CLASSICAL MARXISM AND THE SECOND LAW OF THERMODYNAMICS

Marx/Engels, the Heat Death of the Universe Hypothesis, and the Origins of Ecological Economics

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Today's understanding of the significance of Karl Marx and Frederick Engels's work for the development of both ecological economics in particular and ecology in general has been hindered by persistent claims that Engels (and by imputation Marx) rejected the second law of thermodynamics. It is demonstrated here through textual analysis that Engels criticized not the entropy law itself but the extrapolation of this into the "heat death theory of the universe" hypothesis. The historical debate surrounding this hypothesis is examined, showing that Engels and Marx remained consistent with the natural science of their day. This opens the way to the recognition that Marx's political economy was unique in the 19th century in incorporating thermodynamics into the core of its analysis, thus providing the foundations for an ecological economics. The materialist-dialectical view of classical Marxism led to a dynamic, open, contingent approach to the earth system, reflecting a general evolutionary perspective.

Keywords: *Marx; Engels; thermodynamics; entropy; second law; ecological economics; ecology*

1. INTRODUCTION

Ever since Nicholas Georgescu-Roegen (1971) wrote his magnum opus, *The Entropy Law and the Economic Process*, the entropy law (or the second law of thermodynamics) has been viewed as a *sine qua non* of ecological economics. Georgescu-Roegen argued strongly that both the entropy law and the first law of thermodynamics (conservation of matter–energy) were incompatible with orthodox neoclassical economics. The relation of ecological economics to Marxian economics, however, was much more ambiguous. Attempts to explore the history of ecological–economic ideas, following Georgescu-Roegen's contributions, immediately brought to the fore the close relationship between those thinkers who had pioneered in ecological–economic thinking and classical Marxism.

Georgescu-Roegen (1971) himself pointed, although not uncritically, to Marx and Engels's discussions of energetics and thermodynamic principles. It was, after all, as he noted, the "first pillar" of historical materialism that "the economic

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process is not an isolated system" (p. 316). He also indicated his support for Engels's critique of energy reductionism (Georgescu-Roegen, 1986, p. 9).[1] Both Marx and Engels were well versed in the scientific literature on thermodynamics. As even their most persistent ecological–economics critic, Juan Martinez-Alier, has acknowledged, "Engels . . . had read everything on the fundamental studies on thermodynamics" (quoted in Ravaioli, 1995, p. 130). Anson Rabinbach (1990) claimed in his important study of 19th century applications of thermodynamics to human labor that "the most important 19th-century thinker to absorb the insights of thermodynamics was Marx, whose later work was influenced and perhaps even decisively shaped by the new image of work as 'labor power'" (pp. 69-70). Early contributors to ecological–economics thinking, such as Sergei Podolinsky and Frederick Soddy, were inspired by Marx (see Podolinsky, 1995, pp. 127-129, 138; Podolinsky, 2004, p. 61; Soddy, 1922, pp. 12-13).

Ironically, it is perhaps because of the strong *prima facie* case for a link between classical Marxism and thermodynamic conceptions that the argument is so fervently advanced that Marx neglected thermodynamics. Some of the leading figures in ecological economics have gone to extraordinary lengths to separate at birth the Marxian and ecological critiques and then to deny any direct relationship through a series of disconnects: (a) Marx and Engels's own integration of thermodynamic concepts into their analysis (admittedly not given strong emphasis or even understood in later Marxist thought) is simply ignored, (b) circumstantial evidence is offered to suggest that Marx and Engels actively *rejected* some of the crucial discoveries in thermodynamics in their day, (c) it is alleged that Engels went so far as to cast doubt on the entropy law itself, and (d) the fact that early developments in ecological economics occupied the same intellectual universe as Marxism, which led to much cross-fertilization of thought, is downplayed if not deliberately obfuscated.

The leading role in criticizing Marx and Engels for neglecting and/or misunderstanding thermodynamics has been taken by Martinez-Alier, not only in his very influential book *Ecological Economics* but also in other, frequently cited, writings, appearing in such high-profile journals as *Ecological Economics*, *New Left Review*, and *Socialist Register*. For Martinez-Alier, Marx and Engels's critical standpoint regarding Podolinsky's early attempt at "ecological Marxism," in which Podolinsky supposedly sought to incorporate thermodynamics into the Marxist critique of political economy, is damning in itself (Martinez-Alier, 1987, pp. 46-47, 61-62, 223). This, we are told, virtually negated any possible future connection between Marxism and ecological economics (Guha & Martinez-Alier, 1997, p. 25; Martinez-Alier, 1995, p. 71).

Recent publications by ecosocialists (Burkett, 2006, pp. 142-173; Burkett & Foster, 2006; Foster & Burkett, 2004) have strongly challenged these arguments with respect to Podolinsky and Marx–Engels, demonstrating that Podolinsky's perfect-human-machine model of ecological economics was fundamentally flawed from the standpoint of thermodynamics itself (a fact that the founders of historical materialism clearly recognized at the time). Burkett and Foster (2006) show that Podolinsky's energy calculations in agriculture were crude and incomplete (as Engels noted), leaving out the energy associated with fertilizers, fossil fuels, and even direct sunlight.

It is perhaps not surprising therefore that greater emphasis has recently been placed on the criticism that Engels (and by imputation Marx) rejected the second law of thermodynamics itself. Thus, in an article in the 2007 *Socialist Register*, Martinez-Alier (2006) underscored Engels's alleged "unwillingness to accept that the First and Second Laws of thermodynamics could apply together"—a claim that was often presented previously as simply "another interesting point" (pp. 275-276; also see Martinez-Alier, 1995, p. 71; Martinez-Alier, 2005, p. 5; Martinez-Alier, 2007, p. 224).

Martinez-Alier's current reputation as the foremost historian of ecological economics makes his criticism in this regard particularly important. Nevertheless, it should be noted, he is not the only one to issue such charges. Much earlier, the renowned social theorist Daniel Bell (1966) suggested, "He [Engels] attacked the formulation of the second law of thermodynamics, as set forth by Clausius in 1867, because of its implicit argument that matter is creatable and destructible" (p. 84). It appears as though Bell based this claim largely on the discussion in Wetter (1958, pp. 302-303).

Benedictine priest and distinguished professor of physics Stanley Jaki (1974) authored an attack on Engels's *Dialectics of Nature* in which he contended that for Engels

> there could be no mercy for Clausius of entropy fame. In Engels' eyes Clausius was a bogeyman scientist whom he tried to discredit, ridicule or dismiss whenever opportunity arose. . . . Clausius, entropy, and the heat-death of the universe meant one thing for Engels. They represented the most palpable threat to the materialistic pantheism of the Hegelian left for which the *material* universe was and still is the ultimate, ever active reality. Engels made no secret about the fact that the idea of a universe returning cyclically to the same configuration was a pivotal proposition within the conceptual framework of Marxist dialectic. He saw the whole course of science reaching in Darwin's theory of evolution the final vindication of the perennial recurrence of all, as first advocated by the founders of Greek philosophy. . . . Such a contention depended, of course, on the ability of dissipated energy to reconcentrate itself. This question, an insoluble enigma to the best minds in physics, represented no problem for Engels. While he admitted that radiating heat disappeared, so to speak, into infinite space, he felt sure that the cold bodies of defunct stars must, sooner or later, collide with one another. (pp. 312-313)

More recently, French Marxist Daniel Bensaïd also presented such criticisms in his *Marx for Our Times*. Bensaïd (2002) contended that Engels "adhered to the first principle (conservation of energy), while rejecting the second (its progressive dissipation)." Engels was said to have done so on "ideological" grounds; specifically, Engels objected to "religious extrapolations from the theory of entropy as to a 'thermic death sentence on the universe'" (pp. 330-332). Likewise, Danish professor of the history of science Helge Kragh (2004) dismissed Engels for his criticism of "the idea of an ever-increasing entropy and its consequence, the heat death"—simply because he saw it as "ideologically dangerous" (p. 58). George Steiner (1975) referred to the "strident rejecting of entropy by Engels" (p. 162). Ecological political economist Kenneth Stokes (1994) argued in his *Man and the Biosphere* that "Engels's understanding of the second law of thermodynamics was clearly partial" and implied "that dialectical materialism . . . can contravene the second law" (p. 246). In his book *Pulse*, former *Audubon* contributing editor Robert Frenay (2006) recently repeated Martinez-Alier's basic charges, according to which Podolinsky urged Marx and Engels

> to consider the central role of energy flows, and with that the effect of the 2nd Law. To their discredit they refused, and proceeded down a road that pointedly ignored the 2nd Law (Engels misunderstood it, thinking it contradicted the 1st) and environmental considerations in general. (p. 364)

More pointedly, Leszek Kolakowski (1978) claimed in his *Main Currents of Marxism* that “the second law of thermodynamics . . . appeared to Engels an absurdity, as it posited an over-all diminution of energy in the universe” (Vol. 1, p. 395). Kolakowski went on to disparage what he referred to as “Engels’s statement that the energy dispersed in the universe must also be concentrated somewhere.” This, Kolakowski (1978, Vol. 3, p. 150) claimed, was nothing less than an attempt to dispose of the second law of thermodynamics.

Kolakowski raised his objection to Engels’s notes related to the second law as part of a much broader attack on Marx’s historical materialism and especially on Engels’s dialectics of nature. Similarly, Martinez-Alier (2006) declared that Engels’s “‘dialectics of nature’ failed him there” (p. 275), that is, in the analysis of the first and second laws of thermodynamics. The implication here is that the “dialectics of nature” associated with classical historical materialism, and especially with Engels, is itself thrown into doubt by Engels’s supposed rejection of the entropy law. More important, however—both for Martinez-Alier and for us here—is the contention that by allegedly scorning the second law of thermodynamics, Engels (and by implication Marx) severed any possible connection between classical Marxism and ecological economics.

Bensaïd’s argument can be viewed as somewhat distinct because he defended some of Engels’s contributions to ecological economics while contending that Engels was led astray by cosmological speculations on the heat death of the universe, which produced conclusions that were more “ideological” (having to do with materialist philosophy) than scientific. Thus, Bensaïd (2002) contended that “the law of entropy seemed to [Engels] manifestly to be a breach through which religion could make a return. This is a leitmotiv of the notes on physics in the *Dialectics of Nature*” (p. 332).

All of the above complaints against the founders of historical materialism have only served to feed the widespread myth that classical Marxism was estranged from thermodynamics (e.g., Faber & Grossman, 2000).

We believe that these issues, particularly the allegation that Engels (and by imputation Marx as well) rejected the second law of thermodynamics, can be decided purely on the evidence. Accordingly, Section 2 examines in considerable detail Engels’s notes on thermodynamics and the heat death hypothesis, which have been presented as evidence for the above-mentioned ecological–economic critique of classical Marxism (and for arguments against Engels’s dialectics of nature). We compare these preliminary notes to Engels’s more developed view in his draft introduction to *The Dialectics of Nature* and in *Anti-Dühring*, both of which the critics generally (with the partial exceptions of Jaki and Bensaïd) ignore. Section 3 locates Engels’s notes on the heat death hypothesis in the historical context of 19th-century science and explains that the hypothesis of a guaranteed heat death of the universe was problematic within 19th-century science and is even more questionable from the standpoint of present-day cosmology and astrophysics. Although Engels’s critics see his rejection of the heat death hypothesis as a violation of basic physics, in reality this hypothesis was looked at skeptically by many leading physicists in Engels’s day (including pioneers in thermodynamics such as Mayer, Rankine, Grove, Boltzmann, and, in his later writings, Helmholtz—plus even at one point William Thomson [after 1892 Lord Kelvin]). Engels's notes questioning the heat death hypothesis in fact directly rely on the later criticisms of that hypothesis by none other than Helmholtz, the figure who is usually credited with introducing it!

Following this treatment of Engels and the heat death controversy, Section 4 goes on to examine very briefly (because this has been dealt with at length elsewhere) the contention that Marx and Engels rejected the fundamental principles of ecological economics in distancing themselves somewhat from Podolinsky's perfect-human-machine model. We explain how Marx incorporated thermodynamics into his analysis of human labor and capitalist machine-driven production. Finally, Section 5 addresses the open-system thermodynamics associated with Marx's metabolic–energetic analysis of capitalist environmental crisis and its significance in relation to contemporary ecology and ecological economics.

The ultimate irony associated with the aforementioned criticisms is that Marx and Engels pioneered the analysis of the social implications of thermodynamics by integrating it into their general critique of capitalism, which had a strong ecological dimension. By reconstructing Engels's actual stance on the second law and locating it within Marx and Engels's broader materialist project, we hope therefore to advance Marxian theory and ecological analysis.

2. ENGELS, THE SECOND LAW, AND THE HEAT DEATH OF THE UNIVERSE

The second law of thermodynamics says that in an isolated system, entropy (levels of disorganization or unutilizable energy) will expand to a maximum.[2] The second law (together with the first law, which stipulates that matter–energy can neither be created nor be destroyed) is fundamental to understanding practical problems in the utilization of energy. Indeed, it was largely the development of the steam engine that germinated the science of thermodynamics. Although the entropy law was extrapolated to the cosmological level by some of the founders of thermodynamics to form the notion of the "heat death of the universe," the latter notion was questioned in its day and is now generally considered problematic and misleading, obscuring the real complexity of the evolution of the universe (Schneider & Sagan, 2005, p. 6; Toulmin, 1982, pp. 38-39). Yet it is precisely the notion of the heat death of the universe as a guaranteed final end that Engels opposed in what has wrongly been called his rejection on that basis of thermodynamics.

It was arguably the failure to recognize the distinction between the second law and the heat death theory that led Martinez-Alier and Naredo (1982) to assert 25 years ago that Engels "studied Clausius' Second Law, but dismissed it in unequivocal terms as being contradictory of the First Law" (p. 209; also see Martinez-Alier, 1995, p. 71; Martinez-Alier, 2006, p. 275). In his pathbreaking *Ecological Economics*, Martinez-Alier (1987) went on to claim,

> The second law was mentioned by Engels in some notes written in 1875 which became, posthumously, famous passages of the *Dialectics of Nature*. Engels referred to Clausius' entropy law, found it contradictory to the law of conservation of energy, and expressed the hope that a way would be found to re-use the heat irradiated into space. Engels was understandably worried by the religious interpretation of the second law. (p. 221)

Furthermore, in his recent article in the 2007 *Socialist Register*, Martinez-Alier (2006) stated,

> One intriguing point arises from Engels' unwillingness to accept that the First and Second Laws of thermodynamics could apply together: the "dialectics of Nature" failed him there. As Engels became aware of Clausius' concept of entropy, he wrote to Marx: "In Germany the conversion of the natural forces, for instance, heat into mechanical energy, etc., has given rise to a very absurd theory—that the world is becoming steadily colder . . . and that, in the end, a moment will come when all life will be impossible. . . . I am simply waiting for the moment when the clerics seize upon this theory. (pp. 275-276)

The notion that Engels would have been guilty of either a neglect of thermodynamics or a fundamental misunderstanding of the second law is rather implausible in light of the extensive natural science research of both Marx and Engels. We know from their notes and letters that from the early 1850s onward they studied the works of and/or attended public lectures of many of the scientists involved in the development of the first and second laws—including not only Clausius and Thomson but also Hermann von Helmholtz, Julius Robert Mayer, John Tyndall, William Robert Grove, James Clark Maxwell, James Prescott Joule, Justus von Liebig, Adolph Fick, Jean-Baptiste Joseph Fourier, Sadi Carnot, Peter Guthrie Tait, Ludwig Boltzmann, and Ludwig Büchner (Baksi, 1996, 2001; Burkett & Foster, 2006; Foster, 2000, chap. 5 and 6). Marx and Engels kept abreast of the natural–scientific literature and did not dispute the conclusions of natural–scientific research where there was an actual scientific consensus—although they did raise questions about what appeared to be incomplete, inconclusive, partial, and contradictory results.

Virtually the entire case leveled against Engels (and by implication Marx) for questioning the laws of thermodynamics—and the entropy law in particular—is based on four paragraphs in his work: a single paragraph in a letter that he wrote to Marx in 1869 and three paragraphs separately written in 1874 or 1875 and included in his *Dialectics of Nature*. All of these paragraphs are directed not at the entropy law but at its extrapolation into a theory of the heat death of the universe. Because these four paragraphs constitute the primary (and for Martinez-Alier the sole) basis on which it is claimed that Engels rejected the second law of thermodynamics, they will all be quoted in full below.

The first of these four paragraph-long notes is from a letter that Engels wrote to Marx on March 21, 1869. The boldface is added to highlight the parts of this paragraph that are quoted by Martinez-Alier in his criticism of Engels (Martinez-Alier, 2006, pp. 275-276 [see above]; Martinez-Alier, 2007, p. 224). Capitalized words are those excluded by Martinez-Alier from his quote *without the appropriate ellipses marking their removal*:

> **In Germany the conversion of the natural forces, for instance, heat into mechanical energy, etc., has given rise to a very absurd theory**, WHICH INCIDENTENALLY FOLLOWS LAPLACE'S OLD HYPOTHESIS, BUT IS NOW DISPLAYED, AS IT WERE, WITH MATHEMATICAL PROOFS: **that the world is becoming steadily colder**, that the temperature in the universe is leveling down **and that, in the end, a moment will come when all life will be impossible** and the entire world will consist of frozen spheres rotating round one another.[3] **I am simply waiting for the moment when the clerics seize upon this theory** as the

> last word in materialism. It is impossible to imagine anything more stupid. Since, according to this theory, in the existing world, more heat must always be converted into other energy than can be obtained by converting other energy into heat, so the original *hot state*, out of which things have cooled, is obviously inexplicable, even contradictory, and thus presumes a god. Newton's first impulse is thus converted into a first heating. Nevertheless, the theory is regarded as the finest and highest perfection of materialism; these gentlemen prefer to construct a world that begins in nonsense and ends in nonsense, instead of regarding these nonsensical consequences as proof that what they call natural law is, to date, only half-known to them. But this theory is all the dreadful rage in Germany. (Marx & Engels, 1975a, Vol. 43, p. 246; boldface indicates those words in the quote from Martinez-Alier; capitalized words are those words deleted by Martinez-Alier without ellipses; italics are those in Engels's original)

Martinez-Alier, as we have seen, has repeatedly offered this paragraph from Engels's March 1869 letter to Marx as direct "evidence" that Engels rejected the second law of thermodynamics. However, a close examination of the entire paragraph shows that Engels's criticism is not leveled at the second law of thermodynamics itself but at two controversial hypotheses that were commonly extrapolated from the second law: the steady cooling down of the earth and the heat death of the universe. The reference to "Laplace's old hypothesis," which Martinez-Alier removed from the quote without ellipses, is a clear indication (along with other lines later on not included in Martinez-Alier's quotation from Engels) that the argument is primarily about cosmology, that is, the heat death of the universe, and that by "world" in the first sentence Engels was referring not simply to the fate of the earth itself but to the universe. In short, the context makes it clear that Engels is not concerned with the second law of thermodynamics here as much as with the questionable cosmology that was being built on it.

In an earlier reference to this same letter in his *Ecological Economics*, Martinez-Alier (1987) wrote as follows: "In a letter to Marx of 21 March 1869, when he became aware of the second law, [Engels] complained about William Thomson's attempts to mix God and physics" (p. 221). But we know that Engels read Grove's *The Correlation of Physical Forces* by 1865—shortly after Marx. Grove's work included a detailed treatment of the second law, and there is no possibility that Engels or Marx—both of whom frequently praised Grove's book—missed this discussion (Draper, 1985, p. 83; Marx & Engels, 1975a, Vol. 25, p. 325; Marx & Engels, 1975b, p. 162). Moreover, as Engels was undoubtedly a regular reader of the British *Philosophical Magazine* (the key scientific outlet for British natural philosopher–physicists), he was almost certainly aware of Clausius's concept of "entropy" from the moment it was introduced to British readers in 1868 through the translation of Clausius's 1867 "On the Second Fundamental Theorem of the Mechanical Theory of Heat" (Smith, 1998, pp. 256, 361). From the same source he would have encountered the early work of Thomson, Tait, Rankine and others.

Nor is there any mention, contrary to what Martinez-Alier claims here, of Thomson in the above-quoted letter. Indeed, Thomson was a *Scottish* physicist, whereas Engels's letter refers only to the heat death theory as promulgated *in Germany*.

In his 1869 letter, Engels sees a possible contradiction between *the heat death theory* (specifically its requirement for an exogenous "first heating") and the conservation of energy. Engels sees this "nonsensical consequence" (the heat death hypothesis) as a puzzle for a consistently materialist philosophy of science—one that can be solved only through future scientific research that deepens our knowledge of what is currently "to date, only half-known." Clearly, Engels feels that to accept the heat death theory as "the finest and highest perfection of materialism" would be to hold back the progress of this scientific research. Far from contravening the second law in this March 1869 letter, as Martinez-Alier (1987, p. 221) suggests, Engels does not even mention the entropy law in his letter, which is directed instead against the heat death hypothesis.

In the section of Engels's *The Dialectics of Nature* titled "Notes on Physics," there are three paragraph-long notes written in 1874 or 1875 on the heat death of the universe hypothesis that have been cited but not usually quoted—and never quoted in full—by Engels's critics.[4] These paragraphs have been interpreted by Martinez-Alier, Kolakowski, and others as offering further evidence of Engels's rejection of the second law of thermodynamics. They are therefore included in their entirety below. As in Marx and Engels's *Collected Works*, they are separated from each other by asterisks, indicating that they are separate, if related, notes. All three, as a close reading will show, are unmistakably directed against the heat death hypothesis. The first paragraph establishes the substance of Engels's objections and the following two his sense that the heat death hypothesis creates all sorts of theoretical difficulties (even absurdities) for any consistent materialist interpretation of cosmological developments:

> *Radiation of heat into universal space*. All the hypotheses cited by Lavrov of the renewal of extinct heavenly bodies (p. 109) *involve loss of motion*. The heat once radiated, i.e., the infinitely greater part of the original motion, is and remains lost. Helmholtz says, up to 453/454.[5] Hence one finally arrives after all at the exhaustion and cessation of motion. The question is only finally solved when it has been shown how the heat radiated into universal space becomes *utilisable* again. The theory of the transformation of motion puts this question categorically, and it cannot be got over by postponing the answer or by evasion. That, however, with the posing of the question the conditions for its solution are simultaneously given—*c'est autre chose* [that is quite another thing]. The transformation of motion and its indestructibility were first discovered hardly thirty years ago, and it is only quite recently that the consequences have been further elaborated and worked out. The question as to what becomes of the apparently lost heat has, as it were, only been *nettement posée* [clearly posed] since 1867 (Clausius). No wonder that it has not yet been solved; it may still be a long time before we arrive at a solution with our small means. But it will be solved, just as surely as it is certain that there are no miracles in nature and that the original heat of the nebular ball is not communicated to it miraculously from outside the universe. The general assertion that the *total amount* (die *Masse*) *of motion is infinite*, and hence inexhaustible, is of equally little assistance in overcoming the difficulties of each individual case; it too does not suffice for the revival of extinct universes, except in the cases provided for in the above hypotheses, which are always bound up with loss of force and therefore only temporary cases. The cycle has not been traced and will not be until the possibility of the re-utilisation of the radiated heat is discovered. (Marx & Engels, 1975a, Vol. 25, pp. 561-562)[6]

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> *Clausius—if correct*—proves that the universe has been created, *ergo* that matter is creatable, *ergo* that it is destructible, *ergo* that also force, or motion, is creatable and destructible, *ergo* that the whole theory of "the "conservation of force"

> is nonsense, *ergo* that all his conclusions from it are also nonsense. (Marx & Engels, 1975a, Vol. 25, p. 562)

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> *Clausius' second law*, etc., however it may be formulated, shows energy as lost, qualitatively if not quantitatively. *Entropy cannot be destroyed by natural means but it can certainly be created*. The world clock has to be wound up, then it goes on running until it arrives at a state of equilibrium from which only a miracle can set it going again. The energy expended in winding has disappeared, at least qualitatively, and can only be restored by an *impulse from outside*. Hence, an impulse from outside was necessary at the beginning also, hence, the quantity of motion, or energy, existing in the universe was not always the same, hence, energy must have been created, i.e., it must be creatable, and therefore destructible. *Ad absurdum!* (Marx & Engels, 1975a, Vol. 25, p. 563)

Martinez-Alier and the other critics of Marx do not generally draw extensively from the foregoing passages from *The Dialectics of Nature* but confine themselves to quoting a sentence here or there. We are thus offered on flimsy evidence broad and seemingly authoritative interpretations that the reader unfamiliar with the texts, issues, or historical context has no reason to doubt. As Martinez-Alier (1987) puts it in *Ecological Economics* (in a passage quoted more fully above),

> The second law was mentioned by Engels in some notes written in 1875 which became, posthumously, famous passages of *The Dialectics of Nature*. Engels referred to Clausius' entropy law, found it contradictory to the law of conservation of energy, and expressed the hope that a way would be found to re-use the heat irradiated into space. (p. 221; also see Martinez-Alier, 2006, p. 276; Martinez-Alier, 2007, p. 224).

Here, the use of the words *utilisable* and *re-utilisation* with respect to energy in space by Engels is interpreted by Martinez-Alier in *direct human utilitarian terms*, as if such energy could actually be directly "re-used" by human beings. The wording employed by Martinez-Alier—the substitution of *re-use* for *re-utilization*—doubtless makes it sound to most readers as if this heat dissipated into space is (quite absurdly) to be put back into use by human beings, opening up Engels to ridicule. Yet this fails to acknowledge here that terms such as *work* and *utilizable energy* as employed in physics refer to *physical forces* independent of human action. The notion of utilizable energy is seen as the potential of a system to do "work." As we shall see, nowhere in *The Dialectics of Nature* can be found any suggestion whatsoever that such a purposeful recovery and reuse of irradiated energy on the terrestrial level might be possible. Rather, Engels simply raised the question of a natural, nonpurposeful reconcentration (or "reutilization") of "the heat radiated into universal space" as a countertendency or offset to *universal* heat death on the level of the entire cosmos (Marx & Engels, 1975a, Vol. 25, p. 562).

In other words, Engels's discussion was limited to the cosmological space time frame and in no way implied a rejection of the second law as applied to terrestrial dimensions and time frames. Although Engels's notes raised questions about the ultimate effects of the second law of thermodynamics, they did so not in terms of the physics of the earth or even the solar system but rather in terms of its extrapolation into a theory of the universe, the laws of which, as he indicated, were little understood. In this respect, the real nature of Engels's argument and its connection to similar arguments by natural scientists in his time (though it is acknowledged that Engels was not entirely alone in his views in this respect) are never analyzed by Martinez-Alier.

Bensaïd (2002, p. 332), for his part, quoted three discontinuous sentences from the first of these paragraphs and one sentence from the third paragraph as *prima facie* evidence that Engels rejected the heat death theory and thus the entropy law. But all that was really conveyed was Engels's skepticism regarding the heat death hypothesis, extrapolated from the second law. Bensaïd, interestingly, did note that Engels was not alone in raising these questions and that "for a long time to come, physicists would question whether reconcentration of the enormous quantity of energy radiated in all directions was possible" (p. 331).[7]

Kolakowski, as we have seen, charged in relation to the above passages that Engels wrongly stated "that the energy dispersed in the universe must also be concentrated somewhere"—as Engels sought to refute an "over-all diminution of energy in the universe." This was interpreted by Kolakowski (1978, Vol. 3, p. 150, Vol. 1, p. 359) as an attempt to "dispose" of the second law of thermodynamics. In Kolakowski, in contrast to Martinez-Alier, however, the real issue of the *reconcentration* of energy, as it was raised by leading physicists, including many of the major figures in the development of thermodynamics in Engels's day, was at least acknowledged.

It cannot be repeated too frequently that a close scrutiny of the above passages from Engels's 1869 letter and his notes in *The Dialectics of Nature* reveals that Engels was not challenging the second law of thermodynamics at all—but rather its much more dubious cosmological extrapolation or extension in the form of the heat death of the universe conception, which was being used by physicists such as Thomson and Tait to promote a Christian eschatology. Engels was particularly disturbed by the notion that the universe was simply winding down (like a clock) and would eventually descend into some sort of motionless equilibrium. He was also skeptical regarding the obvious implication that this pointed to a moment of creation, seemingly contradicting the first law. As he had indicated in his March 1869 letter to Marx, theories of the universe were being propounded on the basis of natural laws "only half known." A certain dialectical skepticism was therefore to be maintained.

In order to reconstruct more fully Engels's views reflected in the notes from the *Dialectics of Nature* quoted above and shed some light on the evolution of his analysis, it is necessary to look at his subsequent "Introduction" to the *Dialectics of Nature* and his later work *Anti-Dühring*, both of which the critics (aside from Bensaïd and Jaki) have generally ignored. Engels's "Introduction" was written in 1875-1876, *directly after* his notes on the second law and the heat death hypothesis were jotted down and some *6 or 7 years after* his 1869 letter to Marx on the subjects of the earth cooling and heat death hypotheses. Furthermore, Engels also explored these issues in *Anti-Dühring*, published in 1877-1878, that is, not long after he drafted the "Introduction" to the *Dialectics of Nature*. In contrast to his initial scattered notes, these writings constitute Engels's more developed understanding of these questions.

Engels's 1875-1876 draft introduction to the *Dialectics of Nature*, which in contrast to his earlier hurried jottings on the heat death hypothesis was clearly intended for publication (though he did not publish it in his lifetime), shows the care and circumspection with which he actually approached these issues. He began by explaining the superiority of ancient Greek natural philosophy, by which he meant primarily Heraclitus, Aristotle, and Epicurus, to the mechanistic natural science of the Enlightenment. “For the Greek philosophers the world was essentially something that had emerged from chaos, something that had developed, that had come into being.” In contrast, Newtonian mechanism “everywhere . . . sought and found its ultimate resort in an impulse from outside [God] that was not to be explained from nature itself.” Only in the late 18th century, he argued, did this begin to break down with the nebular hypothesis on the origins of the solar system introduced by Kant and Laplace. For Engels, a dialectical approach was grounded in nature’s (including the universe’s) evolution and could not rely on the “first movers” and “final causes” characteristic of religion. He argued, moreover, that materialist science invariably developed such an evolutionary approach as its overall analysis was extended (Marx & Engels, 1975a, Vol. 25, pp. 322-324).

This set the theme for Engels’s entire introduction in which he recounted the development of science and ended by raising questions about the cooling of the earth and the heat death hypothesis. Engels closed his discussion in the last five pages with a brief narrative of the inevitable death of the solar system because of the eventual cooling of the sun. In 1862, Thomson had published two articles—“On the Secular Cooling of the Earth” and “On the Age of the Sun’s Heat” (the latter article also questioned the heat death hypothesis)—in which he postulated the cooling of the sun over as little as a few million years. Thomson’s results were accepted by Engels and knowledgeable scientific observers at the time. Later scientific discoveries in radioactivity and nuclear physics, however, were to show that this was based on a faulty notion of the source of the sun’s energy and that the sun’s cooling was far slower than had been supposed, on the order of billions of years (Brush, 1978, pp. 34-35; Eiseley, 1958, pp. 233-253; Thomson, 1862, 1891).

Engels even presented the heat death hypothesis as a major conclusion of science, the truth of which he did not directly deny:

> Millions of years may elapse,[8] hundreds of thousands of generations be born and die, but inexorably the time will come when the declining warmth of the sun will no longer suffice to melt the ice thrusting itself forward from the poles; when the human race, crowding more and more about the equator, will finally no longer find even there enough heat for life; when gradually even the last trace of organic life will vanish; and the earth, an extinct frozen globe like the moon, will circle in deepest darkness and in an ever narrower orbit about the equally extinct sun, and at last fall into it. Other planets will have preceded it, others will follow it; instead of the bright, warm solar system with its harmonious arrangement of members, only a cold, dead space will pursue its lonely path through universal space. And what will happen to our solar system will happen sooner or later to all the other systems of our island universe; it will happen to all the other innumerable island universes, even to those the light of which will never reach the earth while there is a living human eye to receive it. (Marx & Engels, 1975a, Vol. 25, pp. 331-332)[9]

But then Engels asked a pregnant question (indicating that this was even more speculative): “And when such a solar system has completed its life history and succumbs to the fate of all that is finite, death, what then? Will the sun’s corpse roll on for all eternity through infinite space?” (Marx & Engels, 1975a, Vol. 25, p. 332).[10]

Engels made it clear that he viewed the solar system as part of a larger "island universe"—a term introduced by Kant in 1755 in his *Universal Natural History and the Theory of the Heavens* to describe what we would now call "galaxies" (Fraser, 2006, pp. 87-88; Gribben, 1998, p. 28)[11]—within a broader perspective that includes other island universes beyond our empirically discernible knowledge. In this view, island universes (or galaxies) rather than stars were the unit of analysis in astronomy, a viewpoint that later triumphed in the early 20th century. This raised the issue of the stellar universe beyond the solar system and even beyond the Milky Way.

Here Engels partly relied on the argument of Pyotr Lavrovich Lavrov in his *Attempt at a History of Thought*, published anonymously in St. Petersburg in 1875 and sent by the author to Engels that same year, which contained a chapter titled "The Cosmic Basis of the History of Thought." In this work, Lavrov had argued that

> isolated island masses . . . gravitate towards one another and move under influence of this gravitation, which thus constitutes the most general cosmic phenomenon accessible to us. . . . We scarcely know even one island universe in immeasurable space, viz. the one to which we ourselves belong. By means of thought we can convince ourselves of the *probability* of the existence of other island universes beyond its boundaries, of the reality of which mankind will never be certain; but everything that we *know* of the *universe* is restricted to *our* single island universe. (quoted in Engels, 1940, pp. 352-353).

Engels's dynamic conception of the "island universe" (and of "island universes," which we, in our expanding concept of the universe—also seen as expanding—now call galaxies) was based not only on the work of Lavrov but also on that of the Italian astronomer Pierro Angelo Secchi and the German astronomer Johann Heinrich von Mädler (Marx & Engels, 1975a, Vol. 25, p. 328). In this conception, the death of one star, and one solar system (and indeed one "island universe"), could possibly become the basis for the formation and evolution of others under the force of gravitation. This theory did not contradict the entropy law because it was conceptualized in open terms, that is, in relation to the interaction of solar systems and island universes (plural), not isolated systems.[12]

As Lavrov explained more fully,

> Dead suns with their dead systems of planets and satellites continue their motion in space as long as they do not fall into a new nebula in the process of formation. Then the remains of the dead world become material for hastening the process of formation of the new world. . . . [A] world long since dead obtains the possibility of entering in the process of formation of a new solar system, there a world in formation which has come close to rigid masses is disintegrated into comets and falling stars. Violent death threatens worlds just as easily as inevitable natural extinction. But eternal motion does not cease, and new worlds eternally develop in place of former ones. (quoted in Engels, 1940, p. 353)

Similarly, Engels himself wrote,

> The sudden flaring up of new stars, and the equally sudden increase in brightness of familiar ones, of which we are informed by astronomy, are most easily explained by such collisions. Moreover, not only does our group of planets move about the sun, and our sun within our island universe, but our whole island universe also moves in temporary, relative equilibrium with the other island universes, for even

> the relative equilibrium of freely floating bodies can only exist where the motion is reciprocally determined; and it is assumed by many that the temperature in space is not everywhere the same. (Marx & Engels, 1975a, Vol. 25, pp. 333-334)[13]

The dynamic analysis of the universe or universes presented here by Lavrov and Engels, building on the work of astronomers Mädler and Secchi, obviously did not contradict the entropy law yet raised questions related to the heat death hypothesis.

Engels significantly quoted an 1872 work by Secchi, which similarly asked "are there forces in nature which can reconvert the dead system into its original state of glowing nebula and re-awaken it to new life?" Secchi's answer was simply, "We do not know" (Marx & Engels, 1975a, Vol. 25, p. 332). After redescribing heat death as a situation where "all existing mechanical motion will be converted into heat and the latter radiated into space, so that . . . all motion in general would have ceased," Engels conjectured that "in some way, which it will later be the task of scientific research to demonstrate, it must be possible for the heat radiated into space to be transformed into another form of motion, in which it can once more be stored up and become active" (Marx & Engels, 1975a, Vol. 25, p. 334).

Engels even suggested, based on the Mädler–Secchi–Lavrov argument on the death and formation of stellar systems, that within infinite space there is the possibility of "an eternal cycle" of universal entropic dissipation, reconcentration, and redissipation of energy, operative over "periods of time for which our terrestrial year is no adequate measure" (Marx & Engels, 1975a, Vol. 25, p. 334).[14] Significantly, Engels in these carefully written passages intended for publication did not employ the easily misunderstood term *re-utilization* in relation to energy radiated into space, which he had jotted down in his preliminary notes.

Nothing in Engels's discussion of the limits of the heat death hypothesis can be viewed as conflicting with the entropy law precisely because Engels's viewpoint, rooted in the astronomical theories of his time (and not simply on extrapolations from thermodynamics), suggests that the universe is in fact an open, dynamic system.

Engels, as we have seen, had an additional reason for questioning the heat death hypothesis related to his dialectical conception that the universe was a natural–material system removed from any supernatural causes. The heat death hypothesis implicitly relied on some initial exogenous source of motion (usually conceived as emanating from God, as the First Mover). Such reliance could be interpreted, Engels argued, as a seeming contradiction between the first and second laws of thermodynamics, but only in the sense of an abrogation of the first law (matter can be neither created nor destroyed) to extrapolate the heat death hypothesis from the second. For Engels, any materialist–scientific theory of the universe's evolution had to be free of initial conditions provided by supernatural creative acts (aka "intelligent design") (see the third of the paragraphs from the *Dialectics of Nature* provided as exhibits above—Marx & Engels, 1975a, Vol. 25, p. 563).

Bensaïd (2002), as noted, argued, based to a considerable extent on Engels's draft introduction to *The Dialectics of Nature*, that "Engels rejected the second principle of thermodynamics on account of its possible theological consequences" (p. 332). But it would be better to say that Engels believed that theological concerns sparked the premature extrapolation of the second law into a hypothesis of the inevitable heat death of the universe—a hypothesis whose validity seemed highly doubtful. Overlooking this possibility, Bensaïd instead selectively quoted from Engels's argument to suggest that it was based on a dialectical–materialist "ideology" and metaphysics that was allowed to override his science. In the process, however, Bensaïd largely passed over Engels's actual scientific arguments, including his reliance on Mädler, Seechi, and Lavrov and the fact that the "reconcentration" hypothesis arose *from within* thermodynamics in the work of Rankine, Helmholtz, and others (see below). To reduce Engels's argument simply to an irrational "profession of faith" (Bensaïd, 2002, p. 332) was therefore a serious error.

The discussion in Engels's 1877-1878 *Anti-Dühring*—the central text on historical materialism published during Marx and Engels's lifetimes—shows still further how misleading it is to describe all of Engels's writings on the heat death theory as "hasty private notes on the second law of thermodynamics" (Martinez-Alier, 1995, p. 71) while ignoring his more considered analysis in this area. In chapter 6 of *Anti-Dühring*, in a section concerned with Dühring's cosmology, Engels adopted the term *motion* for energy (the latter term was only then coming into use), arguing that Dühring arbitrarily "reduces motion to mechanical force as its supposed basic form, and thereby makes it impossible for himself to understand the real connection between matter and motion" (Marx & Engels, 1975a, Vol. 25, p. 55). For Engels, this real connection

> is simple enough. *Motion is the mode of existence of matter*. Never anywhere has there been matter without motion, nor can there be. Motion in cosmic space, mechanical motion of smaller masses on the various celestial bodies, the vibration of molecules as heat or as electrical or magnetic currents, chemical disintegration and combination, organic life—at each given moment each individual atom of matter in the world is in one or other of these forms of motion, or in several forms at once. . . . Matter without motion is just as inconceivable as motion without matter. Motion is therefore as uncreatable and indestructible as matter itself. (Marx & Engels, 1975a, Vol. 25, pp. 55-56)

Note how Engels related the different forms of motion or energy to the *different forms of matter* with which energy is bound up in reality. For Engels, the crucial implication of the intrinsic unity and indestructibility of matter and energy is that all apparent cessations of motion represent only states of equilibrium *relative to* the ceaseless motion inherent to the universe as a *qualitatively variegated* material system:

> All rest, all equilibrium, is only relative, only has meaning in relation to one or other definite form of motion. On the earth, for example, a body may be in mechanical equilibrium, may be mechanically at rest; but this in no way prevents it from participating in the motion of the earth and in that of the whole solar system, just as little as it prevents its most minute physical particles from carrying out the vibrations determined by its temperature, or its atoms from passing through a chemical process. (Marx & Engels, 1975a, Vol. 25, p. 56)

From this perspective, there could be no universal absolute equilibrium in which all motion ceases. Clearly alluding to the heat death theory, Engels did not shy from this conclusion:

> A motionless state of matter is therefore one of the most empty and nonsensical of ideas. . . . In order to arrive at such an idea it is necessary to conceive the relative mechanical equilibrium, a state in which a body on the earth may be, as

> [at] absolute rest, and then to extend this equilibrium over the whole universe. . . . This conception is nonsensical, because it transfers to the entire universe a state as absolute, which by its nature is relative and therefore can only affect a *part* of matter at any one time. (Marx & Engels, 1975a, Vol. 25, p. 56)

In all of his formulations in his draft introduction to *The Dialectics of Nature* and in *Anti-Dühring*, and in his early notes on the heat death hypothesis in *The Dialectics of Nature*, Engels remained consistent throughout with the second law of thermodynamics. He objected only to the extrapolation of the second law into the heat death of the universe hypothesis and to the seeming contradictions that this created within thermodynamics and cosmology as theoretical systems rooted in a consistent materialist outlook.

3. THE HEAT DEATH HYPOTHESIS AND 19TH-CENTURY PHYSICS

The heat death of the universe hypothesis was promoted by such leading figures in thermodynamics as Helmholtz, Clausius, Thomson, and Tait. Nevertheless, a scientific consensus was lacking. Extrapolation of the heat death hypothesis from the entropy law was opposed in various ways by some of the pioneers in thermodynamics, including Mayer, Rankine, Grove, and Boltzmann, whereas Helmholtz and Thomson, who had both played leading parts in the development of the hypothesis, were later to express serious reservations. As Garber, Brush, and Everitt (1995) wrote in their study of Maxwell on heat, “Scientists’ reactions to the idea of heat death were mixed. Acceptance or rejection of the idea followed no disciplinary or national boundaries” (p. 56). Thomson and Tait appear to have been especially attracted to the notion for religious reasons (Smith, 1998, pp. 111, 119-120, 253-254). Others resisted it because of its apparent conflict with materialism. From the mere fact that there were leading figures in thermodynamics on both sides of the controversy—with Helmholtz and Thomson seemingly lending support at different times to both sides—it stands to reason that the mere rejection of the heat death hypothesis did not entail the abandonment of thermodynamics in general or the entropy law more specifically.

What became known as the “heat death of the universe” hypothesis was first suggested by Thomson in reference to the solar system and fate of the earth as early as 1851-1852 (Lindley, 2004, pp. 108-109; Smith, 1998, p. 111). But its origin is conventionally, if somewhat mistakenly, traced to a lecture, “On the Interaction of Natural Forces,” delivered in Königsberg in 1854 by Helmholtz (one of the codiscoverers of the first law of thermodynamics). Helmholtz (1873) made it explicit that this hypothesis was to apply to the entire universe, stating,

> If the universe be delivered over to the undisturbed action of its physical processes, all force will finally pass into the form of heat, and all heat come into a state of equilibrium. Then all possibility of a further change will be at an end, and the complete cessation of all natural processes must set in. The life of men, animals, and plants, could not of course continue if the sun had lost its high temperature, and with it his light. . . . In short, the universe from that time forward would be condemned to a state of eternal rest. . . . At all events we must admire the sagacity of Thomson, who . . . was able to discern consequences which threatened the universe, though certainly after an infinite period of time, with eternal death. (pp. 228-229)

Clausius was later to argue in 1867 that as "*the entropy of the universe tends toward a maximum* . . . and supposing this condition to be at last completely attained, no further change could evermore take place, and the universe would be in a state of unchanging death" (quoted in Brush, 1978, p. 61).

Nevertheless, even before Helmholtz delivered his 1854 lecture, the heat death hypothesis had come under strong attack within thermodynamics. After Thomson presented his early version of the theory under the title "The Universal Tendency in Nature to the Dissipation of Mechanical Energy" to the Royal Society of Edinburgh in April 1852, William Rankine issued a rebuttal, "On the Reconcentration of the Mechanical Energy of the Universe," before the Belfast meetings of the British Association for the Advancement of Science in September of that same year. This is significant because Rankine was one of the foremost contributors to thermodynamics and formulated the basic entropy idea even before Thomson and Clausius (Lindley, 2004, p. 110). He now argued that although there is a tendency toward "an end of all physical phenomena," it was still

> conceivable that, at some indefinitely distant period, an opposite condition of the world may take place, in which the energy which is now being diffused may be reconcentrated into foci, and stores of chemical power again produced from the inert compounds which are now being continually formed.

More specifically, Rankine supposed that there might be a boundary around what he called "the visible world" (by which he probably meant the solar system or at most the Milky Way; i.e., the extent of the visible universe) and that "on reaching those bounds the radiant heat of the world would be totally reflected, and will ultimately be reconcentrated into foci." Thus, despite the second law of thermodynamics, "the world, as now created, may possibly be provided with the means of reconcentrating its physical energies, and renewing its activity and life" (Harman, 1982, p. 68; Martinez-Alier, 1987, p. 61; Rankine, 1852, pp. 359-360). As Crosbie Smith (1998) portrayed Rankine's argument,

> While not disputing Thomson's claim to "represent truly the present condition of the universe, as we know it," Rankine refused to accept the pessimistic conclusion. He therefore speculated that radiant heat—"the ultimate form to which all physical energy tends"—might be totally reflected at the boundaries of the very interstellar medium through which the radiation had been transmitted and diffused. The energy might then be "ultimately re-concentrated into foci; at one of which, if an extinct star arrives, it will be resolved into its elements, and a store of energy reproduced." (p. 142)

This disagreement about the heat death hypothesis was clearly a dispute not about entropy itself but about whether there were other physical processes within the universe at large (or beyond the boundaries of the known universe) that could produce an opposite effect. Questioning the heat death theory in this way did not imply any rejection of the second law as such.

Although Engels doubtless paid close attention to articles published in the *Philosophical Magazine*, he did not cite Rankine's article in his notes on the subject (though he did cite Helmholtz's own discussion of this following Rankine). But Rankine's specific conjecture of the "reflection" of radiant heat from the boundaries of the universe (and Helmholtz's later version of this) continued to crop up in 19th-century physics and astronomy and was central to questions raised about the heat death hypothesis in the scientific literature of the day.

Although Thomson is generally seen to be an originator and strong supporter of the heat death theory, which appealed to him on religious grounds, he nonetheless expressed some reservations in the 1860s. Thus, in his famous 1862 lecture, "On the Age of the Sun's Heat," he argued, in direct opposition to his own 1852 essay on the universal tendency toward the dissipation of energy, that there were metaphysical reasons for doubting that this universal tendency extended to the universe itself:

> The result [of the entropy law] would inevitably be a state of universal rest and death, if the universe were finite and left to obey existing laws. But it is impossible to conceive a limit to the extent of matter in the universe; and therefore science points rather to endless progress, through an endless space, of action involving the transformation of potential energy into palpable motion and thence into heat, than to a single finite mechanism, running down like a clock and stopping forever. (Kragh, 2004, p. 46; Thomson, 1891, pp. 356-357)

Helmholtz also raised questions about the heat death hypothesis that he had helped introduce. Helmholtz (1876) was to declare, in line with Rankine,

> The heat [radiating out into space] was lost for our solar system, but not for the universe. It radiated out and is still moving out into unending spaces, and we do not know whether the medium carrying the vibrations of light and heat has any frontier where the rays must turn back or whether they will continue their journey to infinity forever. (p. 121, translation as quoted in Sternberger, 1977, pp. 37-38; also see Harman, 1982, p. 68; Martinez-Alier, 1987, p. 61; Rabinbach, 1990, p. 62)

What is important is that Helmholtz, often credited with having introduced the heat death hypothesis, suggested that Rankine could be right on the "reconcentration" of energy and frankly admitted that "we do not know" regarding the supposed heat death of the universe.

Significantly, Engels was taking notes from this very same page of Helmholtz's *Populäre Wissenschaftliche Vorträge* (*Popular Scientific Lectures*) when he raised questions about the reconcentration ("re-utilization") of energy radiated out into space. He was therefore clearly influenced by Helmholtz's thinking in this regard (Marx & Engels, 1975a, Vol. 25, p. 562). Engels's brief allusion to the possible "re-utilization" of energy dissipated into space—for which he has been criticized by Martinez-Alier and others—therefore occurred only in notes (not intended for publication) on Helmholtz, who was himself raising the question of the "reconcentration" of energy in response to the heat death hypothesis. In fact, the context of Engels's notes make it difficult to discern to what extent he was simply relating his version of Helmholtz's views and to what extent he was stating his own.

Helmholtz, in the 1870s, in passages with which Engels was familiar, made it even clearer that he was inclined toward a metaphysical–cosmological view that went against any absolute heat death notion:

> The flame . . . may become extinct, but the heat which it produces continues to exist—indestructible, imperishable, as an invisible motion, now agitating the molecules of ponderable matter, and then radiating into boundless space as the vibration of an ether. Even there it retains the characteristics peculiar of its origin,

> and it reveals its history to the inquirer who questions it by the spectroscope. United afresh, these rays may ignite a new flame, and thus, as it were acquire a new bodily existence. (Helmholtz, 1908, p. 194)

At about the same time as Helmholtz, Mayer (1870), also one of the codiscoverers of the conservation of energy, stated his doubts that "the entire machine of creation must eventually come to a standstill" (pp. 566-567; also see Garber et al., 1995, p. 56).[15]

The famed English jurist and physical chemist Sir William Robert Grove, whose work was greatly admired by Marx and Engels, combined an acute understanding of the laws of thermodynamics with a deep skepticism about universal heat death. Grove is known as "the father of the fuel cell" for his development of the platinum–zinc voltaic battery. His theoretical and practical researches greatly enhanced our understanding of the conservation of energy and of the limits to conversion of energy into work. In his main published work, *The Correlation of Physical Forces*, he—much like Engels—questioned the heat death theory on grounds that "we know not the original source of terrestrial heat; still less that of the solar heat" (Grove, 1873, p. 80). And he also—again comparably to Engels—pointed out the likely presence of disequilibrating counters to an entropic "evening out" of energy on a universal scale, suggesting,

> We know not whether or not systems of planets may be so constituted as to communicate forces, *inter se*, so that forces which have hitherto escaped detection may be in a continuous or recurring state of inter change.
>
> The movements produced by mutual gravitation may be the means of calling into existence molecular forces within the substances of the planets themselves. As neither from observation, nor from deduction, can we fix or conjecture any boundary to the universe of stellar orbs, as each advance in telescopic power gives us a new shell, so to speak, of stars, we may regard our globe, in the limit, as surrounded by a sphere of matter radiating heat, light, and possibly other, forces.
>
> Such stellar radiations would not, from the evidence we have at present, appear sufficient to supply the loss of heat by terrestrial radiations; but it is quite conceivable that the whole solar system may pass through portions of space having different temperatures, as was suggested, I believe, by Poisson; that as we have a terrestrial summer and winter, so there may be a solar or systematic summer and winter, in which case the heat lost during the latter period might be restored during the former. The amount of the radiations of the celestial bodies may again, from changes in their positions, vary through epochs which are of enormous duration as regards the existence of the human species. (Grove, 1873, pp. 80-81)

In short, Grove based his argument against universal heat death on the indestructibility and non-homogeneity of material forces and on the general difficulty of treating the universe as a finite isolated system in equilibrium. The issue raised by Grove of the limits of the universe as then known (e.g., "each advance in telescopic power gives us a new shell, so to speak") pointed to the fact that there were too many unknown aspects of cosmological phenomena to arrive at conclusions on the thermal death of the universe based on the second law of thermodynamics alone. Grove clearly believed that the answers were to be found in the expansion of astronomical data and that the role of gravitation was key. His general approach conformed to principles of scientific inference long understood: that where there are multiple conceivable explanations and possibilities, scientific conclusions—especially when they conflict with known principles—must "await confirmation."[16]

Another leading thermodynamic theorist and contemporary of Engels who developed a critique of the heat death theory was the Austrian materialist and physicist Ludwig Boltzmann. Engels was familiar with Boltzmann's work, both directly and via the detailed discussions of Boltzmann in Maxwell's *Theory of Heat*, a book of which Engels made extensive use in *The Dialectics of Nature* (Marx & Engels, 1975a, Vol. 25, pp. 389-390, 407-408, 466, 565). David Lindley (2001) describes the state of Boltzmann's thinking on heat death by the years 1895 and 1896:

> In thinking of the universe as a whole, which was generally presumed at that time to be eternal, it might seem that everything would have to settle down into a perfectly uniform, perfectly stable equilibrium—clearly not the heterogeneous universe of stars and planets and empty space that astronomers were beginning to map out. The notion of an inexorable winding down of the universe into a featureless stasis had been pointed out by Clausius, who called it the "heat death." Boltzmann now suggested that even in such a state, there would be pockets that, strictly for reasons of chance, ran temporarily away from the general equilibrium and then fell back again. The corner of the universe currently occupied by humanity, he suggested, must be just such a place, where entropy happened to have hit a temporary low and was increasing again. Elsewhere there would be pockets of the universe where entropy was running down, and in such places, Boltzmann speculated, it might appear that time itself was running backward. (p. 144)[17]

Thinkers such as Boltzmann, Grove, Thomson, and Engels argued that a "basic error" of the heat death hypothesis lay "in the fact that laws holding for finite [isolated] systems cannot be transferred without further ado to a universe postulated to be infinite" (Wetter, 1958, p. 436).

Biologist Ernst Haeckel (1929, pp. 202-203), famous as the leading promoter of Darwinian ideas in Germany in the 19th century and for coining the word *ecology*, also rejected the heat death hypothesis on the similar grounds to Rankine and Helmholtz, though with a less adequate grasp of the physics involved.[18]

Not only natural scientists but also leading cross-disciplinary thinkers concerned with merging the natural and social sciences propounded the possibility of the "reconcentration" of energy within the universe as a result of still unknown forces, thereby questioning the heat death hypothesis but not the entropy law. Herbert Spencer was a major popularizer of the notion of "universal death" associated with the heat death controversy. Nevertheless, in an analysis that repeatedly referred to Helmholtz's 1854 paper presenting the heat death theory, he asserted, on the basis of gravitational tendencies and astronomical developments suggesting the collision of stars, that concentration of energy in the universe would proceed to be followed later by its diffusion in an *eternal cycle* of attraction and repulsion. As Spencer (1880) put it in his *First Principles*,

> Apparently the universally co-existent forces of attraction and repulsion, which, as we have seen, necessitate rhythm in all minor changes through the universe also necessitate rhythm in the totality of its changes, produce now an immeasurable period during which the attractive forces predominating cause universal concentration and then an immeasurable period during which the repulsive forces predominating cause universal diffusion—alternate eras of evolution and dissolution. (pp. 458, 465; also see Brush, 1978, pp. 63-64)

More significantly, economist William Stanley Jevons included in his 1874 *Principles of Science* a section titled "Speculations on the Reconcentration of Energy" in which he stated that we "cannot deny the possible truth of. . . . Rankine's hypothesis" opposing the heat death theory. It nevertheless remained "practically incapable of verification by observation, and almost free from restrictions afforded by present knowledge." Jevons argued that Rankine's hypothesis meant that we had to admit to "the finiteness of the portion of the medium [within the universe] in which we exist," whereas the heat death hypothesis required assumptions about "the finiteness of [the] past duration of the world" since "progressing from some act of creation, or some discontinuity of existence." In either case, he argued, the unity of our physical view is interfered with and "we become involved in metaphysical and mechanical difficulties surpassing our mental powers" (Jevons, 1900, pp. 751-752; also see Barrow, 1994, p. 25). Jevons's doubts about the universe "progressing from some act of creation," and his clear sympathy for Rankine's argument on "reconcentration"—although he emphasized we have no practical way of ascertaining this one way or another—reflect considerations similar to those of Engels.

In this context, it is very significant that Martinez-Alier acknowledged both Rankine's criticism of the heat death hypothesis and even Helmholtz's own criticism of it, in the context of justifying Jevons's criticisms based on Rankine—indicating at the same time that Jevons was fully cognizant of the second law of thermodynamics (Martinez-Alier, 1987, p. 161). His very favorable treatment of Jevons was part of an attempt to present him as one of the founders of ecological economics. The fact that Engels had used some of the same arguments against the heat death hypothesis and developed them far more fully than Jevons was, however, in *Engels's case*, repeatedly presented by Martinez-Alier as *prima facie* evidence that Engels had rejected the second law of thermodynamics itself. Such intellectual double standards are difficult to fathom.

Today, the Newtonian world of classical physics has been replaced by a much more complex view of the universe. As Peter Coveney and Roger Highfield (1990) write in *The Arrow of Time*, the original heat death argument is widely viewed as simplistic or

> flawed because it ignores the role of gravity (and black holes): when gravity is included, it turns out that the universe must go further and further away from the uniform distribution of matter envisaged in the Heat Death. . . . [Moreover] we know from astronomical evidence that the universe as a whole is expanding, so it cannot be anywhere near a state of thermodynamic equilibrium. (pp. 154-155)

As some of the early critics of the heat death hypothesis, including Grove and Engels, seem to have vaguely suspected in part, it is recognized today that

> there is a struggle between gravity, which pulls stars together and provides the energy which heats them inside to the point where nuclear fission begins, and thermodynamics, seeking to smooth out the distribution of energy in accordance with the second law. . . . The story of the Universe is the story of that struggle between gravity and thermodynamics. (Gribben, 1998, p. 5)

The British cosmologist, theoretical physicist, and mathematician John D. Barrow (1994) provides even stronger reasons to doubt the heat death hypothesis in *The Origin of the Universe*:

> It is only recently that cosmologists have realized that the predicted heat death of ever-expanding universes in a future state of maximum entropy will not occur. Although the entropy of the universe will continue to increase, the maximum entropy it can have at any given time increases even faster. Thus the gap between the maximum possible entropy and the true entropy of our universe continually widens. . . . The universe actually gets farther and farther away from the "dead" state of complete thermal equilibrium. (pp. 26-27)[19]

Stephen Toulmin (1982) has argued on logical grounds that to say that the second law of thermodynamics is a universal law for isolated systems is a different matter from saying that it applies to the "universe-as-a-whole." Indeed, it is impossible to know what it would mean to refer to the universe as an isolated system because if it is bounded it has to be bounded by something. Thus, he concludes that "the conditions necessary for us to apply the Second Law of Thermodynamics to the universe-as-whole are such as *cannot* be satisfied." "The most it [the second law] could do would be to *imply* something about the universe, and it could do that only if we also knew how far the universe was itself a thermally isolated system" (pp. 40-43).

Interestingly, although Georgescu-Roegen, the leading figure in 20th-century ecological economics, frequently referred to the heat death hypothesis of classical physics, he too found it "intellectually unsatisfactory." He considered a number of conceivable alternatives presented by physicists, including (a) the Boltzmann-derived hypothesis that "entropy may decrease in some parts of the universe so that the universe both ages and rejuvenates" and (b) the "steady state" theory "in which individual galaxies are born and die continuously." Both were consistent with the second law, but neither was completely acceptable to him. In the end, he concluded that "the issue of the true nature of the universe is far from settled" (Georgescu-Roegen, 1976, p. 8; cf. Georgescu-Roegen, 1971, pp. 201-202). In considering alternatives to the heat death theory that were consistent with the second law and arguing, in Epicurean-like terms, that the answer must "await confirmation" with an increase of our knowledge, Georgescu-Roegen's general intellectual position on this issue was not unlike that of Engels a century earlier.

What then is left of the claims of Martinez-Alier, Bell, Kolakowski, Jaki, Bensaïd, Kragh, Stokes, Frenay and others that Engels rejected the second law of thermodynamics? Literally nothing. All of the passages in Engels cited above are criticisms of the heat death of the universe hypothesis extrapolated from the second law of thermodynamics, not of the entropy law itself. All of the arguments that Engels used were similar to, or derived from, those of physicists, astronomers, and scientific commentators in general in his day. If Engels's references in his notes to the "reconcentration" (or "reutilization") of energy are to be taken as proof of the rejection of the second law of thermodynamics, then we would arrive at the absurd conclusion that some of the leading foundational figures in thermodynamics, including Mayer, Helmholtz, Rankine, Grove, and Boltzmann (even Thomson), also rejected the second law. In speculating on this issue (and reaching no definite conclusion), Engels was consistent with the best physics of his day as presented in the top scientific journals, such as *Philosophical Magazine* and *Nature*. Furthermore, given that modern physics has continued to question the heat death of the universe hypothesis—but of course not the second law of thermodynamics—the confusion of the heat death hypothesis with the second law by critics of classical Marxism becomes even more untenable.

There is no doubt that Engels always adhered to the entropy law with regard to the terrestrial physics of the earth (and the solar system). *The Dialectics of Nature* contains numerous discussions of friction and other entropic processes—passages that verify Engels's deeply held conviction on the correctness of the second law. As Bukharin (2005) observed in his *Philosophical Arabesques*,

> Engels . . . considered inevitable both the decline of humanity and its extinction, together with the ending of life on the earth as a planet. In other words, human history cannot be divorced in any way from the history of the earth as the base, *locus standi* and source of nourishment of society. (p. 259)

4. MARXISM, THE ENTROPY LAW, AND ECOLOGY

Unfortunately, what was at first a relatively minor point in a critique of Engels's *Dialectic of Nature* has been transformed into a major criticism (though just as completely devoid of foundations, as we have seen) in a wide-ranging debate on the status of classical Marxism within ecological economics. The criticisms of Engels (and by imputation Marx) leveled by Martinez-Alier, Bensaïd, Stokes, and Frenay in particular are all directed at arguing that because Engels allegedly rejected the second law of thermodynamics, he thereby severed at the very start any possible relation between classical Marxism and ecological economics. Usually, this is appended to the wider charge that in failing to take seriously Podolinsky's analysis of energy transfers in agriculture, Marx and Engels closed the door in their day to the development of a Marxist ecological economics, making Podolinsky himself an anomaly in advancing what Martinez-Alier (1987, p. 62) calls his "ecological Marxism." (In Bensaïd's case, it should be noted, Engels's critique of Podolinsky's crude energetics is fully accepted, but Engels is still mistakenly chided for "rejecting" the second law.)

What makes this a high-stakes debate is of course the history and future of ecological economics and with that ecological analysis as a whole, including its relation to Marxism. For Martinez-Alier, the ecological failure of classical Marxism could not be more straightforward: "Marx did live after the second law of thermodynamics was established by Sadi Carnot, Clausius, William Thomson, etc. . . . he took no account of it in his economic and historical doctrines" (Martinez-Alier & Naredo, 1982, p. 209). Similarly, as he stated in 1995, "Although Marx and Engels were contemporaries of the physicists who established the laws of thermodynamics in the mid-19th century, Marxian economics and economic history were based on social and economic analysis alone" (Martinez-Alier, 1995, p. 72). Ecological socialist James O'Connor (1998), following Martinez-Alier, asserts that "Marx did *not* pay sufficient attention to energy economics," including the fact "that capitalist production (like all production) is based on energy flows and transformations" (p. 122).[20]

None of these charges stand in the face of criticisms that have been leveled. The allegation that Marx and Engels simply ignored Podolinsky or rejected his important ecological ideas has been thoroughly refuted elsewhere. Specifically, although Podolinsky's approach has been shown to contradict ecological analysis, it has been established that the founders of historical materialism not only gave close *critical* attention to Podolinsky's ideas but also incorporated the first and second laws of thermodynamics into their analysis of capitalism (Bensaïd, 2002; Burkett & Foster, 2006; Foster & Burkett, 2004).

Indeed, it is simply incorrect to say that thermodynamics was not integrated into Marxian economics in its classical formulations. A growing body of research has demonstrated the enormous extent to which Marx built thermodynamic concepts and other elements of contemporary physics into his entire argument in *Capital* (Burkett & Foster, 2006; Rabinbach, 1990; Wendling, 2006). Thermodynamics is to be found in the very pores of an analysis that to the superficial reader addresses the capitalist laws of exchange value alone.

This is because Marx's dialectical conception of value gives it from the very start a twofold character, both use value and exchange value, which together constitute commodity relations. Use value incorporates the conditions of production and in particular the natural–material properties embodied in production that are universal prerequisites (a fundamental ecological conception). Exchange value, in contrast, is concerned with the enhancement of economic surplus value for the capitalist—a specific social form of production. Marx's method is never to ignore either part of this dialectic but to analyze their developing relations and contradictions together. Hence, every chapter of *Capital* addresses conditions related to physics and economics (Rabinbach, 1990, p. 76).

For Marx, this dialectical conception could be traced all the way back to Greek antiquity. As he wrote in the chapter he authored in Engels's *Anti-Dühring*, "In so far as the Greeks make occasional excursions into this sphere [the economy], they show the same genius and originality as in all other spheres. Because of this, their views form, historically, the theoretical starting-points of modern science" (Marx & Engels, 1975a, Vol. 25, p. 212). In this respect (i.e., ancient Greek contributions to economics), Aristotle's distinction between use value and exchange value, which Marx carried forth into the analysis of capitalist commodity relations, was surely the greatest achievement (Marx, 1970, p. 27).

It is no wonder then that Marx incorporated into *Capital* and other works Liebig's understanding of the metabolic exchange underlying agriculture, Ludimar Hermann's biochemical physiology, Grove's studies of the correlation of physical forces and of electricity, Charles Babbage's treatment of machinery and power, Robert Willis's studies of the mechanics of energy transfer, and so on (Burkett & Foster, 2006, p. 119; Wendling, 2006, pp. 229-232).

The publication of more and more of Marx and Engels's voluminous notes on the sciences—chemistry, physics, mechanical engineering, biology, geology, agronomy, cosmology, anthropology, mathematics, philosophy of science, and so on—allows us to see how this was concretely accomplished. Marx's notes on thermodynamics and energetics begin as early as 1851 with his reading of Büchner and Liebig (Wendling, 2006, p. 76). The very concept of labor power was introduced in Germany by Helmholtz (Rabinbach, 1990, pp. 55-61; Wendling, 2006, pp. 95-96).

The fact that Marx adopted the concept of labor power and used it both in its material–energetic sense and in relation to economic value analysis (i.e., the way labor power was translated into a commodity that generated surplus value for the capitalist) has led such analysts as Rabinbach and Wendling to refer to the "marriage of Marx and Helmholtz" in Marx's work and in particular in Engels's (Rabinbach, 1990, pp. 72-74; Wendling, 2006, p. 96). Rabinbach (1990) points out that Marx always emphasized the energetic basis of labor power and saw it connected to thermodynamics because labor involved mechanical work. Marx's confrontation with thermodynamics in his critique of political economy, Wendling (2006) concludes, was such that it caused him "to superimpose a thermodynamic model of labor over the ontological model of labor he inherits from Hegel" (p. 63).

The study of the role that thermodynamics played in the development of Marx's theory of labor power and machinery (an analysis confirmed from another standpoint elsewhere—see Burkett & Foster, 2006) led Rabinbach to contend (as already quoted at the outset of this article), "The most important nineteenth-century thinker to absorb the insights of thermodynamics was Marx, whose work was influenced and perhaps even decisively shaped by the new image of work as 'labor power'" (pp. 69-70). Wendling, for her part, observes, "Marx begins [his critique of political economy] with a challenge to Proudhon [on machinery], and ends with a partial conversion to a thermodynamic and energeticist view of labor" (p. 267). In her dissertation, Wendling reproduces a page from Marx's unpublished notebooks that shows a meticulous drawing by Marx of a machine and its various motor mechanisms for the transmission of energy (Wendling, 2006, p. 171).

The interpretation of Rabinbach and Wendling might be challenged for its failure fully to delve into Marx's political–economic, value–theoretic analysis and the metabolic basis of Marx's treatment of human labor (Burkett & Foster, 2006; Foster, 2000). Nonetheless, the evidence that they provide on the role of thermodynamics–energetics in Marx's basic concept of labor power and its application to production and machinery is too firmly rooted to be questioned.

Indeed, the Rabinbach–Wendling analysis nicely complements a more economic and metabolic reading. In Marx's *Capital*, the distinction between labor power and labor expended is a distinction between potential work and actual work (see Burkett & Foster, 2006).[21] The amount of productively expendable energy encapsulated in labor power is thus quite a different thing from the caloric quantity of useful work needed to produce the worker's commodified means of subsistence. Indeed, it is the excess of the former over the latter that enables the capitalist to extract surplus value from the worker. As Marx (1976) indicates, "The fact that half a day's labour [for example] is necessary to keep the worker alive during 24 hours does not in any way prevent him from working a full day" (p. 300). In short, the capitalist takes advantage of the fact that "what the free worker sells is always nothing more than a specific, particular measure of force-expenditure," whereas "labour capacity as a totality is greater than every particular expenditure" (Marx, 1973, p. 464). When "the worker . . . sells himself as an effect" and "is absorbed into the body of capital . . . as activity," the result is an energy subsidy for the capitalist who appropriates and sells the commodities produced during the portion of the workday (surplus labor time) over and above that needed to produce the means of subsistence represented by the wage ("necessary" labor time) (Marx, 1973, p. 674).

"For the capitalist," this surplus of energy (and of value) "has all the charms of something created out of nothing" (Marx, 1976, p. 325). But it actually represents capital's appropriation of part of the potential work created by the daily metabolic–energetic regeneration of the worker's labor power. This regeneration occurs largely during nonwork time, through rest, access to fresh air, and various domestic reproductive activities undertaken by the worker and/or by the worker's family members. Put differently, in Marx's theory, surplus labor (including surplus value) has an energetic basis in the distinction between labor power as potential labor and the actual expenditure of this labor power. Marx argued that surplus value originates in the capitalistic extraction of the potential laboring force created mainly during the workers' off hours by rest, domestic labor, and so on. Indeed, the tendency of surplus labor time to encroach on the free time required for these regenerative activities and the attendant need for social restraints on capitalist exploitation are major themes in *Capital*. Energy analysis is thus a crucial element in Marx's famous investigation of the struggle over the working day (Burkett & Foster, 2006).

The thermodynamic substance and implications of Marx's *Capital* go beyond the exploitation of labor power itself. Marx saw capitalism's mechanized industrial productive forces—factory systems—as distributing energy from a primary motor mechanism to the tools or working machines. These new systems of energy transmission underpinned, in Marx's view, capitalism's unprecedented advances in labor productivity, which directly translated into historically huge increases in the throughput of matter and energy drawn from and emitted into the natural environment, that is, into capitalism's surging appetite for raw materials including ancillary materials used as energy sources. Crucially, Marx's analysis explains this whole development as an outgrowth of the separation of workers from control over the tools used in production and the installation of these tools in machines that could then be powered not just by human and other animate energy but by inanimate "motive forces" (Marx, 1976, chap. 15). Georgescu-Roegen and other ecological economists have seen this break from the "solar budget constraint" as a crucial turning point in the transition to an ecologically unsustainable economy—without, however, rooting it in capitalism's specific production relations the way Marx did (Burkett & Foster, 2006).

Marx also developed a theory of ecological crisis based on the metabolic rift between nature and society opened up by capitalist agriculture and urbanization. Soil nutrients (nitrogen, phosphorus, and potassium) are not returned to the soil but shipped hundreds and thousands of miles in the form of food and fiber to the cities, where they add in the end to urban pollution. The search for fertilizers to bridge this rift leads to the development of a global guano trade and then to the development of artificial fertilizers, creating new ecological contradictions (Marx, 1976, pp. 636-639; Marx, 1981, pp. 948-949). These considerations on capitalist agriculture and the recycling of organic wastes led Marx to a concept of sustainability to be implemented in a society of associated producers concerned with the rational organization of their metabolic relation to nature. This analysis was later to inspire Kautsky and Lenin (Foster & Magdoff, 1999, pp. 47-51). Marx's theory of metabolic rift has now been explored and developed in numerous studies (Burkett, 1999; Burkett, 2006, pp. 202-207; Clark & York, 2005; Clausen, 2007; Clausen & Clark, 2005; Dickens, 2004, pp. 58-90; Foster, 1999; Foster, 2000, pp. 141-177; Mancus, 2007; Mayumi, 2001, pp. 79-96, 144). On this basis alone, Marx is increasingly being recognized as one of the founding figures of ecological economics and of ecological analysis more generally.

Although acknowledging recent research that "rediscovered Marx's 'metabolism,'" and its relation to energetics and ecology, Martinez-Alier (2007) claims that "in his published work Marx did not refer to the flow of energy as metabolism" (p. 224). This criticism is overstated, however, because Marx defined the labor process itself as a metabolic process and analyzed this in physical terms as well as in terms of the physiological transfer of energy (even if he did not count calories). It was precisely Marx's definition of labor power in terms of metabolism—and the fact that because of this "when Marx speaks as he frequently does of the 'life process of society' he is not thinking in metaphors"—that in Hannah Arendt's (1958, pp. 93, 99, 106-108) view made him "the greatest of modern labor theorists". As stated by Burkett (2006), "Marx applies metabolic-energy categories *quite literally* to human production, not as a mere *analogy*" (p. 183).

Indeed, far from viewing the question of metabolic–energy cycling simply in metaphorical terms, Marx and Engels raised the question of Liebig's analysis of the soil nutrient cycle and the debates surrounding this in Germany and elsewhere in discussions with their close friend Carl Schorlemmer. Schorlemmer was one of the leading organic chemists of his day: vice-president of the chemical section of the British Association for the Advancement of Science, a fellow of the Royal Society, and the first individual in England to occupy a chair in organic chemistry. He also helped edit proofs of Marx's *Capital*. Through their discussions of this topic with Schorlemmer, whose works they also studied closely, Marx and Engels undoubtedly became better acquainted with the main issues related to plant nutrient cycles and energetics as understood by the most advanced chemistry in their day. Marx made it clear that he viewed this as crucial in his editing of the manuscripts for the third volume of *Capital* (Henderson, 1976, Vol. 1, pp. 262-271; Marx & Engels, 1975a, Vol. 42, pp. 507-508; Stanley, 2002, pp. 46-51).

Martinez-Alier (2007) has also argued more broadly that although Podolinsky in his "ecological Marxism" was a pioneer in trying to quantify energy flows in the economy (and was inspired in this respect by Marx and Engels), there is "no ecological Marxist history based on quantitative studies of material and energy flows" (pp. 223, 229; also see Martinez-Alier, 1987, p. 62).[22] This is hardly surprising, of course, if one recognizes that attempts to quantify such energy flows on the level of the economy as a whole (or even a sector or industry) are enormously difficult if not practically impossible and prone to all sorts of fallacious conclusions (Podolinsky was a case in point). Moreover, such research in the sense of thermodynamically informed ecological economics, much less "history" in this regard, is a relatively new phenomenon in which analysts influenced by Marx have nonetheless played leading roles (Bunker, 1985; Magdoff, 2007; Mayumi, 1991).

Here it is worthwhile adding that Georgescu-Roegen actually sided with Engels regarding reservations about Podolinsky's analysis. After briefly relating Martinez-Alier and Naredo's (1982) version of the dispute between Marx–Engels and Podolinsky, Georgescu-Roegen (1986) comes out in support of Engels's objections regarding "the fallacy of the energy theory of economic value," writing,

> But thoughts such as Podolinsky's must have been ventilated earlier, for Engels had already protested in an 1875 note: "Let someone try to convert any skilled labor into kilogram-meters and then to determine wages on this basis!," a thought that ought to kill in the bud any temptation to replace economics by some energetics. (pp. 8-9)

5. CONCLUSION: THE DIALECTICS OF NATURE AND SOCIETY AND THE SECOND LAW

Marx and Engels's deep concern with thermodynamics and their recognition of its importance for the dialectics of nature and society were appreciated by early Marxists, particularly in the Soviet Union of the 1920s and early 1930s. As a leading early Soviet physicist and sociologist of science Boris Hessen wrote in 1931,

> As soon as the thermal form of motion appeared on the scene . . . the problem of energy came to the forefront. The very setting of the problem of the steam engine (to raise water by means of fire) clearly points to its connection with the

> problem of the conversion of one form of motion into another. It is significant that Carnot's classic work has the title: "On the Motive Force of Fire." . . . [The] treatment of the law of the conservation and conversion of energy given by Engels, raises to the forefront the qualitative aspect of the law of conservation of energy, in contradistinction to the treatment which predominates in modern physics and which reduces this law to a purely quantitative law—the quantity of energy during its transformations. The law of the conservation of energy, the teaching of the indestructibility of motion has to be understood not only in a quantitative but also in a qualitative sense . . . in the circumstance that matter itself is capable of all the endless variety of forms of motion . . . in their self-movement and development. (pp. 202-203)[23]

In this context, it is indeed ironic that Martinez-Alier (2006, p. 275) claims with respect to Engels's remarks on the heat death of the universe hypothesis that "the dialectics of nature failed him there" (a criticism also leveled by Kolakowski). In fact, it was Engels's dialectical conception of nature that allowed him to maintain a healthy skepticism regarding the heat death theory—a skepticism shared by many leading scientists of the day—while still supporting the second law of thermodynamics.

Indeed, a rejection of the second law of thermodynamics would be scarcely conceivable in terms of Marx's (and Engels's) political economy. Marx's *Capital* is permeated throughout with thermodynamic concepts the basis for which lay in Marx and Engels's very detailed scientific investigations into physics, chemistry, physiology, agronomy, and so on. The very concept of "labor power," so central to Marx's analysis, arose in part from the new thermodynamics, beginning with Helmholtz. Marx's detailed analysis of steam engines and other forms of machine power (hydraulic and electrical) led him to address thermodynamic conceptions, as did his analysis of the physiological basis of labor. There is no doubt that Marx's *Capital* was the first major economic treatise—and the only one in the 19th century—to incorporate within its analysis thermodynamic concepts together with economic value categories. Nor was this an accident. It arose from his dialectical treatment of capitalist commodity production as a contradictory relation of use value and exchange value, and labor and labor power. It was part of his larger materialist, dialectical conception of history.

Ironic too—given the repeated claims that Engels rejected the second law of thermodynamics—Marx and Engels's critique of the static character of classical mechanistic physics and of its failure to comprehend the open, dynamic aspects of natural evolution at all levels (including the cosmological) has been lauded by none other than Ilya Prigogine, the 1977 Nobel Prize winner in chemistry and a pioneer in nonequilibrium thermodynamics:

> The idea of a history of nature as an integral part of materialism was asserted by Marx, and, in greater detail, by Engels. Contemporary developments in physics, the discovery of the constructive role played by irreversibility, have thus raised within the natural sciences a question that has long been asked by materialists. For them, understanding nature meant understanding it as being capable of producing man and his societies.
>
> Moreover, at the time Engels wrote his *Dialectics of Nature*, the physical sciences seemed to have rejected the mechanistic world view and drawn closer to the idea of an historical development of nature. Engels mentions three fundamental discoveries: energy and the laws governing its qualitative transformation, the cell as the basic constituent of life, and Darwin's discovery of the evolution of

> species. In view of these great discoveries, Engels came to the conclusion that the mechanistic world view was dead. (Prigogine & Stengers, 1984, pp. 252-253)

For a while, the heat death hypothesis seemed to provide a viable mechanistic answer that aligned with Christian theological conceptions. In his own development of this idea, Thomson had quoted the 102nd Psalm: "They shall perish, but thou shalt endure: yea, all of them shall wax old like a garment; as a vesture shalt thou change them, and they shall be changed" (Smith, 1998, p. 111). Marx and Engels resisted this rigid mechanical philosophy and theology. In the end, they developed a materialist–dialectical conception of history that is far more evolutionary in perspective, more in tune with the complexity of the physics of open systems, and thus more in line with an analysis of ecological necessity—a complex, contingent necessity that does not rule out human freedom.

From the days of Newton and Leibniz, attempts have often been made to wed mechanistic models of the universe both to a strong determinism and a religious cosmology. Gottfried von Leibniz saw God as the supreme and all-seeing clockmaker who determined the world and its outcomes down to the minutest details for all time. As he put it,

> "In the least of substances, eyes as piercing as those of God could read the whole course of things in the universe, *quae sint, quae fuerint, quae mox futura trahantur*" (those which are, which have been, and which shall be in the future). (quoted in Prigogine, 1997, p. 12)

The second law of thermodynamics was interpreted by such early pioneers as Clausius, Thomson, and Tait as an inexorable and unstoppable tendency toward a predetermined final end, eternal death (the heat death of the universe), which fit in with a Christian eschatology.

This, however, ran into a conflict with a more open, dialectical view. This is presented by Prigogine in the first chapter of his *The End of Certainty* as "Epicurus's Dilemma." The ancient Greek atomistic philosopher Epicurus had built his physics on mechanical principles in the movement of atoms that he had drawn from Democritus. But Epicurus introduced a subtle change in the theory. In falling toward the earth, atoms on occasion swerved almost imperceptibly from a straight line, creating contingency. A strict determinism was thus impossible. Prigogine argues that only now are we beginning to understand fully the significance of Epicurus's swerve in the development of nonequilibrium physics, both in relation to ecological developments on earth and in phenomena within the cosmos. Epicurus's swerve "no longer belongs to a philosophical dream that is foreign to physics. It is the very expression of dynamical instability" (Prigogine, 1997, pp. 9-17, 55, 127).

The first modern thinker to focus on and explore in great detail Epicurus's Dilemma, presenting the swerve as an attempt to generate a nonmechanistic materialism rooted in an immanent dialectic, was Karl Marx, who wrote his doctoral dissertation on this problem (Bailey, 1928; Bloch, 1971, pp. 153-158; Farrington, 1967; Foster, 2000, pp. 21-65; Marx & Engels, 1975a, Vol. 1; Schafer, 2006). Marx saw in Epicurus's nonmechanistic materialism the development of an "immanent dialectics" in the materialist conception of nature itself—a rejection of determinism along with teleology.[24] This was to define Marx's materialist conception of nature and his open, historical approach to natural phenomena. As Ernst Bloch explained in an eloquent chapter titled "Epicurus and Karl Marx" in his book *On Karl*

Marx, it was Marx who understood the full implications of the materialist dialectic to be found in Epicurus and who adopted "Epicurus' cuckoo egg, which he alone had laid in the nest of rigid mechanics." The result was a materialist approach to nature and history that allowed for both subjective and objective factors, freedom and determinancy—"and, O Epicurus, vise versa, in mutuality" (Bloch, 1971, p. 158).

Ironically, Marx and Engels anticipated what Karl Popper was to call—in the title of one of his most important works—*The Open Universe*, anticipating as well Popper's (1982, pp. 172-174) rejection of the heat death of the universe hypothesis. In contrast to Martinez-Alier and Kolakowski, we can then definitively say that the dialectics of nature *did not fail Engels and Marx* here. Rather, it was their conception of nature and the cosmos as a complex, open, dynamic, contingent system, building on Epicurus's Dilemma, that represented the core of their dialectical–ecological view.

NOTES

1. Georgescu-Roegen's criticisms of classical Marxism focused on the alleged ecological inadequacies of Marx's labor theory of value and Marx's reproduction schemas. These criticisms have been rebutted by Burkett (1999, chap. 6 to 8; Burkett, 2004).

2. Charles Perrings (1987) explains, in relation to ecological economics (but having a larger applicability), that

> under the Second Law an isolated system (not receiving energy from its environment) is characterized by the fact that its entropy will increase up to the point at which it is in thermodynamic equilibrium and energy flows cease. The entropy of an isolated system cannot decrease. On the other hand, a closed system (receiving energy across its boundaries) will still experience the same irreversible increase in the entropy of its mass, but will be able to avoid the oubliette of the thermodynamic equilibrium by tapping the energy flowing into the system from outside. (p. 148)

3. It was common among scientists in the 19th century and even in the early 20th century to employ the words *universe* and *world* somewhat interchangeably, sometimes using the term *world* for solar system or even universe. For example, see Rankine (1852, p. 360) and the Friedmann-Einstein correspondence quoted in O'Connor and Robertson (1997). Engels uses *world* in both senses in this paragraph (also using *universe*). Yet the context is the cosmological order. (Note by the authors of this paper.)

4. On the dating of the three paragraphs from the *Dialectics of Nature* see Marx and Engels (1975a, Vol. 25, p. 697).

5. Engels is referring here in his notes to Helmholtz's *Populäre wissenschftliche Vortr*äge—a work he utilized extensively in his notes in *The Dialectics of Nature*. Helmholtz included here possible counters to the heat death hypothesis on the lines that Rankine had developed and that Engels was to recapitulate in part in his notes here (Marx & Engels, 1975a, Vol. 25, p. 562; Sternberger, 1977, pp. 37-38). (Note by the authors of this paper.)

6. Engels refers at this point to Volume 1 of Pyotr Lavrovich Lavrov's *Attempt at a History of Thought*, published in St. Petersburg in 1875, in which in a chapter titled "The Cosmic Basis of the History of Thought" Lavrov addresses the question of extinct suns and their systems of planets and how these cannot be revived but may become the material for accelerating the formation of new worlds (Marx & Engels, 1975a, Vol. 25, p. 682). See the discussion of Lavrov's ideas below.

7. Bensaïd quotes a further stand-alone paragraph (in addition to the other three paragraphs from the *Dialectics of Nature* already quoted in the text above) that was taken from

the section on "Mechanics and Heat" and written as early as 1873 (Marx & Engels, 1975a, Vol. 25, pp. 551, 695). This fragmentary paragraph (not even a complete sentence) says, "Newtonian attraction and centrifugal force—an example of metaphysical thinking: the problem not solved but only *posed*, and this preached as the solution.—Ditto Clausius' dissipation of heat." Engels's note here refers to Clausius's lecture "On the Second Fundamental Theorem of the Mechanical Theory of Heat," delivered to the German Scientific Association in Frankfurt on the Maine on September 23, 1867, in which Clausius claimed that the tendency for entropy to reach a maximum level meant that eventually "the universe would be in a state of unchanging death" (quoted in Brush, 1978, p. 61; also see Smith, 1998, p. 256). Given this, and the fragmentary nature of Engels's note (clearly meant for himself), it can hardly be said to provide unequivocal support for the conclusion that Bensaïd imposes on it, that "[Engels] obstinately declined to accept Clausius' principles," meaning the second law of thermodynamics (Bensaïd, 2002, p. 332).

8. Engels's estimate here was based on William Thomson's calculations on the age of the earth and of the sun (considered to be the best estimates of the time), which were later shown to be faulty with the discovery of radioactivity and nuclear energy. See Eiseley (1958, pp. 233-253).

9. Ironically, given all of the criticisms of Engels for supposedly rejecting the second law on the basis of his denial of the heat death hypothesis, Jonathan Hughes (2000, p. 61) quotes the above passage in his *Ecology and Historical Materialism* to demonstrate *that Engels did support the heat death hypothesis*. He is seemingly unaware of both Engels's notes challenging that hypothesis and the wider controversy. Likewise, Nicholas Churchich (1990, p. 216), citing the same passage from Engels, attacks Engels for his "very pessimistic and apocalyptic vision"—his view of "dialectical regression"—resulting from his *adoption* of the heat death of the universe hypothesis rooted in the entropy law.

10. In Newtonian physics, to quote Einstein (2006), "the stellar universe" was usually thought "to be a finite island in the infinite ocean of space" (p. 98).

11. The island-universe theory introduced by Kant claimed that the distant spiral nebulae were other "island-universes" like the Milky Way. This was controversial in the 19th century but embraced by Engels and by some 19th century astronomers and scientists. The theory was to triumph in the 20th century with the discoveries of Hubble (see Fraser, 2006, pp. 87-88). The term *island-universes* is still sometimes used today to refer to other "pocket universes" in inflationary theories of the cosmos. See, for example, Vilenkin (2006, pp. 81-82, 203-204).

12. Johann Heinrich von Mädler (1794-1874) was a distinguished German astronomer. He is most famous for his early attempts to map the moon and his "central sun hypothesis" on the location of the center of galaxy (which proved wrong). He published a general two volume *History of Descriptive Astronomy* in 1873. In the 19th century, the Milky Way, at least a billion times larger than the solar system, was thought to be the entire universe. Mädler, along with others, hypothesized that other cosmological bodies then described as nebulae were similar masses of stars, like our Milky Way galaxy. Likewise, his view of extinct suns is now confirmed (see J.B.S. Haldane's note in Engels, 1940, p. 14; also see Coles, 2001, p. 7; Royal Astronomical Society, 1875). Angelo Secchi (1818-1878) was a famous Italian astronomer (pioneering in the classification of stars), an early astrophysicist, and director of the Rome Observatory ("Angelo Secchi," 1913, pp. 669-671).

13. Engels's discussion of the movement of island universes and the way in which this related to temperatures in the stellar universe as a whole was closely related to the argument of Grove discussed in section 3 below.

14. Haldane included a note in the 1940 English edition of Engels's *Dialectics of Nature* in which he pointed to the fact that cosmologists were then divided between heat death, cyclical, and historical (infinite with respect to both past and future) theories of the universe and that Engels would have been attracted to either of the latter two (see Engels, 1940, p. 24). Jaki (1974, pp. 312-313) is sharply critical of Engels for speculatively raising the issue of an "eternal cycle" in the universe. Yet he does so in a book that is dedicated

almost entirely to criticizing notions of an “oscillating universe” that not only were present in 19th-century physics but also were to achieve a prominent place in 20th (and now in 21st) century physics. Most recently, the notion of a cyclic universe—an endless cycle of expansion and contraction—was revived in 2002 by physicists at Cambridge University (see Vilenkin, 2006, p. 171).

15. The preceding discussion does not exhaust the list of important physicists who rejected the heat death hypothesis in Engels’s day. Two American physicists, H.F. Wailing and Pliny Earl Chase, also rejected it and (as Garber, Brush, & Everitt, 1995, explain) “looked to the reconcentration of energy or rotational break up of dead stars to go on forever creating new worlds, thus preserving the idea of cosmic evolution against the tendency to degradation” (pp. 55-56). Maxwell was apparently motivated to introduce his famous demon hypothesis in examining the second law of thermodynamics as a statistical law to find a way around the divisions in scientific circles generated by the heat death hypothesis.

16. See the discussion of ancient Epicurean rules of scientific inference under conditions of “multiple explanations” in Asmis (1984, pp. 320-330). The same point from Epicurus is emphasized in Marx’s dissertation and Engels’s commentary on that dissertation (Marx & Engels, 1975a, Vol. 1, p. 69; Voden, n.d., p. 332).

17. Because Engels died in 1895, he did not have the benefit of Boltzmann’s more developed views.

18. Engels was a close reader of all of Haeckel’s work, but Haeckel’s critique of the heat death theory in *The Riddle of History* was written 3 years after Engels’s death in 1895. Martinez-Alier mentions Haeckel a number of times in his *Ecological Economics* but takes no note of his critique of the heat death hypothesis.

19. Alex Vilenkin (2006, pp. 170-175), professor of physics and director of cosmology at Tufts University, claims in his *Many Worlds in One* that there are two cosmological theories advanced by physicists today that definitely go against the heat death theory: One is the hypothesis of an inflationary universe (in which “an eternally inflating universe consists of an expanding ‘sea’ of false vacuum, which is constantly spawning ‘island universes’ like ours”), the other is that of a cyclic universe (in which “the universe recollapses and immediately bounces back to start a new cycle. Part of the energy generated in the collapse goes to create a hot fireball of matter”). Although such cosmologies of today’s physicists are still being strenuously debated, the importance of clearly distinguishing the second law from the heat death theory is obvious.

20. Some other ecosocialists are even more critical of Marx in this regard. Thus, Enrique Leff (1993) has made the blanket statement that “Marx’s theory of production does not incorporate natural and cultural conditions that participate in the production of value” (p. 48). Subsequent research has definitively overthrown this view in both respects. See especially Burkett (1999).

21. On Marx’s application (in *Capital*) of the “potential” versus “actual” distinction, as informed by his study of thermodynamics, see Griese and Pawelzig (1995, p. 133).

22. However, it is worth noting in this context that Soviet community ecologists in the 1920s and early 1930s were pioneers in the development of trophic dynamics, that is, in conducting studies in nutrient cycling related to modern ecosystem analysis (Weiner, 1988).

23. The powerful, genuinely dialectical-materialist approach to science reflected by Hessen was severely circumscribed in the Soviet Union in the 1930s, coinciding with Stalin’s rise to power. Hessen himself was purged and died in prison (Graham, 1993, p. 151). The dominant traditions in “Western Marxism,” meanwhile, largely abandoned natural-scientific concerns. An exception was the work of British Left scientists in the 1930s to 1960s. This included figures such as Haldane, Hyman Levy, J. D. Bernal, Lancelot Hogben, Benjamin Farrington, and Joseph Needham, all of whom adhered to the materialist philosophical outlook dating back to Epicurus and were inspired by the work of Marx and especially Engels’s *Dialectics of Nature*. See, for example, Needham (1976).

24. The quotation comes from Voden’s (n.d., pp. 332-333) summary of Engels’s comments on Marx’s dissertation on Epicurus.

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