Chapter 2
Primary Energy/Useful Energy

Abstract While the useful energy delivered by an animal, a windmill, or a worker captured most attention in the preindustrial era, the fossil fuel economy of the nineteenth century shifted the focus toward the energy conversion cycle. Only by following the order of transformations and only by measuring just how much was conserved at each stage could the aggregation of different energy qualities produce meaningful results. This chapter shows how the invention of new units of measurement, such as horsepower and kilocalorie, together with the principle of energy conservation (First Law of Thermodynamics), paved the way for a system of energy accounting based on four input cycles: primary, secondary, final, and useful energy.

2.1 Energy Measurement

2.1.1 Input-Cycle Categories

During industrialization, energy fell under the measuring rod of money. The ability to do work was detached from the indivisibilities of everyday life and turned into a separate commodity, tradable over ever longer distances. Contrasting the traditional fixity of the historically longstanding power sources such as man and animal power or wind and water power, the steam and internal combustion engines ushered in an era of greater mobility where fuel sources did not necessarily overlap with the sites of power generation. Reflecting this commodification and furthermore the underlying need to measure the potential energy contained in the chemical energy of fossil fuels along with the work effectively performed per unit of time, industrial societies devised the solution of gauging the flow of energy through its contribution at different moments in the industrial cycle. Four major sequential "cuts" fell under consideration:

- The first, **total primary commercial energy**, accounts for the raw inputs supplied to the economy and represents the sum of all market energy sources arriving at the entry of energy systems during a single year and expressed in terms of

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production equivalents. This comprises fossil fuels and renewables but not fuel wood on the grounds that much of wood consumption still bypasses the scope of formal market transactions.

- The next, **secondary energy** designates all sources of energy that result from the transformation of primary sources in any one single year and generally termed energy carriers.
- The third, **final commercial energy** accounts for secondary energy products and services delivered by different energy markets to final and intermediate consumers, and again over a single year, and comprises all transformed products such as charcoal, coke, coal, natural gas, gasoline, fuel oil, and electricity, among others.
- The fourth, **useful energy** corresponds to the energy effectively made available to the user in terms of the services delivered through end-user equipment over the course of one single year and expressed in terms of consumption equivalents for the work performed by mechanical power, lighting, heat generation, and travel mileage.

Much of the scope of the input-cycle categories stems from a hands-on approach in which the sequence of categories mirrors the transactional structure in effect in the real economy. Thus, this involved efforts to identify primary energy with upstream activities, accounted for by physical units and not only by energy units; secondary and final energy with the midstream and downstream handling of raw materials by industrial wholesalers and distributors that select, clean, transform, and transport the fuels to their final markets; and, useful energy with the decentralized consumption of heat, mechanical power, light, electrical current, and chemical energy. Owing to their capacity to replicate the logistical pattern of the industrial structure, input-cycle categories incurring low information costs were consequently acknowledged as the official statistical criterion by key international organizations.

One final advantage is that any losses incurred throughout the aforementioned processes are easily identified. It became expected that a significant amount of fossil fuel contained energy would get lost in transportation and in transformation into secondary products and thereby diminishing the volume of final energy relative to primary energy inputs. Likewise, impairments in final distribution in addition to conversion losses of end-user equipment also cut down the amount of useful energy relative to final energy. In the starkest terms, this process serves to define energy efficiency as the differential between primary energy and useful energy.

However, input-cycle categories are anything but problem free. Globally, the further we move away from the classical pattern of fossil fuel combustion, the less engaging the model becomes. It suffices to consider, for instance, the awkward fit of renewable energies within the parameters of the input-cycle framework. What is the “primary energy” of a wind turbine? And just what is the “primary energy” of a hydropower dam? How should we measure them? The standard solution energy economics conceived for these cases display the drawbacks of aggregating different energy qualities: measuring a dam’s primary energy by envisioning it as if a coal power station and representing the kilowatt hour produced by the hydraulic turbines in thermal equivalents for the amount of coal required generating that amount of power. In other words, think black on white (the expression “white coal” constituted a token of the kinetic water stream in hydropower stations). Clearly, one facet to the statistical paradox stems from the fact that input-cycle categories were never designed to grasp intermittent power sources, renewed by the passage of time and, ultimately, by the solar cycle, able to convert mechanical force or heat into electrical current. They had instead been drafted to explain how a tradable organic material might be burned in the presence of oxygen to release the products of carbon dioxide, water, and thermal energy. Whenever energy quantities related to kinetic energy (e.g., hydro, wind) differ in quality from energy quantities related to potential chemical energy (e.g., fossil fuels), the solution envisaged is to express everything under the common formal framework of reference for chemical energy.

The same problem arises in the statistical accounting of nuclear power, further worsened by institutional discrepancies: while some international organizations record primary nuclear energy as the amount of electricity produced through atomic fission, others record primary energy based upon the actual nuclear fuels in use. As the two methodologies are not directly comparable, they readily become a source of error (Lightfoot 2007). Once again, the alternative lies between reasserting the analogy of nuclear and coal power stations (accounting for the energy content of electricity) and estimating the raw inputs supplied to the economy (accounting for the natural uranium consumed). Beyond the large discrepancies between the methodologies, the most serious issue derives from potentially misrepresenting the effective efficiency of energy systems since one dominant technology (generally chemical energy based) subsumes others technologies for statistical purposes. We would note, for instance, that when the energy produced by water falling in a dam is estimated in terms of equivalence to coal burning stations, the kinetic efficiency of turbines is swapped for the standard chemical conversion efficiency of steam boilers. On balance, there is a trade-off between the sheer handiness of decomposing the energy cycle into the statistical profile of primary/secondary/final/useful energy and shaping every energy process according to the yardstick of chemical energy.

To overcome these input-cycle category shortcomings, Ayres (1998), Ayres et al. (2003), Ayres, and Warr (2005) suggest a whole new methodological framework. As an alternative to basing them on the industrial logistical cycle, they propose singling out the useful part of energy, or “energy,” as the core factor of analysis. In some way, this corresponds to inverting the traditional view as it begins where classification should supposedly end and then proceeds backwards along the cycle: the end node is nothing other than the production of energy for services employed in manufacturing, transportation, space heating, lighting, cooking, and so forth. Along with the statistical landscape of the different types of useful energy, Ayres and Warr also undertook research on the primary work of production equipment, disclosing their breakdown and efficiency in energy usage. In fact, this outline by equipment type enabled the authors to show just how much energy is lost in the process of converting it into useful work. Overall, six major statistical categories are considered: muscle work, electricity, mechanical drive, low temperature heat, medium temperature heat, and high temperature heat (Warr et al. 2010). Each form of energy allocated to types of useful work might be further specified, for instance, taking into account the separate contributions of steam engines, electric motor drives, and internal combustion engines in automobiles, trucks, and buses, within the more general category of "mechanical drive."

The inclusion of useful work as a factor of production representing the productive component of energy inputs seeks to pinpoint the impact of energy quality upon economic growth. Since part of the total available consumed energy is actually wasted and does not contribute to growth, it thus makes statistical sense to weigh the other part, the working "lot" or energy.

2.1.2 The Measuring Rod of Money

Overhanging the above considerations is the deep intertwinement of useful work and technology. The way individuals behave, consume, and save hinges upon the catalog of accessible technological choices but also on the infrastructures of knowledge, habits, and physical networks. No less important, it hinges upon available capital. Given this association, the long-lasting disregard that the useful facet of energy consumption has experienced proves somewhat startling. The ensuing pages explain this oversight. Taking a broader view, the key reason is that the costs involved in assembling data on useful energy are considerably higher as this requires mapping end-user production equipment, which is likely to present different temporal layers and competing operational conversion efficiencies. Another way of expressing this is to outline the "end uses as the set of useful functions expressed by a given society, in its various compartments and on different scales" (Giampietro and Sorman 2012: 8). While primary energy typically portrays indicators from national energy accounting processes, useful energy stands for local, decentralized, and consumer-centered indicators. As such, this raises far more specification problems than the bulk account provided by primary physical gradients or secondary energy carriers.

To a large extent, nineteenth-century machinery, science, and institutions led first to the uprooting of energy measurements and ultimately to the globalization of standard units. Step by step, energy ceased being measured in terms of units of a certain commodity obtained from the application of power for a fixed timespan (bushels of milled flour per day, pounds of water leveled per hour, miles of journey covered). Step by step, mechanical power became assessed independently from its practical applications, standing for the force needed to accomplish work rather than as the materialization of useful work itself. As these units sprang from being local conventions, based on discretionary and negotiable standards, to represent the new edge of commercial, national, and universal standards, they became increasingly disembodied from the technologies of everyday life.

Uprooting means detachment from personal settings and local habits. In the modern world, measurement required specialized "bazaar" skills with ample room for negotiation, compliance, influence, coercion, and fraud. The simple determination of the volume of a heap of grain or the weight of a particular bushel had long since proven a tricky business in most of the town hall markets across northern Europe. Kula (1986) testifies to how the regime of negotiation and the discretionary characteristics of weight and volume units were clearly set to favor local interests over central powers and those holding privileged statuses over commoners. In the same vein, Pollard (1983) identifies the persistence of the British tradition to market coal by volume rather than by weight, a procedure that allows for greater variability in measurements, enhancing the trader's leverage and his power to establish beforehand how much coal a basket, a tub, a score, or a wagon should have. Such a preference for units of volume add further margins for haggling, permitting both parties to the transaction to adjust the deal in terms of prices as much as in terms of quantities. Trust and local knowledge were integral parts of the business.

The advent of the steam engine ushered in a change from fuzzy negotiable measurement units. Energy was progressively disconnected from the actions of everyday life, from community habits and turned into a separate commodity, with prices pegged to objective and unbiased measurement units of power. This marked the beginning of the process described above as the "measuring rod of money." Not by accident, the first commercial quantity unit used to gauge mechanical force was dubbed "horsepower," that is, an artificial muscle engine fed by coal rather than by hay.

2.2 Horsepower and "Calories"

2.2.1 The Power of Royalties

Once entrepreneurs succeed in commercializing breakthrough technologies, the catalog of final energy measurements gets increased. Entrepreneurs are compelled to move their products or services to final markets and to convince the customers about the power they are selling. Under these circumstances, it is no surprise that the specification of outputs is generally much more accurate, detailed, and highlighted than the information on inputs. Ultimately, power measurement units can be squared with some marketing scheme and serve as a motto for sales. Such close linkage between selling and the creation of final energy measurement units began with James Watt's invention of horsepower in the eighteenth century.

The walk undertaken by the Scottish engineer in the green fields of Glasgow nearby his house, on a day-off in May 1765, turned out to be one of the most productive walks ever taken by mankind. For the last few months, this self-educated engineer and instrument maker had been working on a solution to improve the atmospheric engine that had come into his hands, trying different ways to economize on steam and reduce the sources of heat loss. Watt was particularly puzzled by the discovery that about three-fourths of the amount of steam used at each stroke of the piston's engine was wasted by the inherent dissipation of coal. The short stroll did not tear the technical quandaries from his thoughts and, after making some short headway into the field, he stumbled on what appeared to be a solution: "having gone as far as the herd's house, the idea came to my mind that as steam was an elastic body, it would rush into a vacuum, and if a communication was made between the cylinder and an exhausted vessel, it would rush into it, and might be there condensed without cooling the cylinder" (Henry 1902). Instead of piecemeal improvements in mechanical engineering tried and tested for so long, Watt envisioned the scope for a breakthrough and an entirely new device. Whereas in the old Newcomen atmospheric engine, it was necessary to heat up the cylinder with steam during the up-stroke and then cool it down by opening a valve that let fresh water pass through a pipe into the cylinder, creating a vacuum for the down stroke, it now became evident that the best way of reducing fuel consumption was to save steam by keeping the piston cylinder constantly hot. This might be achieved by separating the working area of the piston cylinder from a new cooling area in an "exhaust vessel," where the steam would "rush in" and condensate.

Enlightening as the glimpse in the Glasgow greens may have been the fact remained that it still took over a decade to set up a satisfactory working engine. Watt quickly discovered that he had got himself into something far more difficult than he had ever thought: it was an endeavor that required full-time dedication; a highly skilled team of craftsmen able to build, fit, and insulate the engine's components; long-term capital investment; the defense of property rights through patent litigation; and not to mention commercial insight. Furthermore, the early attempts to build a prototype produced disappointing results owing to flaws in the construction of the condenser and steam piston. With the project at risk and the inventor near bankruptcy, a turnaround occurred with the acceptance of a proposal from an experienced Birmingham manufacturer, Mathew Boulton, to take an interest in the patent's development. The new associate not only enhanced the technical and economic basis of the venture but paved the way for one the most productive "joint ventures" in the history of business.

Watt moved to the outskirts of Birmingham in 1774. Once the fundamentals for the commercialization of working machines were set, orders for new engines with separate condensers began pouring in. With Boulton taking charge of general management, business relations, the payment of all expenses, and the advances of stock in trade, the Scottish engineer was unleashed from a good number of day-to-day concerns and able to dedicate himself to raising his invention to still higher standards. In the years ahead, he devised a parallel motion gear that allowed steam to be introduced into both ends of the cylinder to push the piston both up and down; a transmission mechanism that converted the reciprocating motion mostly used for water pumping into a rotary motion in effect in textile mills, breweries, and other industries; a system for shutting down the admission of steam into the cylinder part way, thereby enabling the use of steam power expansively; and a regulatory device that provided closer control over the number of strokes per minute and boosted the smoothness of the mechanical force generated (Hills 1993).

In the meantime, steps were also taken to secure exclusive rights to Watt's registered patent of the separate condenser for an additional period of 24 years (1776–1800), followed by five new patent rights which covered the latest innovations. Sheltered behind this recognition sanctioned by Acts of Parliament, Mathew Boulton devised a strategy to branch out the sources of income: they could earn money either from selling state-of-the-art equipment manufactured under their own supervision or from selling licenses to apply the basic discoveries behind the equipment, thereby extracting a rent from the patent's exclusivity rights. As Watt's engine provided fuel savings when measured up against an improved atmospheric Newcomen engine, Boulton could make his case on the commercial ground of charging an annual royalty based on comparative operational advantage. He, therefore, stipulated that one-third of the value of fuel savings should revert to the owners of the patent in the form of an annual "premium." Through this ingenious scheme, Boulton and Watt might still recover their development costs even while not selling the complete machine but only certain component parts. On the other hand, the greater demand for all engine types, whether atmospheric or steam based, the more justified and less risky became the decision to charge manufacturers switching to up-to-date technologies with an additional payment (an average Watt engine generated another 40 % of the purchase price through 10 years of royalty payments) (Kanefsky and Robey 1980; Tann 1998). The stiff competition meant that manufacturers and mine leasers could choose between simpler and cheaper atmospheric engines but with their higher levels of coal consumption or switch to the more complex separate condenser engine and pay the respective premium for lower fuel expenditure. In either case, the noteworthy point is how the dynamic economic "boom" of British industry after 1770 brought the issues of fuel saving and power measurement right to the forefront of industrial concerns.

The most acceptable way of singling out the amount to be annually paid for a Boulton and Watt engine consisted of setting the royalty in direct proportion to the engine's respective power. The new pricing scheme thus changed the meaning of measurement: whereas estimating power initially served as a planning device to satisfy customer needs for mechanical force, matching each machine to its load, within the new business orientation, it, moreover, became a commercial financial instrument tied to the value of royalties. Furthermore, since the power capacity determined the scale of payments, a corresponding scale of mechanical force with comprehensible, unambiguous, and verifiable units had to be established. Driven on by the increasing need for accurate measurements, Watt worked out a standard figure for his engines based on the cylinder diameter and on the stroke, and assuming an average for atmospheric pressure. To keep a record of the number of strokes, he also developed a "counter" logging the seesawing of the main beam (Hills 1993: 88). The final step was simply to link up the design of the machines with a system of power units. However, just what units to consider? This could be a particularly cumbersome issue in the case of rotative engines, whose power was not easily observable in terms of a weight being lifted or water being pumped in the course of a day from a given depth. The rotary motion had different applications to the reciprocating-pumping ones and the installation of rotative engines involved seldom pulls and gears, with larger losses in transmission and friction. In these circumstances, measuring power by some indicator of the useful energy seemed unsuitable. On the other hand, a measure of the final gross energy delivered was available and had been put into practice for several years: Boulton and Watt knew that whenever an engine was introduced to replace horses in a mill or in a brewery, a direct comparison was made between the size of the engine and the number of horses (Hills and Pacey 1972). Hence, the option for building engines in terms of horse substitution surfaced naturally as the best possible commercial standard and as also providing a clear blueprint for gauging the royalties due for payment.

2.2.2 Blood Horses and Mechanical Horses

Assessing steam horses by the standard of blood horses proved to be a shrewd commercial choice. The new technology was folded back onto the old, thereby rendering it more recognizable or, as a contemporary observer might add, reducing the information search costs for clients in remote locations. Certainly, any reference to "horsepower" in the context of eighteenth-century British industry was not a free standing outline but involved some shared knowledge about the type of horse supposedly found in factories: in all likelihood, to James Watt, the mechanical unit was the embodiment of a heavy horse, farm bred and sold for heavy draught work at the age of four or five and in service until around the age of fourteen. This also focused on the strongest specimens among the breeds, those able to deliver 40–50 % more productive power than a mule or a light horse during a full day's work. In short, the engineer pulled out his horsepower unit from the finest available among the thoroughbred blood horses.

With burgeoning demand for rotative engines from 1783 onwards, the loose representation of "horsepowers" needed to be unambiguously specified. Once again, James Watt resorted to real-life working conditions and drew upon the example of a horse attached to a mill that walked in an endless circle with a 24-foot diameter. By multiplying the speed times versus the force, he came up with 32,580 foot-pounds per minute, subsequently rounded off to 33,000 foot-pounds per minute. Although well above other historical estimates for the average force exercised by a heavy animal, which ranged between 22,000 and 25,000 foot-pounds per minute (with a single exception of 27,500 foot-pounds per minute) (Thurston 1894; Hills 1993; McShane and Tarr 2003), Watt's outsized figure remained the standard for gauging the absolute force of "horsepower" through to current days. This means that, in real terms, a heavy draught horse from the English shires, French percherons, or German rheinlanders was only able to deploy a force of 0.7–0.8 mechanical horsepower/hour, while a light draught horse would attain significantly less, reaching 0.5 horsepower/hour (Thurston 1894; Smil 1994). We would note that the point here is not the theoretical amount of blood horsepower capacity, but rather the average amount developed throughout a day’s work. As every experienced horse-drawn teamster was aware, after 4 h of continuous haulage, the power of the horses dropped significantly, therefore leading to the provision of frequent stops for water and rest so as to avoid premature exhaustion. Though the best equine species could develop the equivalent of three mechanical horsepower for brief periods, the real force deployed in a 6–8-h workday (urban–non-urban haulage) would be about four times less, in the range of 0.7–0.8 HP (horsepower). Watt’s oversized estimate of the power generated by horses is even more striking since steam engines were operated for between 10 and 12 h per day, the customary manufacturing working timetable.

However, and revealingly, a private business unit of measurement settled in Birmingham sprang up over large parts of the world as a trustworthy convention, shaping transactions and shaping the scale of observations made by economic actors. Yet, Watt’s account did not come even close to a reproducible standard as other assessments of horses as prime movers arrived at very different figures to Watt’s 33,000 foot-pounds per minute. Overall, this was a convention without agreement: a blueprint that restated the commercial superiority of the Boulton and Watt engines while providing an acceptable gauge for charging royalties. It was a business and marketing standard as much as a descriptive experimental measurement.

In explaining the passage from local units to this global unit of measurements, two major factors stand out: market power and the shock of innovation. The first stemmed not only from Boulton and Watt’s technological superiority but furthermore from the active stance taken in defending their own patent rights, with the business partnership sparing no efforts to protect their sources of income against illegitimate imitators. By the early 1790s, an organized team of industrial spies had been deployed out working in the field, crossing the most remote spots of Lancashire to collect affidavits and inspect possible pirate engines while also keeping their investigations close secrets so that solicitors in London could prepare court injunctions against the pirates (Musson and Robinson 1959). Raising the Boulton and Watt flag, the next generation of Watt Junior and Matthew Robinson Boulton, took hold of this type of surveillance–punishment operations. These sorts of endeavors strengthened the identity linking the engine with the separate condenser and the business firm which put it into production, at least through to the expiry of the patent in 1800. And since the unit of measurement, horsepower, was imbued in the machine through technical and financial specifications, it spread unaffected alongside Boulton and Watt market power. Likewise, the damage of piracy was smallest in the international arena (Tann and Breckin 1978). Watt’s engine benefited furthermore from the shock of innovation and novelty getting the attention of entrepreneurs and scientists through correspondence, visits and introductions, universities, academies, and foreign publications. The search for information combined with the eagerness to understand the engine’s details proceeded ahead of adoption, thus creating an absorption gap that effectively underpinned the assimilation of technical principles, such as the horsepower unit (Tann and Breckin 1978). Hence, this impregnation proved so strong and convincing that the principle of “horsepower” persisted as a self-evident convention for describing mechanical work.

2.2.3 The Changeover to Heat

Alongside the penetration of the steam engine into manufacturing, mine, and transportation, there also came about a renewed interest in its potential as a scientific and experimental device. It was particularly among French engineering schools that such interest took hold. With a solid reputation for mastery in several domains, the French engineers perceived the steam engine as a puzzling innovation: the British had invented a machine that used coal to produce the "fluid" or "substance" of heat and, moreover, devised a system for circulating this "substance," thereby pushing the piston to generate a continuous mechanical force. As the largest European importer of Boulton and Watt Engines by the end of the revolutionary wars (1815), they were fully aware of the machine's productive efficiency and its wide scope of potential applications. The spurt of tests, research, and theory that ensued consequently focused on practical improvements to its component parts. The optimization path ranged from very specific mechanics, such as determining the optimum piston position or the maximum potential cylinder speeds, through to more ambitious modifications such as searching for a better heat "carrying" medium (for instance, alcohol instead of water) (Kerker 1960). However, the most ambitious agenda was set by the chemistry chair at the Conservatoire des Arts et Metiers in Paris, Nicolas Clément-Desormes.

Distinguished by a highly successful line of manufactures, Clément-Desormes encountered the steam engine prior to his Conservatoire appointment in November 1819. Unlike his colleagues, Clément-Desormes seemed not so interested in optimizing mechanical work but rather in extending the technological possibilities of energy production. From his perspective, the crux of the matter lay in the transition between "states of matter": what maximum effect could be obtained from a given mass of different working substances under various conditions in terms of temperature and pressure? What might be the maximum amount of energy obtainable from 1 kg of coal? What might be the maximum amount of force obtained through the expansion of steam given an absence of any heat transfer? Under his scientific perspective, the hypothesis of an ideal steam engine began to surface: nothing less than a machine bound by scientific engineering to enable operation at or near the theoretical maximum levels of efficiency (Fox 1970).

Before adventuring into such an ambitious program, some preliminary steps in measurement had nonetheless still to be taken. From the conversion's sequence point of view, the coal input could be calculated in kilograms. Likewise, the stroke capacity per unit of time could be estimated in the force deployed in kilogram-meters of work, which was more precise for "laboratory" estimations than the commercial horsepower unit. However, somewhere in the middle, at the heart of the engine, lingered the largely immeasurable steam sequence. To map the full batch of operations inherent to coal-steam mechanical workings, Clément-Desormes had to figure out a unit for the heat delivered by steam. He accomplished this by inventing the "Calorie."

Coined after the French word "calorique," or heat substance, the "calorie" described the amount of heat needed to raise the temperature of 1 kg of water by

1 °C. Following the definition of that which is now called the kilocalorie, all the transformations within the steam engine could be represented in a straightforward manner, through algebraic relations between outcomes and original conditions (for instance, work as a function of the temperature and pressure of the piston and the condenser). In the ensuing decades, the study of heat, closely tied to the steam engine paradigm became the keystone in the advance of physics (Hartman 1982). However, contrary to the commercial recognition of horsepower, the calorie remained a "private" category for scientific research, confined within the walls of universities and conveyed through hand-written notes and dictionaries of science, acknowledged mostly by chemists, physicists, and their students. It was, moreover, largely bound to the French academy and any non-nationals who might be in touch with French teaching. In the sense of being a unit of heat, the calorie only entered the German vocabulary in 1848 and the English in 1863 (Hargrove 2007). The consequence was that other heat measurement standards were adopted in the interim and standards which shied away from the metric system and the "French" calorie unit (henceforth referred to by the modern designation of kilocalorie—kcal). On the other side of the channel, British physicists devised their own unit outside of the metric system, adopting as their standard the amount of energy needed to heat one pound of water 1 °F (to recall, the calorie's definition—the amount of heat needed to heat 1 kg of water by 1 °C). Later on, this standard came to be known as the British Thermal Unit (BTU). As the British thermal unit represented 0.251 of the "French" kilocalorie, the scale of measurement applied by British physicists allowed for representing heat changes in smaller units.

In any case, for those studying in Clément-Desormes' classes, a new conceptual insight was acquired on the steam engine. The engineering components were henceforth linked through a set of linear transformations disclosing the energy potential contained in fuels and the final energy actually obtained: students learned that the heat content of 1 kg of charcoal (7,050 kcal) could be applied to evaporating water, spending 650 kcal of charcoal for each kilogram of water converted into steam, which would finally generate a total amount of 300,000–400,000 kg-m of work. Thanks to the common denominator of the kilocalorie, the sequence of transformations became measurable, comparable, and abbreviated; and thanks to this, Watt's industrial engine could be envisioned as a conversion machine. Final energy was by this means related with primary energy and, power at hand was related with the sources of power.

2.3 Omnipresent Energy

2.3.1 Energy Conservation

Just as horsepower entrenched the rod of money in nineteenth-century measurement, the kilocalorie amplified the experimental scientific approach. With the usage of the steam engine outside the industrial milieu as a laboratorial tool, the conversion of heat into kinetic energy became the overriding issue for European physics. Staying close to the path opened up by James Watt, French engineers attempted to unveil the principles behind engine conversion processes. Twenty-five years later, another researcher, however, proposed the inverse possibility of converting mechanical work into heat. In the event that the amount of heat obtained might be approximately the same as the amount of kinetic energy applied, then the energy conversion could be deemed indifferent to whichever energy switch was employed. Thanks to this standpoint, the issue of relative conversion efficiency (Clément-Desormes) was transformed into the groundbreaking theme of energy conservation.

Hitherto, the overwhelming problem had been measurement itself. The capacity to single out small, almost unobservable variations in temperature proved to be a decisive step toward studying the conversion of energy and dealing with the challenging problem of heat dissipation. Only by resorting to a highly controlled experimental environment and extremely precise instruments could such experiments succeed. Science turned toward the measurement of infinitesimal variations well ahead of progress in the state-of-the-art in scientific instrument making. In these circumstances, groundbreaking discoveries able to pave the way for the understanding of heat in terms of its electrical, chemical, or thermal properties had to be undertaken by someone capable of mastering the construction and calibration of scientific instruments alongside skillful expertise in laboratorial observation. In either field, James Prescott Joule, the son of a prosperous Manchester brewer, proved one of a kind.

Around the time Joule turned adult, the British brewing industry was undergoing change with the spread of new ideas for scientific brewing alongside a more critical stance toward the old craftsmanship traditions. Disclosing a sharp eye for business, Joule's father foresaw the potential of a scientifically minded approach to the delicate process of heat conversion in the germination, fermentation, and mashing of malt. In 1834, he determined that his two sons should give up on the private tuition provided by a resident master to begin studying chemistry under the supervision of Manchester's most famous chemist, John Dalton. In the years ahead, the young James Joule had to split his time between the brewery and chemistry and mathematics lessons, becoming the assistant to his father in managing and supervising the brewery while also attempting to bring about improvements to the productive processes. Most of all, it was the practical dabbling around with mashing heats and more efficient and faster machines that attracted his attentions (Sibum 1998).

At the age of nineteen, Joule also commenced independent experiments in a laboratory installed in his father's house. Although his purposes were rather practical, motivated by the intention of improving an existing electromagnetic engine, he soon got himself involved in hard scientific measurements. Since all measurements drew upon the registration of very small changes, the observer had to be a true authority in the science of observation. Besides a "trained and practiced eye" in reading temperature scales from the most accurate instruments available through to the right timing, the observer had furthermore to control a set of disturbing laboratorial incidents such as the reaction of the thermometers to radiation from the body, variations in room temperature, or the reaction of thermometers to their own displacement (Sibum 1995). As with much of Joule's work, the thermometrical skills acquired in the brewery milieu, in conjunction with the personal interest taken in the construction of scientific instruments in addition to direct acquaintances with skilled instrument makers combined to result in the utter mastery of laboratorial conditions.

Upon assuming electrical action as the prime agent in energy conversion, the experimental physicist shifted his emphasis and became increasingly interested in the study of friction as a perhaps even more important alternative agent for the transformation of mechanical work into heat. A new apparatus was built consisting of a copper vessel with water inside and within which a paddle wheel was fitted. The paddle wheel was set in motion through machinery connected to weights and pulleys that measured the weights' distance while descending. By this means, the mechanical action exerted to rotate the wheel (distance × weight) could be estimated and corresponded to its effect in raising the water temperature. Friction, the conversion agent, turned this mechanical work into higher levels of temperature, thus enabling the assessment of the mechanical value of heat. As usual, Joule's experience bore its own stamp with the creation of a unique controlled laboratorial environment able to ensure the accurate handling of equipment and thermometers. With the apparatus working close to standard conditions, it became possible to gauge how much force (pounds per meter) was needed to raise the temperature of 1 kg of water by 1 °F. Furthermore, once this sort of "quantitative equivalences of natural powers" was ascribed in a reliable and trustworthy manner, a common trait began to surface among factors hitherto separated: the conservation of the same amount of energy in the force that moved the paddle wheel as in the water's temperature.

Irrespective of their differences, "natural powers" like electromagnetism, mechanical force, heat, or light all appeared interlinked through an endless chain of interconversions: "In the conversions nothing is ever lost. The same quantity of heat will always be converted into the same quantity of living force. We can therefore express the equivalency in definite language applicable at all times and under all circumstances" (Joule 1847a: 10). Drawing upon previous experiences, Joule remarked that "the attraction of 817 lb through the space of one foot is equivalent to and convertible into, the living force possessed by a body of the same weight of 817 lb when moving with the velocity of eight feet per second, and this living force is again convertible into the quantity of heat which can increase the temperature of one pound of water by 1 °F" (Joule 1847a: 10, b). No waste or loss actually occurred throughout these changes since the destruction of living force is only apparent. According to the British physicist, it thus proves absurd to suppose that the powers with which God has endowed matter might be destroyed: whenever some force is annihilated by percussion, friction, or by any other means, an exact equivalent of heat is released. Underlying this physical realism is the conviction that all phenomena derive from the manifestation of a single substance whose identity is constantly maintained and thereby ensuring that the total amount of energy in the universe remains constant.

Hence, the principle of the physical conversion of energy sources, which had prevailed throughout the steam engine era paradigm, with fossil fuels being converted into heat and heat into mechanical work, now appeared somehow illusory. Closer inspection, grounded in laboratorial micromeasurements, unveiled the persistence of energy behind these physical conversions. Continuity, indestructibility, and conservation henceforth became the keys for understanding life on earth. The unity of nature, described in terms of the "conservation of natural powers," resulted from the regularities observed in energy transformations.

In hindsight, one may say that Joule's concept of "conservation" stood one step ahead of Nicolas Clément-Desormes principle of "conversion," even though the ideas advanced by the young brewer physicist sounded strange to contemporary ears who at first gave a cold reception to its papers. However, this early distrust quickly dissipated and was replaced by broad scientific recognition. In reality, the principle of the conservation of energy soon became reified as the cornerstone of a new science called thermodynamics and encapsulated under the heading of the First Law of Thermodynamics. After the turn of nineteenth century, a second version of the law of conservation of energy would restate the principle of the indestructibility of energy, adding nonetheless that at each transformation, part of the energy is transformed and part is dissipated (Falk 1985). Hence, while energy is not actually destroyed, there is a loss in the final utility obtained. Subsequent to these discoveries, accounting for the conserved and for the dissipated proportion established, the theoretical grounds for assessing changes throughout input cycles. What was at stake here involved the measurement of the proportion of energy input that attained its final destination?

The First Law of Thermodynamics turned scientific interest toward the common characteristics of the "powers with which God has endowed matter." Energy henceforth appeared as the unifying field for all mutually convertible energy forms, from simple motion to electricity, passing through mechanical work, chemical action, heat, and light. Within this conceptual framework, the units of measurement could be detached from their historical utility and totaled up so as to produce a global balance of everything able to produce work. To the extent that a certain amount of heat could be expressed in terms of the work necessary to move a body, with a certain weight, under a certain velocity, for a determined distance, the heat as physical phenomenon was necessarily dematerialized and turned into "energy." This new dematerialized entity remained aloof to effective usage and instead constituting a convenient outline for singling out a whole new subdivision of society. Once the overarching concept was reckoned as a common characteristic of all mutually convertible energy forms, this spilled over into everything else: "It was in the cyclone that devastated the land, in the cooling zephyr of a summer's eve, in the awful rolling of the thunder and in the lightning's flash, as in the rustle of leaves and in the gentle cooing of the dove" (Atwater 1887b: 398). If energy was everywhere, it had furthermore to be present in men. The thermodynamics of living beings consequently became the next step in research.

2.3.2 Man as a Living Machine

The steam engine offered a vantage point for the study of man and physicists and engineers soon noticed that there was a lot to learn by looking at human beings from the perspective of machines. This proved an entirely new insight, which set apart things once considered the core essence, including intelligence and will, to focus exclusively on the body's automatic system. Beyond the suggestive power of the man–engine analogy, thermodynamics set out a whole new research agenda for the singular "self-contained prime mover," describing his "furnace" his "mechanism of work and energy development," his "mechanism of transmission of power peculiarly and exactly adapted to its purposes," and the controversial issue of heat transformation (Thurston 1894: 34–37). Major problems, however, stood in the way of the spread of thermodynamics. Although the analogy seemed to work well up to a certain point of general description, just as scientists reached the key causal explanations of human metabolism, the theory began to falter. By the end of the nineteenth century, it still remained impossible to agree on whether or not heat was the direct product of the oxidation of food, the result of the oxidation of worn muscle and other tissues, or the product of thermal and other interactions occurring within the body.

A second troublesome question was the absence in animal temperature systems of differences similar to those characterizing and limiting the action of thermodynamic engines. Humans and animals do not display anything like a phase of heat–steam generation followed by the cylinder's expansion and consequent cooling. According to one important prevailing stream of physics, the production of motive power only ever occurs when it proves possible to produce a difference in temperature and "destroy the equilibrium of the caloric" (heat). It thus becomes the temperature difference between two reservoirs that determines the amount of work extractable by a heat engine. Converting heat-based thermal energy into kinetic energy—i.e., doing work, in effect requires recourse to the power of steam to move the piston down through the cylinder in a working stroke, thereby expelling steam into either the atmosphere or a condenser so as to cool down the core nucleus of the engine. The discovery that heat flows from bodies of high temperature to bodies of low temperature laid the ground for the Second Law of Thermodynamics (Kerker 1960; Uffink 2007). As far as animal metabolisms were concerned, no equivalent heat contrasts or heat flows were observed throughout mechanical work production. Resorting to "reductio ad absurdum" arguments, to perform work in consonance with the thermodynamic laws of heat engines, the working parts of the human body would have to reach a temperature of around 140 °C (284 °F), therefore way above the boiling point of water, before then cooling the entire body so that a new cycle of work could begin (Thurston 1894: 47). Without this steaming of the body, the transformations of energy could not really be understood as "thermodynamic." The accumulation of unanswered questions and the rule breaking of basic scientific principles accrued the doubts as to the true nature of living machines.

Finally, there was also the problem of energy conservation. Human beings, just like animals, were seen as agents of energy conversion wedded to the daily transformation of food into mechanical work. This feature had long been understood, and Joule himself had praised the efficiency of the “animal frame” vis-à-vis the best engines of his time. However, unlike the steam engine, the relationship between the amount of food and the quantity of muscular force deployed by man was neither linear nor deterministic. Human beings seemed more like machines in which the coal supply had been disengaged from the movement of the piston. Clerks, for instance, feed themselves with large amounts of foodstuff but accomplish little physical force. From this, it would appear odd to look at muscular force as a means of conserving the energy contained in food. The logical follow-up to this apparent dissipation of energy was to pose the question of whether intellectual work could likewise be a means to conserving the chemical energy of food. Nevertheless, such endeavors ended in deadlock, for no amount of experimental evidence could confirm just how much food was needed to accomplish a given quantity of intellectual labor. Globally, the energy spent on thinking remained a riddle unsolved by nineteenth-century scholarship.

On closer examination, the human body-steam engine analogy violated the Second and the First Laws of Thermodynamics. Moreover, no less problematic was the measurement of inputs. In line with the engine analogy, food would stand for fuel, the body for a heat converter, and muscular force for power. In this context, scientific research stuck to the line of revealing the chemical basis for fuel nutrition, but some questions remained unsettled, especially the methodology for appraising the chemical energy of food: should the heat in proteins be deemed the exclusive source? Was it not preferable to measure the carbon dioxide formed during metabolism? How about estimating the energy expenditure of a man’s body mass while engaged in hard physical effort? (Carpenter 2003). With several hypotheses out in the open, the scientific community became wary that a new paradigm for food classification was looming over them. Whatever the path taken, the new developments would hinge upon the measurement of interchangeable chemical components rather than flavor; upon the economy of muscular effort rather than upon subjective utility; upon technical rationality rather than upon moral and religious judgments.

Despite the great strides made by European laboratories in the field of nutritional chemical analysis, the synthesis of a new scheme to measure the energy value of food was undertaken by the American Wilbur Atwater, while practically in parallel with the work of Rubner in Germany. A chemistry professor at Tennessee and Maine University, Atwater developed his research in an experimental agricultural station that specialized in analyzing the chemical composition of food. The groundwork commenced over 1878 and 1888 underpinned the future growth of his laboratory as a solid institution endorsed with funds, scientific equipment, and overarching project goals. Aware of the German advance in the field of physiology and nutritional chemistry, Atwater took leave of absence to visit Munich whereupon he learned firsthand of the procedures in effect for studying human nutrition by means of digestibility, nitrogen balance trials, and the transformation of heat by calorimetric combustion (Carpenter 1994).

At that stage, European physiology was at a critical juncture on the path to attribute energy values to foods. After his return to the USA, Atwater followed in the footsteps of the German-Munich school and embarked on an ambitious project to standardize American foods according to the protein and energy supplied. Later, in a series of articles published in the popular review "Century Magazine," the chemist decided to extend the analysis by adding the fuel value of proteins to the fuel value of carbohydrates and fats. For each food material such as beef, canned salmon, butter, or rye flour, he summed up the heat contained in the main nutrients, by unit of weight, and consequently arriving at the potential energy available in one pound of beef, one pound of canned salmon, etc. (Fig. 2.1). Applying data from human digestion experiments, the author devised the final "coefficients

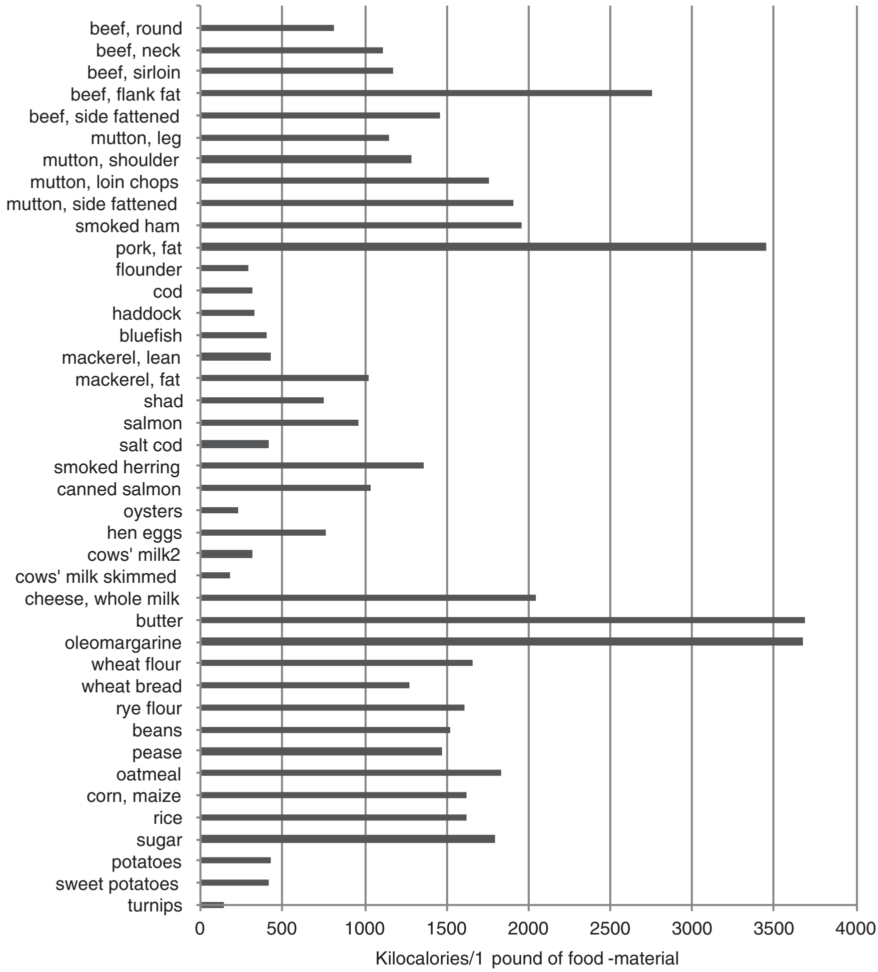

Fig. 2.1 Food energy potential. (kilo) calories in the nutrients of one pound of food material (Atwater 1887b)

of availability," defined as the intake minus fecal excretion divided by intake. By this means, he set forth the concept of "metabolizable energy," or the difference between the gross energy (as measured in the calorimeter), and the energy contained in feces and urine (as also ascertained by the calorimeter).

Lacking any better way to ascertain the energy value of proteins, carbohydrates, and fats, Atwater drew upon the European experiences and particularly laboratorial experiences with the device dubbed the calorimeter (Fig. 2.2). These consisted in measuring the heat produced during the combustion of organic substances (previously dried out) with the oxygen consumed in their burning. The chemical

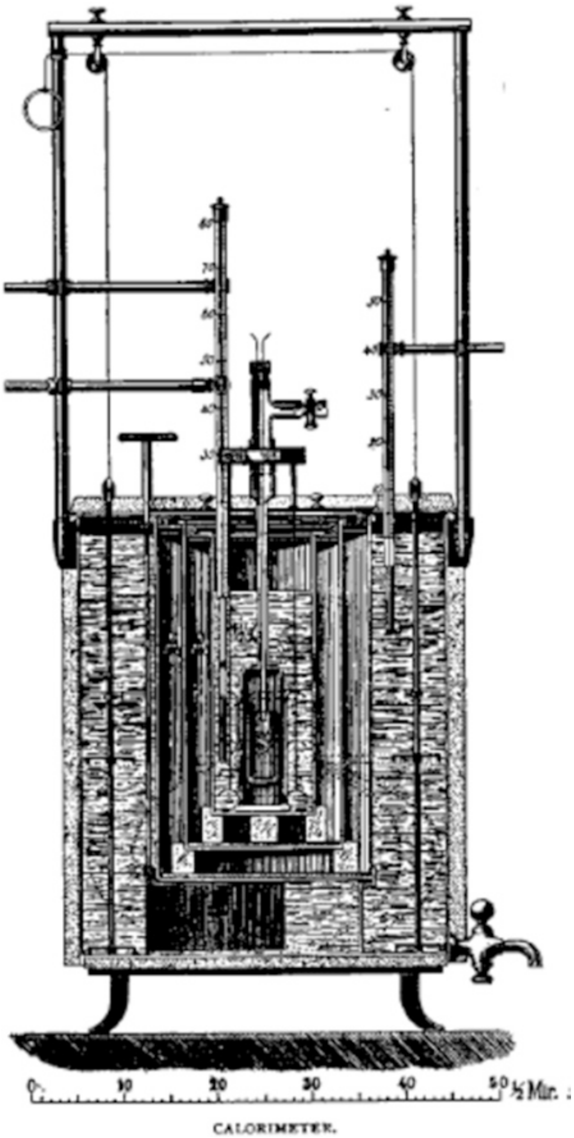

Fig. 2.2 The calorimeter (Atwater 1887b)

energy released through combustion was conveyed from an inner calorimeter container to a cover enclosed in a larger cylinder with water, so that the rise in water temperature, as shown by the attached thermometer, unveiled the amount of energy contained in the organic substance.

Like Watt's steam engine or Joule's paddle wheel device, the calorimeter was fundamentally an energy transformation machine: it converted the potential chemical energy of food into heat. Motivated by the desire to provide nutritious yet inexpensive food for people accustomed to doing physical work, Atwater's decided to present his conclusions to the American public by dubbing the energy value of foods as "calories." This decision prompted the reappearance of the old thermal unit across the Atlantic and completely refurbished with a new meaning. For a better understanding of Atwater's idiosyncrasy, it is important to note that, in the interim, the "calorie" unit had barely been applied by German and American experimental research. Moreover, Atwater defined the calorie not by the Clément-Desormes general gauge of the amount of heat needed to raise the temperature of water by 1 °C but, instead, through its equivalent unit of mechanical force as the potential energy needed to support a given amount of physical work against gravity, calculated as 1.53 foot-tons (Hargrove 2006, 2007).

The food calorie provided a fit in the range of hundreds or thousands of energy units per pound of food, thereby making it substantially easier for consumers to comprehend the nutritional scales. For someone concerned about spreading useful scientific knowledge throughout every layer of the population, the convenience and pedagogical clarity bestowed by quickly identifying foodstuffs on an ordinal scale (three and four digits for each food material) certainly constituted a strong justifying criterion. In any event, even the American physiologist with a strong profile as a publicist was far from imagining the success his tables would attain. At the time the article was published, he was not even sure that the heat produced by human metabolism could be equivalent to the heat produced by the laboratory combustion of organic materials (Atwater 1887a, b). The digestive system of individuals and the burning core of the calorimeter might not turn out so different after all. In such a case, the thermal values measured in laboratories might be susceptible to extrapolation as nutritional guidelines for human beings (broadly speaking, this hypothesis later came to be confirmed although with some adjustments) (Bijal 2009). In spite of the persistence of these and others scientific caveats the "calorie" quickly won a large audience among the American public. Hence, a food calorie actually refers to a kilocalorie, or 1,000 cal. That is, 1 food calorie equals 1 kcal or the amount of energy needed to raise 1 kg of water.

2.3.3 Overturning the Energy Value of Food

As a unit related to the fuel values of foods, the "Calorie" was promoted and disseminated by the Farmers' Bulletin issued by the United States Department of Agriculture, whereupon it found its way into handbooks for clinical and medical practitioners, advertisements, popular receipts, details on cereal boxes, emblazoned across foodstuff packages, newspaper articles, and books dealing with weight reduction (Hargrove 2007). In one fell swoop, food values rippled from the anonymity of academic footnotes to the spotlight of society. And the more the calorie spanned across popular culture, the more it became a reality in itself and a reality detached from energy measurements, almost as if an appropriate attribute of the foodstuff.

The enthusiasm generated by Atwater's tables stemmed from the degree to which a standardized, uniform, and quantitative perspective toward nutritional elements met a preexisting necessity. To the extent that the essentials for fueling humans were properly ascertained, the study of man could borrow at will from the study of thermodynamics and mechanical engineering. Still more importantly, by putting energy values on food, scientists fostered major changes in social relations: on the one hand, they allowed public powers to step into domains formerly reserved to personal choices, local culture, and morals; on the other hand, they unleashed an array of decentralized assessments about food—the personal diets and dietary plans that themselves went onto become an industry.

Scientific food measurements came to the fore at a time when the very notion of individual freedom was being undermined by principles of scientific-based government and technocratic rationalization. Both in the USA and in Europe, engineers and scientists envisioned techniques for the management of populations based upon statistical evidence and the extrapolation of general principles and social laws. Chemists and physiologists specializing in human nutrition began to characterize food as "fuel for the human machine" and nutrition science as a system of physiological "book keeping" susceptible to increasing the cost-effectiveness of human labor. Practical governmental usage of energy–food tables advanced swiftly in the USA, buoyed by ongoing trends to disseminate mutually dependent modes of management and knowledge (Taylor's efforts to establish a methodical science of workplace time and motion), but also by progressives advocating the redefinition of the state's obligations to incorporate the satisfaction of the nation's dietary needs (Desrosières 1998; Cullather 2007. "Progressivism" is further developed in Sect. 6.2). Caught by the call for active reforms, nutrition was brought into the fold of government and equated as standardized food management. Initially, federal interference was limited to an assessment of social and industrial relations by launching surveys, scientific standards of living for the working class and indexes of food consumption. After World War I, there came a bolder turn with recourse to the (kilo) calorie by military planners as a normative gauge to marshal resources and provide relief to stricken areas of Europe. Finally, the inter-war period saw the further imbuement of scientific food management by economic policy with its further spread across Europe and into their imperial dominions.

Within the sphere of population management, the calorie enabled a more rational equilibrium between "fuel" and physical effort, with a global dietary standard set in 1935 by the Health Organization of the League of Nations with the minimum amount of 2,500 calories set per day for a laboring adult (Grigg 1981; Cullather 2007). However, in the private realm, the unit took on a different hue, becoming instead a practical guide to cutting down on uncontrolled fueling, that is, to weight reduction.

While initial scientific concerns tended to underscore the working class food situation, excess weight proved the all-time popular theme, particularly among the middle classes. Due to the fact that Atwater's measurements tapped the heat produced during the combustion of organic substances, his ranks of energy values displayed a bias toward food materials with large proportions of fat nutrients. In terms of the calorimeter, fats constituted the greatest energetic resources anyone could consume. As the Farmers' Bulletin of 1894 explained: "The fats have weight for weight, about two and one-fourth times the potential energy of either the protein or the carbohydrates. Water has no potential energy. Hence the food materials which have the fattest and the least water have the highest fuel value. Butter and fat pork consist almost exclusively of fat. They lead the other food materials in fuel value. Lard, suet, and olive oil have even less water, and hence exceed the butter in this respect. Oleomargarine has about the same composition, fuel value and food value, as butter" (Atwater 1894).

From a thermodynamic standpoint, fat pork assured the best output for a given unit of input. In contrast, fruits, leafy vegetables, and fish registered low-level nutritional values and could scarcely be classified as foods because little muscular work would result from consuming these staples (which explains their absence from the food materials listed in Fig. 2.1). Ranking foods by their fuel value alone for this reason implies a partial viewpoint in which human qualities were extolled through the thermodynamic analogy with heat engines. In Atwater's own words, "the potential energy represents simply the fuel value of the food and hence is only an incomplete measure of its nutritional value" (Atwater 1887b: 400). However, in spite of these warnings, the word "calorie" became entrenched in the very methodology that prompted its revival, looming pragmatically as the single definitive measure of food value up until the "vitamin revolution" of the 1920s (which rehabilitated the in the meanwhile devalued fruits and vegetables). Within this framework, counting "calories," on a daily basis, could either signify an appropriate dosage of fuel for working people or a dosage of "fats" to blue collar employees. Since the ascending caloric scale of food materials was also a scale of fatness, reversing the whole scheme enabled the transformation of the energy values ranking into a blueprint for weight reduction. Through the effects of social usage and social appropriation, nutritional tables became far more useful in their inverted form and serving as practical diet plans. The "calorie" consequently thus became associated with weight reduction rather than with the amount of heat generated. In the view of the middle classes, energy intake ought later to be "burned off" by the mechanical work exercised in gymnasiums.

2.4 Energy Aggregation

The discovery that different qualities of energy could be aggregated under the same hood and summed up was one of the most remarkable achievements of nineteenth-century science. Two critical steps proved essential to accomplishing this aggregation.

In the first place, new measurement units had to be invented to grasp the diverse transformations of kinetic, thermal, and chemical energy. The mechanical work of pistons was sold to end users under the caption of horsepower; the potential of primary chemical energy contained in coal was assessed through the kilocalorie just as the secondary heat generated by steam; the primary fuel value of food along with the secondary metabolized value of its intake were, in turn, estimated according to the heat unit of the food calorie. Briefly, measurement moved from final to secondary and primary energy, encompassing the different qualities of energy. Science aimed at discovering the fundamental physics to the processes behind the functioning of machines and, afterward, behind human metabolism.

In the second place, transformation was explained through the Law of Energy Conservation. The outcome of mechanical work undertaken by a steam engine was nothing other than one way of conserving the energy contained in heat. Its evidence could easily be noticed whenever there was a thermodynamic exchange and part of the “living force” contained in mechanical power (or heat, light, or electromagnetism) was transformed into another energy form. Without this endless chain of conversions, neither nature nor human life would hold up. Since the different physical processes associated with the transformation of energy were perceived as mottled versions of the same thing, in a realistic interpretation of physics, there was a sound basis for aggregating and summing up the different qualities of energy.

As it turned out, aggregation resulted from improved specifications in measurement combined with the dematerialization of that under measurement. While the useful energy delivered by an animal, a windmill or a worker captured most attention in the preindustrial era, the fossil fuel economy of the nineteenth century shifted the focus toward the cycle of energy transformations based on the yardstick of chemical energy. Only following the order of changes and only measuring how much was conserved at each stage could aggregation produce meaningful results. By this means, nineteenth-century discoveries laid the ground for input-cycle assessment: whether of primary, secondary, or final energy. What was missing in this measurement scheme, largely drawing upon the First Law of the Conservation of Energy, was recognition of the differences in the qualities of energy, more specifically that the ability to do useful work varied according to the power sources applied.

At the same time, energy accounting overlooked almost everything that fell short of the measuring rod of money. In official estimates, primary energy registered only commercial carriers, and particularly coal and oil, brushing aside all the useful work of thousands of windmills, watermills, men, and animals. What makes this neglect particularly biased is the fact that in around 1880–1890, humanity reached the peak in the level of muscular force ever deployed by manpower, largely owing to the unprecedented extension of working times (Schor 1991; Costa 2000), the number of working horses, employed both on farms and in cities, also reached its all-time peak in mankind’s history (Thompson 1983; McShane and Tarr 2007; Mom 2009) and a large number of US plants persisted in their use of waterwheels and water turbines despite the growing relative cost disadvantage

(Hollerith 1883; Atack 1979). Swift technological development, however, turned everything that was not modern and tradable at a long distance, irrelevant.

Even though the theme of electrical unit systems is beyond the scope of this chapter, the main lesson imparted by the measurement of resistance, current, and electromotive force illustrates the role of standards set by the ingenuity of individuals and spread spontaneously throughout market interactions or personal scientific networks. A completely different arrangement surfaced at the close of the nineteenth century with the installation of state sponsored national laboratories encharged with the production of standards through systematic scientific research (the German Imperial Institute was the first in 1887), of wide reaching international meetings (the 1893 Chicago Congress was the first to set out a coherent system for electromagnetical units defined by material standards) and, finally, by supranational entities (the International Electrical Commission, following the St. Louis Congress, 1904). It was also according to the framework established by the electrical unit institutions that the measurement units for thermal, kinetic, chemical, and radiant energy came to be reviewed, reformulated, and further standardized.

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