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Metabolism, energy, and entropy in Marx's critique of political economy: Beyond the Podolinsky myth

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Abstract. Until recently, most commentators, including ecological Marxists, have assumed that Marx's historical materialism was only marginally ecologically sensitive at best, or even that it was explicitly anti-ecological. However, research over the last decade has demonstrated not only that Marx deemed ecological materialism essential to the critique of political economy and to investigations into socialism, but also that his treatment of the coevolution of nature and society was in many ways the most sophisticated to be put forth by any social theorist prior to the late twentieth century. Still, criticisms continue to be leveled at Marx and Engels for their understanding of thermodynamics and the extent to which their work is said to conflict with the core tenets of ecological economics. In this respect, the rejection by Marx and Engels of the pioneering contributions of the Ukrainian socialist Sergei Podolinsky, one of the founders of energetics, has been frequently offered as the chief ecological case against them. Building on an earlier analysis of Marx's and Engels's response to Podolinsky, this article shows that they relied on an open-system, metabolic-energetic model that adhered to all of the main strictures of ecological economics – but one that also (unlike ecological economics) rooted the violation of solar and other environmental-sustainability conditions in the class relations of capitalist society. The result is to generate a deeper understanding of classical historical materialism's ecological approach to economy and society – providing an ecological-materialist critique that can help uncover the systemic roots of today's "treadmill of production" and global environmental crisis.

Prominent among the wedges driven between Marxism and ecological economics is the notion that Marx and Engels responded indifferently or even negatively to Podolinsky's insertion of certain elements of thermodynamics into socialist theory. Initially set out by Juan Martinez-Alier and J.M. Naredo, the standard basis for this contention can be summarized via three basic presumptions.[1] First, in the early 1880s Podolinsky published an energetic analysis of human labor that attempted to reconcile Marx's labor theory of value with the first and second laws of thermodynamics. Second, when confronted with Podolinsky's analysis, Marx simply ignored it while Engels cursorily dismissed it without serious consideration – despite Podolinsky's direct solicitation of their opinions and approval. Third, Marx and Engels's negative reaction to Podolinsky helps explain, and is symptomatic of, a general tendency in Marxism to neglect ecological issues in general and thermodynamics in particular.

Variously repeated, the above narrative is now a key element of the conventional wisdom among ecological economists and other environmental thinkers, which argues that Marxism suffers from inherent ecological deficiencies.[2] Section I provides a synopsis of some of the main conclusions of our recent study of the "Podolinsky Business,"[3] that casts serious doubt on all three elements of the standard narrative.[4] The main purpose of this paper is more affirmative, however. We wish to examine the extent to which Marx and Engels's own analyses of capitalism already contain positive responses to the specific concerns raised (or thought to be raised) by Podolinsky's analysis. Section II establishes that Marx's analysis of capitalist production and exploitation is thoroughly infused with a metabolic-energy perspective on human labor, one informed by a close engagement with natural science. Marx treats the value of labor power and capitalist exploitation of workers as subject to both conservation of energy and matter-energy dissipation (or, as it is now called, increasing entropy). Marx's metabolic-energetic perspective jibes with Engels's observations, in both his comments on Podolinsky and *The Dialectics of Nature*, concerning the limitations of energy-reductionist approaches to human labor.

Section III shows how thermodynamic and metabolic considerations enter into *Capital*'s analysis of machinery and large-scale industry. Marx examines capitalist industrialization in terms of the development of machine-systems for transferring motive force toward the points of direct contact between tools and materials, as is consistent with the first law of thermodynamics. His analysis of capitalist mechanization provides a structural, class-based explanation as to how and why human production definitively "broke the budget constraint of living on solar income and began to live on geological capital."[5] It thereby helps explain the unprecedented growth in labor productivity and matter-energy throughput generated by the capitalist system – a consideration reflected in Engels's criticism of Podolinsky's failure fully to account for the system's squandering of "past solar heat" in the form of coal, minerals and forests. At the same time, Marx recognizes the importance of friction and other forces of wear and tear, consistent with the second law, as well as the irreducible biochemical requirements of modern industry (and not just in agriculture). Engels's argument, in response to Podolinsky, that the calculation of pure energy values for industrial products is effectively impossible, may be viewed in part as a simple validation of the complexities revealed by Marx's analysis.

Section IV looks briefly at Marx's treatment of capitalism's metabolic rift between humanity and nature as revealed by industrial agriculture and the division between town and country. Marx's concern with both biochemical and energetic conditions of production is on full display in his analysis of agriculture, where it is obvious that "matter matters." Following Justus von Liebig, Marx argues that an ecologically sustainable agriculture requires the continual restoration of the nutrients of the soil. Moreover, Marx emphasizes how the unhealthy circulation of matter generated by capitalism's urban industry and industrial agriculture vitiates the combined metabolic reproductive capabilities of human labor power and the land. Marx's approach traces environmental crises to the class separation of workers from the land and from other conditions of production, thereby integrating materialist and social concerns in environmental analysis.

In the concluding section we discuss the relation between Marx and Engels's historical and dialectical frameworks, and their grasp of complex ecological and social systems beyond mechanism and reductionism. For Marx and Engels, the emphasis was on irreversible change and qualitative transformation, making their dialectical materialism a precursor of contemporary complexity theory. Although they appreciated the analysis of thermodynamics emanating from Sadi Carnot's closed system model (characterized by reversible processes), they understood that the real concrete answers were to be found in a world in which natural history, like human history, was governed by the arrow of time. In this sense, Marx and Engels's analysis of metabolism, energy, and entropy and their interconnections with human production anticipated (often at a much deeper level) current insights of ecological economics and of the "treadmill of production" model within environmental sociology. (*N.B.*: references in this article to "Carnot" are to Sadi Carnot, unless otherwise noted.)

I. What remains of the Podolinsky myth?

When we first became aware of the significance attached to the Podolinsky debate, we were admittedly skeptical about the claim that by declining to develop an energetic basis for the labor theory of value, Marx and Engels had showed their indifference to environmental issues and thermodynamics specifically. We knew that Marx and Engels had both filled multiple notebooks with extracts from, and commentaries on, the leading natural science writers of their time. We also knew that these notebooks covered a wide range of scientific fields – physics, chemistry, biology, physiology, geology, and agronomy – in each of which the analysis of energy dynamics occupied an important if not central position. In fact, as we studied the matter further we discovered that Marx and Engels had some familiarity with and in some cases had closely studied the works of many of the scientists involved in the development of thermodynamics (both the first and second laws) – including Hermann von Helmholtz, Julius Robert Mayer, James Prescott Joule, Justus von Liebig, Jean-Baptiste Joseph Fourier, Sadi Carnot, Rudolf Clausius, William Thomson, Peter Guthrie Tait, William Grove, James Clark Maxwell, and Ludwig Eduard Boltzmann. In addition, we knew that Marx had attended numerous public lectures on natural science in the years leading up to and following the publication of *Capital*, Volume I in 1867, and that among these was a series of lectures by the English physicist John Tyndall, author of *Heat Considered as a Mode of Motion*.[6] Tyndall, a major figure in the developing physics in his own right, was the principal advocate of the ideas of J.R. Mayer – one of the co-discoverers of the conservation of energy (the first law of thermodynamics). Marx followed Tyndall's research on the sun's rays, particularly as it related to heat. Marx and Engels were also close students of the development of knowledge about electricity, including the work of Michael Faraday who invented the first electric motor. In 1882, Marx followed closely the results of the French physicist Marcel Deprez, whose research was directed at the distant transmission of electricity. In the same year Marx also read Édouard Hospitalier's *Principal Applications of Electricity*, on which he took extensive notes.[7]

Given this interest in both theoretical physics and practical energetic questions, it seemed unlikely to us that Marx and Engels would have exhibited an unreceptive, let alone deaf, ear to any new work by Podolinsky that represented a potential breakthrough in the importation of thermodynamic concepts into socialist theory. Besides, it simply was not like Marx and Engels to be indifferent or silent about contemporary writings that referred to their own works in any way.

Our skepticism only grew as we delved into the chronological development of Podolinsky's work as it related to the working lives of Marx and Engels. What we discovered was that Podolinsky's analysis had been published in four different languages over the years 1880–1883, and that there were significant differences among the four versions. Importantly, the version of Podolinsky's analysis that Martinez-Alier and Naredo used to criticize Marx (for his supposed neglect of Podolinsky's argument) had been published in the German socialist paper *Die Neue Zeit* in 1883, only after Marx's death.[8] Moreover, Engels's comments on Podolinsky, in two letters sent to Marx in December of 1882 (less than three months before Marx's death), were based on the version published in the Italian journal *La Plebe* in 1881 – a version that was much less extensive than the *Die Neue Zeit* article of 1883.[9] The *La Plebe* piece itself was more extensive than an earlier version published in the Parisian *La Revue Socialiste* in June 1880.[10]

All of this took on added significance when we became aware of the fact that Marx had actually taken detailed extracts from Podolinsky's work, but only with reference to a French-language version that Podolinsky had mailed to him in early April, 1880.[11] This version seems to have been an early draft of the *La Revue Socialiste* article.[12] Unfortunately, although we know from Podolinsky's own correspondence that Marx wrote back to him at least once, neither that letter nor any other letter that Marx may have sent to Podolinsky has survived. Still, it seems likely that Marx sent comments on the draft to Podolinsky some or all of which were incorporated into the published French version. (The most likely reason no copy of Podolinsky's original draft was found in Marx's papers, and that all we have are extensive verbatim extracts from Marx's notebooks, is that Marx, as was customary and expected in those days without copying machines, sent the manuscript back to Podolinsky with marginal notes on the manuscript.) Interestingly enough, the text of the *La Revue Socialiste* article, as far as we can deduce from Marx's extracts from the draft-version sent by Podolinsky, contains significant additions to the earlier draft sent to Marx. Among these additions are the main reference to Marx's concept of surplus labor, Podolinsky's own calculation of energy equivalents for agricultural labor and its output, as well as his conjecture about the energy efficiency of labor under the feudal, slave, capitalist, and socialist modes of production.[13]

Although all of this clearly undercut the standard view that Marx and Engels did not take Podolinsky seriously, a full evaluation of this view required a closer look at Podolinsky's analysis. Only then could we determine if Engels had treated Podolinsky fairly in his letters to Marx. More specifically, only then could we determine whether Podolinsky's analysis provided important new insights that could and should have been adapted by historical materialism in general or Marxist value analysis in particular in ways that Marx and Engels (and later Marxists) were unable or unwilling to undertake, due to their own ecological shortcomings. We therefore arranged for a full English-language translation of the *La Plebe* version of Podolinsky's work – the one read and commented upon by Engels. [14]

What we discovered was that Podolinsky had not even come close to establishing a plausible thermodynamic basis for the labor theory of value that could have been adopted by Marx and Engels. In fact, Podolinsky's analysis, although leading off with the question of how accumulation of surplus labor is consistent with the first law of thermodynamics (see below), goes on to make claims that contradict the reality of entropy and its limitations on human action. Podolinsky's analysis has nothing to say that is of direct relevance to the determination of value and surplus value in their specifically Marxist meaning as abstract (homogenous, socially necessary) labor times. Instead, Podolinsky's main analytical themes are that: (1) human labor is uniquely gifted in its ability to accumulate energy in useful forms on the earth; (2) this unique capability implies that the laboring human being fulfills (or even more than fulfills) the thermodynamic requirements of a "perfect machine" as theorized by Carnot;[15] (3) the superiority of socialism over capitalism and other class societies can be conceptualized in terms of socialism's greater potential for maximizing the accumulation of energy on earth by providing the best conditions for utilizing the muscular labor of the perfect human machine. Even Podolinsky's calculations of the energy productivities of different kinds of agricultural labor, we discovered, were not presented as a basis for value analysis, but rather as a demonstration of the greater energy-accumulation capabilities of the human machine compared to plants and animals.

We found these contents of Podolinsky's analysis quite surprising in light of how it had been used to criticize purported ecological shortcomings in Marxism. Podolinsky's framework was not only energy reductionist, but also made the logical error of directly applying idealized concepts applicable only to a closed, isolated system (Carnot's perfect machine concept) to the more complex reality of far-from-equilibrium, non-isolated, non-closed systems such as life in general and human society/labor more specifically. The only way that human labor can be viewed as a form of Carnot's perfect machine is if one ignores such factors as friction, i.e., the natural materiality of labor, along with the inherently biochemical or metabolic nature of the human laboring organism and its interaction with the natural environment.

The limitations of Podolinsky's perfect machine argument will be familiar to most ecological economists from the reaction generated by Elias L. Khalil's recent suggestion that "the economic process should be conceived after the Carnot cycle, and not the entropy law."[16] Similar to Podolinsky, Khalil argued that insofar as human labor and the Carnot cycle are both "designed *purposefully*" to produce net work or "free energy," neither one is limited by "the non-purposeful, mechanistic entropy law."[17] Lozada aptly described this argument as "basically an 'ultravitalist' attempt to deny that living, purposeful beings are completely subject to all laws of elementary matter such as the entropy law."[18] As Williamson pointed out, one should never confuse the possibility that "a purposeful agency . . . may be interposed in an otherwise spontaneous (or natural) process to produce useful work" with the notion that the "purposeful agency may be of unlimited potency."[19] The basic problem, as Biancardi, *et al.* observed, was with Khalil's (and, we might add, Podolinsky's) assumption that "the Carnot cycle has *the same form* as the economic process."[20] Unlike Carnot's ideal frictionless engine, which was conceived as an isolated thermodynamic system (closed to transfers of matter and energy), the human economy is a dissipative system that both draws upon (in fact mines) and dumps waste back into its natural environment. Hence, "each economic process can be regarded as an irreversible transformation," i.e., one that, ecologically speaking, never "returns to the starting conditions."[21] By neglecting this crucial form-divergence, both Khalil and Podolinsky confused the fact that the reproduction of human life feeds upon the (temporary) fixation of low entropy matter-energy in useful forms, with the fantastic notion that this need not involve increasing entropy from the standpoint of the total biospheric system with which the system of human reproduction co-evolves.

Imagine our astonishment, then, when we realized that Engels's main criticisms of Podolinsky already focus precisely on some of the limitations adumbrated above. In his letter to Marx of December 19, 1882, Engels not only rejects Podolinsky's energy-reductionist conception of human labor, posing a more metabolic alternative, but also emphasizes the failure of Podolinsky's energy-productivity calculations to take into account the great extent to which human production has heretofore operated as "a squanderer of *past* solar heat," especially by "squandering our reserves of energy, our coal, ore, forests, etc."[22] Engels's discussion of Podolinsky had apparently been elicited by some comments by Marx on Engels's essay "The Mark." This essay, which was published as an appendix to the German edition of Engels's *Socialism: Utopian and Scientific*, examines socio-ecological pressures on German peasant farmers stemming from the growing influence of landed property and capitalist competition – e.g., reduced peasant access to common lands and the resulting difficulty of maintaining peasant production without access to cattle manure.[23]

In short, our re-examination of the context and substance of Engels's comments, in light of our study of Podolinsky's *La Plebe* article, revealed that Engels's responses were far more advanced ecologically than Podolinsky's analysis (however bold and important the latter's contribution was). Moreover, the fact that Engels's criticisms do not directly address value questions can now be seen as a quite logical non-reaction, given that Podolinsky had nothing significant to say on value theory as such. Indeed, to interpret Podolinsky's energy-productivity calculations as a potential basis for value analysis is not only to embrace a kind of energy reductionism that has been strongly opposed by some of the major figures in ecological economics, including Georgescu-Roegen and Daly,[24] but also to conflate Marx's class-based theory with a Smith-Ricardo (that is, crude materialist) "embodied labor" approach to value.[25]

So what, then, remains of the Podolinsky myth? First, there is the issue as to whether Marx and Engels provided an adequate answer to Podolinsky's initial question bearing on the consistency of surplus value with the first law of thermodynamics (the conservation of energy). As Podolinsky put it:

> According to the theory of production formulated by Marx and accepted by socialists, human labor, expressed in the language of physics, accumulates in its products a greater quantity of energy than that which was expended in the production of the labor power of the workers. Why and how is this accumulation brought about? . . .In accepting the theory of the unity of physical forces or of the constancy of energy, we are also forced to admit that nothing can be *created*, in the strict sense of the word, through labor. . .[26]

Notice that even this statement does not speak of surplus *value*, but rather of the energy equivalent of surplus *labor* in a more general sense applying across different modes of production. Still, insofar as the standard interpretation treats it as a challenge to Marx's value analysis, we should consider how Marx answers Podolinsky's question for capitalism's specific form of surplus labor.

Second, even if one accepts that Engels's comments on Podolinsky embody open-system and metabolic-energy concerns, there remains the question as to how well these concerns are methodologically infused into Marx's and Engels's analysis of capitalism. The debunking of the Podolinsky myth may not be sufficient to overturn the conventional wisdom that, as a general rule, Marx and Engels treat the economy as a self-reproducing system not dependent on its natural environment. Georgescu-Roegen exemplifies this conventional wisdom with his claim that for "Marxist economists," the "patent fact that between the economic process and the material environment there exists a continuous mutual influence carries no weight."[27] Similarly, Perrings asserts that Marx "assumed that the economy may expand without limit at the expense of the environment," in effect treating the environment as "simultaneously a horn of plenty and a bottomless sink."[28] Underpinning this conventional wisdom is the view, well phrased by Hawley, that "Marxian theory" represents a "closed-system" perspective on the economy which "ignores environment as an interaction field."[29]

Although we have already demonstrated the considerable ecological content of Marx's and Engels's thinking in earlier related works,[30] it is important to reconsider the extent to which open-system energy and entropic considerations are incorporated into Marx's *Capital*, and whether this incorporation is consistent with Engels's criticisms of Podolinsky. Only then can we definitively determine the lessons that the Podolinsky episode holds for the relationship between Marxism and ecological economics.

II. Energy in Marx's metabolic analysis of value and exploitation

For Marx, commodity production by wage-labor is the specifically capitalist form of human labor, "the universal condition for the metabolic interaction between man and nature."[31] Capitalism is therefore just as much subject to nature's laws as any other form of human production. "It would," as Marx says, "be absolutely mistaken to attach mystical notions to this spontaneously developed productivity of labour, as is sometimes done."[32] "When man engages in production, he can only proceed as nature does herself, i.e. he can only change the form of the materials. Furthermore, even in this work of modification he is constantly helped by natural forces."[33]

Perhaps the most basic way in which human labor is constantly helped by natural forces is through the effect of solar energy on the terrestrial environment, without which no life, and hence no labor, could occur. In this connection, Engels points out that Podolinsky's energy-productivity calculations take no account of the complexities introduced by "the *fresh* cal" that the worker "absorbs from the radiation of the sun."[34] Engels's observation on the complexity of accounting for the full effects of solar energy can thus be seen as logically consistent with Daly's contemporary criticism of some forms of energetics:

> Even in its own terms of calculating the "solar energy necessary directly and indirectly to produce" all commodities, the actual accounting of embodied energy is very incomplete. It counts only solar energy entering into agriculture, forests, and fisheries. But solar energy obviously enters all production processes by providing light and heat… How this enormous joint cost could be allocated among all its joint products… is beyond my imagination.[35]

In other words, solar energy's role in human labor cannot be fully captured by any simple, mechanistic accounting model, with energy entering as fuel at one end and emerging as useful work at the other. Before delving more deeply into the issue of Marx's combined metabolic-energetic approach to capitalism, we should make three preliminary points. First, Marx's use of "metabolism" is far more than a mere analogy. As pointed out by Griese and Pawelzig, Marx employed and developed metabolic analyses in all his major economic works, from the *Grundrisse* (1857–1858) to his *Notes on Adolph Wagner* (1880–1881).[36] Griese and Pawelzig go on to state that:

> What is involved here is no picture, no metaphor for visualization, but rather a rich concept. The exchange of matter by living systems, according to the physiologists' definition, remains for Marx what it is, neither watered down nor "generalized," as is often done. Exchange of matter is taking up, reshaping, storing, and giving up of matter with an exchange of energy taking place simultaneously. This same content applies – and here lies the discovery of Marx – not only to living but also to social systems, insofar as social life is also actually life in the physiological sense, arising out of social life and developing further its material basis.[37]

Second, Marx saw the labor process itself as constituting the main metabolic relation between humans and nature. But under the influence of Liebig he also explored in great detail the metabolic rift between nature and society, manifested in the extraction of nutrients (such as nitrogen, phosphorus and potassium) from the soil (as food and fiber), and their transportation hundreds and thousands of miles to urban centers, to eventually take the form of human and animal wastes – subverting the natural cycle that would have returned the nutrients to their native soil. In this way Marx explored problems of human dependence on nature, which, while not independent of energy issues, could not be reduced to pure energetics.[38] Marx's adamant refusal to embrace energy reductionism seems to foreshadow Georgescu-Roegen's famous dictum that "matter matters, too."[39]

Third, Marx's metabolic interpretation of commodity production and exchange directly informed his analysis of commodities *as values* (repositories of abstract, socially necessary labor). He thus considers commodity exchange to be a "process of social metabolism," and "the value form of the commodity" to be the "economic cell form" of this metabolism.[40] A commodity is, of course, a useful good or service that is put up for exchange. Recognizing that this "use value. . . is conditioned by the physical properties of the commodity," Marx sees commodity use values as "the material content of wealth" under capitalism.[41] As is well known, Marx also insists that both nature and human labor contribute to the production of all use values.[42] In analyzing commodities and money, therefore, he emphasizes that "the physical bodies of commodities, are combinations of two elements, the material provided by nature, and labour."[43] Marx also insists "nothing can be a value without being an object of utility. If the thing is useless, so is the labour contained in it; the labour does not count as labour, and therefore creates no value."[44] Stated differently: "Value [as abstract labor] is independent of the particular use-value by which it is borne, but a use-value of some kind must act as its bearer."[45] Therefore, because commodities, like all use values, are products of both labor and nature, and because labor is itself an interaction with nature, the production and exchange of commodities is both a social (people-people) and a metabolic (people-nature) relation. The dialectic of value and use value is not a simple dichotomy in Marx's conception, but rather a unity-in-difference or moving contradiction. Capitalism's exploitation of wage-labor is fraught with contradictions largely because of the tensions between the material requirements of value accumulation and the metabolic nature of both wage-labor and the wage-laborers.

Labor power and its value

Marx defines "labour-power, or labour-capacity" as "the aggregate of those mental and physical capabilities existing in the physical form, the living personality, of a human being, capabilities which he sets in motion whenever he produces a use-value of any kind."[46] Labor power "is a natural object, a thing, although a living, conscious thing."[47] It is, "above all else, the material of nature transposed into a human organism."[48] The metabolic-energetic content of Marx's conception is evident not just in his choice of the term labor *power*, but also in an alternative (and more descriptive) translation of the definition just quoted: "Labour-power itself is energy transferred to a human organism by means of nourishing matter."[49]

Energy considerations are accordingly central to Marx's analysis of the value of labor power. As is well known, Marx equates labor power's value with the value of the commodities entering into the consumption of workers and their families. Two aspects of this consumption are distinguished: a physical subsistence component and "a historical and moral element."[50] Our main concern here is with the physical subsistence element. This begins, of course, with the worker's "natural needs, such as food, clothing, fuel and housing" – needs which "vary according to the climatic and other physical peculiarities of his country."[51] Even at this basic level, Marx recognizes both the role of matter-energy dissipation, as well as the energy requirements for the individual worker's reproduction. Precisely because "labour-power exists only as a capacity of the living individual," it is by nature (regardless of what happens in the labor-process) subject to "wear and tear. . . and death."[52] "The owner of labour-power is mortal," and must therefore "perpetuate himself by procreation." [53] Hence, the value of labor power includes the value of commodities "necessary for the worker's replacements, i.e. his children, in order that this race of peculiar commodity-owners may perpetuate its presence on the market."[54] It should perhaps not surprise us that Marx, in addressing the physiological and energetic requirements of production, was always aware of the arrow of time.

But the metabolic dimension only becomes fully apparent with Marx's consideration of the connections between the worker's laboring activity and labor power's value. "The use of labour-power is. . . .labour itself," and "the purchaser of labour-power consumes it by setting the seller of it to work."[55] This is true whether labor is considered to be production of use values or as production of values. Even though the substance of value is abstract labor ("homogenous human labour, . . . human labour-power expended without regard to the form of its expenditure"), the "creation of value" still requires "the transposition of labour-power into labour," i.e., "a productive expenditure of human brains, muscles, nerves, hands, etc., of the labour-power possessed in his bodily organism by every ordinary man."[56] Conservation of labor's value-creating power therefore imposes additional maintenance requirements on the worker:

> However, labour-power becomes a reality only by being expressed; it is activated only through labour. But in the course of this activity, i.e. labour, a definite quantity of human muscle, nerve, brain, etc. is expended, and these things have to be replaced. *Since more is expended, more must be received.* If the owner of labour-power works today, tomorrow he must again be able to repeat the same process in the same conditions as regards health and strength. His means of subsistence must therefore be sufficient to maintain him in his normal state as a working individual.[57]

An alternative translation of the italicized sentence is: "This increased expenditure demands a larger income."[58] Here, Marx is employing an "energy income and expenditure" framework adapted from the work of the great German energy physiologist Ludimar Hermann. We know that Marx studied Hermann's *Elements of Human Physiology*, which treats energy flows in human labor from a biochemical standpoint.[59] In Hermann's analysis, "energy income" connotes consumption of energy sources convertible into work, while "energy expenditure" refers to the laborer's loss of energy when work is performed. Marx evidently found Hermann's approach quite useful for determining the "ultimate or minimum limit of the value of labour-power," i.e., "the value of the commodities which have to be supplied every day to the bearer of labour-power… so that he can renew his life-process" in something more than "a crippled state."[60] In addition, Marx was undoubtedly aware of Liebig's discussion of the application of thermodynamics to physiology in the last chapter of his *Familiar Letters on Chemistry,* entitled "The Connection and Equivalence of Forces."[61]

Marx follows Hermann and Liebig in declining to reduce the content of the energy income and expenditure to pure energetic terms. For Hermann, the biochemical processes of energy income and expenditure, and their degree of compatibility with nutritional and other metabolic functions, help determine whether any given labor situation is consistent with the healthy reproduction of the laborer.[62] Different kinds of labor (in terms of type and intensity) require different biochemical forms of energy income, and are as well impacted by how well rested the worker is from prior labors. The worker cannot be treated like a steam engine that will just keep running as long as adequate coal is shoveled in. Marx applies this aspect of Hermann's approach when discussing the value of labor power in terms of the length of daily worktime:

> When the working day is prolonged, the price of labour-power may fall below its value, although that price nominally remains unchanged, or even rises. The value of a day's labour-power is estimated. . . on the basis of its normal average duration, or the normal duration of the life of a worker, and on the basis of the appropriate normal standard of conversion of living substances into motion as it applies to the nature of man. Up to a certain point, the increased deterioration of labour-power inseparable from a lengthening of the working day may be compensated for by making amends in the form of higher wages. But beyond this point deterioration increases in geometrical progression, and all the requirements for the normal reproduction and functioning of labour-power cease to be fulfilled. The price of labour-power and the degree of its exploitation cease to be commensurable quantities.[63]

In a footnote to the passage just cited, Marx provides a quotation from a work by the "father of the fuel cell" – the English jurist and physical chemist Sir William Robert Grove – entitled *On the Correlation of Physical Forces*, which states: "The amount of labour which a man had undergone in the course of 24 hours might be approximately arrived at by an examination of the chemical changes which had taken place in his body, changed forms in matter indicating the anterior exercise of dynamic force."[64] Marx and Engels had, in fact, read Grove's book with deep interest as early as 1864–1865, as part of their studies of the mechanical theory of heat and the convertibility of different forms of energy.[65] They were familiar with the fourth edition of Grove's work, published in 1862, in which Grove had already provided a detailed discussion of the second law of thermodynamics.[66] Marx obviously found these studies directly relevant to his analysis of the value of labor power.[67]

Marx's analysis of the value of labor power clearly incorporates the conservation of energy as well as the inevitability of matter-energy dissipation. In *Capital*, Marx quotes Lucretius in order to evoke the fundamental materialist principle (the principle of conservation) that "out of nothing, nothing can be created."[68] That Marx does not use the terms "entropy," "thermodynamics," or "first and second laws," is explained by the fact that these terms were only then being introduced into physics and thus were not used widely even within the scientific community at the time of Marx's *Capital*. (Clausius introduced the term "entropy" – from a Greek construction meaning "transformation" – in 1865, two years before the publication of *Capital*, while Clausius's *Mechanical Theory of Heat* appeared in 1867, the same year as *Capital*.

The first use of the term "thermodynamics" in the title of a book was in 1868 in Tait's *Thermodynamics*.[69])

As the entropy law was only just then being recognized, its full implications still had to be worked out by scientists. William Thomson, the leading British proponent of the idea of energy dissipation (or what came to be called entropy), denied in 1852 that animals can be viewed in any sense as thermodynamic machines equivalent to steam engines.[70] Engels in particular was wary of the crude mechanistic and energy-reductionist purposes to which thermodynamics was put in some subsequent analyses. As he wrote in *The Dialectics of Nature*:

> Let someone try to convert any skilled labour into kilogram-metres and then to determine wages on this basis! Physiologically considered, the human body contains organs which in their totality, *from one aspect*, can be regarded as a thermodynamical machine, where heat is supplied and converted into motion. But even if one presupposes constant conditions as regards the other bodily organs, it is questionable whether physiological work done, even lifting, can be at once fully expressed in kilogram-metres, since within the body *internal* work is performed at the same time which does not appear in the result. For the body is not a steam-engine, which only undergoes friction and wear and tear. Physiological work is only possible with continued chemical changes in the body itself, depending also on the process of respiration and the work of the heart. Along with every muscular contraction or relaxation, chemical changes occur in the nerves and muscles, and these changes cannot be treated as parallel to those of coal in a steam-engine. One can, of course, compare two instances of physiological work that have taken place under otherwise identical conditions, but one cannot measure the physical work of a man according to the work of a steam-engine, etc.; their external results, yes, but not the processes themselves without considerable reservations.[71]

Seven years after the above commentary was written, Engels was confronted with Podolinsky's naive attempt to calculate "the physical work of a man according to the work of a steam-engine," i.e., by simply comparing the caloric food intake of the laborer to the calories embodied in the physical output of the (agricultural) labor process.[72] Conveying his opinion of Podolinsky's energy-accounting exercises to Marx, Engels reprised his prior critique of energy-reductionism. As noted earlier, he pointed out that Podolinsky's calculations ignored the energy metabolically absorbed by all workers from the sun. He also observed that the food-calories consumed by a worker (a figure of 10,000 calories per day is used) "are known in practice to lose on conversion into other forms of energy as a result of friction, etc., a portion that cannot be put to use. Significantly so in the case of the human body. Hence the *physical* labour performed in economic labour can never = 10,000 cal; it is invariably less."[73]

After this initial clear recognition of matter-energy dissipation, Engels considers further metabolic qualifications to Podolinsky's energy productivity calculations. He points out how Podolinsky assumed that all "physical labour is *economic* labour," when in reality much of the energy expenditure of the worker is "lost in the increased heat given off by the body, etc., and such useful residue as remains lies in the fertilising property of excretions."[74] "In hunting and fishing," for example, "assuming the individual concerned takes normal nourishment, the amount of protein and fat he obtains by hunting or fishing is independent [logically and temporally] of the amount of these substances he consumes [while hunting or fishing]."[75] Compared to Podolinsky's energy-reductionist framework, Engels's more metabolic approach – one fully consistent with Marx's analysis of the value of labor power – is clearly more sensitive to the complex and entropic nature of the labor process.

It is worth noting at this point that Engels has sometimes been criticized in ecological literature for skepticism regarding the second law of thermodynamics. As Martinez-Alier writes,

> The second law was mentioned by Engels in some notes written in 1875 which became, posthumously, famous passages of the *Dialectics of Nature.* Engels refers to Clausius' entropy law, found it contradictory to the law of the 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 about the religious interpretations of the second law. In a letter to Marx of 21 March 1869, when he became aware of the second law, he complained about William Thomson's attempts to mix God and physics.[76]

The particular fragment in Engels's *Dialectics of Nature* to which Martinez-Alier refers was given the heading "Radiation of Heat into Universal Space" and was devoted to the broader, cosmological implications tied to the second law of thermodynamics.[77] These were questions of materialism vs. idealism/religion, connected with alternative conceptions of the creation and possible future destruction of the universe. Engels laid out some of the complications and logical difficulties. To claim on the basis of this that Engels demonstrated skepticism toward or even rejected the second law of thermodynamics, as Martinez-Alier and some others have done, is presumptuous. Such a conclusion is particularly unacceptable since elsewhere in *Dialectics of Nature*, Engels expresses his deep respect for the results of Carnot and Clausius and conforms his own observations and analyses to the strictures of the second law.

Equally erroneous is the suggestion Martinez-Alier advances (in the above quote) that in his March 21, 1869 letter to Marx, Engels showed that he had become aware of the second law of thermodynamics only at that time. We know that Engels read Grove's *Correlation of Physical Forces* (probably the fourth edition of 1862) by 1865 – shortly after Marx. Grove's work included a very detailed treatment of the second law in the key chapter on "Heat," in the context of a discussion of the discoveries of Carnot, Clausius, and Thomson. There is no possibility that Engels or Marx – both of whom praised Grove's book – missed this discussion. Moreover, since Engels referred a number of times to Thomson's and Tait's classic 1867 text on physics, *A Treatise on Natural Philosophy* (and not to any of the later editions of that work) it is quite probable that he also encountered the second law upon reading that work when it first appeared. If that weren't enough, no direct reference to the second law of thermodynamics appears in the letter that Martinez-Alier cites (nor any mention of Thomson by name there) so the point seems to be a gross extrapolation. Instead Engels's letter deals with the hypothesis of the "heat death" of the universe, associated with Helmholtz, Clausius, Thomson, and others. Engels complained that cosmological claims asserting the cause of the eventual "heat death" of the universe, and also its origins in an "original hot state," based on the entropy concept alone, were absurd because they would have had to have been founded on a "natural law [that] is, to date, only half-known to them."[78] In short, no unfavorable conclusions about Engels's position on thermodynamics can be derived from these comments.

How Marx answers Podolinsky's question

If Marx's approach to energy and value did not align with Podolinsky (who in any case made only suggestive comments in this regard), what was the specific nature of Marx's argument? At several points in *Capital* and its preparatory works, Marx considers the creation of surplus value in terms of the difference between: (1) the energy equivalent of the value of labor power, as determined by the labor required to produce the means of subsistence purchased with the wage, and (2) the energy expended by labor power, insofar as it corresponds to the energy content of the commodities in which value is objectified. But, given the inability of the commodity (value) form to adhere to the metabolic-energetic requirements of labor power and the work it performs, it is as incorrect to identify the energy equivalent of labor power's value with *all* the energy that enters into the reproduction of labor power as it is to identify the energy content of commodity values with *all* the energy entering into their production. Podolinsky's opening question, as to how the first law of thermodynamics is consistent with an excess of energy-product over the energy "expended in the production of the labor power of the workers," is thus full of misapprehensions insofar as it is meant to refer to Marx's theory.[79] For Marx, moreover, the production of surplus value is a social and material effect specific to capitalism; it is not susceptible to a purely natural scientific proof. Nonetheless, Marx's application of the energy income and expenditure approach to surplus value demonstrates the thermodynamic consistency of his theory.[80]

For Marx, the possibility of surplus value stems from labor power's "specific use-value. . . of being a source not only of value, but of more value than it has itself."[81] This use value has two important characteristics. First, given capitalism's reduction of "value" to abstract labor time, "the use value of labour capacity, as value, is itself the value-creating force; the substance of value, and the value-increasing substance."[82] Second, "the past labour embodied in the labour-power and the living labour it can perform, and the daily cost of maintaining labour-power and its daily expenditure in work, are two totally different things."[83] While the value of labor power is determined by the value of workers' commodified means of subsistence,

> The *use* of that labouring power is only limited by the active energies and physical strength of the labourer. The daily or weekly *value* of the labouring power is quite distinct from the daily or weekly exercise of that power, the same as the food a horse wants and the time it can carry the horseman are quite distinct. The quantity of labour by which the *value* of the workman's labouring power is limited forms by no means a limit to the quantity of labour which his labouring power is apt to perform.[84]

In energy terms, "What the free worker sells is always nothing more than a specific, particular measure of force-expenditure"; but "labour capacity as a totality is greater than every particular expenditure."[85] "In this exchange, then, the worker. . . sells himself as an effect," and "is absorbed into the body of capital as a cause, as activity."[86] The result is an energy subsidy for the capitalist who appropriates and sells the commodities produced during the portion of the workday over and above that required to produce the means of subsistence represented by the wage. The apparently equal exchange of the worker's labor power for its value thus "turns into its opposite. . . the dispossession of his labour."[87] Marx develops this point in terms of the distinction between surplus labor and the "necessary labor" objectified in workers' commodified means of subsistence:

> During the second period of the labour process, that in which his labour is no longer necessary labour, the worker does indeed expend labour-power, he does work, but his labour is no longer necessary labour, and he creates no value for himself. He creates surplus-value which, for the capitalist, has all the charms of something created out of nothing.[88]

Of course, this value (energy) surplus is not really created out of nothing. Rather, it represents capitalism's appropriation of portions of the *potential* work embodied in labor power recouped from metabolic regeneration largely during non-worktime. And this is only possible insofar as the regeneration of labor power, in both energy and biochemical terms, involves not just consumption of calories from the commodities purchased with the wage, but also fresh air, solar heat, sleep, relaxation, and various domestic activities necessary for the hygiene, feeding, clothing, and housing of the worker. Insofar as capitalism forces the worker to labor beyond necessary labor time, it encroaches on the time required for all these regenerative activities. As Marx observes,

> But *time* is IN FACT the active existence of the human being. It is not only the measure of human life. It is the space for its development. And the ENCROACHMENT OF CAPITAL OVER the TIME OF LABOUR is the appropriation of the *life*, the mental and physical life, of the worker.[89]

Viewed in this way, Marx's metabolic-energetic analysis of surplus value is an essential foundation for his analysis of capitalism's tendency "to go beyond the natural limits of labour-time" – a tendency "that forcibly compels even the society which rests on capitalist production. . . to restrict the normal working day within firmly fixed limits."[90] Unless forcibly constrained from doing so, capitalist production encroaches not just on the time the worker needs "to satisfy his intellectual and social requirements," but also on "the physical limits to labour-power":

> Within the 24 hours of the natural day a man can only expend a certain quantity of his vital force. Similarly, a horse can work regularly for only 8 h a day. During part of the day the vital force must rest, sleep; during another part the man has to satisfy other physical needs, to feed, wash and clothe himself. . . But what is a working day? At all events, it is less than a natural day. How much less? The capitalist has his own views of this point of no return, the necessary limit of the working day. As a capitalist, he is only capital personified. His soul is the soul of capital. But capital has one sole driving force, the drive to valorize itself, to create surplus-value, to absorb. . . the greatest possible amount of surplus labour.[91]

Capitalism's inherent drive to extend worktime beyond labor power's metabolic-energetic limits is, in fact, one of the major themes in Volume I of *Capital*. But the more basic point is that Marx's analysis of surplus value already answers Podolinsky's question: it is completely consistent with not only the first but also the second law of thermodynamics. Ironically, Podolinsky's answer to his own question regarding the relation of the labor process to the transfer and transformation of energy violates the second law by treating the worker as a "perfect machine" – and doubly so insofar as, in the real world, it is precisely capitalism's attempt to convert labor power into a surplus-labor machine that threatens the worker's metabolic reproduction:

> But in its blind and measureless drive, its insatiable appetite for surplus labour, capital oversteps not only the moral but even the merely physical limits of the working day. It usurps the time for growth, development and healthy maintenance of the body. It steals the time required for the consumption of fresh air and sunlight. It haggles over the meal-times, where possible incorporating them into the production process itself, *so that food is added to the worker as to a mere means of production, as coal is supplied to the boiler, and grease and oil to the machinery*. It reduces the sound sleep needed for the restoration, renewal and refreshment of the vital forces to the exact amount of torpor essential to the revival of an absolutely exhausted organism. It is not the normal maintenance of labour-power which determines the limits of the working day here, but rather the greatest possible daily expenditure of labour-power, no matter how diseased, compulsory and painful it may be...[92]

As a prelude to the next section, it is worth noting that Marx's use of metabolic-energetic analysis led him to a direct comparison between the overextension of worktime and the overexploitation of land. After all, he closely studied the works of the leading agronomists of his time, including Justus von Liebig and James Johnston – works emphasizing the biochemical recycling processes required to maintain soil fertility.[93] In Marx's view, capitalism's incessant pressure to produce as much surplus value as possible within any given time period caused it to violate the metabolic conditions for sustaining the productive vigor of land and labor power.[94] Referring directly to the work of Johnston, Marx argued in *Capital* that

> The way that the cultivation of particular crops depends on fluctuations in market prices and the constant changes in cultivation with these price fluctuations – the entire spirit of capitalist production, which is oriented towards the most immediate monetary profit – stands in contradiction to agriculture, which has to concern itself with the whole gamut of permanent conditions of life required by the chain of human generations.[95]

Similarly, in the case of forestry, Marx suggested that:

> The long production time (which includes a relatively slight amount of working time), and the consequent length of the turnover period, makes forest culture a line of business unsuited to private and hence to capitalist production. . . .The development of civilization and industry in general has always shown itself so active in the destruction of forests that everything that has been done for their conservation and production is completely insignificant in comparison.[96]

The common element in capitalism's tendencies to overexploit land and labor power is the failure to provide sufficient time (and biochemical energy inputs) for the restoration of productive power. In both cases, this productive power winds up being depleted insofar as free competition reigns:

> Capital asks no question about the length of life of labour-power. What interests it is purely and simply the maximum of labour-power that can be set in motion in a working day. It attains this objective by shortening the life of labour-power, in the same way as a greedy farmer snatches more produce from the soil by robbing it of its fertility.[97]

Hence, when considering the forces behind the English Factory Acts, which placed a cap on worktime, Marx suggested that:

> Apart from the daily more threatening advance of the working-class movement, the limiting of factory labour was dictated by the same necessity as forced the manuring of English fields with guano. The same blind desire for profit that in the one case exhausted the soil had in the other case seized hold of the vital force of the nation at its roots.[98]

That this analogy was underpinned by the energy income and expenditure framework is clear from the following passage in *Theories of Surplus Value*, written just a few years before the publication of *Capital*, Volume I:

> Anticipation of the future – real anticipation – occurs in the production of wealth in relation to the worker and to the land. The future can indeed be anticipated and ruined in both cases by premature overexertion and exhaustion, and by the disturbance of the balance between expenditure and income. In capitalist production this happens to both the worker and the land. . . What is shortened here exists as power and the life span of this power is shortened as a result of accelerated expenditure.[99]

Given this parallel, it is not surprising that Marx developed a full-blown ecological critique of capitalism – one that synthesized his metabolic-energetic analyses of capital's exploitation of labor and of the land. But an essential place in this synthesis was occupied by the capitalist mechanization of production.

III. Capitalist industrialization, matter-energy, and entropy

Thermodynamic considerations – the conservation of energy, its entropic dissipation through friction in particular, and the correlation of physical forces – play a crucial role in Marx's analysis of "Machinery and Large-Scale Industry" in Chapter 15 of *Capital*, Volume I. This chapter represents the core of Marx's analysis of industrial development under capitalism.

Energy, friction, and biochemical processes in capitalist industry

Marx depicts the industrial revolution using a model of machinery systems consisting of "three essentially different parts, the motor mechanism, the transmitting mechanism and finally the tool or working machine."[100] He perceives machine-based production as a transfer of force from one part of the system to another – starting from the motor mechanism which "acts as the driving force of the mechanism as a whole," on through the transmission mechanism which "regulates the motion, changes its form where necessary, and divides and distributes it among the working machines," and finally to the working machine which "using this motion . . . seizes on the object of labour and modifies it as desired."[101] This entire framework is clearly informed by an extensive theoretical and practical study of both energy conservation and the mechanics of energy transfer.[102]

Indeed, in an 1863 letter to Engels outlining his research for "the section on machinery," Marx wrote that he had not only "re-read all [of his] note-books (excerpts) on technology," but was "also attending a practical (purely experimental) course for working men given by Prof. Willis."[103] The lecturer he referred to was the Reverend Robert Willis (1800–1875), the brilliant British architect and mechanical engineer (and, from 1837 onward, Jacksonian Professor of Natural and Experimental Philosophy at the University of Cambridge). That the mechanics of energy transmission were a central theme in these lectures is clear from the working models that Willis used – models he had himself designed and integrated into an instructional system.[104] As described by technology-educator Eric Parkinson:

> Willis developed a special construction kit which could be used as a means of demonstrating principles of mechanisms to his students. It was devised so that mechanical components could be added, removed, or re-positioned with speed and accuracy during a lecture-demonstration.[105]

When combined with Marx's theoretical and historical studies, such practical instruction led him to argue that the industrial revolution started not with the motor mechanism and its energy sources but rather with the tool or working machine – specifically with the mechanization of the portion of labor that incorporated directly the principal material(s). As explained in *Capital*,

> The entire machine is only a more or less altered mechanical edition of the old handicraft tool. . . The machine, therefore, is a mechanism that, after being set in motion, performs with its tools the same operations as the worker formerly did with similar tools. Whether the motive power is derived from man, or in turn from a machine, makes no difference here.[106]

This argument "establish[ed] a connection between human social relations and the development of these material modes of production."[107] After all, the ability of the capitalist to separate the tool from the worker and install it in the machine – and the subsequent application of science to the technical improvement of machinery on the capitalist's profit-making behalf – presumed that the worker had already been socially separated from control over the means of production.[108] But this historical primacy of social relations, and corresponding primacy of machine-tools over energy sources and mechanisms, hardly prevented Marx from emphasizing the crucial enabling role of power supply and transmission in the industrial revolution. For one thing, the mechanization of tools means they are freed from the limitations of the individual worker's labor power as the direct motive force. "Now assuming that [the worker] is acting simply as a motor, that a machine has replaced the tool he is using, it is evident that he can also be replaced as a motor by natural forces."[109] Once installed in machines, tools may be driven by a greater variety of power sources and on a much larger energy-scale. Indeed, the growing scale of machinery itself precludes the continued use of labor power as motive force:

> An increase in the size of the machine and the number of its working tools calls for a more massive mechanism to drive it; and this mechanism, in order to overcome its own inertia, requires a mightier moving power than that of man, quite apart from the fact that man is a very imperfect instrument for producing uniform and continuous motion.[110]

The replacement of labor power with other motive forces starts with "a call for the application of animals, water and wind as motive powers," but it soon graduates to the development of coal-driven steam-engines and eventually (as Marx projected) electric power mechanisms.[111] It is here, with the development of motor mechanisms and their power sources in response to the energy demands of increasingly complex and large-scale machine-tool systems, that Marx emphasizes the role of friction as a fundamental entropic process.[112] Hence, in explaining that the "increase in the size of the machine and its working tools calls for a more massive mechanism" and motor force to drive it, Marx observes that the question of force (or energy) became critical when water power, which in Britain had hitherto been the main source of power, no longer seemed adequate: "the use of water-power preponderated even during the period of manufacture. In the seventeenth century attempts had already been made to turn two pairs of millstones with a single water-wheel. But the increased size of the transmitting mechanism came into conflict with the water-power, which was now insufficient, and this was one of the factors which gave the impulse for a more accurate investigation of the laws of friction."[113]

Here Marx demonstrates an acute understanding of the way in which water and steam, as contemporaneous power technologies, affected the early history of industrialization. Although the "take-off" associated with the industrial revolution is usually seen as occurring around 1760 or 1780, water power remained the principal motive force for industry in Britain until well into the nineteenth century. In the eighteenth and early nineteenth centuries scientist-engineers such as Parent, Smeaton, Déparcieux, and Lazare Carnot explored the efficiency requirements of water power, the problem of friction, and, in Lazare Carnot's case, the maximum efficiency under ideal conditions from a given fall of water. At this time, despite the improvements of Watt's steam engine, the water wheel provided far more motive power. The steam engine was thus commonly used as a supplement to water power. However, the increasing efficiency of the steam engine, coupled with its greater versatility (the areas of serviceable water power in Britain – principally Scotland and the North – were already in use) led to its steady displacement of water power as the nineteenth century progressed.[114]

Not only do Marx's comments seem to be cognizant of these developments, but his point here may reflect awareness of the fact that the Scottish physicists James Thomson and his brother, William Thomson (the future Lord Kelvin), were initially drawn to their research into thermodynamics by their practical explorations into fluid friction.[115] It was William Thomson who rediscovered and promoted Sadi Carnot's 1824 work on thermodynamics, which had hitherto fallen on deaf ears. The very term "thermodynamics" (referring initially to the laws of heat as a source of power) was introduced by Thomson in 1849.

In any event, despite common misinterpretations regarding Marx's polemic with Proudhon, in which Marx glibly stated that "the hand-mill gives you society with the feudal lord, the steam engine society with the industrial capitalist," Marx clearly did not adopt the view that the steam engine literally generated either the capitalist or industrialization.[116] He recognized that water power not only dominated in the early manufacturing/mercantilist period preceding industrialization but even led the way in the initial phase of industrialization proper (the age of "machinofacture"). In fact, his analysis emphasizes that steam power only displaced water power as the entire mechanism of production (itself a product of developing socioeconomic relations) began to demand increasingly large concentrations, and more versatile forms, of energy.

Specifically, Marx observes that with "tools... converted from being manual implements of man into the parts of a mechanical apparatus," it becomes possible to reduce "the individual machine to a mere element in production by machinery"; but this presumes that the motive mechanism is "able to drive many machines at once."[117] Thus, the required "motor mechanism grows with the number of the machines that are turned simultaneously, and the transmitting mechanism becomes an extensive apparatus."[118] Insofar as "the object of labour goes through a connected series of graduated processes carried out by a chain of mutually complementary machines of various kinds," the power-source must meet demanding scale, flexibility and transmission requirements.[119] In industries using machines to produce precision machines, especially, an "essential condition ...was a prime mover capable of exerting any amount of force, while retaining perfect control."[120] The material nature of water power precluded its use for such purposes beyond a certain level and locality, given problems of friction, containment, storability and transportability:

> The flow of water could not be increased at will, it failed at certain seasons of the year, and above all it was essentially local. Not till the invention of Watt's second and so-called double-acting steam-engine was a prime mover found which drew its own motive power from the consumption of coal and water, was entirely under man's control, was mobile and a means of locomotion,... and, finally, was of universal technical application and little affected in its choice of residence by local circumstances.[121]

Obviously, "matter matters, too," in *Capital*'s analysis of the energetics of capitalist industrialization. One can then understand why Marx paid such close attention to the physical wear and tear of machinery. In the chapter on machinery and large-scale industry, we are told that:

> The physical deterioration of the machine is of two kinds. The one arises from use, as coins wear away by circulating, the other from lack of use, as a sword rusts when left in its scabbard. Deterioration of the first kind is more or less directly proportional, and that of the second kind to a certain extent inversely proportional, to the use of the machine.[122]

Such physical deterioration is central to the analysis of the costs of fixed capital replacement and repair in Volume II, Chapter 8 of *Capital*, where Marx again distinguishes between wear and tear from "actual use" and "that caused by natural forces," showing through various real-world examples how the labor necessitated by each type enters into the values of commodities.[123]

Aside from friction, another reason why Marx eschewed energy-reductionism in his analysis of industry was his awareness that capitalism's "development of the social powers of labour" involved not just machines and their motive forces, but also "the appliance of chemical and other natural agencies" in a way that is not reducible to pure energy-transmission.[124] This is most evident from Marx's analysis of capitalist agriculture, where the "conscious, technological application of science," in the service of profit-making, confronts a barrier in "the fertility of the soil," with its necessary basis in "the metabolic interaction between man and the earth."[125] But there is an irreducible biochemical element to any kind of production wherein something is "added to the raw material to produce some physical modification of it, as chlorine is added to unbleached linen, coal to iron, dye to wool."[126] "In all these cases," as Marx puts it when considering their effect on value accumulation, "the production time of the capital advanced consists of two periods: a period in which the capital exists in the labour process, and a second period in which its form of existence – that of an unfinished product – is handed over to the sway of natural processes, without being involved in the labour process."[127] Such biochemical production processes obviously reduce the relevance of analyses anchored solely in energetics.[128]

For Podolinsky, the primary goal of socialism was to maximize the accumulation of energy on earth through full utilization of the perfect human-laboring machine – an analog derived from Carnot's ideal reverse cycle model.[129] Carnot's model, however, was that of an abstract, isolated system – a purely theoretical construct used as a means of determining the maximum efficiency of a heat engine under ideal conditions. Although it was to be the basis for the development of thermodynamics, his ideal model was conceived in terms of reversible processes. Hence, Carnot's cycle abstracted from those irreversible processes such as conduction, friction, percussion, etc. that later came to be seen as particular manifestations of entropy (the second law of thermodynamics). Podolinsky's error was to attempt to apply a model of an isolated system to human production, which is better understood as an open, dissipative system. By attributing to human labor the characteristics of Carnot's perfect machine (assuming complete reversibility and hence the absence of entropy), Podolinsky set up an analysis that in effect denied the relevance of the second law of thermodynamics to human production. In fact, Podolinsky's model in places seems to point beyond Carnot's idealized cycle of perfect reversibility to the notion that human beings can simply, through the expenditure of their labor (without drawing on any source of energy outside of themselves), create a net increase in work, i.e., fire their own engines. This would be a perpetuum mobile, something that Carnot's model of course negates as transcending all physical laws.[130]

Given that Podolinsky's analysis of labor failed to recognize the entropic processes in real world production, it is not at all surprising that his calculations of energy expenditure were simplistic to an extreme, especially when applied to industry. As Engels writes:

> In industry all [such] calculations come to a full stop; for the most part the labour added to a product simply does not permit of being expressed in terms of cal. This might be done in a pinch in the case of a pound of yarn by laboriously reproducing its durability and tensile strength in yet another mechanical formula, but even then it would smack of quite useless pedantry and, in the case of a piece of grey cloth, let alone one that has been bleached, dyed or printed, would actually become absurd. The energy value conforming to the production costs of a hammer, a screw, a sewing needle, is an impossible quantity.[131]

Hence, in a manner similar to Marx, Engels's argument against energy-reductionism emphasizes the irreducible biochemical character of human labor and its products, and the fact that use value is not reducible to pure energy. The metabolic processes within the human body, reflexive of humans' interactions with their physical environment, are of a qualitative nature, not easily incorporated in such calculations of energy input-output.[132] In this, Engels's argument is consistent with that of many later ecological economists.[133]

Another important connection between Marx's analysis and ecological economics – specifically the entropy school – involves the latter's view that human production became unsustainable when it "broke the budget constraint of living on solar income."[134] However, although Daly limits this post-solar income regime to "the last 200 years," neither he nor Georgescu-Roegen venture a structural explanation for it – that is, an explanation combining specific social production relations with the development of specific technologies relying on fossil fuels and other "geological capital."[135] As we've seen, Marx's analysis of machinery and large-scale industry (and industrialized agriculture under capitalism) provides just such an explanation for the growing industrial mechanism's voracity for materials and energy. Apart from the standard interpretation of the Podolinsky debate, perhaps what has bolstered ecological economists' misperceptions of Marx's views are passages such as the following, extracted from its proper context:

> In the first place, in machinery the motion and the activity of the instrument of labour asserts its independence *vis-à-vis* the worker. The instrument of labour now becomes an industrial form of perpetual motion. It would go on producing for ever if it did not come up against certain natural limits in the shape of the weak bodies and the strong wills of its human assistants.[136]

The "perpetual motion" of which Marx speaks here, replaced in its proper context, concerns the entire social mechanism behind the instrument of production, as perceived from the standpoint of the individual worker alienated from the means of production. This "perpetual motion" is that of a material-social class relation; it is not an inherent physical property, a matter only referred to metaphorically and hence inviolate of the laws of thermodynamics. Marx's main point involves how the machine-system "confronts the worker as a pre-existing material condition of production":[137]

> An organized system of machines to which motion is communicated by the transmitting mechanism from an automatic centre is the most developed form of production by machinery. Here we have, in place of the isolated machine, a mechanical monster whose body fills whole factories, and whose demonic power, at first hidden by the slow and measured motions of its gigantic members, finally bursts forth in the fast and feverish whirl of its countless working organs.[138]

Marx's reference to the "working organs" of this machine monstrosity goes back to the original Greek term *organon*, which refers both to tools and to bodily organs, in what amounts to a theory of natural technology. In this view, carried forward by Marx, tools are essentially inorganic extensions of the organs of the body.[139] The distinction between human bodily organs and their instrumental extensions also has a long history in ecological economics – the crucial difference being that ecological economists have not integrated it into a class analysis of production as Marx did.[140] At any rate, one can certainly imagine from the above-quoted passages how Marx must have felt about Podolinsky's designation of workers as "perfect machines," i.e., idealized steam engines. Indeed, the main way in which "Podolinsky went astray," as Engels put it in his December 19, 1882 letter to Marx, was to bypass the alienated character of real-world machinery and mechanized labor under capitalism.[141] Instead, Podolinsky "sought to find in the field of natural science fresh proof of the rightness of socialism," and thus "confused the physical with the economic."[142] Although contemporary ecological economics does not (for the most part) champion socialism, it arguably suffers from a similar tendency to confuse the physical with the economic, due to its failure to grapple with the deep material-social contradictions of capitalist production and monetary valuation.[143] By debunking the Podolinsky business, we hope to help clear the air for a more productive dialogue between Marxism and ecological economics, regarding the changes in socio-economic conditions necessary if humanity is to live within its solar income and other environmental conditions. An important sub-topic in that dialogue is Marx's analysis of the matter-energy throughput generated by capitalist industry, to which we now turn.

Matter-energy throughput under capitalism

Marx emphasizes that capitalism's development of "the productive powers of labour" is dependent upon "the *natural* conditions of labour, such as fertility of soil, mines, and so forth."[144] Capitalist industrialization is a process in which "science presses natural agencies into the service of labour" under the pressures of private profit-making and competition.[145] Nature provides capitalist enterprise with use values that act not only as bearers of value, but also as "free natural productive power[s] of labour."[146] Both functions are evident in Marx's analysis of raw materials in the capital accumulation process.

Marx's main theme here is that capitalism's development of machine-based production, and of a complex division of labor among competing enterprises, generates an unprecedented increase in labor productivity that necessarily corresponds to an unprecedented demand for raw materials. As he says, "the increasing productivity of labour is expressed precisely in the proportion in which a greater quantity of raw material absorbs a certain amount of labour, i.e. in the increasing mass of raw material that is transformed into products, worked up into commodities, in an hour, for example."[147] "The growth of machinery and of the division of labour has the consequence that in a shorter time far more can be produced," so that "the part of capital transformed into raw materials necessarily increases."[148] As labor productivity grows, so grows the quantity of materials that capital must appropriate and process in order to achieve any given expansion of value.

As has been shown, Marx was also well aware of the crucial importance of power supplies for capitalist industry. Accordingly, he includes energy sources in capital's growing demand for "auxiliary" or "ancillary" materials, defined as those materials which, while not forming part of "the principal substance of the product," are nonetheless required "as an accessory" of its production.[149] They provide heat, light, chemical and other necessary conditions of production distinct from the direct processing of principal materials by labor and its instruments. Obviously, consumption of energy sources ("coal by a steam-engine. . . hay by draft-horses," or "materials for heating and lighting workshops") is a large part of such ancillaries' usage.[150] As Marx observes, "After the capitalist has put a larger capital into machinery, he is compelled to spend a larger capital on the purchase of raw materials *and the fuels required to drive the machines*."[151] In short, capitalist industrialization results in "more raw material worked up in the same time, and therefore a greater mass of raw material *and auxiliary substances* enters into the labour process."[152]

This is not to say that the goal of capitalist production is simply to maximize matter-energy throughput. Capitalism is a competitive system in which individual enterprises feel a constant pressure to lower costs. Hence, in its own historically limited way, capitalism does penalize waste of materials and energy. As Marx observes, "value is not measured by the labour-time that [an] article costs the producer in each individual case, but by the labour-time socially required for its production."[153] Competition thus penalizes excessive matter-energy throughputs by not recognizing the labor time objectified in them as necessary, value-creating labor. In this sense, "all wasteful consumption of raw material or instruments of labour is strictly forbidden, because what is wasted in this way represents a superfluous expenditure of quantities of objectified labour, labour that does not count in the product or enter into its value."[154] Such waste also includes any "refuse" that could have been "further employed as a means in the production of new and independent use values" – at least insofar as competitors are able to implement the necessary recycling operations.[155] "As the capitalist mode of production extends," Marx argues, "so also does the utilization of the refuse left behind by production."[156]

Nonetheless, such competitive economization and recycling of materials only operates along a path of rising labor productivity, i.e., of the processing of matter-energy into commodities on an ever-growing scale. The main "motive for each individual capitalist" is "to cheapen his commodities by increasing productivity of labour."[157] By lowering cost per commodity produced, such productivity gains enable manufacturers to reap surplus profits and/or an increased market share. Although they still feel pressure to keep throughput at or below the normal level, this level is itself a positive function of the constant drive to boost output per labor hour.

Moreover, capitalism's competitive enforcement of its own standards of matter-energy use does nothing to counter the throughput produced by the "moral depreciation" of fixed capital precipitated by the development of more advanced machinery and structures, or by rising labor productivity in the industries producing them.[158] Through such moral depreciation (loss of capital values objectified in machinery and buildings), "competition forces the replacement of old means of labour by new ones before their natural demise" – a clear acceleration of material throughput resulting in environmental degradation.[159] The constant threat of moral depreciation also compels individual enterprises to speed up the turnover of their fixed capital stocks by prolonging worktime and intensifying labor processes, further magnifying the system's normal matter-energy throughput.[160] Advanced capitalism's extension of such accelerated turnover to consumer "durables" (personal computers, televisions, audio equipment, kitchen appliances, etc.) only worsens these entropic dynamics.[161]

Given this background, one can better understand Engels's critique of Podolinsky's attempt to calculate the energy productivity of agricultural labor. In Marx's view, capitalist development of productive forces translates into a growing throughput of matter and energy per labor hour. This explains Engels's observation, in response to Podolinsky, that "whether the *fresh* cal stabilised by the expenditure of 10,000 cal of daily nourishment amount to 5,000, 10,000, 20,000 or a million is dependent solely upon the level of development of the means of production."[162] In other words, the amount of energy that each hour of labor (temporarily) stabilizes depends on the total amount of matter-energy processed per hour as well as the amount of ancillary energy used per unit of output – both of which correlate to the development of production. Given that the increase in labor productivity under capitalism is generally accompanied by increases in material throughput, Podolinsky's failure to include non-labor inputs in his calculations is a serious omission indeed, seeing as how "the energy value of auxiliary materials, fertilisers, etc., must . . . be taken into consideration" – and increasingly so.[163] The general lesson, Engels tells his life-long comrade (in a statement already referred to above), "is that the working individual is not only a stabiliser of *present* but also, and to a far greater extent, a squanderer of *past*, solar heat. As to what we have done in the way of squandering our reserves of energy, our coal, ore, forests, etc., you are better informed than I am."[164]

IV. The metabolic rift and entropy

Engels's critique of Podolinsky's energy-reductionist framework is fully consistent with Marx's more complex metabolic-energetic approach to wage-labor and industrial capital accumulation. For Marx, the capitalist economy is an open system reliant on environmental inputs of labor power and non-human matter-energy. Marx emphasizes capitalism's tendency to deplete and despoil the land, while exploiting the worker. Stated differently, Marx argues that the metabolic systems that reproduce the productive powers of labor and the land are susceptible to adverse shocks from the system of industrial capital accumulation to which they are conjoined.

It is thus no accident that Marx chooses the final section of his chapter on machinery and large-scale industry as the place to develop an initial synthesis of capitalism's tendency to "simultaneously [undermine] the original sources of all wealth – the soil and the worker."[165] This was for Marx a major consequence of the industrialization of agriculture, which led to the systematic and intensive robbing of the soil, as well as exploitation of the worker. Here, Marx invokes Liebig's theory of biochemical reproductive cycles to argue that capitalism "disturbs the metabolic interaction between man and the earth."[166] Specifically, capitalism concentrates population and manufacturing industry in urban centers in a way that "prevents the return to the soil of its constituent elements consumed by man in the form of food and clothing; hence it hinders the operation of the eternal natural condition for the lasting fertility of the soil."[167] In short, the capitalist division of town and country disrupts the soil's reproductive cycle, and this disruption is accentuated by the tendency of industrial capitalist agriculture towards "robbing the soil" and "ruining the more long-lasting sources of [its] fertility."[168]

Marx returns to his critique of the metabolic rift associated with capitalist industrialization when he analyzes the origins of agricultural land rent in Volume III of *Capital*, arguing that:

> Large landed property reduces the agricultural population to an ever decreasing minimum and confronts it with an ever growing industrial population crammed together in large towns; in this way it produces conditions that provoke an irreparable rift in the interdependent process of social metabolism, a metabolism prescribed by the natural laws of life itself. The result of this is a squandering of the vitality of the soil, which is carried by trade far beyond the bounds of a single country.[169]

The metabolic rift between town and country created by the industrial capitalist system vitiates the reproduction both of labor power and the land, two things that in reality constitute a unified metabolic system, however much capitalism may treat them merely as separable external conditions. To quote Marx once again,

> Large landed property undermines labour-power in the final sphere to which its indigenous energy flees, and where it is stored up as a reserve fund for renewing the vital power of the nation, on the land itself. Large-scale industry and industrially pursued large-scale agriculture have the same effect. If they are originally distinguished by the fact that the former lays waste and ruins labour-power and thus the natural power of man, whereas the latter does the same to the natural power of the soil, they link up in the later course of development, since the industrial system applied to agriculture also enervates the workers there, while industry and trade for their part provide agriculture with the means of exhausting the soil.[170]

Marx's analysis is fully consistent with the central concept of Liebig's agricultural chemistry paradigm: "the cycle of processes constitutive for the reproduction of organic structures."[171] This concept is not energy-reductionist, but it does abide by the first and second laws of thermodynamics. As Krohn and Schäfer describe it, "plant and animal life, together with meteorological processes, jointly circulate certain 'substances'; apart from the irreversible transformation of energy into heat, living processes do not 'use up' nature, but reproduce the conditions for their continued existence."[172]

Capitalism's assault on the biochemical processes necessary to sustain the human-land system does not create or destroy matter-energy, but it does degrade its metabolic reproductive capabilities. This degradation can clearly be seen as a form of entropic matter-energy dissipation. In Marx's view, this phenomenon – to some extent inherent in production – is dramatically worsened by capitalism's specific form of industry, which is based on the social separation of the producers from the land and other necessary conditions of production. Hence it is possible for society to achieve a "systematic restoration" of its reproductive metabolism with the land "as a regulative law of social production, and in a form adequate to the full development of the human race."[173] But this requires "co-operation and the possession in common of the land and the means of production," based on "the transformation of capitalist private property... into social property."[174]

V. Conclusion

"The idea of a history of nature as an integral part of materialism," writes Ilya Prigogine, winner of the 1977 Nobel Prize in chemistry,

> 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 transformations, 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.[175]

Unfortunately, many nineteenth-century materialists and socialists were reluctant to let go of the mechanistic world view. They were not aware, as Marx and Engels were, that the rigid, mechanistic approach to nature had been displaced by a natural science that was increasingly historical in character (concerned with irreversible processes). So-called "scientific materialism" (or mechanism) lacked a sufficiently dialectical approach to materialism. Cartesian dualism had promoted a rationalist/idealist conception of the mind on the one hand and a mechanistic conception of animals and the body on the other. It should come as no surprise then that among the first reactions to Carnot's advances in thermodynamics, in which he presented an idealized model of engine efficiency in a closed, reversible system, was to see the work of animals and human beings in the terms of the steam engine. This first took the form in many cases of concrete comparisons of human labor power, horsepower, and steampower – studies with which Marx and Engels were familiar.[176]

Podolinsky made a bold departure in applying Carnot's model directly, claiming that human labor was the "perfect machine" – a kind of steam engine able to restart its own firebox. But although drawing out some important relationships, he fell prey to crude mechanism and energy reductionism. The question of labor power was divorced from its historical and social context, from all qualitative transformations of nature, as well as from humans' relation to nature, and was viewed from a purely mechanistic and quantitative perspective. Appearing to believe that he had unlocked the physical basis of the labor theory of value, Podolinsky in fact lost sight of the qualitative relations among nature, labor, and society that underlie Marx's value theory. Ironically, by applying Carnot's closed, reversible model of the machine to the actual world of human labor, Podolinsky essentially denied that such labor was tied up with irreversible processes and hence, in effect, denied that entropy was applicable to human labor. At the same time he left out of his analysis the full complexity of human-nature transformations and even many aspects of more quantitative/energetic relations, such as the solar budget, the use of coal, fertilizers, etc.

For Podolinsky, the creation and accumulation of value was essentially the same thing as the accumulation of terrestrial energy through the exercise of human labor – the prevention of the dispersion of heat/energy back into space. Podolinsky did not (and obviously could not be expected to) understand what scientists know so well today: "Earth's temperature is whatever is required to send back to space the same amount of energy that the planet absorbs. If less energy is sent back than is received, the planet warms, 'glowing' more brightly and sending more back until a new balance is reached."[177] This is in fact what is happening today with global warming. Through the buildup of carbon dioxide and other greenhouse gas emissions in the atmosphere, humans have finally achieved the goal that Podolinsky sought, of increasing the energy stored on the earth. But the consequence endangers the conditions required for perpetuity of all current forms of terrestrial life.

The fact that Marx and Engels did not embrace Podolinsky's mechanistic and reductionist applications of quantitative energetics to human labor (and by implication, value) does not indicate their rejection of thermodynamics or their lack of sophistication where issues of energy were concerned. On the contrary, the founders of historical materialism followed the development of the physical sciences very closely and made sure that their analyses were consistent with the latest developments in thermodynamics, evolutionary theory, etc. Yet, their dialectical instincts and emphasis on the qualitative rather than simply the quantitative nature of energy transformations (together with their wider metabolic approach) kept them from capitulating to crude energetics. Attentive to the irreversible processes related to production, Engels complained of Podolinsky's inability to comprehend the fact that capitalist industrialism squandered limited supplies of coal and other resources. As famed early Soviet physicist and sociologist of science Boris Hessen observed, 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."[178]

What Marx and Engels generated in their historical-dialectical materialism was a theory of the capitalist labor, production, and accumulation process that was not only consistent with the main conclusions of thermodynamics originating in their time, but also extraordinarily amenable to ecological laws. Although attentive to the quantitative aspects of energy transfers, they nonetheless emphasized, dialectically, the qualitative transformations such transfers involve. All tendencies toward mechanism or reductionism were excluded from their analysis. At the same time Marx developed a sophisticated theory of the metabolic character of the human labor process and of the metabolic rift that appears within capitalism. This analysis not only recognized that "matter matters" but was sensitive to the biochemical processes of life itself and to emerging evolutionary theory. In other words, classical Marxism, contrary to widespread myth, has an extraordinary affinity for what has become known as "ecological economics," while in many ways prefiguring the leading tradition in environmental sociology in the United States, the neo-Marxian "treadmill of production" perspective, associated in particular with the work of Alan Schnaiberg.[179] Indeed, Marx's metabolic-energetic analysis is a forerunner and in some ways a deeper theoretical rendition (though obviously lacking much contemporary historical specificity associated with developments of the last century and a half) of the treadmill of production model. Marx himself had written about the "treadmill," in reference to labor conventions of his time, but also as a larger metaphor for modes of production that debase the human condition and thus negate sustainability in an ecological sense, disallowing for the propagation of the vital bases of life. It was therefore associated in his mind with the "barbarism" that continued to exist within bourgeois society.[180] While present-day ecological economics together with environmental sociology, in its neo-Marxian treadmill model, have emphasized that contemporary economic growth violates the solar (and overall environmental) budget constraint on sustainable human production, this violation was already recognized in many ways in Marx's complex theory of metabolic rift. As British environmental sociologist Peter Dickens has written,

> Marx's early background led him to undertake no less than an analysis of what would now be called "environmental sustainability." In particular he developed the idea of a "rift" in the metabolic relation between humanity and nature, one seen as an emergent feature of capitalist society. . . .The notion of an ecological rift, one separating humanity and nature, and violating the principles of ecological sustainability, continues to be helpful for understanding today's social and environmental risks. These risks are becoming increasingly global in extent. This is partly because they directly impact on environmental mechanisms operating at a global scale.[181]

The contrast with Podolinsky's vision of energy accumulation as the key to human productivity – an extreme version of productionism, borne out of mechanism – could not be more stark. Marx, for all his commitment to the expansion of human productive capabilities, recognized the rift between humanity and nature, as it is amplified by capitalism, and both he and Engels were acutely aware of problems of degradation, waste, and resource loss – the environmental arrow of time. Even climate change due to human environmental depredations was an issue they considered. For Marx, environmental problems were not subject to mechanical solutions (as in the concept of a "perfect machine") but only to social ones – namely, the creation of a society of associated producers capable of rationally regulating the metabolism of society and nature. With its organic synthesis of open-system materialism and class analysis, Marx's perspective can help us to broaden and deepen the critique of the political-economic system provided by contemporary ecological economics and radical environmental sociology (particularly the treadmill critique of the latter).

How should we account for the remarkable resonance of Marx's environmental critique in this respect? In the end, this has only one possible explanation: the fact that ecology is perhaps the most exemplary science where dialectics is concerned.[182] It follows that an ecological critique of the existing political economy built on Marxian materialist and dialectical foundations is likely to go further and faster – because it goes to the root of the matter while rejecting all forms of mechanism and reductionism, all rigid separations of nature and society. Many of those problems that have most bedeviled ecological economists and treadmill theorists within environmental sociology, such as the deeper social dynamics underlying the environmental juggernaut of capitalist society, have their answers, we believe, in the classical Marxian framework and its development.

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Notes

1. Juan Martinez-Alier and J.M. Naredo, "A Marxist Precursor of Ecological Economics: Podolinsky," *Journal of Peasant Studies* 9/2 (1982): 207–224; see also Juan Martinez-Alier, *Ecological Economics* (Oxford, UK: Basil Blackwell, 1987).
2. That Podolinsky's work elicited an indifferent or dismissive reaction from Marx and Engels is commonly cited as an established fact by ecological economists, environmental sociologists, environmental historians, and ecosocialists, among them, Robert Kaufmann, "Biophysical and Marxist Economics," *Ecological Modeling* 38/1–2 (1987): 91; Anna Bramwell, *Ecology in the Twentieth Century* (New Haven: Yale University Press, 1989): 86; Jean-Paul Deléage, "Eco-Marxist Critique of Political Economy," in Martin O'Connor, editor, *Is Capitalism Sustainable?* (New York: Guilford, 1994): 49; Tim Hayward, *Ecological Thought: An Introduction* (Cambridge, UK: Polity Press, 1994): 226; David Pepper, *Modern Environmentalism* (London: Routledge, 1996): 230; Ariel Salleh, *Ecofeminism as*

Politics (London: Zed Books, 1997): 155; Alf Hornborg, "Towards an Ecological Theory of Unequal Exchange," *Ecological Economics* 25/1 (1998): 129; James O'Connor, *Natural Causes* (New York: Guilford, 1998): 3; Cutler J. Cleveland, "Biophysical Economics," in John Gowdy and Kozo Mayumi, editors, *Bioeconomics and Sustainability* (Northampton, MA: Edward Elgar, 1999): 128; John Barry, "Marxism and Ecology," in Andrew Gamble, David Marsh, and Tony Tant, editors, *Marxism and Social Science* (Urbana: University of Illinois Press, 1999): 277–278; Juan Martinez-Alier, "Marxism, Social Metabolism, and Ecologically Unequal Exchange," Paper Presented at the Conference on World System Theory and the Environment. Lund University, Sweden, September 2003, 11.

3. To use Engels's description of the issues raised by Podolinsky's work, in his December 19, 1882 letter to Marx (Karl Marx and Frederick Engels, *Collected Works*, Vol. 46 (New York: International Publishers, 1992): 410).
4. John Bellamy Foster and Paul Burkett, "Ecological Economics and Classical Marxism: The 'Podolinsky Business' Reconsidered," *Organization & Environment* 17/1 (2004): 32–60.
5. Herman E. Daly, *Steady-state Economics*, Second Edition (London: Earthscan, 1992): 23.
6. John Tyndall, *Heat Considered as a Law of Motion* (London: Longman, Green & Co., 1863).
7. On these and other aspects of Marx and Engels's natural scientific studies, see Pradip Baksi, "Karl Marx's Study of Science and Technology," *Nature, Society, and Thought* 9/3 (1996): 261–296; Pradip Baksi, "MEGA IV/31: Natural Science Notes of Marx and Engels, 1877–1883," *Nature, Society, and Thought* 14/4 (2001): 377–390. Additional specific examples are noted in Sections II and III of the present paper.
8. Martinez-Alier and Naredo, "A Marxian Precursor of Ecological Economics"; Martinez-Alier, *Ecological Economics*. The German version of Podolinsky's article was published in two installments: Sergei Podolinsky, "Menschliche Arbeit und Einheit der Kraft," *Die Neue Zeit*, 1/9 (1883): 413–424 and 1/10 (1883): 449–457.
9. Engels's two letters to Marx are dated December 19, 1882 and December 22, 1882; see Marx and Engels, *Collected Works*, Vol. 46, pp. 410–414. The Italian version of Podolinsky's work, like the German one, was published in two installments: Sergei Podolinsky, "Il Socialismo e l'Unita delle Forze Fisiche," *La Plebe*, 14/3 (1881): 13–16 and 14/4 (1881): 5–15.
10. Sergei Podolinsky, "Le Socialisme et l"Unitédes Forces Physiques," *La Revue Socialiste*, 8 (1880): 353–365.
11. These extracts, roughly 1800 words long, are to be published sometime in the next few years in Volume IV/27 of *Historisch-Kritische Gesamtausgabe*, commonly known as MEGA, the plan of which is to provide the first truly comprehensive collection of Marx and Engels's writings in their original languages.
12. A much longer rendition of Podolinsky's analysis was published in the Russian journal *Slovo* in 1880. It has recently been reprinted (in Russian) in book form: Sergei Podolinsky, *Human Labor and Its Relation to the Distribution of Energy* (Moscow: Noosfera, 1991). This Russian version contains more extended discussions of energetics and of the general importance of plants, animals, and human beings for the terrestrial distribution of energy.

13. This is based on our comparison of Marx's notes to an unpublished English translation of Podolinsky's *La Revue Socialiste* article by our colleague Mark Hudson.
14. See Sergei Podolinsky, "Socialism and the Unity of Physical Forces" (translated by Angelo Di Salvo and Mark Hudson), *Organization & Environment* 17/1 (2004): 61–75.
15. Sadi Carnot, *Reflections on the Motive Power of Fire* (Gloucester, MA: Peter Smith, 1977).
16. Elias L. Khalil, "Entropy Law and Exhaustion of Natural Resources: Is Nicholas Georgescu-Roegen's Paradigm Defensible?," *Ecological Economics* 2/2 (1990): 171.
17. Ibid., 170, emphasis in original.
18. Gabriel A. Lozada, "A Defense of Nicholas Georgescu-Roegen's Paradigm," *Ecological Economics* 3/2 (1991): 157.
19. A.G. Williamson, "The Second Law of Thermodynamics and the Economic Process," *Ecological Economics* 7/1 (1993): 70–71.
20. C. Biancardi, A. Donati, and S. Ulgiati, "On the Relationship Between the Economic Process, the Carnot Cycle and the Entropy Law," *Ecological Economics* 8/1 (1993): 9, emphasis added.
21. Ibid, 10.
22. Marx and Engels, *Collected Works*, Vol. 46, 411, emphasis in original.
23. Frederick Engels, "The Mark," in Karl Marx and Frederick Engels, *Collected Works*, Vol. 24 (New York: International Publishers, 1978): 439–456. That Marx would raise ecological, including metabolic, issues at this time is unsurprising in light of his reaffirmation, less than two years earlier in his *Notes on Adolph Wagner*, of the open-system character of his own analysis of capitalism. Referring to the method used in *Capital*, Marx wrote: "I have employed the word [*Stoffwechsel*] for the 'natural' process of production as the material exchange . . . between man and nature." (Karl Marx, *Texts on Method* (Oxford, UK: Basil Blackwell, 1975): 209.) *Stoffwechsel* translates as *metabolism*.
24. Nicholas Georgescu-Roegen, "Energy and Economic Myths," *Southern Economic Journal* 41/3 (1975): 347–381; Nicholas Georgescu-Roegen, *Energy and Economic Myths* (New York: Pergamon, 1976); Herman E. Daly, "Postscript: Unresolved Problems and Issues for Further Research," in Herman E. Daly and Alfred F. Umaña, editors, *Energy, Economics, and the Environment* (Boulder, CO: Westview, 1981): 165–185.
25. Alfredo Saad-Filho, *The Value of Marx* (London: Routledge, 2002); Paul Burkett, "The Value Problem in Ecological Economics: Lessons from the Physiocrats and Marx," *Organization & Environment* 16/2 (2003): 137–167.
26. Podolinsky, "Socialism and the Unity of Physical Forces," 61, emphasis in original.
27. Nicholas Georgescu-Roegen, "The Entropy Law and the Economic Problem," in Herman E. Daly, editor, *Economics, Ecology, Ethics* (San Francisco: W.H. Freeman, 1973): 50.
28. Charles Perrings, *Economy and Environment* (New York: Cambridge University Press, 1987): 5.
29. Amos H. Hawley, "Human Ecological and Marxian Theories," *American Journal of Sociology* 89/4 (1984): 912.

30. Paul Burkett, *Marx and Nature* (New York: St. Martin's Press, 1999); John Bellamy Foster, "Marx's Theory of Metabolic Rift: Classical Foundations for Environmental Sociology," *American Journal of Sociology* 105/2 (1999): 366–405; John Bellamy Foster, *Marx's Ecology* (New York: Monthly Review Press, 2000); Foster and Burkett, "Ecological Economics and Classical Marxism."
31. Karl Marx, *Capital* (Three Volumes) (New York: Vintage, 1981), Vol. I, 290.
32. Ibid., 647.
33. Ibid., 133–134. Marx castigated the Gotha Programme for asserting that "labour is the source of all wealth," because to do so was to ascribe "*supernatural creative power* to labour." Karl Marx, *Critique of the Gotha Program* (New York: International Publishers, 1966): 3, emphasis in original.
34. Engels to Marx, December 19, 1882, in Marx and Engels, *Collected Works*, Vol. 46, 411, emphasis in original.
35. Daly, "Postscript," 169.
36. Anneliese Griese and Gerd Pawelzig, "Why Did Marx and Engels Concern Themselves with Natural Science?," *Nature, Society, and Thought* 8/2 (1995): 132; see also Foster, *Marx's Ecology*, 157–158.
37. Griese and Pawelzig, "Why Did Marx and Engels Concern Themselves with Natural Science?," 132–133. Engels's use of the metabolism concept in *Dialectics of Nature* also adhered to "the physiologists' definition." This is clear from the following definition of *life*: "Life is the mode of existence of protein bodies, the essential element of which consists in *continual metabolic interchange with the natural environment outside them*, and which ceases with the cessation of this metabolism, bringing about the decomposition of the protein. . . . [M]etabolism is the characteristic activity of protein bodies." Frederick Engels, *Dialectics of Nature* (Moscow: Progress Publishers, 1964): 306–307, emphasis in original.
38. Burkett, *Marx and Nature*, Chapters 9 and 10; Foster, *Marx's Ecology*, Chapters 4 and 5. For historical applications of Marx's metabolic rift theme (including the rift between city and country) from a world-system perspective, see Jason W. Moore, "Environmental Crises and the Metabolic Rift in World-Historical Perspective," *Organization & Environment* 13/2 (2000): 123–157; Jason W. Moore, "The Modern World-System as Environmental History?: Ecology and the Rise of Capitalism," *Theory and Society* 32/3 (2003): 307–377.
39. Nicholas Georgescu-Roegen, "Energy Analysis and Economic Valuation," *Southern Economic Journal* 45/4 (1979): 1039.
40. Marx, *Capital*, Vol. I, 198, 90.
41. Ibid., 126.
42. See Burkett, *Marx and Nature*, 26, for a full documentation of this point.
43. Marx, *Capital*, Vol. I, 133.
44. Ibid., 131.
45. Ibid., 295.
46. Ibid., 270.
47. Ibid., 310.
48. Ibid., 323.
49. Karl Marx, *Capital*, Vol. I (New York: International Publishers, 1967): 215. When quoting from this edition of Volume I of *Capital* we will refer to it as the "International Edition"; Otherwise all quotes of *Capital* are from the 1981 Vintage edition.
50. Marx, *Capital*, Vol. I, 275.

51. Ibid.
52. Ibid., 274.
53. Ibid., 275.
54. Ibid. The physical requirements of reproduction not only of the individual laborer but also whole families supported by, and supporting, the worker are always explicit in Marx. While "a certain mass of necessaries must be consumed by a man to grow up and maintain his life,. . . another amount" is required "to bring up a certain quota of children." In order "to maintain and reproduce itself, to perpetuate its physical existence, the working class must receive the necessaries absolutely indispensable for living and multiplying." Karl Marx, *Value, Price and Profit* (New York: International Publishers, 1976): 39, 57.
55. Marx, *Capital*, Vol. I, 283.
56. Ibid., 128, 323, 134–135. Marx was always very careful to explain that there was no new materiality being created. Rather, matter-energy takes a new form as a result of labor. See, for example, his footnote to Lucretius (Ibid., 323).
57. Ibid., 274–275, emphasis added.
58. *Capital*, Vol. I, International Edition, 171.
59. Ludimar Hermann, *Elements of Human Physiology*, Fifth Edition (London: Smith and Elder, 1875); Baksi, "MEGA IV/31," 378.
60. Marx, *Capital*, Vol. I, 276–277.
61. Justus von Liebig, "On the Connection and Equivalence of Forces," in Edward L. Youmans, editor, *The Correlation and Conservation of Forces* (New York: D. Appleton & Co., 1864): 387–397.
62. Hermann, *Elements of Human Physiology*, 199–200, 215–225.
63. Marx, *Capital*, Vol. I, 664.
64. Ibid.
65. In a letter to Lion Philips, written on August 17, 1864, Marx reports: "I recently had an opportunity of looking at a very important scientific work, Grove's *Correlation of Physical Forces*. He demonstrates that mechanical motive force, heat, light, electricity, magnetism and CHEMICAL AFFINITY are all in effect simply modifications of the same force, and mutually generate, replace, merge into each other, etc." Karl Marx and Frederick Engels, *Collected Works*, Vol. 41 (New York: International Publishers, 1985): 551, capitalization in original. Marx reaffirmed his excitement with Grove's work two weeks later in a letter to Engels, suggesting that Grove "is beyond doubt the most philosophical of the English (and indeed German!) natural scientists" (Ibid., 553). Marx did not dispense this kind of praise very often.
66. William Robert Grove, *On the Correlation of Physical Forces*, in Edward L. Youmans, editor, *The Correlation and Conservation of Forces* (New York: D. Appleton & Co., 1864): 1–208; Karl Marx and Frederick Engels, *Selected Correspondence* (Moscow: Progress Publishers, 1975): 162.
67. Cf. Kenneth M. Stokes, *Man and the Biosphere* (Armonk, NY: M.E. Sharpe, 1994): 52–53; Baksi, "MEGA IV/31," 385.
68. Marx, *Capital*, Vol. I, 323.
69. Crosbie Smith, *The Science of Energy: A Cultural History of Energy and Physics in Victorian Britain* (London: The Athlone Press, 1998): 255; David Lindley, *Degrees Kelvin: A Tale of Genius, Invention, and Tragedy* (Washington, DC: Joseph Henry Press, 2004): 110.

70. Silvanus P. Thompson, *The Life of Lord Kelvin*, Two Volumes (New York: Chelsea Publishing Co., 1976): Vol. I, 289.
71. Engels, *Dialectics of Nature*, 315–316, emphases in original.
72. Podolinsky, "Socialism and the Unity of Physical Forces," 64–65; Foster and Burkett, Ecological Economics and Classical Marxism," 39–40.
73. Engels to Marx, December 19, 1882, in Marx and Engels, *Collected Works*, Vol. 46, 410, emphasis in original. The figure of 10,000 calories of daily food intake per worker seems to have been chosen by Engels without much thought. It is hard to see how even a worker engaged in extremely heavy labor for 16 hours per day could approach such an energy requirement. But the validity of Engels's point does not hinge on the accuracy of his illustrative numbers.
74. Ibid., emphasis in original.
75. Ibid.
76. Martinez-Alier, *Ecological Economics*, 221; see also Juan Martinez-Alier, "Political Ecology, Distributional Conflicts, and Economic Incommensurability," *New Left Review* 211 (1995): 71.
77. Engels, *Dialectics of Nature*, 289–291.
78. Engels to Marx, March 21, 1869, in Karl Marx and Frederick Engels, *Collected Works*, Vol. 43 (New York: International Publishers, 1988): 245–246.
79. Podolinsky, "Socialism and the Unity of Physical Forces," 61.
80. Throughout this discussion we follow Marx's assumptions, in Volume I of *Capital*, that commodity prices = commodity values, and that competition among firms has converted all concrete labors into abstract labor simultaneous with the formation of commodity prices (Saad-Filho, *The Value of Marx*, Chapter 5). Our discussion of the energetics of surplus value builds upon the work of Elmar Altvater, especially "The Foundations of Life (Nature) and the Maintenance of Life (Work)," *International Journal of Political Economy* 20/1 (1990): 20–25; *The Future of the Market* (London: Verso, 1993): 188–192; "Ecological and Economic Modalities of Time and Space," in Martin O'Connor, editor, *Is Capitalism Sustainable?* (New York: Guilford, 1994): 86–88.
81. Marx, *Capital*, Vol. I, 301.
82. Karl Marx, *Grundrisse* (New York: Vintage, 1973): 674.
83. Marx, *Capital*, Vol. I, 300.
84. Marx, *Value, Price and Profit*, 41, emphases in original.
85. Marx, *Grundrisse*, 464.
86. Ibid., 674.
87. Ibid.
88. Marx, *Capital*, Vol. I, 325. "The matter can also be expressed in this way: If the worker needs only half a working day in order to live a whole day, then, in order to keep alive as a worker, he needs to work only half a day. The second half of the labour day is forced labour, surplus-labour. . . . One half a day's work is objectified in his labouring capacity – to the extent that it exists in him as someone ALIVE or as a LIVING instrument of labour. The worker's entire living day (day of life) is the static result, the objectification of half a day's work. By appropriating the entire day's work and then consuming it in the production process with the materials of which his capital consists, but by giving in exchange only the labour objectified in the worker – i.e. half a day's work – the capitalist creates the surplus value of his capital; in this case, half a day of objectified labour." Marx, *Grundrisse*, 324, 334, capitalizations in original. Note that Marx

here looks at the labor time required to reproduce the worker from the point of view of the capitalist, i.e., as identical to the labor-time equivalent of the commodities purchasable with the wage.

89. Karl Marx, "Economic Manuscript of 1861–63, Continuation," in Karl Marx and Frederick Engels, *Collected Works*, Vol. 33 (New York: International Publishers, 1991): 493, emphases and capitalizations in original.
90. Ibid., 386.
91. Marx, *Capital*, Vol. I, 341–342.
92. Ibid., 375–376, emphasis added.
93. Wolfgang Krohn and Wolf Schäfer, "Agricultural Chemistry: The Origin and Structure of a Finalized Science," in Wolf Schäfer, editor, *Finalization in Science* (Boston: D. Reidel, 1983): 32–39; Baksi, "Karl Marx's Study of Science and Technology," 272–274; Baksi, "MEGA IV/31," 380–382; Foster, *Marx's Ecology*, 149–154.
94. Burkett, *Marx and Nature*, 88–90; Kozo Mayumi, *The Origins of Ecological Economics* (New York: Routledge, 2001): 81–84.
95. Marx, *Capital*, Vol. III, 754.
96. Marx, *Capital*, Vol. II, 321–322.
97. Marx, *Capital*, Vol. I, 376.
98. Ibid., 348. In the same passage (Ibid., 348–349), Marx points to "the diminishing military standard of height in France and Germany" as evidence of labor power's deterioration under the duress of capitalist exploitation – citing data compiled in Liebig's *Die Chemie in ihrer Anwendung auf Agricultur und Physiologie* (Chemistry in its Application to Agriculture and Physiology), Seventh Edition (Braunschweig: F. Vieweg und Sohn, 1865): 117–118.
99. Karl Marx, *Theories of Surplus Value*, Part III (Moscow: Progress Publishers, 1971): 309–310.
100. Marx, *Capital*, Vol. I, 494.
101. Ibid.
102. Baksi, "Karl Marx's Study of Science and Technology," 274–278.
103. Marx to Engels, January 28, 1863, in Marx and Engels, *Collected Works*, Vol. 41 (New York: International Publishers, 1985): 449.
104. Robert Willis, *A System of Apparatus for the Use of Lecturers and Experimenters in Mechanical Philosophy* (London: John Weale, 1851).
105. Eric Parkinson, "Talking Technology," *Journal of Technology Education* 11/1 (1999): 67 (wysiwyg://18/http://scholar.lib.vt.edu/ejournals/JTEv11n1/parkinson.html). Parkinson adds that Willis's model-based approach "was something of a benchmark in education in mechanics. Willis was a clear leader in his field, established a novel, practically-based teaching mode, and communicated his ideas to an influential cadre of future engineers" (Ibid., 67).
106. Marx, *Capital*, Vol. I, 494–495.
107. Marx to Engels, January 28, 1863, in Marx and Engels, *Collected Works*, Vol. 41, 450.
108. For details on Marx's analysis of capitalism's development and application of science as a form of workers' alienation from the means of production, see Burkett, *Marx and Nature*, 158–163.
109. Marx, *Capital*, Vol. I, 497.
110. Ibid.
111. Ibid., 496.

112. That Engels also had a keen interest in friction, but on a more theoretical level, is clear from the numerous passages on this subject in *Dialectics of Nature*, e.g., 95–96, 108, 110, 228–229, 252, 258–260, 284, 297. This may help explain why Georgescu-Roegen seems to have very much liked the book. (See Juan Martinez-Alier, "Some Issues in Agrarian and Ecological Economics, In Memory of Nicholas Georgescu-Roegen," *Ecological Economics* 22/3 (1997): 231.) It is harder to explain how Georgescu missed the more practical discussions of friction in Marx's *Capital*.
113. Marx, *Capital*, Vol. I, 497–498.
114. D.S.L. Cardwell, *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age* (Ithaca: Cornell University Press, 1971): 67–88; Lindley, *Degrees Kelvin*, 64–65.
115. Smith, *The Science of Energy*, 39, 48.
116. Karl Marx, *The Poverty of Philosophy* (New York: International Publishers, 1963): 109–110; Foster, *Marx's Ecology*, 280.
117. Marx, *Capital*, Vol. I, 499.
118. Ibid.
119. Ibid., 501.
120. Ibid., 506.
121. Ibid., 499.
122. Ibid., 528; cf. Ibid., 289–290.
123. Marx, *Capital*, Vol. II, 248–261.
124. Marx, *Value, Price and Profit*, 34.
125. Marx, *Capital*, Vol. I, 637–638.
126. Ibid., 288.
127. Marx, *Capital*, Vol. II, 317.
128. These kinds of processes have been termed "eco-regulated" by Ted Benton, "Marxism and Natural Limits," *New Left Review* 178 (1989): 51–86. For a detailed rebuttal of Benton's claim that Marx's analysis failed to take such processes into account, see Paul Burkett, "Labor, Eco-Regulation, and Value," *Historical Materialism* 3 (1998): 125–133; Burkett, *Marx and Nature*, 41–47. It should be noted in relation to biochemical and energetic processes that the more sophisticated purely energetic approaches do not deny the qualitative aspects of biochemical processes but nonetheless attempt to subsume them under a kind of energetic reductionism. For a contemporary example see Vaclav Smil, *General Energetics* (New York: John Wiley and Sons, 1991).
129. Carnot, *Reflections on the Motive Power of Fire*.
130. See, for example, Mario Giampietro and Kozo Mayumi, "Complex Systems and Energy," in Cutler Cleveland, editor, *Encyclopedia of Energy*, Vol. I (San Diego: Elsevier, 2004): 617–631.
131. Engels to Marx, December 19, 1882, in Marx and Engels, *Collected Works*, Vol. 46, 411.
132. Ibid., 410–411.
133. Compare, for example, Georgescu-Roegen, "Energy and Economic Myths" and Daly, "Postscript." For further discussion see Burkett, "The Value Problem in Ecological Economics," 140–141.
134. Daly, *Steady-state Economics*, 23.
135. Ibid.; Paul Burkett, "Entropy in Ecological Economics: A Marxist Intervention," *Historical Materialism* 13/1 (2005): 117–152.

136. Marx, *Capital*, Vol. I, 526.
137. Ibid., 508.
138. Ibid., 503.
139. John Bellamy Foster and Paul Burkett, "The Dialectic of Organic/Inorganic Relations: Marx and the Hegelian Philosophy of Nature," *Organization & Environment* 13/4 (2000): 412–413.
140. Herman E. Daly, "On Economics as a Life Science," *Journal of Political Economy* 76/2 (1968): 396–398; John Bellamy Foster and Paul Burkett, "Marx and the Dialectic of Organic/Inorganic Relations," *Organization & Environment* 14/4 (2001): 452; Foster, *Marx's Ecology*, 200–204.
141. Marx and Engels, *Collected Works*, Vol. 46, 412.
142. Ibid.
143. Paul Burkett, *Marxism and Ecological Economics: Toward a Red and Green Political Economy* (Leiden, The Netherlands: Brill, 2006), forthcoming.
144. Marx, *Value, Price and Profit*, 34, emphasis in original.
145. Ibid.
146. Marx, *Capital*, Vol. III, 879; Burkett, *Marx and Nature*, Chapter 6.
147. Marx, *Capital*, Vol. III, 203.
148. Karl Marx, "Wages," in Karl Marx and Frederick Engels, *Collected Works*, Vol. 6 (New York: International Publishers, 1976): 431.
149. Marx, *Capital*, Vol. I, 288; see also Ibid., 311. "Under raw material we also include the ancillary materials such as indigo, coal, gas, etc. . . . Even in branches of industry that do not use any specific raw material of their own, there is still raw material in the form of ancillary material or the components of the machinery, etc." (Marx, *Capital*, Vol. III, 201).
150. *Capital*, Vol. I, 288.
151. Marx, "Wages," 431, emphasis added. The ancillary materials category also helped Marx analyze situations, mentioned earlier, where biochemical processes make up an essential phase of production. See Burkett, *Marx and Nature*, 42–43.
152. Marx, *Capital*, Vol. I, 773, emphasis added. Similarly, when specifying capitalism's inventory requirements, Marx includes "material for labour at the most varied stages of elaboration, *as well as ancillary materials*. As the scale of production grows, and the productive power of labour grows through cooperation, division of labour, machinery, etc., so does *the mass of raw material, ancillaries, etc.* that go into the daily reproduction process." *Capital*, Vol. II, 218–219, emphases added.
153. *Capital*, Vol. I, 434.
154. Ibid., 303.
155. Ibid., 313.
156. *Capital*, Vol. III, 195.
157. Marx, *Capital*, Vol. I, 435.
158. Ibid., 528; *Capital*, Vol. II, 208–209.
159. *Capital*, Vol. II, 250; for details see Stephen Horton, "Value, Waste and the Built Environment: A Marxian Analysis," *Capitalism, Nature, Socialism* 8/1 (1997): 127–139.
160. Marx, *Capital*, Vol. III, 208–209.
161. Ursula Huws, "Material World: The Myth of the Weightless Economy," in Leo Panitch and Colin Leys, editors, *Socialist Register 1999: Global Capitalism Versus Democracy* (New York: Monthly Review Press, 1999): 29–55; Susan

Strasser, *Waste and Want: A Social History of Trash* (New York: Henry Holt and Company, 1999).

162. Engels to Marx, December 19, 1882, in Marx and Engels, *Collected Works*, Vol. 46, 411, emphasis in original.
163. Ibid., 411.
164. Ibid., emphases in original. Far from dismissing energetic considerations, Engels's comments – informed by Marx's analysis of capitalist productivity growth – show a healthy awareness of how a faulty specification of the relevant dimensions of energy use can generate misleading results. As two leading energy analysts emphasize, one cannot overestimate "the importance of the choice of space and time boundaries" for any "assessment of the energetic requirement of human labor." Mario Giampietro and David Pimentel, "Energy Efficiency: Assessing the Interaction Between Humans and Their Environment," *Ecological Economics* 4/2 (1991): 119. Engels's approach to energy accounting, unlike Podolinsky's, encompasses "all the energy consumed at societal level to raise the workers and to support their dependents." Ibid.
165. Marx, *Capital*, Vol. I, 638.
166. Ibid., 637.
167. Ibid. "The natural human waste products, remains of clothing in the form of rags, etc. are the refuse of consumption. The latter are of the greatest importance for agriculture. But there is a colossal wastage in the capitalist economy in proportion to their actual use." *Capital*, Vol. III, 195.
168. *Capital*, Vol. I, 638.
169. Marx, *Capital*, Vol. III, 949.
170. Ibid., 949–950.
171. Krohn and Schäfer, "Agricultural Chemistry," 32.
172. Ibid.
173. Marx, *Capital*, Vol. I, 638.
174. Ibid., 929–930.
175. Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos* (New York: Bantam Books, 1984): 252–253.
176. See John Chalmers Morton, "On the Forces Used in Agriculture," *Journal of the Society of the Arts* (December 9, 1859): 53–68; Marx, *Capital*, Vol. I, 497–498.
177. Richard B. Alley, *The Two-Mile Time Machine* (Princeton, NJ: Princeton University Press, 2000): 132.
178. Boris Hessen, "The Social and Economic Roots of Newton's 'Principia'," in Nikolai Bukharin, et al., *Science at the Cross Roads* (London: Frank Cass and Co., 1971): 203.
179. The foundational work of the treadmill of production perspective is Alan Schnaiberg, *The Environment: From Surplus to Scarcity* (New York: Oxford University Press, 1980). For more recent perspectives on this tradition in environmental sociology see Richard York and John Bellamy Foster, editors, "The Environment and the Treadmill of Production," *Organization & Environment*, two-part special issue, 17/3 (2004): 293–362 and 18/1 (2005): 5–107.
180. Karl Marx, *Early Writings* (New York: Vintage, 1974): 360; Karl Marx and Frederick Engels, *Collected Works*, Vol. 6 (New York: International Publishers, 1976): 434; Karl Marx and Frederick Engels, *Collected Works*, Vol. 8 (New York: International Publishers, 1977): 218; John Bellamy Foster, "The Treadmill of Accumulation," *Organization & Environment* 18/1 (2005): 7–18.

181. Peter Dickens, *Society and Nature: Changing Our Environment, Changing Ourselves* (Cambridge, UK: Polity, 2004): 80–81. Marx's concept of metabolic rift is integrated into a general assessment of climate change connected to the treadmill model in Richard York, Eugene Rosa, and Thomas Dietz, "A Rift in Modernity? Assessing the Anthropogenic Sources of Global Climate Change with the Stirpat Model," *International Journal of Sociology and Social Policy* 23/10 (2003): 31–51. For a more general theoretical analysis of the relation of the metabolic rift to global warming, see Brett Clark and Richard York, "Carbon metabolism: Global capitalism, climate change, and the biospheric rift," *Theory and Society* 34/4 (2005): 391–428. On the relation of the metabolic rift to ecological imperialism, see John Bellamy Foster and Brett Clark, "Ecological Imperialism: The Curse of Capitalism," in Leo Panitch and Colin Leys, editors, *Socialist Register 2004: The New Imperial Challenge* (New York: Monthly Review Press, 2004): 186–201.
182. See Richard Levins and Richard Lewontin, *The Dialectical Biologist* (Cambridge, MA: Harvard University Press, 1985); Brett Clark and Richard York, "Dialectical Nature: Reflections in Honor of the 20th Anniversary of Levins and Lewontins's *The Dialectical Biologist*," *Monthly Review* 57/1 (May 2005): 13–22.

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