Clausius' thermodynamics, the logical conclusion of the conceptual differentiation of caloric in terms of the two laws of thermodynamics

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Abstract

Thermodynamics is the theory of energy resulted from the conceptual differentiation of caloric, circa 1850-1865, into energy, entropy, and heat (a disorganized form of energy) in terms of the two laws of thermodynamics, the first law and the second law. The theory is often referred to as the Clausius-Kelvin theory as a single theoretical system. In actual fact, it is a blend of Kelvin's contribution and Clausius' contribution. Orthodox engineering thermodynamics is instead an update of the energy physics formulated by Kelvin circa 1850-55 based on the *energy premise*, which stops short of the conceptual differentiation in the exact sense. It is the Clausius version of the theory that was transformed by Gibbs into Gibbsian thermodynamics, which is the result of the conceptual differentiation. As a result, engineering thermodynamics is a defective theoretical system while Gibbsian thermodynamics is a successful one. This paper makes the case that Clausius' theorem of entropy can be developed for reforming engineering thermodynamics into a coherent system by rejecting the energy premise.

Keywords: Carnot's theorem, equivalence of heat and work, energy physics, "compensation" and "equivalence" of transformations.

1. Introduction

Thermodynamics is the theory of energy. The standard definition of energy is that energy is *the capacity for doing work*[1]. Although this definition identifies the feature why energy is important to us, the feature it identifies is ***that of work*** and what drives the production of *work* and where the *work* comes from. Energy is important only because it is a proxy of ***which*** under certain situations, while the adoption of the standard definition, a recent article argued, leads to serious misunderstanding of energy's true role in the production of work. The article made the case with the following highlights[2]:

1. Mechanical energy as the capacity for doing work had been the pre-industrialization (i.e., pre-discovery-of-the-motive-power-of-heat) understanding of energy.
2. By defining energy in the post-discovery-of-heat-energy of 1712 (Newcomen)-1843 (Joule) as the capacity for doing

work, the *energy premise* perpetuated the single, monolithic view of energy.

3. In the industrialization age of the post-discovery-of-heat-energy, the view of energy as the single, monolithic drive for work should have been replaced by the two separate questions of what drives the production of work and where the work comes from, which will be referred to as the *what-where work questions*.

This paper supports the case made in Article[2] with an investigation of the structure of engineering thermodynamics which is based on the two fundamental laws, the first law and the second law of thermodynamics. It reviews the historical development of engineering thermodynamics as energy physics and argues that the premise of energy physics, the energy premise, led the splendid conclusion that it took two laws for the explication of the new energy to go awry by failing to recognize the contradiction between the premise and the fact of requiring two laws for the explication of energy. The substance of the paper makes the case that we can find in Clausius' theorem of entropy the framework of a reformed engineering thermodynamics reformulating the two laws in alignment with the duality of the what-where work questions.

Before it became the theory of energy, the precursor of thermodynamics had been theories of heat or caloric, the study of heat/caloric and work. There had been mainly two theories, Carnot's theory and Joule's theory. Coppersmith described the state of the scientific study of heat and work in the mid-nineteenth century, "While developing the absolute scale of temperature, Thomson still (in 1849) hadn't come round to accepting that heat could be converted into work. He thought that Carnot's conclusions would come crashing down if the axiom of the conservation of heat/caloric was abandoned. But he couldn't reconcile this axiom with Joule's experiments, which showed that heat and work were interconvertible, and that heat was actually consumed or generated in the process … It seemed as if both Carnot's and Joule's opposing theories were becoming more and more confirmed and entrenched. Thomson couldn't resolve this conflict: nor could he explain the conundrum of workless heat conduction; or the fact that Joule appeared to have shown conversions of work to heat, but not of heat into work"[3].

Thomson had the intuition that the creation of a useful theory of heat depended on the reconciliation of the conflict between Carnot's theory and Joule's theory, or the equivalence theorem, the theorem of the equivalence of heat and work. This has been sometime called Thomson's problem. [[3]:284, [4]:4] Both Thomson and Clausius carried out their versions of the synthesis of the equivalence theorem and Carnot's theory. A historical study of how Thomson carried out the synthesis is given by Smith in *William Thomson and the Creation of Thermodynamics: 1840-1855*[5]. How Clausius carried out his version of synthesis can be found in the book *Energy, the Subtle Concept*[[5]:281-285 and 288-291] by Coppersmith, and in the article *A History of Thermodynamics: The Missing Manual* by Saslow [6].

Thermodynamics was the outcome of this synthesis project. Smith wrote, "What was emerging by the early 1850's, then, was classical thermodynamics as a science based on two axioms or laws" [[5]:278]. This paper makes the case that while both Thomson and Clausius indeed contributed to the synthesis project which resulted in the formulation of the two principal laws of thermodynamics, the orthodox thermodynamics we have today is at its core an updated version of the *energy physics* formulated by Thomson circa 1850—55.[5] In Sect. 2, the case that thermodynamics began its formative years as energy physics, or the energy physics synthesis, is presented. On the other hand, Tisza identified the key advance made in the synthesis project to be the conceptual differentiation (or bifurcation or splitting) of caloric, circa 1850-1865, into energy, entropy, and heat (a disorganized form of energy). [[7]; [8]:22, 30-36] Correspondingly, this paper also argues that in their paths moving towards the formulation of the two principal laws, there was a fundamental difference between the Thomson version and the Clausius version in another sense: only the Clausius version matched exactly Tisza's conceptual differentiation resulting in the equilibrium thermodynamics of Gibbs. That is, orthodox thermodynamics and equilibrium thermodynamics reflect distinctive legacies to Thomson and to Clausius respectively, rather than a single theoretical system of the Clausius-Kelvin theory [[8]: 104]. Appreciation of this fact will be necessary for better understanding of thermodynamics as a whole.

Sect. 3 introduces Clausius' 1854 Fourth Memoir *On a modified form of the second fundamental theorem in the mechanical theory of heat*[9][10], in which he called the equivalence of heat and work the first fundamental theorem and proposed a second fundamental theorem. In the Memoir,[9] Clausius chose for "the analytical expression of the second fundamental theorem [for reversible processes]" the equation *Eqn. (II)*. The entropy law resulted from Eqn. (II) has been referred to as the entropy selection law[11][12]. The law was then transformed and developed by Gibbs, which is referred to as the Clausius-Gibbs synthesis, into the theoretical system of Gibbsian thermodynamics. It is emphasized here that this is a theory based on both fundamental theorems, the first fundamental theorem and the second fundamental theorem. That is, the foundation of equilibrium thermodynamics is different from that of energy physics: unlike energy physics which did not formulate a second law as a law of entropy, equilibrium thermodynamics was the result of the conceptual differentiation, explicitly, of caloric into energy and entropy. Section 3.2 also contains a review of how Tisza introduced an axiomatic form for Gibbsian thermodynamics, which he called macroscopic thermodynamics of equilibrium (MTE).

Sect. 4 considers orthodox thermodynamics, as an update of energy physics. When the MIT School of thermodynamics updated energy physics with its formulation of exergy analysis, it had the full benefits of Gibbsian equilibrium thermodynamics. The entropy law was incorporated in the update as a selection law, as it was mentioned in the above and is still the standard view of the law. Sect. 4 of the paper makes the point that orthodox thermodynamics, the Dresden/MIT-School-update of energy physics, despite its incorporation of the entropy selection law is still within the framework of energy physics with its energy conversion doctrine. While Tisza referred to the Clausius-Kelvin theory as a single theoretical structure system, this paper and the analysis of Sections 3 and 4 emphasize that the "Clausius-Kelvin theory" is in fact a blend of Thomson's (Kelvin's) contribution and Clausius' contribution: Clausius' has its lasting impact through Gibbs leading to MTE and, though MTE have been incorporated into an element of orthodox thermodynamics, Kelvin's energy physics still exerts controlling role of orthodox thermodynamics. That is, the single, monolithic view of energy (the energy conversion doctrine), not the conceptual differentiation of caloric into energy and entropy, remains to be the DNA of orthodox thermodynamics.

This paper makes its main point that there are two parts of the second fundamental theorem: "equivalence" of transformations and "compensation" of transformations. I shall relabel in Sect. 5 *Eqn. (II)*, Clausius' first part of the second fundamental theorem, as *Eqn. (**II.1**)*, correspondingly, designating a proposed second part as *Eqn. (**II.2**)*. The first part led, in the 1865 paper by Clausius, [[3]:327-365] to the introduction of entropy—with the inequality for general processes, allied with equality *Eqn. (II.1)* for reversible processes, to the entropy law. Sect. 5 of the paper proposes a new synthesis of thermodynamics, a new Clausius synthesis, based on the first fundamental theorem and *both* parts of the second fundamental theorem. In the Clausius-Gibbs synthesis, it did not involve the second part of the second fundamental theorem, *Eqn. (**II.2**)*, because equilibrium thermodynamics did not need it. In contrast, engineering thermodynamics needs something like the second part as causal agency. However, the orthodox engineering thermodynamics, in Sect. 4, did not involve the second part because of its energy conversion doctrine which assigned energy the role of causal agency as well as that of conservation constraint. That is, energy conversion doctrine resulted from the discovery of heat energy kept the "previous habits"[13][14] of the single, monolithic drive thinking[2] of the pre-discovery world. One problem is that the doctrine acquired the causal power on the truism that the energy dissipation principle is a universal principle that is interchangeable with the entropy law. The truism is false. As a result, orthodox engineering thermodynamics as a theoretical system is riddle with puzzlement and contradiction. In Fig. 5 and Fig. 6, it suggests the problem of the monolithic drive thinking has to do with the *absorption* of the entropy law by the doctrine in a "circle" of the first law/the doctrine/the entropy law/exergy analysis/energy analysis—which, called the energy premise circle[2], deprived the entropy law of its independent status. Contrasting Fig. 8 to Fig. 5, we can see that supplementing orthodox thermodynamics' energy conversion doctrine with the second part of the second fundamental theorem, i.e., the *second fundamental theorem of reversible-like compensation*—restores the entropy law as an independent law, a selection law and a causal law.[12]

After reflection on energy conversion doctrine's deficiency, Sect. 6 reiterates the root to be its conflation of the what-where work questions, the former is the purview of the second law or the second fundamental theorem while the latter that of the first law or the first fundamental theorem. Orthodox thermodynamics and the simple Carnot cycle conflate the two in terms of energy, in which the causal power of the entropy is erroneously given to energy or the first law resulting in limiting the entropy law to be a selection law only. The new Clausius synthesis cuts the Gordian knot of energy-conversion-conflation removing false inferences of the entropy law resulted from the conflation.

2. Energy Physics Synthesis

Humankind had relied on fire for heat and light and on human power and animal power for power since antiquity. In the last two millenniums, human learnt how to harness natural mechanical power in the forms of waterpower and wind power for food processing, manufacturing, and transportation. Then, in the period of 1712-1824, Newcomen, Watt, and Carnot, collectively, (Newcomen invented atmospheric steam engine in 1712, Watt made significant improvement in steam engine efficiency, and Carnot formulated a theory of heat engine in 1824) discovered the "motive power of fire." That is, fire, the erstwhile source for heat and light, was discovered to be a source, much more reliable and of abundant supply than animal sources and natural mechanical ones, for mechanical power as well.

The discovery of the motive power of heat proved to be a watershed event. Following Carnot's idea that work was derived from the transfer of heat from a hot body to a cold body (in which Carnot assumed that the transferred heat is a conserved quantity), Joule established empirically that when work is transformed into heat, the ratio of the amount of disappeared work to the amount of produced heat is a universal constant. Joule posited that for the opposite change or transformation, the same ratio held. Although Thomson initially held against the latter claim of Joule, he came to accept the claim. Today, the idea of equivalence of heat and work in both directions, as a cornerstone of energy physics as shown in blue block in Fig.1, is universally accepted. I shall refer to these advances collectively (Newcomen invented atmospheric steam engine in 1712, Watt made significant improvement in steam engine efficiency, Carnot formulated a theory of heat engine in 1824, and Joule established the equivalence of heat energy and work, i.e., mechanical energy) as the NWCJ discovery of motive power from heat energy.

The equivalence theorem led to the introduction of a new state function, the internal energy. In modern reconstruction, the concept of "adiabatic work" can be used to show the existence of the state function. With the introduction of internal energy, the equivalence theorem led directly to the first law of thermodynamics as shown in Fig. 1.

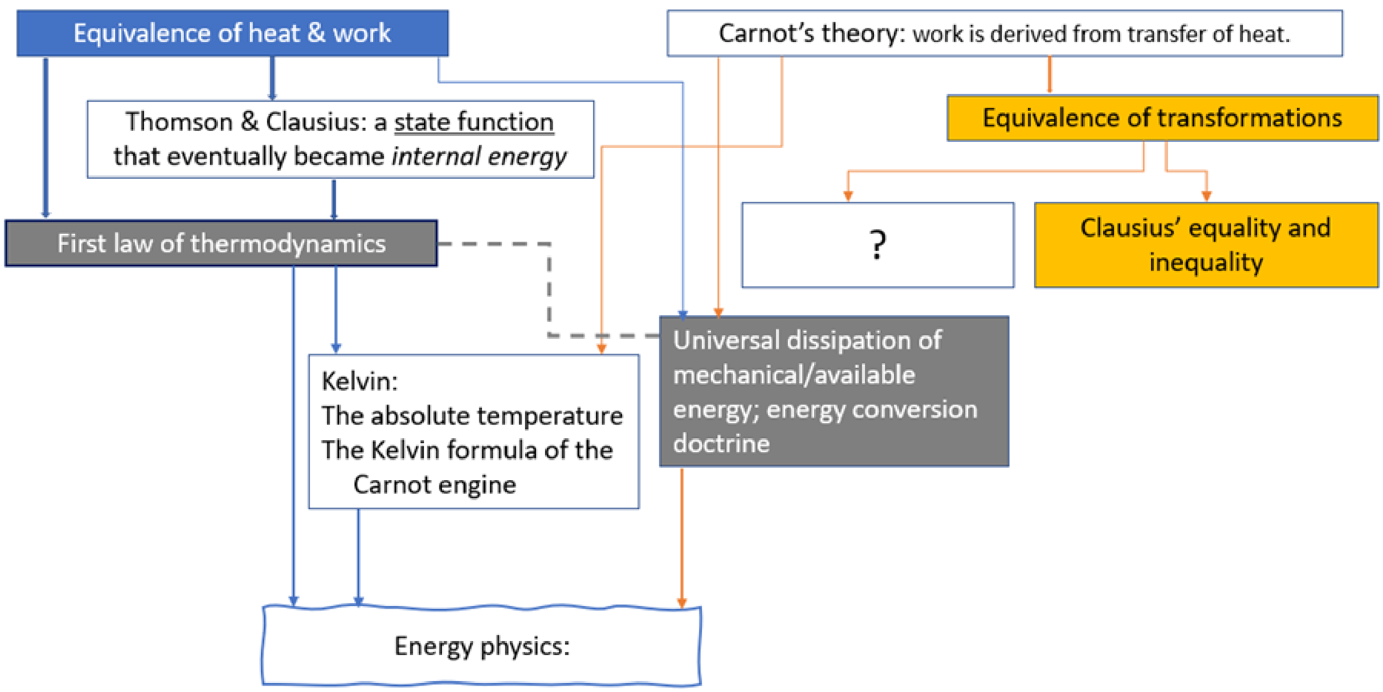

Figure 1: Energy physics, circa 1854-55

With the equivalence theorem and the first law firmly in place, both Thomson (later, Lord Kelvin) and Clausius saw that the key to a new branch of physics was how to reconcile the equivalence theorem that work is derived from the consumption of heat with Carnot's theory of heat engine that work is derived from the transfer of heat from a hot body to a cold body. As Tisza noted, "classical thermodynamics was born out of the reconciliation of two apparently contradictory ingredients.

The striking unification of the most diverse phenomena by the Mayer-Joule principle is to be contrasted with a peculiar new duality implicit in Carnot's principle: We have to draw the line between reversible and irreversible processes, a distinction characteristic of thermodynamics that is not predicted, or even allowed, by the fundamental equation of mechanics or electrodynamics. The precise and detailed description of this dichotomy is a most difficult problem, one of the central themes of this book" [[8]:30]. It, a detailed description of the reconciliation of this dichotomy through "splitting the concept of caloric into heat quantity, energy, and entropy" [[8]:22], is also one of the central themes of this paper.

Both Kelvin and Clausius realized that the application of Carnot's idea to heat engines did not have to assume heat is conserved. Clausius approached the reconciliation project methodologically taking a giant step in 1850 and painstakingly between 1854 and 1865 taking a number of steps on "the road to entropy"[15]. This will be described in Section 3. In contrast, Kelvin in 1854 was able to, by reconciling Carnot's idea with the requirement of energy conservation instead of heat conservation without having to introduce the concept of entropy, derive the formula for the Carnot engine (see Fig. 1, [[16],[17]: Sects. 4.4 and 4.5]),

$$W = Q_1\left(1 - \frac{T_2}{T_1}\right)$$

where T_1 is the temperature of the hot heat source and T_2 the temperature of cold heat sink, and Q_1 heat supplied to the engine from the hot heat source. The derivation was a tour de force as a first step towards reconciliation.

The reconciliation was completed in terms of the conceptualization of energy physics: Kelvin came to see that energy cannot be destroyed nor created (the first law) but energy is dissipated all the time. By that, he meant that available energy is dissipated spontaneously. He finally was able to explain the conundrum of workless heat conduction that while no energy can be destroyed available energy is dissipated/degraded in the process of workless heat conduction. In 1852, he published a short paper [[18]:511-514] proclaiming, without proof, that mechanical energy and available energy dissipate spontaneously and universally. His claim of universal dissipation of available energy has been universally accepted as a truism by everyone—except Planck, see below in Sect. 4.

This conceptualization is basically the energy conversion doctrine conceptualization. This doctrine, see the "universal dissipation…energy conversion…" block in Fig. 1, as well as the real meaning of "conversion" and that of "equivalence" (of heat and work) will be the investigative focus of this paper. In the paper, "conversion" is used in a different sense from "transformation," which is used in the same general sense as process (as Clausius did in his Fourth Memoir, see below). Although Fig. 1 includes the block of the "equivalence of transformations," it should be noted that "energy physics, 1854-55" represents the understanding achieved by Kelvin in terms of energy conservation and available energy dissipation without incorporating the "equivalence of transformations." That role is assumed by the "universal dissipation of mechanical/available energy; energy conversion doctrine" block in Fig. 1. At this stage, the ideas of "equivalence of transformations" and "equivalence values" (or "entropy") were afoot but not yet at the center stage. The way Kelvin achieved the reconciliation of the equivalence theorem and Carnot's theory is not by "splitting the concept of caloric into heat quantity, energy, and entropy" in the exact sense—unless one accepts the mistaking notion of energy degradation as the synonym of entropy growth, as many do.

The tour de force derivation and the truism of energy degradation as the synonym of entropy growth are the manifestation that Kelvin theory of energy physics has succeeded too well that it made hidden of "the precise and detailed description of this dichotomy being a most difficult problem."

3. The Second Fundamental Theorem

Clausius began in his 1854 Fourth Memoir[9] "rebuilding" Carnot's idea into the equivalence of transformations, which is sometime called the second equivalence theorem or the second fundamental theorem. This rebuilding is a major move by Clausius to "move beyond" Carnot's theory. In the case of the first equivalence theorem, the equivalence of heat and work, both Thomson (Kelvin) and Clausius were able to apply which to develop the concept of a new state function, internal energy *U*—thus, arrived at the formulation of the first law, the energy law. Unlike that case, Carnot's theory did not lead directly to the concept of entropy as a new state function. The road to entropy had to go through Clausius' second equivalence theorem, the equivalence of transformations.

Clausius adopted the terms of "Carnot's theorem" and, for the first equivalence theorem, "first fundamental theorem." He expressed analytically the first fundamental theorem ("the first fundamental theorem will be expressed by the equation" [[9]:113]) as *Eqn. (**I**)*, which is here slightly modified into the modern form,

$$Q_{1-2} = (U_2 - U_1) + W_{1-2} \qquad (I)$$

With regard to Carnot's theorem, he wrote in the Fourth Memoir, "Carnot's theorem, when brought into agreement with the first fundamental theorem, expresses a **relation** [bold added] between two kinds of transformations, the transformation of heat into work, and the passage of heat from a warmer to a colder body … In deducing this theorem, however, a process is contemplated which is of too simple a character; for only two bodies losing or receiving heat are employed, and it is tacitly assumed that one of the bodies between which the transmission of heat takes place is the source of the heat which is converted into work. Now by previously assuming, in this manner, a particular temperature for the heat converted into work, the influence which a change of this temperature has upon the relation between the two quantities of heat remains concealed, and therefore the theorem in the above form is incomplete" [[9]:116-117].

Carnot introduced for the first time in physics the idea of unidirectionality in the physical processes of heat transmission and proposed that the production of work can be derived from managing these unidirectional processes. Carnot had demonstrated these ideas in the four steps Carnot cycle, in which there is no separate account of heat transmission transformation and the production of work transformation. Clausius saw a crucial improvement to be made on describing the Carnot engine with a modified cyclical process to talk about these transformations distinctively.

3.1. Clausius' two types of transformations and the Aequivalenzwerth of a transformation

"With Carnot, he [Clausius] postulated that heat could drop from a high temperature to a low temperature in what we shall call a 'transmission transformation.' Contrary to Carnot, however, he also assumed that heat could be converted to work in a 'conversion transformation.' Clausius was impressed by the fact that both kinds of transformations had two possible directions, one 'natural' and the other 'unnatural' [these were not Clausius' terminology; instead, he called them 'positive transformations' and 'negative transformations' respectively]. In the natural direction, a transformation could proceed by itself, spontaneously and unaided, while the unnatural direction was not possible at all unless forced by some outside influence" [[15]:1068]. Clausius himself put the last point this way, "*an uncompensated transmission of heat from a colder to a warmer body can never occur.* The term 'uncompensated' here expresses the same idea as that which was intended to be conveyed by the words 'by itself' " [[9]:118].

That is, Clausius generalized Carnot's ideas into

(i) the notion that there are processes or transformations of preferred direction; these are new kind of processes different from mechanical processes;
(ii) one difference is that each type of the new kind of processes, to adopt the terms of Cropper[15], can be divided into "processes or transformations of natural direction" and "processes or transformations of unnatural direction";
(iii) another is the notion of "compensation" or "compensated," and that an uncompensated process of unnatural direction of the new kind of processes can never occur; furthermore,
(iv) that compensation of a heat transmission of natural direction and a heat into work process/transformation of unnatural direction can be demonstrated with a six-stage Clausius cycle (following Cropper[15], see Fig. 2) in which Steps 2 (2→3), 4 (4→5), and 6 (6→1) are adiabatic steps; while, at Step 1 (1→2), a quantity Q is supplied to the cycle's working fluid **in communication with a body** K at temperature t, between Step 3 (3→4) and Step 5 (5→6), a quantity Q_1 is supplied to the cycle **in communication with a source body** K_1 at temperature t_1 at Step 3 and the same quantity is discharged by the cycle **in communication with a sink body** K_2 at temperature t_2 at Step 5 representing heat

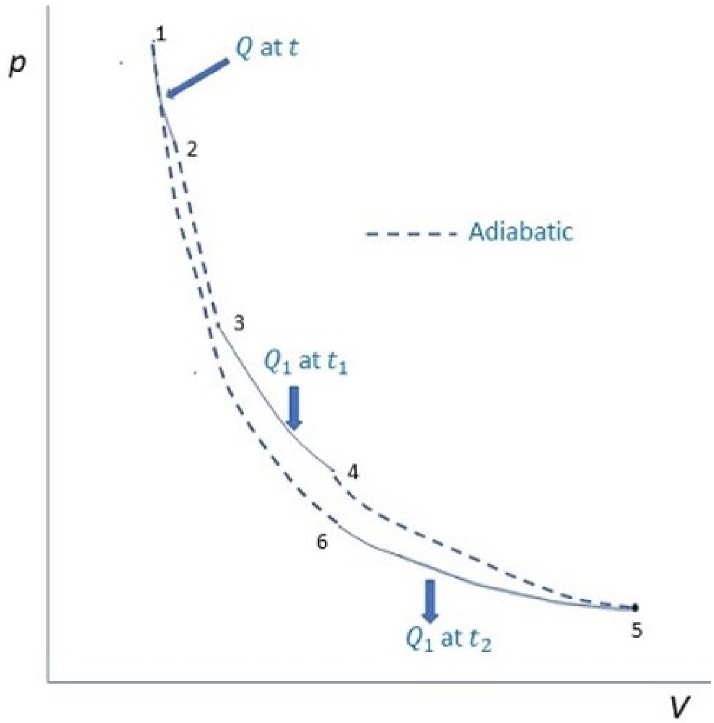

Figure 2: The six stage Clausius cycle

transmission of Q_1 from t_1 to t_2; the consideration of the first fundamental theorem leads to the conclusion that the supplied Q at Step 1 is transformed through the cyclic process completely into work; and

(v) that compensation of a transformation, e.g., a heat transmission of natural direction or a heat into work process of unnatural direction, can be *quantitatively* expressed in terms of the *equivalence value (Aequivalenzwerth)* of the transformation.

Clausius introduced the concepts of *equivalence-value* and *equivalence.* Transformations are characterized by equivalence-value (Aequivalenzwerth) of positive sign of natural direction or negative sign of unnatural direction. In the Fourth Memoir[9] and in Cropper's paper[15] and Saslow's paper[6], details of mathematical argument of Clausius' reasoning are given. A brief summary of the initial steps with regards to the forms of equivalence values and the condition of reversible compensation (which Cropper called the condition of balance [[15]:1070]) are reproduced here.

It is assumed that the equivalence value for one kind of transformations, the transformation of work to heat appears in the form $Qf(t)$ as positive transformation and conversely, for heat to work transformation, $-Qf(t)$. The other kind of transformation, the positive heat transmission transformation from t_1 (higher temperature) to t_2 (lower temperature), its equivalence value appears in the form of $\bar{Q}f(t_1, t_2)$ and conversely, the negative heat transmission transformation from t_2 (lower temperature) to t_1 (higher temperature) to be $\bar{Q}f(t_2, t_1)$. Therefore, $\bar{Q}f(t_2, t_1) = -\bar{Q}f(t_1, t_2)$.

Clausius now considers the reversible compensation of two transformations, one positive (heat transmission from t_1 to t_2) and one negative (transformation of heat to work). He suggests the condition of reversible compensation *equivalence of transformations* to be a criterion in terms of the equivalence values of the two transformations. The criterion is a vanishing algebraical sum of the two equivalence-values ("…in every reversible cyclical process of the above kind, the two transformations which are involved must be equal in magnitude, but opposite in sign, so that their algebraical sum must be zero" [[9]:123]). As $\bar{Q}$ in Fig. 2 is Q_1, we have

$$-Qf(t) + Q_1 f(t_1, t_2) = 0 \qquad (1)$$

I now paraphrase the steps of Clausius, Cropper and Saslow. Note that the same equivalence of transformations holds for a six stage Clausius cycle in Fig. 2 with a different t, e.g., t', as long as the "compensation" of the positive heat transmission, $Q_1 f(t_1, t_2)$, remains the same. In such cases, t' can be any temperature: whereas Clausius considered $t' > t > t_1$, we may consider a t'' to include t_1 and t_2. That is, by repetitive application of (1), we have,

$$Qf(t) = Q'f(t') = Q''f(t'') = Q^{t_1}f\left(t_1\right) = Q^{t_2}f\left(t_2\right) \qquad (2)$$

At this point Clausius considered a simple heat-pump Carnot cycle operating between t' and t. In view of (2), instead, we consider a five-stage Clausius cycle operating between t_1 (T_1) and t_2 (T_2): as shown in Fig. 3, a cycle receives $Q^{t_1} + Q_1$ from a K_1 heat source-body and discharges Q_1 to a K_2 heat reservoir. We have, from (1), for the five-stage Clausius cycle (with Q^{t_1} supplied in $1^{t_1} \rightarrow 2^{t_1}$(3) step, and Q_1 transmitted between 3→4 and 5→6 steps),

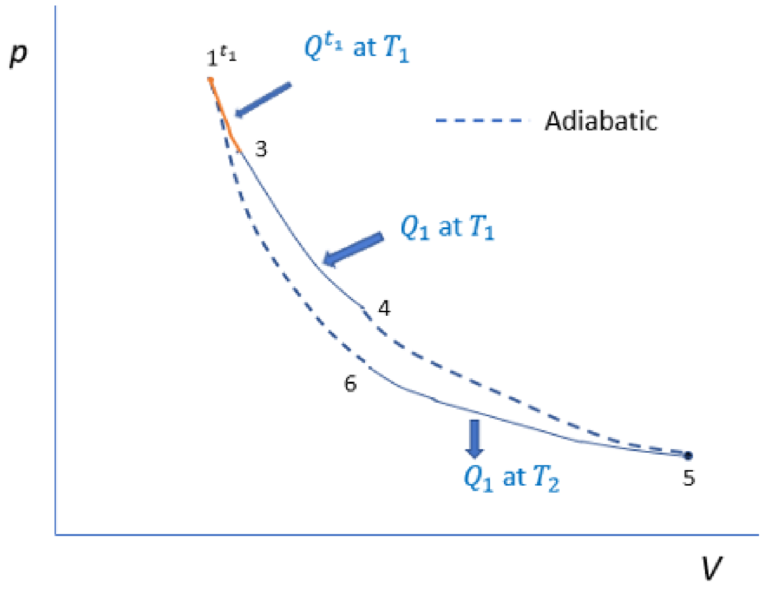

Figure 3: A five-stage Clausius cycle as reduced from the six-stage Clausius cycle

$$-Q^{t_1} f\left(t_1\right) + Q_1 f(t_1, t_2) = 0 \qquad (3)$$

And from (2) as applied to the cycle as a simple Carnot cycle (with $1^{t_1} \rightarrow 4$ as a single step),

$$(Q^{t_1} + Q_1) f\left(t_1\right) = Q_1 f\left(t_2\right) \qquad (2a)$$

Substitution of $Q^{t_1} f(t_1)$ from the above into Eq. (3) yields,

$$f(t_1, t_2) = f(t_2) - f(t_1) \qquad (4)$$

"This was another cornerstone of Clausius' transformation theory. It showed that a *single* function, the still undetermined *f(t)*, sufficed for equivalence-value determinations" (Cropper[[15]:1071]). At this point, Clausius rewrote *f* in terms of a new but still unknown function,

$$f(t) = \frac{1}{T} \qquad (5)$$

where *T(t)* is a new, material-independent function of temperature *t* involved in the equivalence-values. That is, equivalence of transformations in Fig. 2, Eq. (1), takes the form,

$$\frac{Q_1}{T_2} - \frac{Q_1}{T_1} - \frac{Q}{T} = 0 \qquad (6)$$

Clausius, at this point, stated the *theorem of the equivalence of transformations*, his statement of which is reproduced here,

> *If two transformations which, without necessitating any other permanent change, can mutually replace one another, be called equivalent, then the generation of the quantity of heat Q of the temperature t from work [the first kind], has the equivalence-value*
>
> $$Q/T$$
>
> *and the passage of the quantity of heat Q from the temperature T_1 to the temperature T_2 [the second kind], has the equivalence-value*
>
> $$Q[(\frac{1}{T_2}) - (\frac{1}{T_1})]$$
>
> *wherein T is a function of the temperature, independent of the nature of the process by which the transformation is effected.* [[9]:125-126]

Here, Clausius used the term, equivalence, as replacement of one transformation with another. But throughout the Fourth Memoir he also used the term in another sense, which is stated by Libb Thims as follows:

> *In all cases where a quantity of heat [Q] is converted into work, and where the body effecting this transformation ultimately returns to its original condition, another quantity of heat [Q_1] must necessarily be transferred from a warmer to a colder body; and the **magnitude** of the last quantity of heat, in **relation** to the first, depends only upon the temperatures of the bodies between which heat passes [and the temperature of the body where Q is converted], and not upon the nature of the body effecting the transformation.*[19]

We may surmise a definition of equivalence. *Equivalence is the quantitative relationship between two transformations in terms of their equivalence values*, the relationship in two senses: as replacement of one with another if the two transformations involved are equal in magnitude and of the same sign, and as condition-of-balance in reversible existence when the two transformations involved are equal in magnitude but opposite in sign (or, when the transformations which occur exactly cancel each other so that their algebraical sum is zero).

From equivalence as replacement, Clausius was able to argue that every transmission of heat of the second kind can be considered as a combination of two opposite transformations of the first kind, i.e., the conversion-transformation of work into heat and the transformation of heat into work.

From equivalence as condition-of-balance, Clausius was able to prove that any reversible cycle can be broken down to an infinite number of steps so that the overall cyclic equivalent "compensation" (i.e., reversible compensation) can be represented by a vanishing sum of equivalence-values. Thereby, the "analytical expression for all reversible processes of the second fundamental theorem" is the equation,

$$\oint dQ/T = 0 \qquad (II)$$

With *(II)*, Clausius was on the way to in his 1862 Sixth Memoir [[10]:215-250] the concept of "disgregation" and, finally, in the 1865 Ninth Memoir [[10]:327-365], the concept of entropy and, with the inequality version of *(II)*, i.e., *(**II.2**.2)* as given in Sect. 5.1. below, the formulation of the entropy law.

Before he arrived at that final goal, he in Fourth Memoir proceeded, by noting that *dQ/T* is a perfect differential and Joule's law of ideal gases, to prove that

$$T = a + t \qquad (7)$$

where a is 273^{o} C and t is in Celsius, so T is the ideal gas scale T_g. As Saslow noted, "Clausius's work is still not fully appreciated as forming the basis for both entropy and temperature. The unit of temperature is indeed the Kelvin, and to Kelvin we owe a great debt for early thermometry. However, it was Clausius who rigorously established that the ideal gas, or Kelvin scale, is the unique thermodynamic temperature" [[6]:40].

3.2. The Clausius-Gibbs synthesis

In assessing Clausius' scientific body of work, Cropper noted, "… his place in the beautifully clear line of development of thermodynamics between 1824 and 1875—from Carnot to Clausius, and then to Clausius' greatest successor, Willard Gibbs. Clausius' role in this was pivotal. He knew exactly how to interpret and rebuild Carnot's message, and then to express his own conclusions so they could be used by another genius, Gibbs" [[15]:1073]. Eqn. (II) and its allied inequality led directly to Gibbs' starting point of *maximum entropy principle of thermodynamic equilibrium* (see Fig. 4).

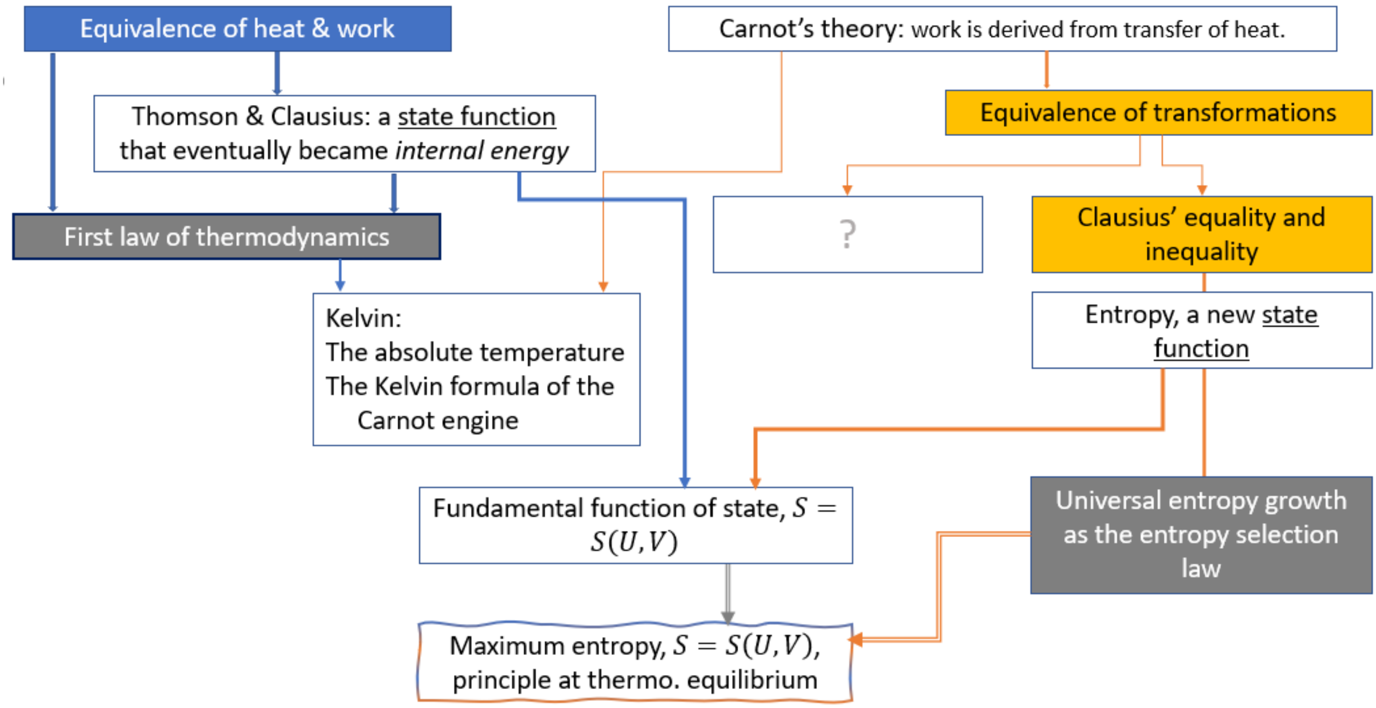

Figure 4: Gibbsian equilibrium thermodynamics, a branch of physics resulted from the conceptual differentiation of caloric into energy and entropy

Between 1873 and 1878, Gibbs single-handedly developed the theory of equilibrium thermodynamics, a shining example of building an edifice of thermodynamics on the cornerstone of the first fundamental theorem and the second fundamental theorem.

Gibbsian thermodynamics was given an axiomatic treatment by Tisza[[8]:104; [20]] and Callen [[21]]. Tisza spoke of "the classical theory of equilibrium is a blend of two essentially different logical structures: we shall distinguish the theory of Clausius and Kelvin, on the one hand, from that of Gibbs, on the other." Furthermore, Tisza pointed out that the Clausius-Kelvin theory received the axiomatic investigation of Caratheodory and he suggested to referred to which as the CKC theory. That "no comparable axiomatic investigation of the Gibbs theory has been performed thus far. Accordingly, in the existing texts the CKC and the Gibbsian thermodynamics are intricately interwoven…The first objective of the paper is to formulate a postulational basis from which a theory, almost identical to that of Gibbs, is derived as s self-contained logical structure. We shall call this theory thermostatics, or alternatively the macroscopic thermodynamic of equilibrium (MTE)" [[8]:104-105]. The goal of Tisza's axiomatic project is to formulate the Gibbs theory "as an autonomous logical structure" [[8]:106].

Caratheodory made the concept of *quasistatic processes* the central feature of his formalism, which is referred to as classical formalism in [17]. An investigation on that issue was made in[17], with the following conclusion: "A reversible machine remains the best or natural approach to start the consideration of the concept of entropy. Once the introduction is made, classical formalism is correct in pointing out that reversibility is a too restrictive condition for defining entropy. Classical formalism is mistaken, however, in replacing reversibility with quasi-staticity. The modern formalism shows that quasi-staticity in the classical formalism is *in fact* internal reversibility, which is the necessary and sufficient condition for the definition of entropy" [[17]:152]. Leaving aside the CKC theory, this paper focuses on the intricately interwoven relation between the classical CK theory and Gibbsian thermodynamics. The analysis taken here suggests that the CK theory is not a coherent single system but a blend of two systems: the energy physics theory, in Section 2, and Clausius' second fundamental theorem-based theory, in this section, which by extension includes Gibbsian thermodynamics. We do not have a logical structure of the CK theory to speak of and surely have no such structure of "Gibbsian thermodynamics embedded in the CK theory" to speak of. What Tisza realized was that Gibbsian thermodynamics could be investigated to discover its own structure free from the CK theory. Transforming it into MTE, therefore, is an improvement both logically and pedagogically. Generations of students of thermodynamics learning thermodynamics using Callen's excellent text can attest to it.

4. Orthodox Engineering Thermodynamics

The analysis in Section 3 places Gibbsian thermodynamics to be embedded in the Clausius' second fundamental theorem-based theory, rather than in a single system of CK theory. The latter notion is the result of a misunderstanding of the CK theory by confusing which with orthodox thermodynamics. This section argues that there is no CK theory as a single theoretical system and we should not call orthodox thermodynamics the CK theory.

The incorporation of the entropy selection law that entropy grows universally into engineering thermodynamics took the form of what I call the Dresden/MIT-School update of energy physics. It has two new elements: fundamental function of state for calculating thermodynamic relationships; control-volume formulation with exergy analysis (in addition to control-volume energy analysis first formulated by Zeuner of Dresden[22]).

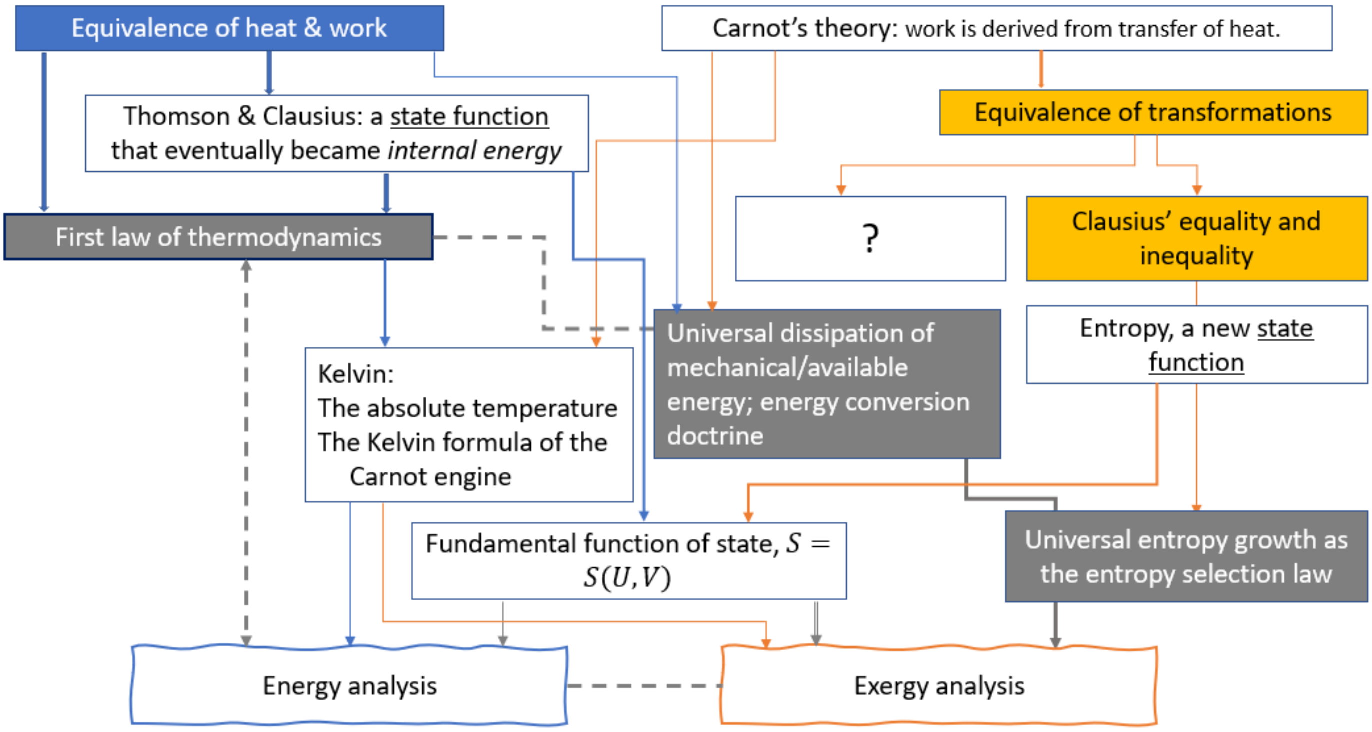

Figure 5: Orhtodox thermodynamics, the Dresden/MIT-School update of energy physics

I call the Dresden/MIT-School update *orthodox thermodynamics*, as shown in Fig. 5. With the two elements, engineers have been able to apply orthodox thermodynamics, expediently, to using fossil fuels energy with improving efficiency. Improving efficiency, famously as discovered by the economist Jevon, rather than reducing the consumption of fuels which it does in individual applications, instead leads to increase in *total* consumption of fuels. This has become known as the Jevon paradox or the rebound effect. The positive-feedback-loop of efficiency gain to increase in production/profit to rebound effect to exponential economic growth explains what has made possible the Anthropocene—the explosive industrialization and economic growth since the 1712-1843 NWCJ discovery of motive power from heat energy.

It is this orthodox thermodynamics, which is referred to as the CK theory based on two independent fundamental laws of nature, the first law and the second law—which Fig. 5 seems to suggest. That would be a mistaking interpretation.

This paper does not question orthodox thermodynamics as a milestone of scientific/engineering development and its impact on industrial/social phenomena. But it does argue that, as shown in Figs. 1 and 5, the same energy physics premise of universal dissipation of mechanical/available energy by Thomson (Kelvin), which was a declared premise without proof, was carried over in orthodox thermodynamics. Exergy analysis, therefore, reflects the absorption of the entropy selection law into that premise as suggested in Fig. 5.

In an important sense, the "Universal dissipation of mechanical/available energy" block, let us call it the "Energy-conversion doctrine" block, ***absorbed*** the entropy law as suggested in Fig. 5 manifested as the iron-chain circle (see also Fig. 6, in which the circle is referred to as the "energy physics premise circle"[1]) of "the first law ↔ the energy-conversion doctrine ↔ the entropy law ↔ exergy analysis ↔ energy analysis ↔ the first law," with the energy-conversion doctrine block wielding the control power.

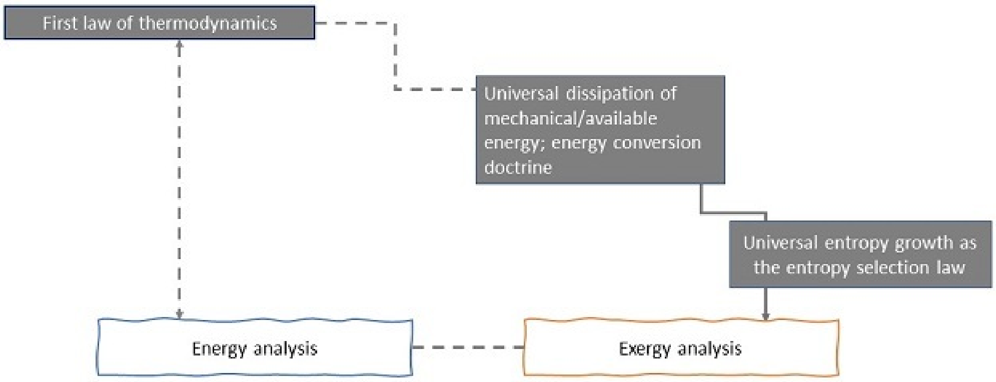

Figure 6: ***The energy premise circle*** *or the* ***energy-physics premise circle***

It is important to note that Max Planck rejected that premise:

> *The real meaning of the second law has frequently been looked for in a "dissipation of energy." This view, proceeding, as it does, from the irreversible phenomena of conduction and radiation of heat, presents only one side of the question. There are irreversible processes in which the final and initial states show exactly the same form of energy, e.g., the diffusion of two perfect gases or further dilution of a dilute solution. Such processes are accompanied by no perceptible transference of heat, nor by external work, nor by any noticeable transformation of energy. They occur only for the reason that they lead to an appreciable increase of the entropy.* ([[23]: 103–104])

Despite Planck's analysis, the damage of energy physics has been persistent: As Daub, the history-of-science scholar, noted, "Entropy and the dissipation of energy are as inseparable as Siamese twins in the thought of every student of thermodynamics"[24]. But Planck's critique of energy physics premise is incontrovertible (see Sect. 5.10 of A Treatise[17], the paragraph below, and Sect. 5.3).

Uffink, the historian of science, in a detailed analysis of the second law literature, commented on the issue spot-on,

> *Planck puts the second law, the concepts of entropy and irreversibility at the very centre of thermodynamics. For him … Increase of entropy is therefore a necessary and sufficient criterion for irreversibility. Before Planck's work there were also alternative views. We have seen that Kelvin attributed irreversibility to processes involving special forms of energy conversion. This view on irreversibility, which focuses on the 'dissipation' or 'degradation' of energy instead of an increase in entropy was still in use at the beginning of the century; see e.g., Bryan (1904). Planck's work extinguished these views, by pointing out that mixing processes are irreversible even though there is no energy being converted or degraded* ([[25]:42-43]).

There is a dichotomy between the Clausius-Gibbs synthesis, which is free from the energy premise's grasp, and orthodox thermodynamics under the clutch of the energy premise. Contrary to the common wisdom, this dichotomy prevented the CK reconciliation of the dichotomy between Carnot and joule to its successful conclusion. In the second fundamental theorem, I shall argue in Sect. 5, we can find the tool that finally extinguishes the energy physics premise circle of equating dissipation of energy with entropy growth.

5. A New Clausius Synthesis: *Reversible-like compensation of transformations*

5.1. The two parts of the second fundamental theorem

The above summary of Clausius' arrival at the result *(II)* is well-known and hugely important, but it represents only one slice of his generalization of Carnot's ideas as given in **(i) to (v).** And the statement of the **fundamental theorem** itself, which was repeated by him in the Ninth Memoir "to show the general importance of the magnitudes which I have introduced…":

> *The second fundamental theorem asserts that all transformations occurring in nature may take place in a certain direction, which I have assumed as positive, by themselves, that is, without compensation; but that in the opposite, and consequently negative direction, they can only take place in such a manner as to be compensated by simultaneously occurring positive transformation"* [[10]:364]

Rather than emphasizing *the quantitative equivalent relationships* between/among transformations as the theorem of the equivalence of transformations does, here Clausius reasserts the ideas underlying replacement and condition-of-balance to be the three *qualitative ideas* of preferred direction (i), the fact that for each preferred direction there are positive (natural) and negative (unnatural) directions (ii), and the idea of compensation (iii). The basic problem remains "a relation between two kinds of transformations, [e.g.,] the transformation of heat into work, and the passage of heat from a warmer to a colder body" [[9]:116]. Compensation is the general term for describing this relation. When the relations between the two kinds are reversible, the relations are called equivalent compensation (i.e., reversible compensation) with the algebraical sum of equivalence-values being zero. For each idealization of reversible compensation, there are an infinite number of "reversible-like compensated transformations." Focus on equivalence, correspondingly on the definition of entropy, is clearly only one slice of Clausius' innovation.

There is a good reason for such a narrower focus of students of thermodynamics as it is evident in Gibbs' influential obituary article on Clausius, "Rudolf Julius Emanuel Clausius" in the *Proceedings of the American Academy* (new series, vol. XVI, pp. 458–465, 1889)[26], and the volume on *The Second Law of Thermodynamics* edited by J. Kestin[27]. In both such widely accessible and influential sources on Clausius' body of work, the selected papers by Clausius are First Memoir, which Gibbs called "an epoch in the history of physics," in which "the science of thermodynamics came into existence," and Sixth Memoir and Ninth Memoir, in which the significance of the second fundamental theorem is linked with the introduction of *entropy*. Both sources did not select the Fourth Memoir, the importance of which has been made only in relatively recent time by Cropper[15], Zwier[28], and Saslow[6].

Going back to Clausius' Fourth Memoir, we find Eqn. (11), $N = \oint \frac{\delta Q}{T}$ ([[9]:127]). It is at this point that Clausius wrote, "If the process is *reversible*, then, … , we can prove …*that the transformations which occur must exactly cancel each other, so that their algebraical sum is zero.*" Which is, for the case of two transformations in reversible relation, the equivalence of transformations (6) relabeled as *(II.1.1),*

$$Q_1[(1/T_2) - (1/T_1)] - Q/T = 0 \qquad (II.1.1)$$

For the case of an arbitrary reversible cycle that can be broken down to an infinite number of steps,

$$\oint dQ/T = 0 \qquad (II.1.2)$$

That is, if the processes are **approximately reversible** (i.e., reversible-like), the condition of compensation of the six-stage cycle is

$$Q < T \cdot Q_1[(1/T_2) - (1/T_1)] \qquad (II.2.1)$$

That of a cycle of an infinite number of steps is,

$$\oint dQ/T > 0 \qquad (II.2.2)$$

Which are referred to as the "second fundamental theorem of reversible-like compensation" (see Fig. 8 in Sect. 5.3 below). I use the term here to mean the inclusion of reversible-like compensated transformations: while in its reversible idealization it becomes the **single event** of compensated transformations in equivalence characterized by equality of Q/T and $Q_1[(1/T_2) - (1/T_1)]$, compensation in general or reversible-like compensation comprises **all events** within a Poincare range (see Sect. 5.2 for the meaning of which).

Consider another five-stage Clausius cycle (alternative to Fig. 3 in which a converted heat Q^{t_1} is supplied at T_1), in this version a converted heat Q^{t_2} is supplied at T_2. That is, the original $1 \rightarrow 2$ step is now $1^{t_2} \rightarrow 2^{t_2}$. For this case, *(II.1.1)* and *(II.2.1)* reduce to, respectively,

$$W_{rev} = Q = Q_1 T_2[(1/T_2) - (1/T_1)] = Q_1[1 - (T_2/T_1)], \qquad (8)$$

which is the Kelvin formula of the Carnot engine, and

$$W_{rev-like} = Q < Q_1[1 - (T_2/T_1)] \qquad (9)$$

In the Kelvin formula, (8), a partial amount of supplied heat Q_1, $Q_1[1 - (\frac{T_2}{T_1})]$, is converted into work with the rest, $Q_1(\frac{T_2}{T_1})$, discharged into a T_2 heat sink. Note that the same physical interpretation can apply to the five-stage cycle in Fig. 3 interpreted as a simple Carnot cycle with the amount of heat supplied being $Q_1 + Q^{t_1}$. In this case, the converted heat and discharged heat according to (8), $(Q_1 + Q^{t_1})[1 - (T_2/T_1)]$ and $(Q_1 + Q^{t_1})(T_2/T_1)$, can be shown by using (6) to be Q^{t_1} and Q_1, respectively. However, such conventional interpretation in accordance with a simple Carnot cycle is that based on the single, monolithic drive perspective, which, while correctly representing the Carnot engine as a specific "heat to work transformation," distorts the true nature of generalized "heat to work transformation" making the essence of reversible or reversible-like compensation hidden.

For that, we need to consider this new five-stage Clausius cycle by adjusting the $1^{t_2} \to 2^{t_2}$ step to be $1' \to 2'$ at a temperature infinitesimally lower than T_2 as shown in Fig. 7. In *(II.1.1)*, as Clausius intended, the heat transmission of natural direction is separated from the transformation of heat into work of unnatural direction. The Clausius formula of the Carnot engine, in accordance with Fig. 7, is

$$W_{rev} = Q = T_2 \cdot Q_1[\frac{1}{T_2} - \frac{1}{T_1}] \qquad (10)$$

In which, an amount of $Q = Q^{t_2}$ corresponding with the area under curve 1' -2' is extracted from the t_2 (T_2) heat reservoir (as suggested by the arrow direction in Fig. 7) having it delivered as work of the area enclosed by 3-4-5-7-3 to a work reservoir. We shall refer the cycle as interpreted in Fig. 7 as the Carnot-Clausius cycle of the Carnot engine.

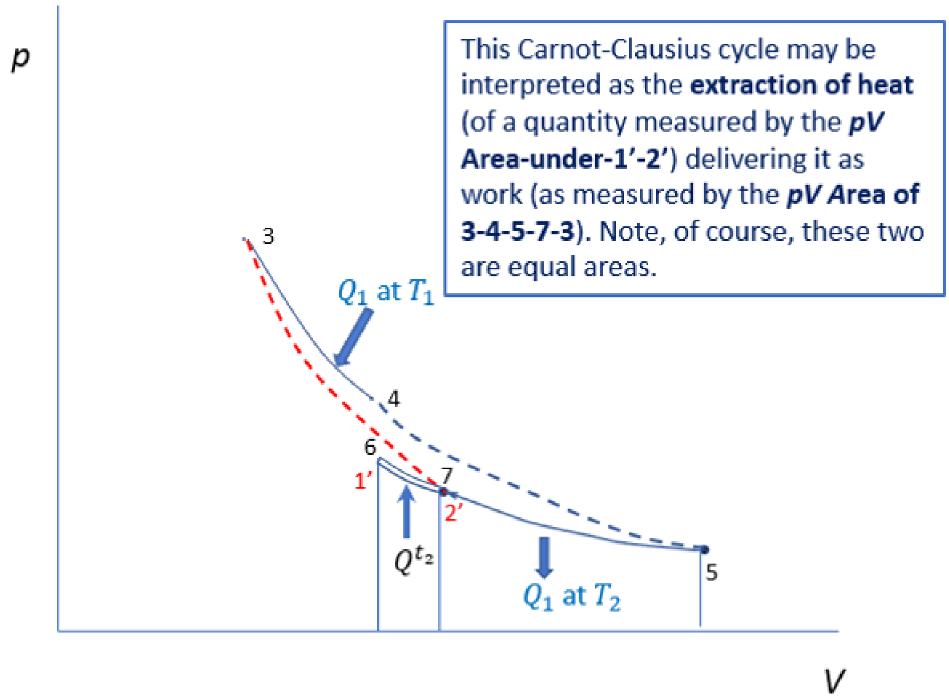

Figure 7: The Carnot-Clausius cycle of the Carnot engine

Once the step $1' \rightarrow 2'$ in Fig. 7 is identified to be a heat extraction process, as a matter of operational steps we see no difference among the "step $1^{t_1} \rightarrow 2(3)$ in Fig. 3," the "step $1 \rightarrow 2$ in Fig. 2," and the "step $1' \rightarrow 2'$ in Fig. 7." All three requires temperature differences maintaining the necessary heat transmission processes. Operationally, the so-called conversion-of-heat transformations are all identifiable to be extraction-of-heat transformations. The question is then, "is to name them conversion or extraction simply a semantic question?" In the following, reasons why the naming is a substantive matter are made. This being the case, of the three figures, Fig. 2, Fig. 3, and Fig. 7, graphically speaking Fig. 3 is easily to be interpreted as a single Carnot cycle leading to the interpretation of conversion. For this reason, it is advisable to think of the Carnot engine as a five-stage cycle such as Fig. 7. When one does think of the Carnot engine in terms of Fig. 3, it should be as a five-stage cycle in terms of $W_{rev} = Q^{t_1} = T_1 \cdot Q_1\left[\frac{1}{T_2} - \frac{1}{T_1}\right]$, not as a four-stage simple Carnot cycle in terms of the Kelvin formula, $\left(Q_1 + Q^{t_1}\right)\left[1 - \left(\frac{T_2}{T_1}\right)\right]$. Even though the two expressions yield the same value.

Though he was not always consistent, that both step$1 \rightarrow 2$ in Fig. 2 and step $1' \rightarrow 2'$ in Fig. 7 should not be called "conversion of heat into work" is in line with Clausius' true thinking as he noted in Eighth Memoir:

> *The starting point of my treatment of the second fundamental theorem in the mechanical theory of heat, was the difference which exists between the transfer of heat from a warmer to a colder body, and that from a colder to a warmer one; the former may, but the latter cannot, take place of itself. This difference between the two kinds of transmission being assumed from the commencement, it can be proved that an exactly corresponding difference*

> *must exist between the conversion of work into heat, and the transformation of heat into work; that heat, in fact, cannot simply transform itself into work (another simultaneous change, serving as a compensation, being always necessary thereto), whereas the opposite transformation of work into heat may occur without compensation.*

A clear difference was made by Clausius in this paragraph between "conversion" and "transformation" rejecting symmetry between the two directions. One may surmise that "conversion" is used for a particular kind of transformations that may occur uncompensated or like mechanical transformations in accordance with efficient causation. This identification of "conversion" with "transform itself" of efficient causation has been made in another paper[14]. A discussion of the meaning of causations, including the difference between efficient causation and efficacious causation, can also be found in paper[14][28]. The first reason that name matters is that "conversion" carries the baggage of efficient causation of mechanical science with implication of false symmetry of transformation of heat into work and transformation of work into heat.

With the drive-force (the equivalence value of heat transmission) in Figs. 2 and 7 a given fixed value, the amount of transformed heat into work is proportional to the temperature of the heat reservoir T, i.e., lower amount of extracted heat with lower reservoir temperature. Whereas a widely shared idea of students of thermodynamics is that a heat engine output becomes greater (of higher amount) with lower reservoir temperature in accordance with the Kelvin formula (8). This is explained by noting that in this case when the drive-force, the equivalence-value of the transformation of natural direction, $Q_1[\frac{1}{T_2} - \frac{1}{T_1}]$, is not a fixed value, instead, being a strongly dependent function of T_2. So that the product of a lower T_2 and an even higher $Q_1[\frac{1}{T_2} - \frac{1}{T_1}]$ becomes higher with lower reservoir temperature T_2. This happens when the heat reservoir in the Kelvin formula doubles as "sink" for the source-sink drive and as "reservoir" for heat supply to the cycle. The second reason that name matters is that "conversion" fails to decipher the role of heat reservoir, the true roles of which become clear only when we look at the problem as extraction of heat (see Sect. 6 for more on the role of heat reservoir).

5.2. A common property, entropy growth potential

In recent years, I, before a close reading of Fourth Memoir to appreciate the implication of Clausius' second fundamental theorem as articulated in the above, have arrived at a result,

> *For a given initial state of an system-surroundings arrangement and its defined final state for the system that the system will proceed to under spontaneous condition, change in the entropy of the universe(system + surroundings) for this spontaneous event has a special meaning: Following an insight of Poincare that this "spontaneous change in total entropy" is a common property ("property common to all possibilities") shared by all events (as defined by the pair of initial state and final state) falling within the range delineated by the bookends of*

> *spontaneous event and reversible event.*[12][17]

I called this common property *entropy growth potential (EGP).* That is, EGP is the drive-force, or the equivalence-value of the transformation of natural direction, that compensates the process for work production of unnatural direction; every event within the Poincare range is compensated by the same common equivalence-value with specific resulting entropy growth corresponding with the specific work produced.

The analytical expressions of which are, for the case of system-surroundings with EGP being a function of surroundings' temperature, T_0,

$W_{rev} = Q = T_0 \cdot EGP\left(T_0\right)$, correspondingly,

$$W_{rev-like} \leq T_0 \cdot EGP\left(T_0\right) \qquad (II.2.3)$$

For the case of isolated composite systems with their EGP to be independent of surroundings,[29][17][2]

$W_{rev} = Q = T_{Reservoir} \cdot EGP$, correspondingly,

$$W_{rev-like} \leq T_{Reservoir} \cdot EGP \qquad (II.2.4)$$

Where $T_{Reservoir}$, like T in ***(II.2**.1)*, can be the temperature of any available reservoir.

This independently arrived result in[12][17] is consistent with the second fundamental theorem: For cyclic processes involving two transformations, EGP is interchangeable with the equivalence values of the transformations of natural direction that compensate the other transformations; for generalized processes, EGPs represent their driving forces as equivalence values of transformations of natural direction do for cyclic processes; another innovation in the concept of EGPs is the explicit reference to the Poincare range in its application and that of calling a specific event in the range a reversible-like event/process.

5.3. A new Clausius synthesis

I call the second part of the second fundamental theorem the *second fundamental theorem of reversible-like compensation.* The incorporation of the "second fundamental theorem of reversible-like compensation" is shown in purple color in Fig. 8. The two parts of the second fundamental theorem are "equivalence of transformations," the first part, and "*reversible-like* compensation of transformations," the second part. In the figure, the first fundamental theorem is shown in blue, the first part of the second fundamental theorem in brown-yellow, and the second part of the second fundamental theorem in purple.

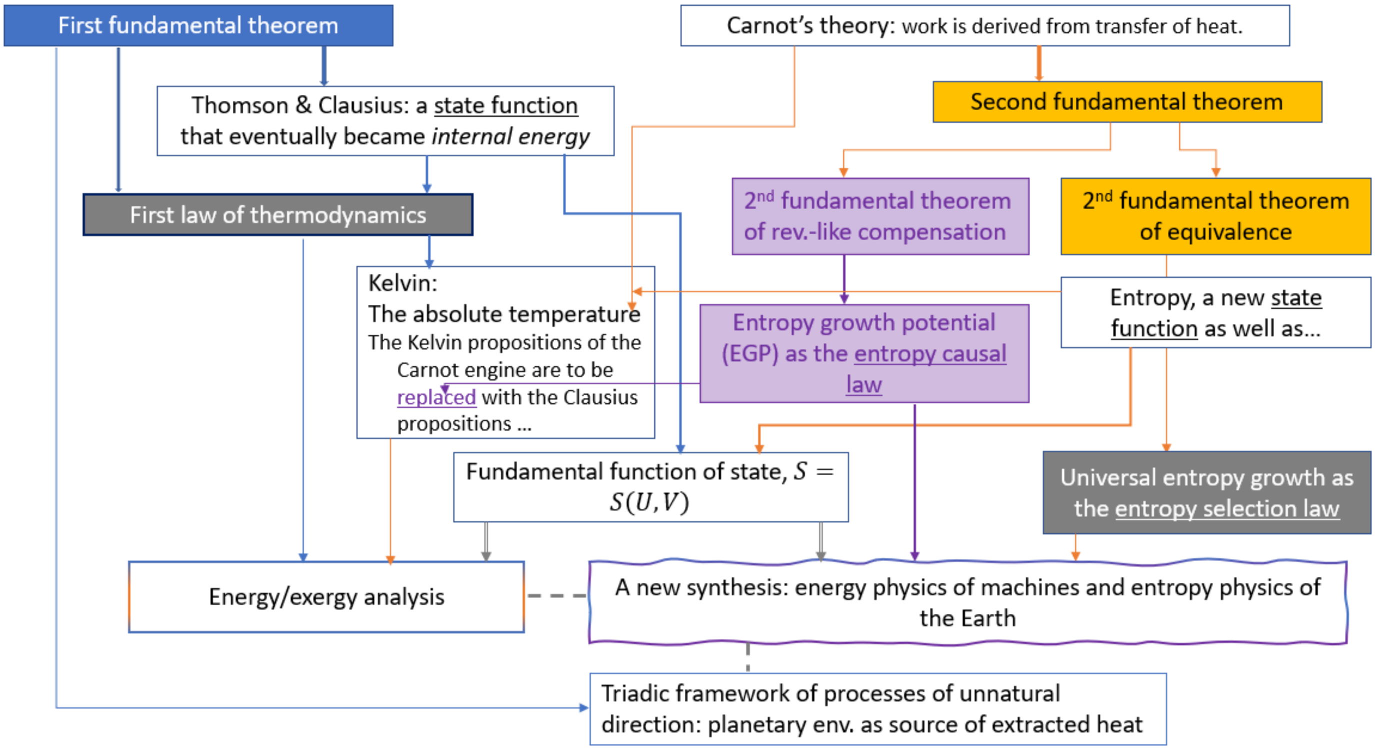

Figure 8: ***A new Clausius synthesis****, a theory resulted from the conceptual differentiation of caloric into energy/mechanical-energy, entropy, and heat as based on two fundamental laws: the first law which is stripped of its causal agency and the second law which has two parts, as a selection law and a causal law.*

The NWCJ discovery of the motive power from heat energy discovered that the erstwhile source for heat and light, fire, can also be source for mechanical power. Sadi Carnot pointed out that mechanical power is derived from the unidirectional transfer of heat though he assumed that heat is "conserved" during the process (Carnot's theorem). James Prescott Joule demonstrated that in the production of work heat is consumed, instead, energy is "conserved." William Thomson erected the energy physics edifice by the synthesis of the first fundamental theorem and Carnot's theorem, which he transformed it into the energy-physics premise of universal-dissipation-of-energy/energy-conversion-doctrine. The "consumption" of heat energy became the defining notion in energy physics in Fig. 1 and orthodox thermodynamics in Fig. 5. And the definition of energy was and still is[1][30][31][32] the "capacity for doing work."

Rudolf Clausius, "by his restatement of Sadi Carnot's principle known as the Carnot cycle, he gave the theory of heat a truer and sounder basis" (from a Wikipedia page). His restatement includes the above-stated five points of (i) to (v). Clausius' original notion of compensation (iii) was eventually developed into the "*equivalence* of transformations," which, the first part of the theorem as *Eqn. (**II**.1.2)*, is widely known. In the new Clausius synthesis as shown in Fig. 8, the above (iii) is restated as,

> *"Compensation of two transformations, a transformation of natural direction and a "heat into work" transformation of unnatural direction, is quantitatively expressed in terms of reversible-like-compensation of transformations."*

This is shown in Fig. 8 as the second part of the second fundamental theorem, which results in the EGP principle as the entropy causal law. Note that *(**II.2**.2)* is of course an integrated part of the second fundamental theorem of equivalence but its use is in the sense of the entropy law as an entropy selection law, whereas *(**II.2**.1), (**II.2**.3),* and *(**II.2**.4)* collectively represent an entropy law as an entropy causal law. The entropy causal law, the law that a transformation of natural direction enables the extraction of heat from a heat reservoir delivering it into work, supplements the energy physics premise in Fig. 5 and Fig. 6. That is, the concept of reversible-like compensation of Clausius' synthesis cuts the Gordian knot of the energy premise, the "circle" of Fig. 6, finally succeeding in reconciliating the dichotomy between Carnot and Joule to its logical conclusion.

Hicks noted, "The definition of energy as the capacity to do work is generally presented in the same chapter as the definitions of kinetic energy, potential energy, and mechanical energy. Since mechanical energy can be fully used to do work, no problem arises in that context" ([[24]:530]). Mechanical energy indeed is the capacity for doing work. But the newly discovered energy (the NWCJ discovery) cannot be fully used to do work. Energy physics and orthodox thermodynamics, therefore, "have been applying thermodynamics in the context of the pre-industrialization of mechanical-sciences"[2]. That means: the common "energy" view inherited from the equivalence of heat and work is a mischaracterization of the NWCJ discovery. The real discovery is the discovery—in accordance with the concept of reversible-like compensation—of the production of work to be derived/compensated from "transformations of natural direction" found in fuels and in renewables, not of the production of work to be derived from energy found in fuels.

6. Discussion

A crucial advantage exists in separating what drives the production of work from where the work comes from, the former is the purview of the second law or the second fundamental theorem while the latter that of the first law or the first fundamental theorem. Separating the what-where work questions should have been a logical follow-up to the formulation of two laws. Orthodox thermodynamics and the simple Carnot cycle have failed to take the logical step, which was the source of all the puzzlement.

More than that, the industrialization based on orthodox thermodynamics' understanding on heat and energy was a Faustian bargain: There is a school of thought by the name of entropy pessimism. Entropy pessimists believe that human use of energy intrinsically degrade our ecosystem because the entropy law asserts the inevitable entropy growth and with that the inevitable accumulation of waste heat. But, with what drives the production of work to be EGP, a new insight emerges from the realization that EGP in itself does not automatically leads to the production of work as a process of efficient causation does. Instead, in the EGP framework the real meaning of equivalence of heat and work is found—once heat is relieved of "a schizophrenic double role that it cannot fulfill" ([[33]:179-180])— in the requirement of a heat reservoir so that the EGP can enable the extraction of heat from which delivering the heat in the form of work, i.e., mechanical energy, to a mechanical-energy reservoir—i.e., a triadic framework of EGP, heat reservoir, and mechanical-energy reservoir[1]. That is, heat of a heat reservoir is where the work comes from. In orthodox thermodynamics and the simple Carnot cycle, however, with the conflation of the two questions the same heat-reservoir is used as a heat reservoir-source from which heat is obtained and as a heat sink for what drives the production of mechanical energy. When the heat reservoir serves a double roles, which is the case with the usage of fossil fuels, activities in the production of work and power always result in the production of waste heat. Humankind acquired the power of "unlimited" supply in fossil fuels but with the bargain of inevitable accumulation of waste heat.

As a practical and social-consideration matter, a simple Carnot cycle and orthodox thermodynamics represented the *philosophical/scientific accord* of the Anthropocene, the accord that has enabled incredible economic growth. The bargain is that the economic growth is unsustainable as a result of accumulation of waste heat.

Entropy does grow inevitably. But the accumulation of waste heat is not inevitable. Accumulation of waste heat is the result of fossil fuel usage which necessitates the planetary environment serving as both heat reservoir and heat sink. The latter is not an intrinsic role of heat reservoir thermodynamically speaking but the consequence of the fossil-fuel energy-regime, the consequence that entropy growth potential (EGP) requires a heat sink. That physics and thermodynamics do not require "transformations of unnatural direction" to have a heat sink has been demonstrated with the examples of isolated composited systems in References [[29] 2014], [[17] 2019], and [[2] 2022]. For isolated composite systems, their EGPs are independent of any heat reservoir temperature since no heat sink is required. Unlike fossil fuels energy its burning requires a heat sink, the transformation of isolated composite systems into work requires only a heat-reservoir for heat source. Instead of producing waste heat, such activities of production of work lead to the extraction of heat from the environmental heat reservoir. The last point applies to the application of renewables as well.

The use of renewables does not require a planetary environment as a heat sink; the radiative interactions occur among the Sun, the Earth, and space; the planetary environment is not a part of the equation for EGP (the planetary environment is energy-neutral in this radiative heat exchange). The environmental heat reservoir in the case of renewables-EGP serves only as a heat-reservoir-source. In the fossil fuel energy regime, we have been blinded to the possibility of freedom from energy-powered economic activities leading to inevitable production of waste heat. This has been sometime referred to as entropy pessimism. Moving forward to the renewables-powered regime, we can see compelling advantage of renewables not only for the benefit that their energy forms are renewed diurnally but also for the fundamentally changed nature of the footprint of their usage. That is, the more we apply renewables-EGP the more heat is extracted from the planetary heat-reservoir-source. The third reason that name matters is, therefore, rejection of the term is a part of cutting the Gordian knot, which (the separation of the what-where work questions) unfolds the true meaning of the NWCJ discovery, thus, resolves the dilemma facing the Anthropocene of entropy pessimism vs. economic growth.

Unfoldment of the true meaning of the NWCJ discovery will serve as a philosophical accord for Anthropocene 2.0.[34] This results in the possibility of an incremental decrease in the entropy of the planet, a Gaia-like[35] processes/transformations for the planet Earth. [[34] 34] It is noteworthy that William James Sidis cited, in his 1925*The Animate and the Inanimate*[36], Lord Kelvin,

> *It is conceivable that animal life might have the attribute of using the heat of surrounding matter, at its natural temperature, as a source of energy for mechanical effect . . . .The influence of animal or vegetable life on matter is infinitely beyond the range of any scientific enquiry hitherto entered on. Its power of directing the motions of moving particles, in the demonstrated daily miracle of our human free-will, and in the growth of generation after generation of plants from a single seed, are infinitely different from any possible result of the fortuitous concurrence of atoms.*

The miracle Kelvin alluded to has a perfectly rational account in Clausius' thermodynamics. Animals and vegetable life can do it, so can a planetary-wide Anthropocene 2.0.

7. Conclusion

The NWCJ discovery of the motive power from heat energy signaled the beginning of the Anthropocene and at the same time posed a long-standing intellectual challenge in physics of the Carnot vs. Joule dichotomy. The conventional wisdom is that Clausius and Kelvin have reconciled the dichotomy in the form of the Clausius-Kelvin theory. A key element of the resolution is the conceptual differentiation of the concept of caloric into energy, entropy and heat in terms of the two laws of thermodynamics. Analysis in this paper rejects the conventional wisdom concluding that there is no Clausius-Kelvin theory as a single system of theory: Kelvin's treatment and Clausius' treatment are fundamentally different; the energy premise of Kelvin precluded his theory from achieving conceptual differentiation in the true sense whereas Clausius' theory did achieve that in its progeny, Gibbsian thermodynamics, leading to macroscopic thermodynamics of equilibrium; we can find in Clausius' theorem of entropy the framework for reforming engineering thermodynamics reformulating the two laws in alignment with the duality of the what-where work questions. An outline of reforming engineering thermodynamics is put forward with the cutting of the Gordian knot of the energy premise resulting in an engineering thermodynamics having similar structure, as shown in Fig. 8, to that of Gibbsian thermodynamics in Fig. 4. The conceptual differentiation of caloric into energy, entropy, and heat is also reflected in the theory's triadic framework of mechanical-energy, entropy growth potential, and heat reservoir.

A case that, as a part of rejecting the energy premise, we should not refer to the production of work from heat to be the conversion of heat into work has been made, reasons for which are summarized:

- The first reason that name matters is that “conversion” carries the baggage of efficient causation stricture of mechanical science whereas compensation of processes of unnatural direction requires efficacious causation.
- The second reason is that “conversion” fails to decipher the role of heat reservoir, the intrinsic role of which is heat reservoir-source not as heat sink; sustainable economic activities in the long run become possible only when we see the planetary environment as heat-reservoir as source for the extraction of heat.
- The third reason, therefore, is that rejection of the term is an integral part of the cutting the Gordian knot, which unfolds the true meaning of the NWCJ discovery, thus, resolves the dilemma facing the Anthropocene of entropy pessimism vs. economic growth. Unfoldment of the true meaning of the NWCJ discovery will serve as a philosophical accord for Anthropocene 2.0.

In the reformed engineering thermodynamics, the real discovery of the NWCJ discovery is the discovery of the production of work to be derived from *spontaneous transformations* found in fuels and in renewables, not of work to be derived from *energy*found in fuels. Anthropocene 2.0 is basically the idea that only spontaneous transformations found in renewables are sustainable.

The existential threat facing the Earth is greenhouse-gas emissions in the short term but in the long run the Earth faces global entropic disorder, sometime referred to as the existential threat of entropy pessimism. We may call the former the proximate threat and the latter the ultimate threat. Nuclear energy is being promoted by some since it does not emit greenhouse-gas. That is true but it is noted that nuclear energy is not a solution to the ultimate threat while the renewables is solution to both threats based on the analysis of this paper.

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NOTE: Kelvin used the same kind of terms as quoted here in “On the Miracle of Life”: Excerpt from an address at the annual meeting of the Christian Evidence Society, May 23, 1889, as quoted in Heros of the Telegraph by J. Munro.

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