Developing Compatible Metrics for Distinctive Forms of Energy

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Abstract

The development of practical metrics allows for a more accurate and precise measurement and comparison of different products and processes. Clearly defining these measures not only allows for the standardized comparison of raw materials or finished products through life cycle assessments, but also important considerations regarding the sustainability of material transformations and energy consumption. Though we know there exist distinctive forms of energy, from examples such as mechanical to electrical and even dark energy, the derived unit of Joule or an equivalent unit is used to quantify phenomenon that are inherently incompatible with the Joule's composite base units (eg. charge and kilogram). Herein we explore a set of derived units to quantify the extensive properties of energy not relating to the motion of masses and develop relations equating changes in mass, charge, and distance over time to chemical, gravitational, ionization, electrical, and magnetic energy. Using natural constants to form limits for mass and charge flow akin to the speed of light it is possible to come up with simple relations to both accurately describe these forms of energy and more precisely relate them. This may serve to not only allow for a more clear understanding of different forms of energy and work, but also serve to help those interested in quantifying and minimizing energy inputs by clearly delineating between forms of energy.

Main Text

Green chemistry and sustainability metrics seek to evaluate nearly all facets of chemical reactions from fundamental concepts such as the material efficiency of a process to applied ideas such as toxicity and social impacts.[1–3] Though there are a wide array of metrics used to describe different chemicals and materials, concerns regarding energy are sometimes limited to discussions regarding either capital and operational inputs or energy sources due to the lack of metrics specific to concerns ranging from electricity production to wasted chemical energy.[4,5] As it is understood that there are several distinctive forms of energy it would serve the green chemistry and engineering community to develop a set of metrics to quantify and thus compare different forms of energy.[6,7] This should allow theorists, experimentalists, and industry practitioners to better work together and further focus analyses of chemical transformations. From here they may more clearly define where energy inputs are greatest, where energy is wasted, and where downstream impacts from specific forms of energy production and use originate. [8,9]

Of the forms of energy that exist, of interest to the chemistry and engineering community are mechanical energy, which includes kinetic and potential energy, gravitational, chemical, magnetic, electrical and ionization energy.[10,11] Despite these forms describing distinct phenomenon such as changes in masses or charges across space and over time, we use the unit of Joules (or an equivalent unit such as the electronvolt) to capture the extensive quantity of energy which is defined as the capability to do work.[12]

One relation we use to understand energy is the iconic formula presented to us by Albert Einstein:

$$E = mc^2 \tag{1}$$

Where E represents energy in Joules (J), m, the mass of a system in kilograms (kg), and c is our cosmic limit for velocity (m/s), the speed of light, expressed in meters per second (equation 1).[13,14] This equation allows us to plainly see that there is an equivalence between energy and mass, and it is governed by the square of the speed of light. It is helpful to explore the equation using dimensional analysis of its units to better understand the pieces fit together (equation 2).

$$Joule\ (J) = \frac{kgm^2}{s^2} = kg * \left(\frac{m}{s}\right)^2 \tag{2}$$

Though equation 1 was the beginning of many important advances in understanding how the universe works, it is by no means the end of an ongoing discussion about energy and its forms. We are currently left without a clear understanding of how charge relates directly to energy, or how other composite changes are related to energy. This is despite the two phenomenon of charge [measured in Coulombs (C)] and distance or displacement [both measured in meters (m)] being fundamental to some of the other non-mechanical forms of energy including gravitational, magnetic, chemical, ionization, and electrical energy (defined in Table 1).

Type of Energy	**Simple Description**
$Mechanical$	relating to the motion of a massive system across space, be it kinetic or potential in nature
$Electrical$	relating to the motion of charges across space, be it kinematic or a potential
$Magnetic$	relating primarily to static charges and the production or change in magnetic fields or their potential
$Gravitational$	relating to relative motion of masses, their flows, forces and acceleration, and their potential to change
$Chemical$	relating to the bonding (or binding) of masses via charge and their changes and potential to change
$Ionization$	relating to the charges or currents in a massive system and the potential to become ionized and potentially separate into ions

Table 1: Types of energy and a short description of what distinguishes each form

We can look back to Planck's efforts to develop natural units to reveal that there are two other cosmic limits that have been suggested, one for mass flow [measured in kilograms per second (kg/s)], and one for charge flow, better known as current [measured here in Coulombs per second (C/s)].[15] These limits come to us from combinations of natural fundamental constants (Table 2):

Limit for	**Derivation from Natural Constants**	**Value**	**Units**
$Mass\ flow$	$\frac{c^3}{G}$	$4.01\ x\ 10^{35}$	$^{kg}/_{s}$
$Current$	$c^3 * \sqrt{\frac{4\pi * \varepsilon_0}{G}}$	$3.45\ x\ 10^{25}$	$^{C}/_{s}$

Table 2: Calculation of mass and charge flow limits where c, the speed of light, is 2.997 x 10^8 *m/s, G, the gravitational constant is 6.674 x* 10^{-11} m^3/kgs^2*, and* ε_0*, the permittivity of free space, is 8.854 x* 10^{-12} kgm^2/C^2s^2

While these limits may be less familiar to us than the rather fashionable speed of light, we can quickly see the similarity in their structure, and explore the consequences of these values. Even if we disagree on these as the values of these limits, we must wonder why we rarely if ever see or use strict upper limits for mass and charge flow outside of applied fields.[16,17] We might imagine that this mass flow limit represents the point at which a celestial body becomes a black hole, and the charge flow limit a similar upper bound for current. At the very least as suggested by Planck's units it is above these limits that our practical methods for dealing with these flow phenomenon break down, and thus it becomes important that we define where these limits may exist.

Using these limits and the format of Einstein's equation we can construct equations relating the fundamental values for mass, charge, and distance to these limits to practical extensive properties which would serve to measure distinctive forms of energy (equations

3 – 7). Here we use the word extensive to denote a quantifiable property relating to size or amount, compared to an intensive quality related to a state (such as temperature or density).[18] The five remaining metrics represented by their units are:

$$charge\ (C) * [speed\ of\ light\ \left(\frac{m}{s}\right)]^{\,2} = \left(\frac{Cm^2}{s^2}\right) \tag{3}$$

$$charge\ (C) * [mass\ flow\ limit\ \left(\frac{kg}{s}\right)]^{\,2} = \left(\frac{Ckg^2}{s^2}\right) \tag{4}$$

$$distance\ (m) * [charge\ flow\ limit\ \left(\frac{C}{s}\right)]^{\,2} = \left(\frac{C^2m}{s^2}\right) \tag{5}$$

$$distance\ (m) * [mass\ flow\ limit\ \left(\frac{kg}{s}\right)]^{\,2} = \left(\frac{kg^2m}{s^2}\right) \tag{6}$$

$$mass\ (kg) * [charge\ flow\ limit\ \left(\frac{C}{s}\right)]^{\,2} = \left(\frac{C^2kg}{s^2}\right) \tag{7}$$

At first glance these new units which describe different forms of energy look like a jumble until we begin to examine them in the same manner we explore Einstein's equivalency. As his equation shows us how mass becomes energy when it approaches the limit of velocity, these new equations give metrics for capturing the transformation of charge, distance, and mass following an increase in the mass flow, charge flow, and velocity to their cosmic limits.

We know that charges can bond together becoming more massive, and masses may become polarized and ionize into separate charges. Similarly we know space may become filled or depleted of flowing masses and charges. What these units and equations give to us is a simple set of relations for determining the equivalent forms of different energies not best described by the Joule or mechanics or thermodynamics quantities.

Above we have five relations to measure electrical, chemical (or bonding), magnetic, gravitational, and ionization energy corresponding to equations 3 – 7 respectively.

These equations and these units may aid in demystifying dark energy as not something we would expect to be measured with the Joule, but rather with congruent units, such as the Coulomb, which complement the phenomena they seek to describe, such as electrical energy. All of these extensive measures should be quantized and all of the transformations and equations we use to determine what we traditionally know as energy should hold when modified to address other phenomenon beyond the movement of masses.

Take for example magnetic dipole moment, measured here with units of Coulomb-meters squared per second (Cm^2/s), a measure of current across an area.[19] To change a magnetic dipole moment over time, a form of energy must be expended to change the current, or else shift the orientation, much like with spin, a complementary form of angular momentum measured with units of kilogram-meters squared per second (kgm^2/s). As practical charges have mass, if we are interested only in the energy related to the change in the magnetic dipole moment, we might think to not measure anything in this system using kilograms. The derivative of the magnetic dipole moment with respect to time gives us the units we see in equation 3, which may also be achieved by taking the curl of the product of a current multiplied by its volumetric flow, the latter measured in meters cubed per second (m^3/s) shown in equation 8.

$$\begin{aligned}&\frac{\partial}{\partial t} Magnetic\ Dipole\ Moment\ \left(\frac{Cm^2}{s}\right)\\ &= \nabla \times \left[Current\ \left(\frac{C}{s}\right) * Volumetric\ Flow\ \left(\frac{m^3}{s}\right)\right]\end{aligned} \tag{8}$$

$$= Electrical\ Energy\ \left(\frac{Cm^2}{s^2}\right)$$

Without our new extensive measures this might look like little more than a Maxwell-like relation. We might see equation 8 and think little of what the derivative or curl both equal. But by understanding that the change in magnetic dipole moment over time is a valuable extensive measure on its own,[20] we can begin to understand what form of energy is doing the work to shift the magnetic dipole. Here we can begin to see that flowing currents are being described across space and over time, and though we are talking about a magnetic dipole moment, it is the complementary phenomenon of electrical energy that this energy best serves to measure. Looking at the units of Coulomb-meters squared per second squared (Cm^2/s^2) we can also see in the numerator the electric quadrupole moment, with units of Coulomb-meters squared (Cm^2), identifying this further as electrical in nature, surely not mechanical, nor any other form of energy.

Briefly exploring the other units and the moments that make them, we can see in the construct for chemical energy a simple descriptor of bonding (Ckg^2) for two masses and one charge (equation 4). In the unit for magnetic energy we see two charges separated by a distance (C^2m) touching on electrostatics and magnetic fields (equation 5). Equation 6 describes two masses separated by a distance (kg^2m) and can take into account their changes over time of their flows. Lastly equation 7 serves to quantify transformations of distinctive charges in a given mass (C^2kg) relating to polarization and potentially ionization given enough of this energy.

How we have not previously developed specific extensive measures for distinctive forms of energy is not surprising. We must remember that we exist as masses moving through space and have until now seen most other types of work and energy to be mechanical and relating to mass and motion, or else we can describe phenomena relating to charge through their relation to mass as with the electric potential (with units of kgm^2/Cs^2), or magnetic flux density (kg/Cs). Look no further than how we transform both electrical and gravitational forces describing multiple bodies into the same units of Newtons that we use to describe the acceleration of single masses. What we can do going forward is to use this framework to quantify distinctive forms of energy more accurately and precisely.

With all of this said, we would not be human if we did not try and push these limits of what we already know. After glimpsing these extensive measures of distinctive form of energies it becomes clear that we must develop viable ways to relate them as systems with charge(s) and mass(s) occupying space will possess changing quantities of all of the energy forms over time. Beyond this, we must also consider if there is a more holistic metric for a universal descriptor of energy, or at least a placeholder that will allow us to discuss these energies of moving masses with charge at the same time. At the center of this six-sided construct is another measure, something that even though it may seem impractical at first, should serve a greater purpose of using a unique moment to describe or relate nearly any set of changes as it simultaneously includes information about the change of the charge, the mass, and the occupied space of a system over time:

$$\frac{C * kg * m}{s^2} \tag{9}$$

To use any of these novel extensive measures in experimental settings we must first understand what we have, what we need, and where we want to go. There are no doubt subdisciplines or fields which may gravitate towards one metric or become polarized by another, but in the end these new metrics should serve to first separate out different forms of energy such that we can then unite distinctive natural phenomenon and their changes to help build a more unified theory to describe our universe.

Conclusion

In an effort to mitigate energy inputs, identify wasted forms of energy, and more clearly understand the impacts of specific forms of energy in a given transformation it is necessary that versatile and accurate metrics for assessing energy are developed.

Though the many different forms of energy describe inherently different physical and chemical phenomenon, here constructed complementary metrics for assessing different forms of energy with natural constants and basing them on the widely used unit of the Joule should allow for a more easy adoption of these metrics in practical assessments. As life-cycle assessments and techno-economic analyses seek to incorporate more comprehensive evaluations of energy inputs and impacts these novel measures of extensive energy properties will aid in comparing chemical and material transformations.

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