as treated in Bejan et al. [9]: The exergy change between two states, state 1 and state 2, of a closed system is determined as,

$$E_2 - E_1 = (U_2 - U_1) + p_0(V_2 - V_1) - T_0(S_2 - S_1) + (KE_2 - KE_1) + (PE_2 - PE_1) \tag{6}$$

2.2. Closed system exergy balance

The exergy balance for a closed system is developed by combining the energy balance and entropy balance, which result in,

$$(U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) = \int_1^2 \delta Q - W + T_0 \left[(S_2 - S_1) - \int_1^2 \left(\frac{\delta Q}{T} \right)_b - S_{gen} \right] \quad (7)$$

The terms inside the [] in the above expression represent the balance of entropic entities— entropic change, entropic transfer, and entropic generation—according to the second law. Moving $T_0(S_2 - S_1)$ to the left side of the equation and introducing Eq. (6) after adding $p_0(V_2 - V_1)$ to the left side as well as the right side, then collecting terms involving δQ on the right side, this equation can be rewritten as,

$$E_2 - E_1 = \left\{ \int_1^2 \left(1 - \frac{T_0}{T_b} \right) \delta Q - \left[W - p_0(V_2 - V_1) \right] \right\} - T_0 S_{gen} \quad (8)$$

The term on the left side of Eq. (8) is the exergy change of the closed system. The terms on the right side depend on processes: The first group represents two kinds of exergy transfers. The exergy transfer associated with the transfer of heat, E_q, is shown as

$$E_q = \int_1^2 \left(1 - \frac{T_0}{T_b} \right) \delta Q \quad (9)$$

The exergy transfer associated with the transfer of work, E_w, as

$$E_w = W - p_0(V_2 - V_1) \quad (10)$$

The last term on the right-side accounts for the destruction of exergy due to irreversibilities within the system as related to the entropy generation or entropy growth,

$$E_D = T_0 S_{gen} \quad (11)$$

In the literature, the expression of E_D is also known as the Gouy-Stodola theorem.

As long as both pure exergy energies and physical exergy are core parts of the theory of exergy, the theory is rest on both the first definition and the second definition—with the aforementioned contradiction between them. The only escape out of the dilemma is for the first definition to accept the restriction implied in the second definition, *energy = exergy + anergy*. That is, the energetic interpretation. This interpretation-restriction is in fact the widely held understanding of thermodynamics since Kelvin. In this interpretation, energy is then divided into four kinds, inclusively:

- Pure exergy energy: electrical energy, kinetic energy, and potential energy

- High exergy energy: high temperature heat

- Low exergy energy: low temperature heat

- Zero exergy energy: heat of a body that is in thermodynamic equilibrium with its environment.

The common definition of energy, *energy is the capacity for doing work*, is clearly applicable only to the pure exergy energies and inapplicable to low exergy energy and zero exergy energy. A better definition will be: *exergetic content of an energy system is the capacity for doing work*, which is applicable to all four cases.

2.3. Kelvin, origin of the exergy concept, and the notion of universal energy conversion

As Maxwell stated, "Thomson…does not even consecrate a symbol to denote the entropy, but he was the first to clearly define the intrinsic energy of a body, and to him alone are due the ideas and definitions of the available energy and the dissipation of energy," two important points were made in this sentence: Thomson (Later, Lord Kelvin) was the originator of the idea of available energy or exergy; secondly, the two papers, one paper on the universal dissipation of mechanical energy [15] and another paper on dynamical theory of heat [16], which originated the idea of available energy, also represented Thomson's formulation of the second law. Both points are not widely known, but deserve to be better disseminated for better appreciating the real meaning of the theory of exergy.

While the universal dissipation paper, though a short one, *is* widely disseminated, Thomson's idea on available energy was not explicitly shown in the 1851 paper, though the paper was Thomson's most significant publication. Rather, the idea was recorded in a passage of the draft for the paper:

> *The difficulty which weighed principally with me in not accepting the theory so ably supported by Mr Joule was that the mechanical effect stated in Carnot's Theory to be* absolutely lost *by conduction, is not accounted for in the dynamical theory otherwise than by asserting that* it is not lost [*i.e., the assertion of energy conservation*]; *and it is not known that it is available to mankind. The fact is, it may I believe be demonstrated that the work is* lost *to* man *irrecoverably; but [even though energy is] not lost in the material world. Although no destruction of energy can take place in the material world without an act of power possessed only by the supreme ruler, yet transformations take place which removes irrecoverably from the control of man sources of power which, if the opportunity of turning them to his own account had been made use of, might have been rendered available [17, 18].*

This passage was identified by Kelvin's biographers [18] to have a critical role in the evolution of Kelvin's scientific thought. Taking these two papers together, they represent Thomson's contribution to the second law by adding to the idea of the conservation of energy the idea of the availability of energy: the first law is in terms of the conservation of energy, while the second law is, in Thomson's formulation, in terms of the availability of energy. This (second part of) understanding has been called the *energy principle* [19], noting that the energy principle is different from the principle of the conservation of energy (the first part).

In a series of papers on the Clausius inequalities which cumulated in the 1864 entropy paper, Clausius formulated the second law in terms of entropy and universal growth of entropy—which has been universally accepted to be *the* second law of thermodynamics, especially since Boltzmann and Planck. The intriguing question is whether the energy principle is synonymous with the entropy principle. Many students of thermodynamics view them to be synonymous.

This would be a mistake [7, 19]. The correct view is that the energy principle is subsumed under the entropy principle [7, 19, 20]. Nonetheless, the energy principle is very important because the entropy principle, though universally true, has been viewed by physicists and chemists to have a negative degradation meaning only, as Prigogine recounted,

> *Among all those perspectives opened by thermodynamics, the one which was to keep my interest was the study of irreversible phenomena, which made so manifest the "arrow of time." From the very start, I always attributed to these processes a constructive role, in opposition to the standard approach, which only saw in these phenomena degradation and loss of useful work…The fact is that it appeared to me that living things provided us with striking examples of systems which were highly organized and where irreversible phenomena played an essential role…Those problems had confronted us for more than 20 years, between 1947 and 1967, until we finally reached the notion of "dissipative structure" [21].*

What Prigogine described was the view of physicists and chemists he had been striving to overcome to achieve his *dissipative structure* breakthrough. For engineers, however, the energy principle interpretation of Kelvin has long been developed by Gibbs and others into the theory of exergy, which views pure exergy energy and high exergy energy to be the driving constructive force of making things happen.

That understanding is the understanding of universal energy conversion or transformation. In this understanding, the Carnot heat engine is interpreted as "a theoretical power cycle of maximum efficiency for converting thermal into mechanical energy" [22]. In fact, every change in nature and in man-made world can be viewed in terms of energy transformation. This understanding is the great contribution of Joule, Thomson, and the theory of exergy. The modern world would not have existed without this understanding. Except, it comes to a point today that this understanding also hinders our going forward from this point.

3. The predicative entropic theory of heat

Joule, Thomson, and Clausius formulated MTH by correcting, famously, the categorical error in the then prevalent theory of heat, the caloric theory of heat, which considered heat to be an invisible and weightless substance. Instead, MTH considered heat and its nature, namely its category, as: "heat is not a substance, but a dynamical form of mechanical effect" [16] as noted by Thomson.

But, this correction also created its own problem in that MTH committed the classical mistake of conflating correlation, or connection, with causality. It interpreted the connection between heat and work according to Joule's principle of *mechanical equivalent of heat* (MEH) to be the existence of causality between heat and work: not only work (mechanical energy) causes heat but also heat causes work. That is, MEH has been universally interpreted to be the principle of heat and work interconvertibility. Correspondingly, thermodynamics is the subject that mainly concerned with the transformations of heat into mechanical work and the opposite transformations of mechanical work into heat. In this understanding, we find heat's apparent utility.

3.1. Energy and its exergetic content

As it was pointed out above, Kelvin also formulated the second law in terms of what is called the *energy principle*—the concept of availability of energy and the idea that, whereas energy never disappear, its availability dissipates. For instance, mechanical energy and high-grade energy dissipate universally. In the paper [15], in which he declared the universal dissipation of mechanical energy, he did not so much prove the assertion as simply declared it to be a self-evident proposition. Remarkably, those who followed Kelvin accepted it so as well and Von Baeyer was typical with this assessment, "Inasmuch as the second law is one of the pillars of physics, this was Thomson's most significant contribution to the science of thermodynamics, and overshadowed his invention of the absolute scale of temperature, his early recognition of the importance of James Joule's work…" [23].

But, in fact, the energy principle is not synonymous with the entropy principle. The energy principle can be shown to be subsumed under the entropy principle [19] rather than being a universal principle. Nonetheless, the energy principle, though defective as a universal principle, remains to have an important role in MTH. Without it, we only understand "heat's apparent utility" in terms of the Carnot-Kelvin formula. The role of any energy system in the production of mechanical work would have to go through the heat release phase, that is, only indirect energy conversion would be physically possible.

This is clearly not true as evinced by the existence of direct energy conversion, for example, direct energy conversions corresponding to Gibbs free energy or Helmholtz free energy, as well as photovoltaic effect and fuel-cell processes [22]. These concepts have been generalized into the concept of exergy.

The theory of exergy affirms the importance of the energy principle by going beyond the idea of heat's apparent utility as the driver of nature to the more general idea of energy, more precisely the *exergetic content in energy*, to be the driver of nature. Furthermore, by incorporating the entropy principle into the meaning of exergy, the theory of exergy discloses the constructive meaning in the entropy principle in addition to the principle's usual destructive meaning. This last point is no small matter—which is pretty much how MTH or thermodynamics should be understood as encapsulated in the notion that all processes in nature are energy conversion or transformation processes.

With this advance, we took the step from "thermodynamics is mainly concerned with the transformations of heat into mechanical work and the opposite transformations of mechanical work into heat" to the notion that thermodynamics deals with universal energy transformation.

Note that energy would be, without the concept of exergy, a lame concept; it is the exergetic content in energy that gives energy its capacity or usefulness.

3.2. Entropy growth potential

This is how heat and energy enter every student of thermodynamics' mind concerning their importance. However, this understanding is deeply misleading: both the idea of the *consumption*

of heat as the cause of work production, and the notion that exergy is a *part* or *portion* of energy, are wrong.

In the latter case, as it was already pointed out that the notion was self-imposed one, one that is contradicted by known facts, for the sole purpose of avoiding the contradiction between the first exergy definition and the second exergy definition. Exergies considered in the theory of exergy are incomplete, and there are driving forces outside the set of pure exergy energy, high exergy energy, and low exergy energy; the theory of exergy and, correspondingly, MTH are contingent or provisional.

For the former case, the idea of consumption appears when during high-temperature heat being transferred to a low-temperature sink, a part of this high-temperature heat is converted into work with the balance of heat going to the sink. In association with this picture, the accepted way of defining heat emphasizes the fact that heat is defined only as a process associated with its transition not as an entity: *heat is energy in transit.* There is an awkwardness in handling the notion of heat in the literature [19, 24, 25].

The awkwardness in explaining heat in the absence of heat in transition can be avoided: it was the mistaken result of giving heat the role that it cannot fulfill to begin with. The problem in both cases has to do with the question, what is the causation driving all phenomena in nature? The difficulty of considering energy (and heat) as *the* driver is removed once it is shown that the real driver is *entropy growth potential* (EGP), a concept formulated in Refs. [7] and [19]. Energy is only the proxy of the real driver because of its EGP or exergy.

The way to understand **heat's apparent utility** is that there exists EGP in association with heat transfer process, and this EGP drives the heat-to-work conversion by extracting heat from the heat reservoir (while it was considered to be a heat sink to the transfer process) converting extracted heat into work. The correct way to understand MEH is that equivalence exists between *extracted* heat and work, not *consumed* heat and work.

The way to understand **energy with its exergetic content** is that, again, there exists EGP in association with energy conversion process and it is this EGP which drives the conversion process involving the "energy system." If EGP in this case is greater than energy in the "energy system," this would explain that this is a case of negative anergy. Other than these special cases, for the cases in which anergy is positive the concept of energy with its exergetic content remains serviceable: the language of exergy is useful in its proper context; it is just not a universal language.

We see the evolution of the ideas from heat's apparent utility to energy with its exergetic content to entropy growth potential. MTH succeeded in placing heat in its ontological category; PETH succeeds in placing heat in its predicative category. MTH is obviously an important phase in this evolutionary arc: there will be no PETH without going through MTH. But, MTH, which is beset with inconsistencies because of predicative-category error, is a provisional theory of heat. The logical conclusion of the evolutionary arc is PETH.

3.3. PETH and heat extraction: energy thinking vs. entropy thinking

MTH is encapsulated in the notion that all processes in nature are energy conversion or transformation processes. The new theory of heat, PETH, points out that Kelvin's energy

principle is not a universal principle: mechanical energy dissipates spontaneously not universally, and there are EGPs that do not involve degradation of energy, [19] that is, conversion of energy. That is, not all processes in nature are energy conversion processes and that there are processes of "purely spontaneous" kind [19] involving no energy conversion. In PETH, the expanded set of "exergies" is made of the following:

- #1_Purely spontaneous systems: system EGP does not involve change in system energy; this characteristic applies to all isolated systems with spontaneous tendency

- #2_Negative-anergy energy: energy systems whose "exergy" are greater than change in system energy

- #3_Pure exergy energy: electrical energy, kinetic energy, and potential energy

- #4_High exergy energy: high-temperature heat

- #5_Low exergy energy: low-temperature heat

- #6_Zero exergy energy: heat of a body that is in thermodynamic equilibrium with its environment.

Furthermore, EGPs can be divided into *stock* EGPs and *ongoing* or *natural* EGPs. Examples of the latter are solar phenomena and wind phenomena for which the entropy growth is ongoing. Unlike systems of stock EGPs (i.e., stock energies) for which accelerating entropy growth happens only when the systems are brought into use, natural EGPs are phenomena that entropy growth is ongoing [19]. Therefore, unlike for systems of stock EGPs, their use always leads to increase in entropy growth in accordance with the second law, the management of natural EGPs does not intrinsically lead to faster entropy growth [19]. That is, the second law asserts only that entropy growth cannot be negative, not that the rate of ongoing entropy growth cannot be slowed. Therefore, a further insight on the kind of "exergetic" phenomena is the addition to the above list of the phenomena:

- #7_Natural entropy growth potentials (EGPs) phenomena

In this list of seven, #1, #2, and #7 are new conceptual advance PETH brings forth to the theory of heat.

An important inference of PETH [7, 19] is that all reversible processes and reversible-like processes are heat extraction processes. Heat pump is one example of heat extraction process. Notably, heat engine and Carnot heat engine are also examples of heat extraction processes: in so far as a Carnot heat engine is the perfect inverse of a Carnot heat pump, the interpretation of the Carnot heat engine as a device of perfect heat extraction driven by EGP is obviously a more satisfactory way of seeing it. Consequently, the essence of the new theory of heat, PETH, is that the pathway to reach high efficiency is through thinking in terms of heat extraction, entropy, and natural EGPs, rather than the old fashion way of thinking in terms of energy transformation, energy balance, and stock energy alone (see **Table 1**).

It is useful, therefore, to go beyond energy thinking to apply entropy thinking, more specifically heat extraction thinking, to understand nature as well as contrive engineering devices and systems. In the following, we shall make the case that by going beyond the conventional

Energy problems are in terms of…in MTH	Energy efficiency are achieved in terms of…in PETH
Energy transformation efficiency	Heat extraction
Energy balance	Entropic management minimizing entropy production
Stock energy	Natural EGPs

Table 1. Different approaches to energy efficiency in MTH and in PETH.

framework that all devices are energy transformation devices, for short energy transformers, a new way of viewing what a heat pump is will introduce a better way of using the heat pump technology for space heating.

4. The LowEx system approach: reduction in exergy input to buildings

Energy requirement for building heating is a form of low-temperature heat. An evaluation of how we used low-temperature heat in the twentieth century was reported in a study by Ayres and Warr [5], a tabulated summary of the study is reproduced as **Table 2**. The numbers in **Table 2** are the exergy efficiencies (i.e., the second law efficiency) of five categories of energy uses and progresses made in their practices in the twentieth century; what the numbers show is that efficiency in *low temperature space heat* category was singularly poor by one order-of-magnitude in comparison with the other four categories. Intuitively, this gap suggests, as a matter of physics, that there is a large room for improvement. It is this situation giving rise to the idea that we should be able to make very significant strides in the twenty-first century toward high performance buildings (easy goals as low hanging fruits).

Year	Electric power	Transportation	High temperature industrial heat	Medium temperature industrial heat	Low temperature space heat
1900	3.8%	3	7	5	0.25
1910	5.7	4.4			
1920	9.2	7			
1930	17.3	8			
1940	20.8	9			
1950	24.3	9			
1960	31.3	9			
1970	32.5	8	20	14	2
1980	32.9	10.5			
1990	33.3	13.9	25	20	3%

Table 2. The exergy efficiencies of five categories of energy applications in the twentieth century.

On the other hand, what the gap suggests is not that improvement can be easily made but, instead, our poor comprehension of the science of heat leading to persistency of the gap, which, unless a new course set on a better understanding of heat is formulated, will persist.

Such a correct course was pointed out by IEA-ECBCS in ECBCS Annex 49 [4]: it is necessary to treat the problem of energy in terms of its exergy content and to recognize that some of what buildings need is not high exergy energy, but low exergy energy. The reason that the twentieth century record of handling low temperature heat in buildings was so appalling and the twenty-first century result is not much better is because we satiated and continue to satiate the building low exergy energy need with high exergy energy.

On our understanding of energy, IEA_ECBCS Annex 49 has this to say:

> *The quantity of energy is given by the first law of thermodynamics, and is calculated from energy balances for a system. Current energy systems in buildings are designed and improved based on this law. This means that of course the quantity of energy supplied is matched with the quantity of energy required. Highly efficient condensing boilers, with efficiency of up to 98% are a straightforward result of such an analysis framework…In the case of the highly efficient boilers mentioned above when used to supply low temperature heat, the potential to produce work (exergy) of the fuels fed into the boiler is almost completely lost in the combustion process. Due to this loss of energy potential, a large consumption of exergy occurs. Exergy efficiencies for such building systems are lower than 10% ([4], 7).*

Such conclusion is consistent with Ayres and Warr's analysis as shown in **Table 2**, as well as with our findings [3]. The bold step taken by EU's Ecodesign Standards [26] banning the sale of inefficient boilers of non-condensing kinds as of 26 September, 2015, in view of this analysis, was not bold enough: the step from inefficient boilers to highly "efficient" condensing boilers was only a timid step. As a practical matter (of short-term energy savings), though, it was a courageous move by European Commission and the move was made possible only "after years of grueling negotiation between the Commission and industry representatives" [26]. From energy efficiency point of view, the move was as significant as the phasing out of incandescent lightings.

For long-term energy saving, IEA_ECBCS argued for the application of exergy method for building operation: "*The core and first principle of the exergy method applied to the design of energy systems is to match the quality levels of the energy supplied and the energy demanded*" ([4], page 33). This first principle of the exergy method is reiterated in its conclusions:

> *The energy approach, both on a building and community levels, intends to reduce energy demands in buildings by increasing insulation levels or increasing the air tightness of the building envelope, that is, optimizing the building shell. The exergy approach at both levels focuses on matching the quality levels between the energy supply and demand. Therefore, it requires the use of low quality sources for low quality demands like space heating. Demands requiring higher quality levels, such as lighting, electrical appliances or mobility, would in turn need the use of high quality sources*" ([4], 69).

That is, the exergy approach intends to reduce exergy input to buildings by inputting energy of the exergy level closer to the actual exergy level demanded for heating buildings.

IEA_ECBCS argued against using combustion processes for providing the low-temperature heat demands in buildings, but did not oppose the use of combustion processes generally: district heating and CHP systems are good examples of "matching the quality levels between the energy supply and demand" by generating power for meeting demands of high-quality level and heat for demands of low-quality level.

In this chapter, the author suggests an alternative way of achieving the goal of LowEx, reduction in exergy input to buildings. It is a case for eliminating combustion processes generally for *electrification of heating*.

5. Clean electricity and heat pumps for space heating

Heating has been achieved since the dawn of civilization with the discovery of fire. In contrast, there had been no reliable way of space cooling before the nineteenth century, that is, even though there had had assorted ways of cooling devised by mankind in the past, but none of them was reliable enough to become dominant practice at any given time. That of course changed in the later part of the nineteenth century with the invention of heat pump, or air-conditioning equipment, which has become the universally adopted practice of space cooling. Again, this reliable cooling came into existence only about a little over one century, a tiny fraction of the long duration that man has mastered fire for heating.

It should be noted that the concept of heat pump was introduced by Kelvin [27] for application for both cooling and heating. Furthermore, the conceptualization and invention of heat pump was made by Carnot and Kelvin at the same time with the conceptualization and invention of heat engine. Carnot famously introduced the concept of reversible machine, which can serve as a heat engine, as well as a heat pump when the heat engine machine reverses its operation. As the invention of heat engines amounted to the invention of the *second use of fire* by mankind (see Ref. [19]), the invention of heat pump can be viewed to be an integral part of that giant step taken by mankind. The intrigue point is that why this progress in cooling has not been accompanied with similar technological-progress in heat pump based heating, instead of continuingly relying on the same old combustion process, that is, condensing boilers are the ultimate perfection of that ancient practice.

One reason is that while heat pump is the only reliable means for cooling, the use of heat pump for heating must compete with the long-established practice of fire for heating. Absence of competition, heat pump for cooling achieved instant success. With the low-cost combustion process, heat pump must compete in terms of cost and reliability.

Performance of heat pumps is measured in terms of coefficient of performance (*COP*), which is the ratio of heat supplied by the HP unit to the electric energy required by the HP compressor. However, the real measure of a heat pump system is the system's overall COP_{System}, the ratio of

heat supplied by the HP system to the sum of all electric energy required by the whole system, including compressor requirement as well as all pumps requirement and, especially, the energy requirement of the auxiliary heating.

Since the thermal efficiency of a conventional power plant is approximately 33%, it takes 3 unit of primary energy to produce 1 unit of electricity. Consider a perfect condensing boiler of 100% boiler efficiency. To have a HP system to compete with a condensing boiler, the HP system's COP_{System} must be higher than 3.

The kinds of HP systems include air source heat pump (ASHP), ground source heat pump (GSHP), and combined solar and heat pump (S+HP, see [28]), which is also known as solar-assisted heat pumps (SAHPs, see [29]). Freeman et al. [30, 31] investigated the energy used for heating the 120 m² floor area house, located in Madison, Wisconsin, with stand-alone ASHP, conventional active solar, series SAHP, and parallel SAHP with a 3-ton heat pump unit and solar collectors of collector area of **30 m²**. Their result, which did not include GSHP, is reproduced in **Figure 1**.

There are important conclusions to be drawn from these findings on the breakdown of heating contributions: What matters are the purchased heats (which is purchased electrical energy), which include the auxiliary electrical resistive heat and the portion of heat delivered by heat pump associated with compressor energy input. The total heat delivered by the heat pump unit is the sum of that portion *and* the Q_{Air} portion in the case of parallel SAHP or the Q_{Solar} portion in the case of series SAHP. *COPs* shown in the captions are the COP of the heat pump
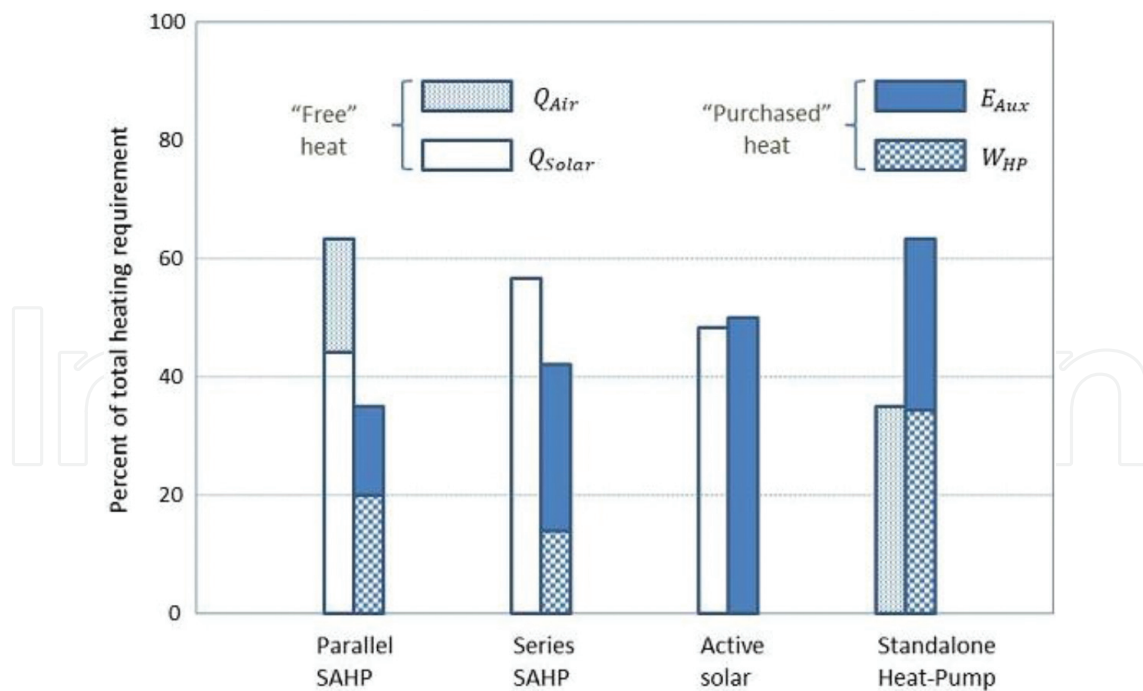

Figure 1. Heating contributions from all sources for standalone heat pump system, standalone active solar system, series SAHP system, and parallel SAHP system. Collector areas for the three cases using collectors are 30 m². The *COPs* of standalone heat pump, series SAHP, and parallel SAHP are 2.07, 2.84, and 2.00, respectively.

units, while the system COP_{System}, as read from the figure (taking the right column value in units X, $COP_{System} = 100/X$), are as follows:

Standalone heat pump: COP_{System} is smaller than 2

Active solar: COP_{System} is about 2

Series SAHP: COP_{System} is above 2 but smaller than 3

Parallel SAHP: COP_{System} is a shade short of 3

The results suggest that both series and parallel SAHPs, two examples of S+HPs, show much improvement over the baselines of standalone heat pump and standalone solar, but, so far as this study for heat pump use at Madison, Wisconsin is concerned, none of the four heat pump systems can overtake the performance of condensing boiler. The key reason for that is that, for all cases, auxiliary heating is required (and allowed).

But heat pump systems do have an important advantage if the electric grids become less dependent on fossil-fired power plants and more dependent on renewable energies. Such renewables powered grid is called *clean electricity*. Energy Transitions Commission, a leading industries, investors and climate advocates group, in its 25 April, 2017 press-release made the case, "Falling costs of renewables and batteries make cost-effective, clean electricity unstoppable and essential to the transition to a low-carbon, energy abundant world." It is *clean electricity* that makes electrification of transport unstoppable. Clean electricity and electrification of buildings is another potentially unstoppable combination if heat pump system for heating can achieve a clear-cut advantage in COP_{System} of multiples of 3. The following outlines a pathway of reaching the goal.

6. The PETH interpretation of LowEx approach: LowEx S+HP systems

In MTH, the Carnot heat engine is interpreted as "a theoretical power cycle of maximum efficiency for converting thermal into mechanical energy" [22]. In fact, every change in nature and in man-made world can be viewed in terms of energy transformation. PETH, however, suggests that there are processes that cannot be captured in terms of energy conversions in the traditional understanding of MTH and these processes are represented by the three kinds of processes: #1_Purely spontaneous systems: system EGP does not involve change in system energy; #2_Negative-anergy energy; #7_Natural entropy growth potentials (EGPs) phenomena (see also **Table 1**). While the first two kinds are of theoretical interest, the last one, natural EGPs, is of special significance in formulating a way for a sustainable future.

The concept of heat extraction is the new central concept in PETH for harnessing natural EGPs. The concept is derived from the proposition that equivalence exists not between consumed heat and produced work but between extracted heat and produced work. Not only a Carnot heat pump should be approached as a heat extraction machine, but also a Carnot heat engine is better comprehended as a heat extraction machine that is powered by EGP associated with the heat transfer tendency of temperature difference. In the strict sense heat is never consumed thus converted, but extracted in a process driven by EGP.

Unfortunately, in the MTH dominated physics students of thermodynamics are trained to think in terms of energy transformation instead of heat extraction. Emden in the 1938 Nature article, *Why do we have Winter Heating?* offered these responses:

> *The layman will answer: "To make the room warmer." The student of thermodynamics will perhaps so express it: "To import the lacking (inner, thermal) energy." If so, then the layman's answer is right, the scientist's wrong.*

The scientist thinks in terms of energy transformation and, by importing the energy which is guaranteed by physics to be transformed into heat in accordance with the energy conservation principle, heat is delivered to meet the demand.

LowEx approach offers a better response by matching the quality levels between the energy supply and demand. That is, to import the lacking energy with energy of a closely matched quality level. This is a response that is half way between the first law that thinks in terms of demand and supply and the second law in terms of quality of energies.

The advent of clean electricity offers a third response—instead of a matter of demand and supply—"To make the room warmer" suggests that the solution can be a matter of reversible-like operation driven by clean electricity. Clean electricity, a form of pure exergy energy, is the perfect driver of heat extraction operation, a reversible-like operation, for harnessing natural EGPs such as solar → infrared radiation phenomenon.

Evidence shown in **Figure 1** shows that S+HP systems enjoy significant improvement over standalone heat pumps. What is also obvious is that in the world of seeing every process in terms of energy transformation the use of auxiliary heating is allowed without hesitation. With such compromise, S+HP systems are no longer straightforward heat extraction devices, but are partial energy transformation devices, or for short, energy transformers.

6.1. Parallel S+HP vs. series S+HP, searching for LowEx S+HP

We propose a different definition of LowEx approach. The term LowEx is hereby used as the general goal of reduction in exergy input to the building (see definition in [4], Fig. 4.2, page 33). This goal can be met by matching of the exergy level of the input energy with the low exergy level of demanded energy, or by the following approach.

LowEx approach is defined not by excluding the use of high exergy energy, but by limiting high exergy energy or pure exergy energy use for maximizing the application of natural EGPs. A LowEx S+HP is, therefore, a *pure* heat extraction S+HP system of adequate solar collector area and sufficient TES capacity for eliminating auxiliary heating under normal operation.

Note that normal operation is defined to be the time during which 99% of a building heating need is called for. That is, for a "pure" heat extraction system equipped building its auxiliary heat is no more than 1% of the annual heating need of the building.

The following gives an outline of determining the requirement of collector area and TES tank capacity of a 200.1 m² floor area building in Stony Brook, NY, location, for meeting the LowEx goal. Simulation is used for this determination. The assumptions of simulation are as follows.

ACTIVE SOLAR

	5 STPs					
	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered (kW-hr)	5510	8019	4800	7712	4100	7435
Electric energy input(kW-hr)	5510	6006	4800	5330	4100	4654

PARALLEL S+HP

	5 STPs					
	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered	?	11,750	?	12,010	?	12,270
Electric energy input	?	3083.2	?	2943.2	?	2932.7
	10 STPs					
	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered	?	12,368			?	13,509
Electric energy input	?	2840.4			?	2639.2
	15 STPs					
	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered					?	14,696
Electric energy input					?	2439

SERIES S+HP

	5 STPs					
	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered	585	?	247	12,183	212	11,710
Electric energy input	585	3729	247	2012	212	1898
	10 STPs					
	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered	149.5	11162.5	121	11,189	107	11,015
Electric energy input	149.5	1581.2	121	1401	107	1296
	15 STPs					

	200 gal TES tank		700 gal TES tank		1500 gal TES tank	
	Electric→heat	System total	Electric→heat	System total	Electric→heat	System total
Heat delivered					51.8	10309.8
Electric energy input					51.8	898.4

Table 3. Three heating systems' simulation results for determining their ability in meeing LowEx crit.

- Building envelope: ASHRAE 90.1-2008 zoon 4A minimum requirement

- Climate: TYM3 data

- Equipment:
  - ASHP-WH-MDC12C9E8

  - WSHP-DAIKIN WRA 036

  - STP-SunMaxx ThermoPower-VDF30 (Aperture area of each panel = 2.67 m^2)

The simulation results are shown in **Table 3**.

As shown by Freeman et al. [30] the electric energy consumption of active solar systems is high unless very large solar collector area is used. In that case, however, the cost will be prohibitive. Combined solar and heat pump system (S+HP), therefore, "has the potential of alleviating the limitations each system [i.e., standalone solar system or standalone heat pump system] experiences individually in cold weather" [29], and "has great potential for improving the energy efficiency of house and hot water heating systems" [32]. By the comparative study in **Table 3** of parallel S+HP and series S+HP, this potential in the feasibility of combined systems for meeting LowEx goal can be assessed.

6.2. Discussion

In the literature as cited by Andrews et al. [33] series S+HP was judged inferior to parallel S+HP. Same conclusion has been made by IEA-Task 44. [32]. The principal reason was pointed out in [33] that it is due to, for series system with inadequate solar collector area, heat pump starvation, the phenomenon that when water temperature becomes too low the water source heat pump is starved from source thermal energy—necessitating the input of electric→heat auxiliary heating. Our result agrees with this assessment in the case of 5 STPs and 200 gal tank, which shows electric energy input (i.e., pure exergy energy input) of 3729 and 3083 kW-hr for series and parallel, respectively.

On the other hand, series combined system is the pure expression of heat extraction configuration, the configuration that can benefit from "alleviating the limitations each system experiences individually in cold weather," while the parallel combined system does not enjoy the

same level of synergy. For instance, the solar collector of a series S+HP operates at lower temperature, thus, has higher performance and can be made of lower-cost construction. It is, therefore, interesting to examine the impact of TES tank thermal storage and the impact of larger solar collector area on mitigating heat pump starvation.

It is significant that for the case of small solar collector area, the impact of thermal storage on energy input for parallel combined system is $3083 \rightarrow 2943 \rightarrow 2933$, while for series combined system $3729 \rightarrow 2012 \rightarrow 1898$, a drastically greater reduction in pure exergy energy input as a result of thermal storage application.

The impact of solar collector area on energy input can be seen for the case of 200 gal thermal storage for parallel combined system $3083 \rightarrow 2840$ vs. for series combined system $3729 \rightarrow 1581$. Also, for the case of 1500 gal thermal storage for parallel combined system $2933 \rightarrow 2639 \rightarrow 2439$ vs. for series combined system $1898 \rightarrow 1296 \rightarrow 898$. In fact, theoretical consideration would conclude that as solar collector area approach infinitely large, the parallel combined system would forfeit any synergetic advantage and have the same performance as standalone active solar, which is of course a poor performer.

6.3. Pure heat extraction process: LowEx S+HP

Even though **Table 3** shows only incomplete simulation results of our study, which is ongoing, the above discussion offers sufficient evidence to support our theoretical argument on the superiority of pure heat extraction process as manifested in the form of series combined solar and heat pump system. With adequate solar collector area and adequate thermal storage, the *electric → heat* becomes less than 1% of *System total heat delivered* (e.g., 107, which is 0.97% of 11,015), such series S+HP meets the LowEx criterion and becomes LowEx series S+HP.

7. Conclusion: beyond energy transformation

This chapter presents an alternative approach of achieving the goal of LowEx, reduction in exergy input to buildings.

In describing the original approach to the LowEx goal, IEA-ECBCS argued, "combustion processes should not be used for the production of low temperature heat" ([4], 33). This is a partial step against the practice of combustion energy transformation since it did not argue against combustion processes generally. Undoubtedly, IEA-ECBCS made a good case against boilers and condensing boilers, a bad example of using combustion, in favor of district heating with combined heat and power (CHP), example of better use of combustion.

The author makes here the general case of beyond energy transformation, that is, against combustion processes generally in favor of clean electricity of solar and wind farms powered grids *and* the corresponding electrification of transport and electrification of buildings. In making the specific case of electrification of building heating, the author has introduced two innovations: The first is the recently formulated new theory of heat, PETH, which represents the logical conclusion of MTH by establishing the theory of heat on the solid cornerstone of

correct categories of heat ontologically as well as predicatively. The case is an application of the first innovation as shown in **Table 1**. The second innovation is in the details, as suggested in **Table 3**, of how the application should be carried out: improvement of the series combined solar and heat pump systems (series S+HPs) by using thermal-storage/STPs for "eliminating" the energy conversion process of auxiliary heating so that the improved systems, LowEx S+HPs, can achieve clear-cut efficiency superiority over condensing boilers.

Both combined systems, combined heat and power and combined solar and heat pump systems, can supplant condensing boilers with superior efficiency. The new heat pump-based heating and cooling systems have the additional advantage of facilitating the goal toward clean electricity ecosystem.

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