Article

2024 *Key Reflections* on the 1824 Sadi Carnot's *"Réflexions"*

Milivoje Kostic *

Posted Date: 13 February 2024

doi: 10.20944/preprints202402.0605.v1

Keywords: Sadi Carnot; Carnot cycle; Reversibility; Heat Engine; Contradiction impossibility; Maximum engine efficiency; Thermodynamics; Second law of thermodynamics

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 February 2024 doi:10.20944/preprints202402.0605.v1

Article

2024 *Key Reflections* on the 1824 Sadi Carnot's *"Réflexions"*

Milivoje M. Kostic

Professor Emeritus of Mechanical Engineering, Northern Illinois University and USA
* Correspondence: *kostic@niu.edu* * kostic.niu.edu/ * http://Carnot.MKostic.com

Abstract: This author is not a philosopher nor historian of science, but an engineering thermodynamicist. In that regard and in addition to various philosophical *"why & how"* treatises and existing historical analyses, the physical and logical *"what it is" reflections, as successive Key Points*, where *a key reasoning infers the next one*, along with novel contributions and original generalizations, are presented. We need to keep in mind that in Sadi Carnot's time (early 1800s) the steam engines were inefficient (below 5%, so the heat in and out were comparable within experimental uncertainty), the conservation of *caloric* flourished (might be a fortunate misconception), and many critical thermal-concepts, including the conservation of energy (The *First Law*) were not even established. *If Clausius and Kelvin were "fathers of thermodynamics" then Sadi Carnot was the "grandfather" [Kostic, 2023 July 24], or better yet,* ***Sadi Carnot was the "Forefather of Thermodynamics-to-become"*** *[Kostic, 2023 October 29].*

Keywords: Sadi Carnot; Carnot cycle; Reversibility; Heat Engine; Contradiction impossibility; Maximum engine efficiency; Thermodynamics; Second law of thermodynamics

---

"The motive power of heat is independent of the agents employed to realize it; its quantity is fired solely by the temperatures of the bodies between which is effected, finally, the transfer of the caloric." – by Sadi Carnot, English Translation by Robert H. Thurston [1].

★★★

Sadi Carnot, at age 28, published in 1824, now famous "*Réflexions sur la puissance motrice du feu* (Reflections on the Motive Power of Fire [1])." Carnot's reasoning of *"heat engine reversible cycles and their maximum efficiency"* is in many ways in par with Einstein's relativity theory in modern times. It may be among the most important treatises in natural sciences.

No wonder that Sadi Carnot's masterpiece, regardless of flawed assumption, was not appreciated at his time, when his ingenious reasoning of ideal "*heat engine reversible cycles*" was not fully recognized, and may be truly comprehended by a few, even nowadays. We are often trapped in our own thoughts and words (especially if nonnative) and the subtle holistic meanings are to be read "between the lines."

The "*Key Reflections*" presented here are founded on the Sadi Carnot's *Reflexions* (English translation by Robert H. Thurston [1]) and on the developments of thermodynamics by the pioneers [2,3], emphasizing this author's views as an engineering thermodynamicist [4,5,6], as a complement to the existing science historians and science philosophers' analyses [7,8,9,10,11]. Therefore, a key thermodynamic logic is used to recognize and infer the most probable sequential developments of Sadi Carnot's ingenious discoveries, as well as to reflect on the related analyses and misconceptions, considering the current state of knowledge. The sequential *Key Points*, where a key reasoning infers the next one, along with *Miss Points* (persistent post-misconceptions and fallacies by others), including novel contributions and original generalizations as *Key NOVEL-Points* with *Key Takeaways*, are presented.

 doi:10.20944/preprints202402.0605.v1

Key Points: Most probable sequential developments of Sadi Carnot's ingenious discoveries

I. *The source of the heat engine "motive power" is "caloric fall" ("temperature fall" or difference of the caloric)*
II. *The "temperature fall," as source of engine motive power, should "not be wasted," but minimized in any "work-less heat transfer process"*
III. *All motive frictions and other dissipative processes should be minimized in order to maximize engine power and efficiency*
IV. *Reversible Cycles: Isothermal heat transfer and other frictionless processes make an engine process or cycle reversible*
V. *Reversible cycles must all have equal and maximum efficiency*

Miss Points: Persistent post-misconceptions and fallacies by others

1. *The well-known Carnot efficiency formula, $\eta_{Carnot} = W_{Rev|Max}/Q_H = (1 - T_L/T_H)$, was not established by Sadi Carnot, but much later by Kelvin and Clausius*
2. *The cause and source for motive power is the temperature difference, in principle, but not directly, not linearly dependent as misstated by some*
3. *The heat transferred out of the Carnot cycle at lower temperature is "not a waste heat" as often stated, but it is "useful quantity", necessary for completion of the cycle*
4. *Sadi Carnot could not had been thinking of "any other caloric" but heat, to imply "entropy-like quantity" as speculated by some*

Key NOVEL-Points: Novel contributions and original generalizations

1. *"Reversible and Reverse" Processes and Cycles Dissected*
2. *Maximum Efficiency and "Reversible Equivalency" Scrutinized*
3. *Reversible Contradiction Impossibility ("Reductio ad absurdum")*
4. *Reversible Carnot Cycle Efficiency Is Misplaced — It is NOT the "Cycle efficiency" but a "Thermal energy-source 'work-potential efficiency'"*
5. *The Carnot (Ratio) Equality and Clausius Equality (Cyclic integral) are special cases of relevant "Entropy boundary integral" for reversible stationary processes*

★★★

Key Point I: *"The source of the heat engine "motive power" is "caloric fall" ("temperature fall" or difference of the caloric)*

Hot *caloric* (heat at high temperature) has been the cause and source of the motive power (produced work) in the steam engines (the heat engines in general). Since at the time the *caloric* was believed to be conserved (might be a fortunate misconception leading to the critical analogy with the waterwheel), then Sadi Carnot inferred that its hotness is producing the motive power while being cooled: "*motive power due to the [temperature] 'fall of the caloric'* " Therefore, all else the same, if temperature of heat is higher than the surrounding's, the higher 'temperature fall' through an engine, the more motive power will be (the more efficient engine), analogous to the more power from more "water-fall" from higher elevation through a water-wheel per unit of water flow. In Sadi Carnot's words, *"The temperature of the fluid should be made as high as possible, in order to obtain a great fall of caloric, and consequently a large production of motive power [1]."*

Key Point II: *The "temperature fall," as source of engine motive power, should "not be wasted," but minimized in any "workless heat transfer process"*

This is the most critical and ingenious reasoning by Sadi Carnot ["*wherever there exists a difference of temperature, motive power can be produced. [1]*"] that led to inference of ideal reversible cycles, the most critical concept of Carnot's discovery. If the temperature difference is the cause and source of motive power, then, if it is "consumed" during the heat transfer without work extraction, then its work potential would be lost, so the temperature difference during heat transfer should be minimized, i.e., be infinitesimal, ideally the heat transfer should be isothermal: *"need for re-establishing temperature equilibrium for caloric transfer … in the bodies employed to realize the motive power of heat there should not occur any change of temperature which may not be due to a change of volume [1]."*

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 February 2024 doi:10.20944/preprints202402.0605.v1

Key Point III: *All motive frictions and other dissipative processes should be minimized in order to maximize engine power and efficiency.* Mechanical processes should be ideally frictionless to avoid work waste, i.e., dissipation losses.

Key Point IV: *Reversible Cycles: Isothermal heat transfer and other frictionless processes make an engine process or cycle reversible*

This is a monumental and crucial "*reversibility concept*" with far-reaching consequences. Reversible processes and cycles could effortlessly (without external compensation) reverse back-and-forth in perpetuity (like *perpetual motion*), therefore without any degradation or loss, being perfect and with maximum possible efficiency. They take place at infinitesimal potential difference in either direction (in limit equipotential process, no potential loss of quality), without any quantity nor quality degradation, including conservation of the motive power or work potential. More details at *Key NOVEL-Point 1*.

Key Point V: *Reversible cycles must all have equal and maximum efficiency*

This "*key discovery*" (*Carnot Theorem*) was ingeniously inferred by Sadi Carnot by reasoning that otherwise would result in creation of conserved caloric and/or perpetual motion: *"the maximum of motive power resulting from the employment of steam is also the maximum of motive power realizable by any means whatever [1]."* This powerful perception is the most important and ingenious reasoning of Sadi Carnot, and it has far reaching consequence as demonstrated much later by Kelvin and Clausius, and other Sadi Carnot's followers. It is further elucidated in *Key NOVEL-Point 2*, and in *Key NOVEL-Point 3* it is further generalized as "*Reversible Contradiction impossibility*."

The selected and persistent post-misconceptions and fallacies by others are also presented as *Miss Points* next:

Miss Point 1: *The well-known Carnot efficiency formula,* $\eta_{Carnot} = W_{Rev|Max}/Q_H = (1 - T_L/T_H)$ *, was not established by Sadi Carnot, but much later by Kelvin and Clausius*

Sadi Carnot inferred in 1824 the maximum heat engine efficiency as implicit function of thermal source-and-sink reservoirs' *High*-and-*Low* temperatures only [$\eta_{Rev|Max} = W_{Rev|Max}/Q_H = f_C(t_H, t_L)$]. However, the well-known *Carnot efficiency* formula, $\eta_{Carnot} = W_{Rev|Max}/Q_H = (1 - T_L/T_H)$, sometimes attributed as developed by Sadi Carnot, was actually developed much later in 1850s, first by Kelvin using ideal gas and later by Clausius in general, and named "*Carnot efficiency*." Paradoxically, it is shown here that Carnot, Kelvin and Clausius concepts of maximum, reversible cycle efficiency is misplaced, since fundamentally the Carnot cycle efficiency is not the "reversible cycle efficiency" *per se*, but a thermal energy-source *'work-potential efficiency'*, see *Key NOVEL-Point 4*. After all the Carnot cycle efficiency does not depend on the cycle in any way, but depends on the thermal reservoirs' temperatures only.

Miss Point 2: *The cause and source for motive power is the temperature difference, in principle, but not directly, not linearly dependent as misattributed by some*

Carnot stated that temperature difference is, in principle, cause and source for motive power, but not directly, not linearly dependent as misquoted by some [$W_{Max} = Q_H \cdot f_C(t_H, t_L) \neq f(t_H - t_L)$, not function of $\Delta t = t_H - t_L$ only]. *"In the fall of caloric the motive power undoubtedly increases with the difference of temperature between the warm and the cold bodies; but we do not know whether it is proportional to this difference. … The fall of caloric produces more motive power at inferior than at superior temperatures [1]."*

Miss Point 3: *The heat transferred out of the Carnot cycle at lower temperature is "not a waste heat" as often stated, but it is "useful quantity", necessary for completion of the cycle*

The heat transferred out of the ideal Carnot cycle at lower temperature is *"not a waste"* as often stated but it is necessary for completion of the cycle (the entropy balance), and therefore *useful quantity*. The only waste is additional heat generated by irreversible work dissipation accompanied by *entropy generation* in real cycles, that must be also be taken out to complete the cycle.

Miss Point 4: *Sadi Carnot could not had been thinking of "any other caloric" but heat, to imply "entropy-like quantity" as speculated by some*

We need to keep in mind that in Sadi Carnot's time (early 1800s) the steam engines were inefficient (below 5%, so the heat in and out were comparable within experimental uncertainty), the conservation of caloric flourished, and many critical thermal-concepts, including the conservation of energy (*The First Law*) were not even established. At that time the entropy concept was not known even remotely.

Novel contributions with deeper physical insights and related generalization are formalized in the following *Key NOVEL-Points*:

Key NOVEL-Point 1: *"Reversible and Reverse" Processes and Cycles Dissected*

Ideal, *"Reversible processes"* take place at infinitesimal potential difference (temperature, pressure and similar) at any instant within and between a system and its boundary surroundings, but they may and do change in time (*process* is a change in time). Namely, the spatial gradients are virtually zero at any instant while time gradients and related fluxes may be arbitrary as driven by ideal boundary surroundings and facilitated by ideal (arbitrary or infinite) transport coefficients. Note that time and energy rates are irrelevant for the *reversible analysis* of energy balances and properties. Therefore, the potential qualities of flux quantities (heat and different kinds of works) are not degraded but equi-potentially transferred and stored between the system and its boundary surroundings, and thereby 'truly' conserved in every way.

Namely, if an ideal elastic gas or ideal spring is *reversibly* compressed, then the pressure may change in time but is equal everywhere at any instant across the system and the boundary surroundings (equipotential driving force). Similarly, if heat is *reversibly* transferred, the temperature may change in time but is equal everywhere at any instant and if it varies in time, it is driven by varying, but spatially equipotential surrounding temperature so the energy potential quality is stored and conserved (may be reversed *back-and-forth in perpetuity* without external compensation) everywhere in every way.

A *"Cycle"* is a special case of quasi-stationary process when flow inlet and outlet quantities are the same and may feed into each other and close the cycle. Like a stationary process, a cycle does not accumulate flux quantities and may repeat and last in perpetuity (quasi-stationary). Note that all processes, particle-wise, are transient in time (in *Lagrangian* sense, from inlet to outlet) but for the steady-state or stationary processes (in *Eulerian* sense) the properties do not change in time at a fixed location (zero temporal gradients), and for the cyclic process the flow inlet quantities are the same as the outlet's.

A *"Reverse"* concept is independent from and should not be confused with the *reversible* concept. If reversible, a *reverse-process* is reversed effortlessly (with infinitesimal change of potential difference in opposite direction and without external work compensation), while to reverse an *irreversible* process it would require an external work compensation.

A "*Reverse process*" and/or "*Reverse cycle*" would take place if the driving (forced) potentials of a reversible process or a cycle are reversed (by infinitesimal change in opposite direction), then such a reversible process would be reversed with all quantities changing direction from input to output and similar (e.g., a *refrigeration cycle* is a *"reverse"* of a *power cycle* or vice versa). For stationary processes, no temporal gradients, and no accumulation of flux-quantities within a system, and for quasi-stationary cycles no accumulation of flux-quantities after completion of a cycle. The input and output quantities would be conserved and could be *reversed back-and-fort in perpetuity* like perpetual motion.

In reality, there is a need for at least infinitesimal temperature difference (and/or pressure and similar) to provide a *process "sense of direction,"* and to resolve directional ambiguity by chance. Therefore, every process must be at least infinitesimally irreversible (infinitesimally imperfect), the reversibility being an asymptotic, limiting ideal concept. For this reason, even reversible equilibrium is unachievable, like absolute zero temperature or any other ideal concept, only achievable asymptotically.

Key NOVEL-Point 2: *Maximum Efficiency and "Reversible Equivalency" Scrutinized*

Maximum efficiency of an energy process or cycle entails *maximum possible work extraction* from a system (while coming to equilibrium with a reference system, usually the surroundings), or *minimum work expenditure* in a *reverse process* of formation of original system (from within the same reference state). Since the reversible processes do not degrade any potential and could be effortlessly reversed, the two works must be the same for all reversible processes and they represent the maximum *work potential* for the given conditions. Therefore, the reversible processes are perfect and "*equally and maximally efficient,*" and they define the concept of "*Reversible Equivalency,*" — the '*true equality*' of input and output, where relevant quantities and qualities are conserved in perpetuity. In real processes there will be some work dissipation losses (degradation of work to heat), so that *less work* would be extracted than the maximum possible, and *more work* would be needed than the minimum required, reducing the maximum possible efficiency for real, *irreversible processes*.

Since the reversible processes take place at virtual equipotential (virtually the same temperature, pressure, and similar), then potential quality of all relevant quantities would be conserved without any degradation (without any dissipation) and could be effortlessly reversed back-and-forth. With infinitesimal reversal of relevant potentials, all flux quantities will change directions while conserving the qualities. Therefore, the work extraction in a *reversible cycle* would be equal to the expenditure of work in the '*reverse' reversible cycle*. Furthermore, all reversible cycles must have equal and maximum efficiency, otherwise any '*under-achieving*' reversible cycle (with lower work extraction than another [reference] cycle) when reversed would consume less work than the reference cycle and thus be '*over-achieving*' with higher than reference maximum efficiency, resulting in a '*contradiction impossibility*', see *Key NOVEL-Point 3*.

Key NOVEL-Point 3**:** *Reversible Contradiction Impossibility ("Reductio ad absurdum")*

As stated above, the reversible efficiency implies *maximum* work extraction and *minimum* work expenditure in the reverse process, thereby the two must be equivalent for given conditions, thus establishing the *Reversible Equivalency*, see *Key NOVEL-Point 2*. Otherwise, any reversible cycle "*under achievement*" (getting less than maximum possible) would become an "*over-achievement*" when such cycle is reversibly 'reversed' (accomplishing with less than minimum required), and such "*over achievement*" would be physically impossible, would be the "*reversible equivalency* violation" and may violate the *conservation laws*, thus implying the "*Reversible Contradiction Impossibility*" of a well-known fact.

Therefore, an *under-achieving* reversible process when reversed would produce an *impossible over-achieving* reversible process, i.e., the "*Reversible Contradiction Impossibility*" with numerous consequences: Namely, miraculous creation of 'perpetual motion' or creation of assumed 'conserved caloric', regardless of Sadi Carnot's misconception. The 'contradiction impossibility' is so strong and universal a concept that any pertinent or quasi-relevant criteria, even if misunderstood, like conservation of caloric, will be sufficient to reason fundamental inferences.

Further consequences of the "*Reversible Contradiction Impossibility*" would be spontaneous generation of a conserved quantity, or generation of nonequilibrium work potential, or energy transfer from lower to higher potential, like spontaneous heat transfer from lower to higher temperature and generation of thermal nonequilibrium and destruction of entropy, see more details in [4, 5] and elsewhere. Or in general, spontaneous creation of non-equilibrium from within an equilibrium being the physical contradiction of always observed "spontaneous process direction from non-equilibrium towards mutual equilibrium," and never experienced otherwise. It will amount to the "*directionality contradiction*" of the *irreversible process-directionality* from a higher to lower potential towards mutual equilibrium, like forcing in one direction and accelerating in opposite direction, as well as *impossibility to reverse dissipation*. It would be logically and otherwise impossible and absurd ("*Reductio ad absurdum*") to have a spontaneous process "*the one way and/or the opposite way*" [to have heat transfer "*from hot to cold* or "*from cold to hot*" by chance], arbitrarily in opposite directions, as casual by chance. *It would be a violation of the Second law of thermodynamics.*

The reversible processes are equipotential and therefore do not degrade nonequilibrium but store and/or convert one kind to another, like a reversible cycle converts 'heat at high temperature' to 'work and heat at lower temperature', and in reverse in perpetuity, defined in [6] as "*Carnot-Clausius Heat-Work Reversible Equivalency, CCHWRE*" ('potential-like' heat at high temperature to 'kinetic-like' work and heat at lower temperature, and vice versa, analogous to a reversible pendulum converting potential to kinetic energy, and in reverse in perpetuity). Therefore, all reversible processes are perfectly "equivalent in every way" and the most efficient, without any dissipative degradation.

Key NOVEL-Point 4**:** *Reversible Carnot Cycle Efficiency Is Misplaced – It is NOT the "Cycle efficiency" but a "Thermal energy-source 'work-potential efficiency'"*

The *reversible processes and cycles, as a matter of concept, are 100% perfec*t without any degradation and must be equally and perfectly (maximally) efficient, not over nor below 100% efficient (would be the *Reversible Contradiction Impossibility*). Therefore, all reversible processes and cycles have 100% "true" efficiency (they extract 100% of "available *work*

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 February 2024 doi:10.20944/preprints202402.0605.v1

potential" as does any ideal waterwheel and any other reversible engine or motor). The 100% perfect "*true reversible efficiency (CCHWRE)*[6]" should not be confused with "*maximum work-thermal efficiency*" of a thermal energy source, that represents the "*work potential of heat*" or *Exergy* of heat (or nonequilibrium thermal energy) of the relevant thermal reservoirs [E_x=$W_{Rev|Max}$ = $Q(1\text{-}T_0/T_H)$].

Sadi Carnot [1] and his followers, including Kelvin and Clausius [2,3], ironically referred to the maximum heat-engine cycle efficiency (they "agonizingly" developed at the time when most thermal concepts were unknown), with the *absurd conclusion*, that "it does not depend on the cycle design itself nor its operation mode," hence, the proof that it is not the efficiency of ideal Carnot cycle *per se*. Therefore, their attribution is misplaced since the efficiency they developed should had referred to the "maximum motive power or *'work potential'* of the thermal reservoirs" since it depends on their temperatures only, and hence, being the proof of the claim presented here.

It would be equally misplaced to attribute the maximum efficiency of an ideal water-wheel (water turbine), based on its motive power per unit of input water flow, and then it would also mistakenly depend on the water-reservoirs' elevations only. A motive power efficiency (i.e., a device's *work efficiency*) should be consistently based on the *work potential* of an energy source (not on a "convenient nor arbitrary input quantity," like heat input or water-flow input, etc.), and then the "'true' *Carnot cycle efficiency"* would be 100% as for all other efficiencies for ideal, reversible engines and motors.

We now have the advantage to look at the historical developments more comprehensively and objectively than the pioneers [6]. Sadi Carnot defined engine cycle efficiency, logically and "empirically," as "work *output per* heat *input*," long before the concept of "*work potential*" of an energy-source and *energy conservation* were established. An exact "*reverse*" of the reversible "*Power Carnot cycle"* is the ideal "*Heat-pump cycle"* ("*Reverse Carnot cycle"*) whose efficiency or "performance" is defined 'in reverse' as "heat *output per* work *input*." It is always over 100% (as the "fundamental inverse" of the *Carnot cycle efficiency*, always smaller than 100%) and is named as the *"Coefficient of Performance (COP)"* since "such efficiency" over 100% would not be fundamentally (nor "politically") proper. For the same fundamental reason, the efficiency of the perfect, *ideal* Carnot cycle (below 100%) would also be inappropriate (as if there are "some *losses*" in the ideal reversible cycles). It is fundamentally inappropriate, as often stated, to call the heat transferred out of the Carnot cycle at lower temperature, the "*waste heat* or *loss*", since it is the "*useful quantity,*" *necessary* for the completion of the perfect, ideal cycle, and together with the cycle work, it is the "*reversible equivalent*" to the heat input at the high temperature (*CCHWRE* [6]). The only waste or loss would be any *irreversible work dissipation* into additional heat and entropy generation in real cycles, that must be also taken out to complete the cycle. For the same reason, it should be called *"Carnot cycle COP"* but *not the efficiency*. A device's efficiency should not be higher than 100% and only could be lower for irreversible degradation losses. After all, all ideal, reversible cycles must be [100% efficient, and] "*equally and maximally efficient*," as reasoned by Carnot and confirmed later by Kelvin and Clausius.

The "original," nowadays well-known *Carnot cycle efficiency* is misplaced and should be renamed for what it is: the work efficiency of a heat-source or *Work potential (WP)* or *Exergy* of a thermal-energy source. We now know that "true" Carnot efficiency, the *Second-Law* or *Exergy efficiency* is 100%. It is a goal here to rectify and clarify what is fundamentally misplaced. However, it would be hard *"to let go"* of the 200 yearlong "habit and addiction."

Key NOVEL-Point 5*: *The Carnot (Ratio) Equality and Clausius Equality (Cyclic integral) are special cases of related "Entropy boundary integral" for reversible stationary processes

The balance equations (to be later used for definition of a new property, the *entropy*) were first developed by Kelvin and Clausius, based on Carnot's discovery of "maximum efficiency and equality for all reversible cycles," namely *Carnot equality*, as ratio Q_H/T_H=Q_L/T_L for constant high- and low-temperature of the thermal reservoirs, to be the precursor for *Clausius equality*, as circular integral for a reversible cycle, $\oint \delta Q/T = 0$. Then from those correlations a new property, *entropy*, was inferred by Clausius, to be later generalized as the *entropy balance*, as "quantification" of the *Second Law* of thermodynamics.

The *Carnot equality* is the balance of "entropy-in equal to entropy-out" of the reversible Carnot cycle, while the *Clausius equality* is the balance of net-entropy (in-minus-out) of a reversible cycle with varying temperatures, a cyclic integral around the cycle boundary. They both represent special cases of the *entropy balance* for the steady-state (stationary) processes with zero mass flow into or out of the cycle and no accumulation of entropy after the completion of the cycle, that may repeat in perpetuity, thus representing quasi-stationary cyclic process.

Note that engines are designed to run and produce power perpetually (except for necessary maintenance and repair). Therefore, their processes have to be either steady-state (stationary processes), or quasi-steady cyclic processes, achieved by rotating or reciprocating piston-and-cylinder machinery, or any similar energy conversion devices. The both, steady-state and cyclic processes do not accumulate mass and energy but convert input to output while interacting with the energy-reservoirs, energy source and reference surroundings.

Conclusion and "*Key Takeaways*"

The most important and the most probable sequential developments by Sadi Carnot, regarding the *reversible cycle maximum efficiency* and his ingenious reasoning of the *reversible contradiction impossibility*, as well as related consequences developed by his followers, and this author's novel contributions and generalization, are presented above and summarized by the *Key Takeaways* below.

Key Takeaways:

1. Conservation of *caloric* misconception was probably a fortunate catalyst leading to analogy with the waterwheel and Carnot's hypothesis that the *motive power* of steam engine was caused and produced by the *"fall of caloric"* (cooling of hot caloric) since he believed that there was no "consumption" of the caloric (*Key Point I*).
2. Carnot's reasoning that *"wherever there exists a difference of temperature, motive power can be produced"* and not be wasted for workless heat transfer, was the most critical and ingenious reasoning (*Key Point II*) that led to inference of the most critical concept of Carnot's discovery (*Key Point IV & V*).
3. The "*Key discovery*" ingeniously inferred by Sadi Carnot, that *Reversible cycles must all have equal and maximum efficiency*, by demonstrating that otherwise would result in creation of conserved caloric and/or perpetual motion: *"the maximum of motive power resulting from the employment of steam is also the maximum of motive power realizable by any means whatever [1]* (*Key Point V*)*."*
4. The selected and persistent post-misconceptions and fallacies by others are also presented as *Miss Points 1-4*, including the misconceptions that the heat transferred out of the ideal Carnot cycle at lower temperature is the "*waste heat* or *loss*" as often stated. However, it is the "*useful and necessary quantity,*" required for the entropy balance and completion of a perfect, reversible cycle.
5. The *"Reversible and Reverse"* processes and cycles are re-examined in *Key NOVEL-Point 1*. Among others, it is emphasized that the potential qualities of flux quantities (heat and different kinds of works) are not degraded but equi-potentially transferred and stored between the system and its boundary surroundings, and thus conserved in every way. The spatial gradients are virtually zero at any instant while time gradients and related fluxes may be arbitrary since the time and energy rates are irrelevant for the *reversible analysis* of energy balances and properties.
6. The reversible cycle "M*aximum efficiency"* and *"Reversible equivalency"* are scrutinized in *Key NOVEL-Point 2*. The reversible efficiency implies *maximum* work extraction and *minimum* work expenditure in the *reverse* process, thereby the two must be equivalent for given conditions, thus establishing the *'reversible equivalency'*. The reversible processes are perfect and "*equally and maximally efficient,*" and they define the concept of *"Reversible Equivalency,"* — the *'true equality'* of input and output, where relevant quantities and qualities are conserved in perpetuity.
7. *Reversible Contradiction Impossibility ("Reductio ad absurdum")* is scrutinized in *Key NOVEL-Point 3.* Namely, any reversible cycle "*under achievement"* (getting less than maximum possible) would become an *"over-achievement"* when such cycle is reversibly '*reversed*' (accomplishing with less than minimum required), and such "*'reversed' over achievement*" would be physically impossible (would be the "*'reversible equivalency' violation*" and may violate the *conservation law*s), thus establishing the *"Reversible Contradiction Impossibility"* of established fact with numerous consequences as detailed in *Key NOVEL-Point 3.*
8. Sadi Carnot and his followers, including Kelvin and Clausius, ironically referred to the maximum heat-engine cycle efficiency they developed (at the time when most thermal concepts were unknown), with the *absurd conclusion*, that it does not depend on the cycle design itself nor its operation mode, therefore, the proof that it is not the efficiency of ideal Carnot cycle *per se*. Therefore, their attribution is misplaced since the correlation they developed should had referred to the "maximum motive power or *'work potential'* of the thermal reservoirs"

since it depends on their temperatures only, and hence, being the proof of the claim presented here, see *Key NOVEL-Point 4.*

9. *The Carnot (Ratio) Equality* and *Clausius Equality (Cyclic integral)* are elucidated to be the special cases of related *"Entropy boundary integral" for reversible stationary processes,* see *Key NOVEL-Point 5.*

In conclusion, even though Sadi Carnot has been often called as the "*Father of thermodynamics,*" with all farness if conceivable, it might be more appropriate for Clausius and Kelvin to be named as the *Fathers of thermodynamics*, since they meticulously developed the most critical concepts of thermodynamics, staring from thermodynamic temperature to entropy and to formulation of the *Laws* of thermodynamics, among others — whereas Sadi Carnot would be the *"Forefather of thermodynamics-to-become"* in honor of his ingenious discovery and reasoning of *heat engines reversible cycles* at the time when steam engines were in initial developments, when the concepts of heat and work where not fully recognized, and even the energy conservation was not established at that time.

References

[1] Carnot, S. *Reflections on the Motive Power of Heat*; Thurston, R.H., Translator; Chapman & Hall, Ltd.: London, UK, 1897. Available online: https://books.google.com/books?id=tgdJAAAAIAAJ (Accessed on Nov. 15, 2023).

[2] Thomson, W. (Lord Kelvin). On the Dynamical Theory of Heat. Transactions of the Royal Society of Edinburgh, March 1851, and Philosophical Magazine IV. 1852. Available online: https://zapatopi.net/kelvin/papers/ (Accessed on Nov. 15, 2023).

[3] Clausius, R. *The Mechanical Theory of Heat*; Macmillan: London, UK, 1879; pp. 21–38, 69–109, 212–215. [Google Scholar] (Accessed on Nov. 15, 2023).

[4] Kostic, M. Sadi Carnot's Ingenious Reasoning of Ideal Heat Engine Reversible Cycles. In Proceedings of the 4th IASME/WSEAS International Conference on Energy, Environment, Ecosystems and Sustainable Development (EEESD'08), Algarve, Portugal, 11–13 June 2008; Available online: https://www.researchgate.net/publication/228561954 (Accessed on Nov. 15, 2023).

[5] Kostic, M. Revisiting the Second Law of Energy Degradation and Entropy Generation: From Sadi Carnot's Ingenious Reasoning to Holistic Generalization. *AIP Conf. Proc.* 2011, *1411*, 327. Available online: http://kostic.niu.edu/kostic/_pdfs/Second-Law-Holistic-Generalization-API.pdf [CrossRef][Green Version] (Accessed on Nov. 15, 2023).

[6] Kostic, M. Reasoning and Logical Proofs of the Fundamental Laws: "*No Hope*" for the Challengers of the Second Law of Thermodynamics. *Entropy* 2023, *25*, 1106. Available online: https://doi.org/10.3390/e25071106 (Accessed on Nov. 15, 2023).

[7] Jaynes, E.T. The Evolution of Carnot's Principle. Orsay, France, 1984. Available online: http://bayes.wustl.edu/etj/articles/ccarnot.pdf (Accessed on Nov. 15, 2023).

[8] Pisano, R. On Principles In Sadi Carnot's Thermodynamics (1824). Epistemological Reflections, Almagest 2(2), January 2010. Online ISSN: 2507-0371, Print ISSN: 1792-2593. DOI: 10.1484/J.ALMA.3.16. https://www.researchgate.net/publication/265680441 (Accessed on Nov. 15, 2023).

[9] Fox, R. *The Savant and the State*: Science and Cultural Politics in Nineteenth-Century France. The John Hopkins University Press, ISBN 1-4214-0522-9, 2012. https://books.google.com/books?id=EGn3fJfMRxQC and https://a.co/d/diV1suX

[10] Yamamoto, Y, Yoshida, H. Historical Development in the Thought of Thermal Science—Heat and Entropy. *IHTC-16 Fourier Lecture, 2008.*At https://ihtcdigitallibrary.com/conferences/ihtc16,677693cb75c8b2ed.html.

Also (PDF): http://www.aihtc.org/pdfs/IHTC-16-Yoshida-paper.pdf (Accessed on Nov. 15, 2023).

[11] Norton, J.D. How Analogy Helped Create the New Science of Thermodynamics. *Synthese.* **200** (2022), article 269, pp. 1-42. Available online: https://sites.pitt.edu/~jdnorton/papers/Analogy_Carnot.pdf (Accessed on Nov. 15, 2023).