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# A functional approach for studying technological progress: Extension to energy technology ☆

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**Abstract**

This paper extends a broad functional category approach for the study of technological capability progress recently developed and applied to information technology to a second key case—that of energy based technologies. The approach is applied to the same three functional operations—storage, transportation and transformation—that were used for information technology by first building a 100 plus year database for each of the three energy-based functional categories. In agreement with the results for information technology in the first paper, the energy technology results indicate that the functional approach offers a stable methodology for assessing longer time technological progress trends. Moreover, similar to what was found with information technology in the first study, the functional capability for energy technology shows continual—if not continuous—improvement that is best quantitatively described as exponential with respect to time. The absence of capability discontinuities—even with large technology displacement—and the lack of clear saturation effects are found with energy as it was with information. However, some key differences between energy and information technology are seen and these include:

- Lower rates of progress for energy technology over the entire period: 19–37% annually for Information Technology and 3–13% for Energy Technology.
- Substantial variability of progress rates is found within given functional categories for energy compared to relatively small variation within any one category for information technology. The strongest variation is found among capability progress among different energy types.
- More challenging data recovery and metric definition for energy as compared to information technology.

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These findings are interpreted in terms of fundamental differences between energy and information including the losses and efficiency constraints on energy. We apply Whitney's insight that these fundamental differences lead to naturally modular information technology artifacts. The higher progress rates of information-based as opposed to energy-based technologies follows since decomposable systems can progress more rapidly due to the greater ease of independent as opposed to simultaneous development. In addition, the broad implications of our findings to studies of the relationships between technical and social change are briefly discussed.


*Keywords:* Functional tradeoff metrics; Technological progress; Social change; Energy technology

## 1. Introduction

In a previous paper [1], the authors have extended the study of quantitative technological progress to a broader functional approach and studied the case of information technology. In this approach, functional performance metrics based on tradeoffs are chosen in a manner similar to that done in previous work on quantitative technological progress and thus the approach is quite closely related to much previous work [2–6]. The first distinction of the broad functional approach from this previous work is that rather than choose metrics specifically important in a single underlying technology (or even more narrowly for specific embodiments of the technology), metrics are chosen for each of the functional categories shown in Table 1 [7–11] which is a slightly modified version of a similar table in reference [1]. The second distinction is that for these broad functional categories, data is examined for much longer time periods (typically >100 years when data is available) than is usual in other quantitative technological progress studies. Thus, the broad functional approach to technological progress is not aimed at or as capable of making device-dependent or short-term technological projections as the preceding approaches. Koh and Magee [1] showed that at least for information technology, this shorter-term and specific device shortfall is offset by superior stability and capability for longer term comparisons for the broad functional approach. The previous paper studied the transform, transport and store operations for the information operand as shown bolded in Table 1.

Information technology is generally associated with late 20th century and beyond economic, social and cultural changes [12,13]. Such broad societal changes in the 18th, 19th and early 20th century (the first and second "Industrial Revolutions" or the first four Kontradiev waves — see [14]) have been at least partially associated with "energy technologies" (steam engines, internal combustion engines, oil etc.). Since we believe that the functional category approach is more suitable for study of long-term major changes, this suggests that extending the approach to energy technology was an appropriate step to explore what this quantitative,

Table 1
Functional technological classification with operands and operations

| Operand | | | |
|---|---|---|---|
| | Matter (M) | Energy (E) | Information (I) |
| *Operation* | | | |
| Transform | Blast furnace | ***Engines, electric motors*** | **Analytic engine, calculator** |
| Transport | Truck | ***Electrical grid*** | **Cables, radio, telephone and Internet** |
| Store | Warehouse | ***Batteries, flywheels, capacitors*** | **Magnetic tape and disk, book** |
| Exchange | eBay trading system | Energy markets | World wide web, Wikipedia |
| Control | Health care system | Atomic energy commission | Internet engineering task force |

empirical approach may offer relative to understanding a key aspect of large scale economic, social and cultural trends. In addition to the understanding of social change as a reason for studying energy technology in the same way as information technology, there are technical reasons [15–17] for considering energy and information as the most fundamental operands shown in Table 1. Thus motivated by fundamental technical as well as social history interests, the functional category approach was extended to energy technologies. We study the same three operations as previously but now for the energy operand (the bolded, italicized categories in Table 1). The empirical assessment reported here examines the long-term trends of progress in energy technologies in a manner consistent with the functional framework. In doing this, we examine the time dependence of various functional performance metrics, explore whether different possible metrics in a given functional category yield similar progress trends and compare progress rates in the three operational categories for energy technologies. After describing the energy technology findings, we then will compare them to those found previously for information technology.

## 2. Functional performance metrics for energy technology

The Functional Performance Metrics desired for our study are ones that measure the functional technological capability (as opposed to the total output or economic impact) of each category. As with specific devices [2,3,5,6], such capabilities are best assessed in terms of key tradeoffs facing the technology. The tradeoff based FPMs take the form output (desired performance) divided by input (traded off attribute). Table 2 shows the three functions and 8 FPMs used to characterize energy technology for the purposes of this study.

Storage is the operation where usable energy that can immediately empower a device is attempted to be preserved (no change in state) for a certain time. Volume is almost always an important engineering constraint in designing devices and systems and thus the first FPM for energy storage is the *Stored Specific Energy* or the amount of energy stored per unit volume (Watt-hours/liter). Since Energy is quite often used to achieve locomotion, another important tradeoff involves the mass of the storage technology and thus the *Energy Storage Density* or the amount of energy per unit mass (Watt-hours/Kg) is the second FPM in energy storage. In order to assess the always important cost constraint, our third FPM in energy storage is the *Stored Energy per unit cost* (Watt-hours/$). The monetary cost is in 2005 U.S. dollars using the GDP deflator as the inflation adjustor.

Transportation is the operation whereby active energy is moved over a distance without state change in a given time in order to be utilized at another location. Losses and other costs generally limit the distance

Table 2
Operation and functional performance metrics for measuring the progress in energy technology

| Operation | FPM name | FPM units |
|---|---|---|
| Storage | Stored specific energy | Watt-hours per liter |
| | Energy storage density | Watt-hours per kg |
| | Stored energy per unit cost | Watt-hours per U.S. dollars (2005) |
| Transportation | Powered distance | Watts × km |
| | Powered distance per unit cost | Watts × km per U.S. dollars (2005) |
| Transformation | Specific power | Watts per liter |
| | Power density | Watts per kg |
| | Power per unit cost | Watts per U.S. dollars (2005) |

over which such power is moved. The distance moved and the amount of power moved have both been increased through technological progress. For transportation over a distance, time is considered the first key constraint so the amount of energy transported over a given distance in a given time—*the Powered Distance* (Watts × km) is the first energy transportation FPM. The cost constraint is studied as an input in the second energy transportation FPM *the Powered Distance per unit cost* (Watts × km/$) where the monetary cost is again in 2005 U.S. Dollars using the GDP deflator as the inflation adjustor.

Transformation is the operation whereby energy is changed to other states. In the case of energy technology, transformation between chemical, heat, inertial and electrical forms (states) by engines, generators, motors and other devices have been studied in this paper (transformation of matter to energy by nuclear fusion and fission is not examined here). One key constraint in all transformation activities is time and thus this input is active in all three FPMs for energy transformation. In the first energy transformation FPM, volume is also a studied input and the resulting FPM is *Specific Power* or the energy per unit time per unit volume (Watts/liter). In the second FPM, mass is the constraint examined and the resulting FPM is the *Power Density* or the energy per unit time per unit mass (Watts/kg). The always important cost constraint is active in the third energy transformation FPM which is the *Power per unit cost* (Watts/$) where the monetary cost is again in 2005 U.S. Dollars using the GDP deflator as the inflation adjustor.

## 3. Data and data reduction

Human use of fire (utilization of chemical energy stored in wood) is arguably the first energy technology. Energy technologies expanded as agriculture, city life and human culture evolved over time. Use of energy from animals and simple waterwheels where hydro power is used also predate the eras we are focusing upon. With the onset of the Industrial Revolution in the eighteenth century, modern energy technology might be said to have begun and it is this period for which we have more successfully found data. However, for the most part we have restricted ourselves to the period from the mid-late nineteenth century until the present because of limited data availability and reliability for earlier periods. Reliable cost data for energy storage technologies has been only retrieved for the period after 1945 so this particular FPM is only studied in this more recent period.

Since the historical data that constitutes the comprehensive database has been collected during the last 150 or so years, the reliability of the historical data is a significant factor in determining the quality of our progress estimations. As the historical data were recorded at different places and by different people and measurements are reported in various publications, the possibility of data errors or *inconsistency* cannot be eliminated in long-term studies such as this one. Therefore, the historical database is established according to the following standards in order to have adequate consistency and reliability. Historical data of government reports were generally considered fairly reliable but data found in multiple sources were given the most weight. In addition, we preferred utilizing data from reviewed journals where ongoing data appeared (e.g. IEEE transactions and IEEE books) as opposed to trade magazines or journals that published only one-off studies. In this study, cost is represented by monetary value in U.S. dollars. Inflation was applied to the cost (2005) and is accounted for with the GDP deflator method [18,19]. The GDP deflator is a measure of the change in prices of all new, domestically produced, final goods and services in an economy. It is not based on a fixed market basket of goods and services. Therefore, costs associated with changes in technological capability appear to be best normalized by the GDP deflator.

The performance data for the storage function are investigated from 1884 to 2005 using various public journals and books. The rechargeable lead-acid battery was first commercialized late in the nineteenth century and pertinent data were found in the various issues of IEEE transaction and historical books so that the historical database could be constructed [20–28]. Many other battery-based energy storage technologies were invented during the last 100 years [29–37].

Devices to store mechanical energy have been researched since the 1960s centering around NASA. Thus, data about flywheel energy storage were found in the reports of NASA and IEEE transactions [38–42]. Electrical energy storage devices, specifically capacitors, underwent development particularly from the 1960's and became widely used. Although capacitors are originally charge storage devices, the development of devices that store charge at higher voltages have allowed these to evolve into devices that are potentially competitive with other energy storage devices and thus they are assessed in this work. IEEE transactions are an important source for technology development of electronic storage devices [43,44]. Detailed data, data transformation methods and complete references for energy storage devices are listed in Table A1.1 and A1.2 in the supplemental material at Ref. [45].

In the energy transportation functional category at this time, electrical transmission is clearly superior to mechanical transmission and much of the data for FPMs in this functional category were obtained from historical data about electric energy transmission in various books, papers, and statistical yearbooks of the electric utility industry [46–51] published by the Edison Electric Institute. The transportation functional category has not been widely studied by others interested in technological progress. Thus, the functional performance metrics suggested by the analysis in Section 2 for energy transportation have not been calculated by others. Data on line voltage, transmitted power, average length of transmission line, and the construction and maintenance cost per unit length of installed line were obtained to construct these metrics (see Table A2 for data details, data reduction methods, FPM calculation and complete references [45]). Reliable cost data for specific cases was particularly difficult to find and the estimation and extrapolation methods used are also explained in A2. For mechanical energy transmission, it was only possible to get reliable measures for more recent energy transportation capability [42–44,46–56] and these details are also in Table A2 in the supplemental material [45].

In the energy transformation functional category, the progress of technological change was investigated using generated power per unit mass and unit volume as well as the generated power per unit cost. The historical data for engines that transform chemical energy to mechanical energy were retrieved in various books and papers [57–63]. The data for transformation of electrical to mechanical energy was found in references [65,66] and that for chemical to heat to mechanical (Turbine) was found in references [30,64]. Detailed data and complete references are found in Table A3 [45].

## 4. Results

### 4.1. Energy storage

Energy storage technology may have started with use of natural spring materials (possibly in traps or weapons) and later evolved to explosive artifacts.[2] The devices we consider cover energy storage technology beginning with the onset of the nineteenth century when Volta invented the first device that

[2] Explosive devices are not studied partially because of low effectiveness of obtaining useful work from such devices.

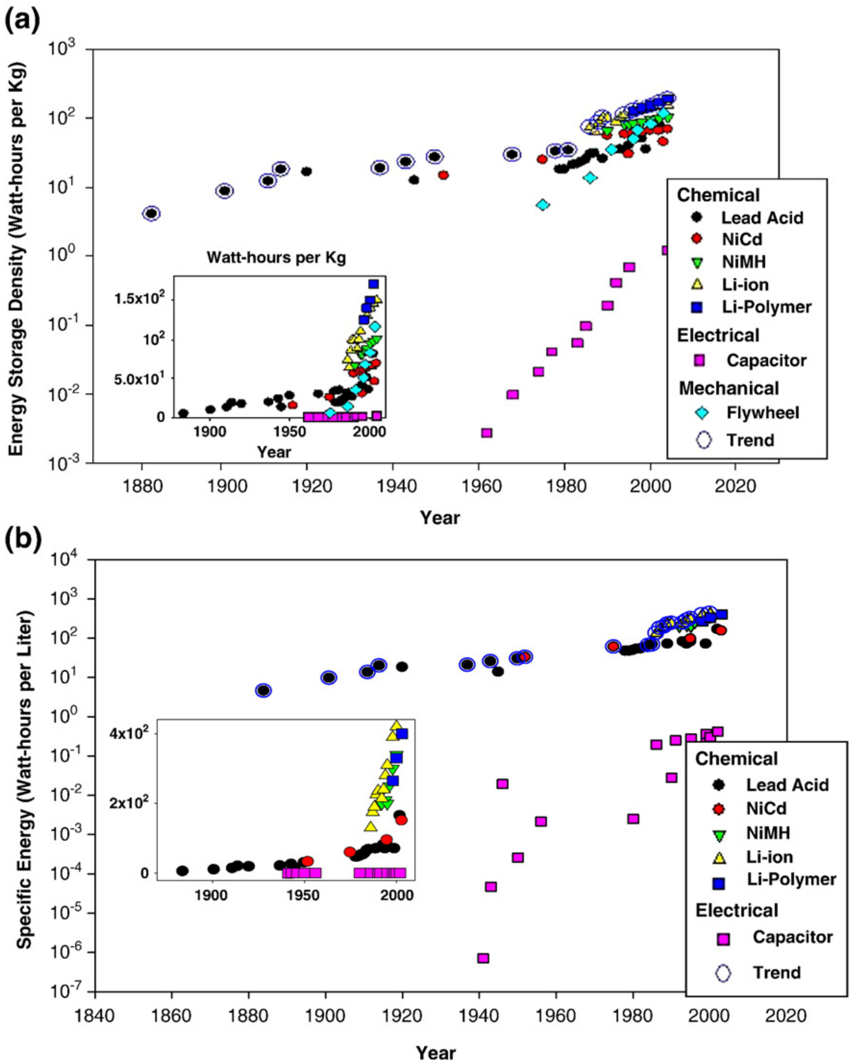


Fig. 1. Historical progress in energy storage; (a) by energy storage density and (b) by stored specific energy in logarithmic scale.

converted chemical energy to electrical energy [20,21]. But this device did not store energy. In 1859, the lead-acid battery which could store and reproduce electrical energy was invented [67]. Since that time, continuous improvement and inventions have occurred to overcome various constraints—some beyond those considered explicitly in our FPMs. For example, long charge times and inconsistent power output from existing lead-acid batteries were partially responsible for the invention of the Ni–Cd battery in 1899 which was introduced commercially in 1949. Partially in response to environmental issues with Ni–Cd batteries, Ni–MH was later developed [68] and the Li-ion battery with higher energy density and no memory limits on discharge cycles was invented in the 1980s [67,69]. The Li-polymer battery was also developed in same period [69] with advantages in shape control and stability.

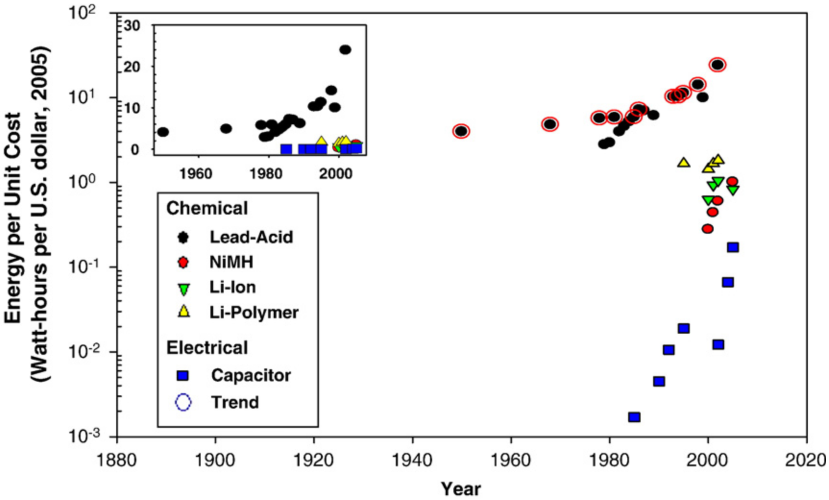


Fig. 2. Historical progresses in energy storage capability by stored energy per unit cost (2005) in logarithmic scale.

In order to assess the progress of technological change in energy storage, we plot the log of each of the three FPMs against time. The first FPM is Energy Storage Density as the measure of technological capability progress and this is shown in Fig. 1a whereas Fig. 1b shows the Stored Specific Energy.

Overall, Fig. 1 shows reasonably consistent progress (on this logarithmic graph) rather than any tendency to bend over and exhibit "saturation" of progress for either FPM or for any of the three energy types. We also note that the linear version of the plot—see insert-distorts the progress to make it seem as if all progress occurred since about 1970 whereas there is clear earlier progress which is consistent with an exponential relationship. Fig. 1 includes storage technology for three different energy types: mechanical (flywheels), electrical (capacitors) and chemical (several battery technologies). The preceding paragraph discussed some qualitative aspects of battery technology development; some quantitative aspects are apparent in Fig. 1. First, over the entire period, batteries are superior to all other forms of energy storage studied for both the volume and mass constraints.[3] From about 1980 onwards, the graphs show the superiority of Li-Polymer and Li-ion batteries relative to Lead-acid batteries and their lead position relative to all energy storage devices studied in Fig. 1a. A last point is that there are continuous trends in capability despite substantial change in the leading technologies (lead-acid to Li-polymer for example).

Fig. 1a also shows that flywheels (mechanical energy storage) have improved significantly over the time when we have data for them (post 1970). Although their rate of improvement in Energy Storage Density appears higher than for batteries, flywheels still trail the best batteries in this FPM (117 Wh/kg vs. 190 Wh/kg). The data are consistent with the fact that large-capacity flywheels are not applied generally for longer term energy storage but are used with common electrical and mechanical devices for short-term storage. For long-term energy storage, the application exception is the weight sensitive space shuttle since the 1990s [38,39]. Flywheels have particular merit in minimizing stored energy losses in the vacuum environment of space.

[3] Storage of fuel (hydrocarbons and others) is clearly superior and responsible for their widespread use in transportation.

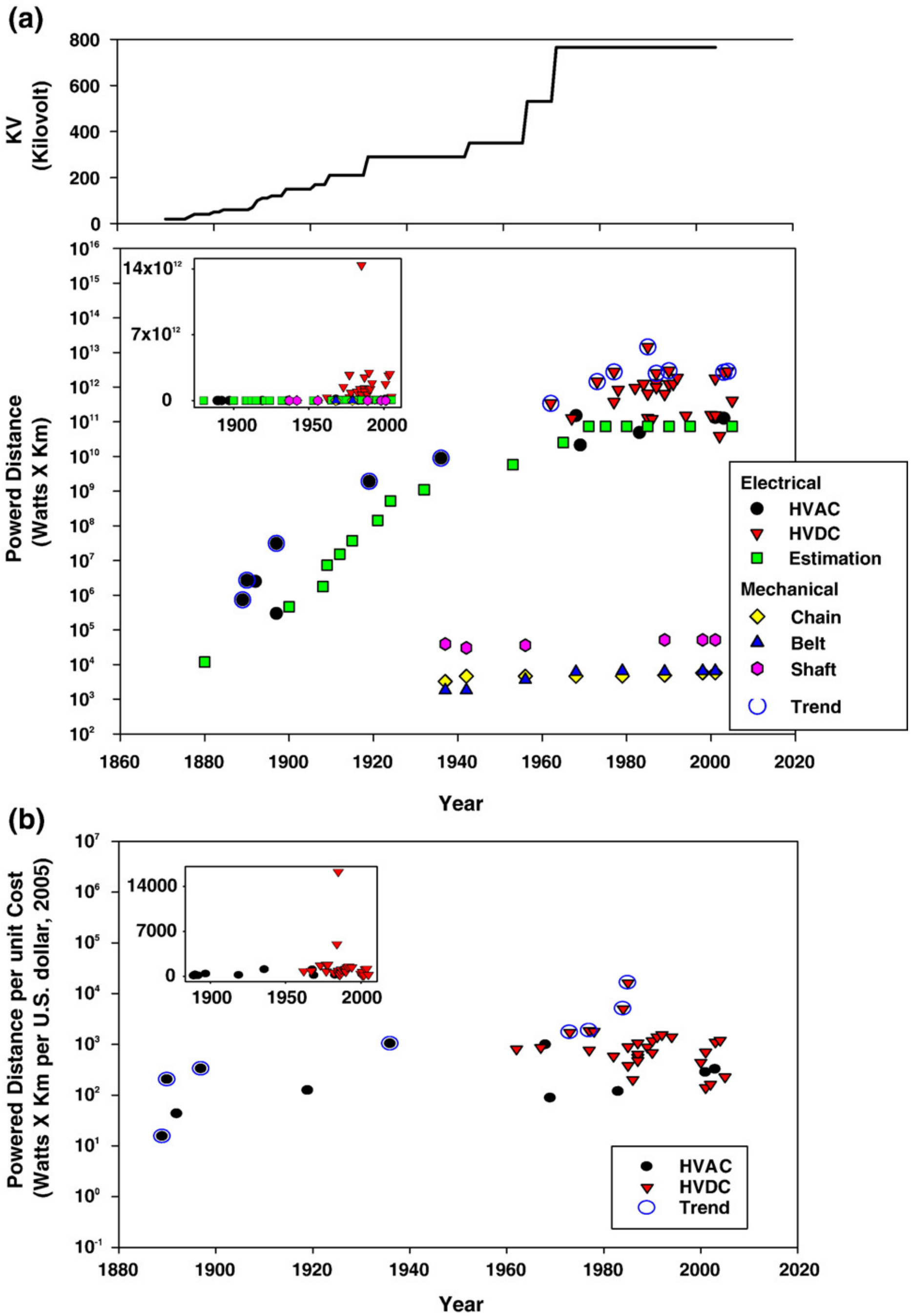


Fig. 3. Progress of energy transportation; (a) powered distance and (b) powered distance per unit cost.

Fig. 1a and b indicate that the rate of progress of capacitors exceeds that for any other energy storage devices studied and ongoing work on ultra-capacitors is promising [42]. However, despite the rapid rate of improvement, capacitors still fall short of the best batteries (and flywheels) by about 2 orders of magnitude in Energy Storage Density and Stored Specific Energy (Fig. 1a and b).

Fig. 2 shows the cost-constrained FPM, the Stored Energy per unit cost plotted vs. date. Continuous improvement in Battery performance over this post 1940 period is seen. The figure also shows that in Stored Energy per US dollar ($) that no other battery system has achieved superiority to Lead-acid despite the high volume and mass specific energy of the Li-ion and Li-polymer batteries. Indeed the data at this point in time show no consistent trend to anticipate such superiority.

### *4.2. Energy transportation*

The transport of power (active rather than stored energy) has been technologically assisted starting perhaps with animal connections to carts and plows and evolved to also include primary mechanical power transport devices such as ropes, belts, shafts, etc associated with the industrial revolution. Starting with the late nineteenth century, significant separation of generation and utilization of power became normal because of the significant increases possible in power transportation with electricity. Fig. 3 shows the quantitative progress of energy transportation with the two FPMs we defined in Section 2. Fig. 3a shows the Powered Distance (the product of transported power and the distance that the power is transported). In this figure, the trend points used in later fitting of the results are from references that give specific power and distance data. However, the figure also shows estimated points that come from more broad based data from the Edison Institute yearbooks (see A2 for details [45]) and the broad estimations show the same trend as the specific data.

Fig. 3 a shows the continuing improvement of the energy transport functional capability over the past 120+ years on this logarithmic scale. This figure also shows the substantial improvement in energy transport capability due to increasing AC voltage (shown at the top of Fig. 3a) made possible by technological developments in cable design particularly new dielectric materials. The results in Fig. 3a indicate that recent improvements in energy transportation capability are associated with new technology-specifically high voltage direct transmission [70] which is supplanting HVAC without an apparent discontinuity in capability. The figure also clearly shows the present superiority of energy transportation by electrical as opposed to mechanical means. An interesting uncertainty (due to lack of data about 19th century mechanical energy transport and very early electrical transport capability) is the magnitude of the change in capability when electricity was first introduced. In 1890, the capability of transporting electrical power was perhaps 2 orders of magnitude greater than the capability of transporting mechanical power. The superiority of transporting electrical energy in 2005 is approximately 8 orders of magnitude greater than the (slowly improving) transportation of mechanical energy showing the importance of the difference in technological capability progress.

Fig. 3b shows the Powered Distance divided by the construction cost of the power line. Except for data from the past 20 years, we were only able to find overall data about line construction costs. Section A2 in the supplemental material [45] details the methodology used for extracting costs at specific voltages and years but the reliability of these estimates is unfortunately low. Nonetheless, we believe that the relatively slow increase in this FPM is a real effect that is explained by increases in power, voltage and distance causing cost increases that almost fully counter the more rapid progress displayed in Fig. 3a.

Overall, Fig. 3a and b show no sign of bending over but instead continuing progress even as certain prior leading technologies (mechanical transmission, AC power transmission) have been supplanted.

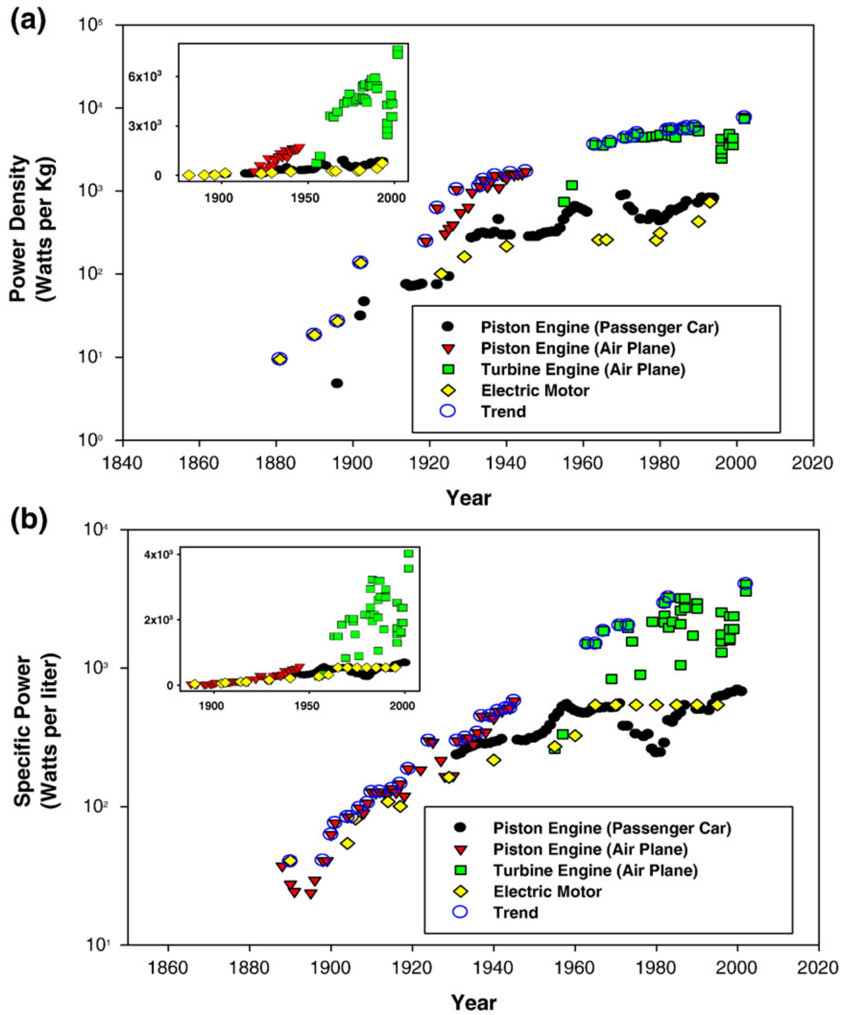


Fig. 4. Progress of energy transportation; (a) power density (Watts per kg) and (b) specific power (Watts per liter).

Thus, the overall functional category shows continuing (perhaps nearly continuous[4]) progress despite the fact that individual technological approaches show evidence of saturation.

## *4.3. Energy transformation*

The transformation of energy (as opposed to storage and transportation) is most closely associated with technological progress in popular perception. The transformation of naturally stored energy in wood to useful heat and light (the "invention of fire") is arguably the start of energy transformation technology. In this paper, we focus on the developments that started with the invention of the steam engine. We include data for chemical

[4] There is at least a significant change in slope with the introduction of electrical transmission and perhaps a modest capability discontinuity.

to heat to mechanical energy transformation (engines) as well as some for electrical to mechanical energy transformation (electric motors). For all of these cases we use the three FPMs defined in Section 2 to assess the technological progress. The first two of these (Specific Power and Power Density) are shown in Fig. 4.

Overall both of these figures show continuing progress throughout the period. Fig. 4 also shows that the gas turbine energy transformation capability surpassed the internal combustion engines in Power Density (4a) and Specific Power (4b) after its invention and development in the 1930s and 1940s. The results for electrical motors show similarity to the progress rate for energy transformation for the heat engines in Specific Power and Power Density but at a comparable recent time, the electrical motor value for each FPM is about a factor of 10 smaller than for turbines.

Fig. 5 shows the Power per unit cost for internal combustion engines, gas turbines, and electric motors. One obvious feature of this figure is the (unsurprising) superiority of cost-effectiveness for automotive relative to aircraft engines. For the period where reliable cost data could be found (1894 to present), there is only little progress in this FPM and very little progress over the past 60 years. This is the only clear indication of possible "technology saturation" seen in the 14 FPMs studied (Ref. [1] plus this paper). The apparent saturation may be due to additional requirements adding to cost over this period. Fuel efficiency, noise and emission controls are three of the obvious possibilities in this regard. Qualitative observation of these systems indicates that the overall tradeoff surface is continuing to expand but that for this specific cost-constrained FPM (which embodies only the constraints of initial interest in these technologies), progress is now slow enough to be showing at least apparent saturation.

### 4.4. Overall quantitative trends in progress

All eight FPMs studied for the progress of energy technology show progress over the time period studied. Although only little evidence of saturation is seen, it is clear that progress rates differ among (and within) the various functional categories. This section explores the quantitative rates of change and the variation seen between categories and between different FPMs within a category.

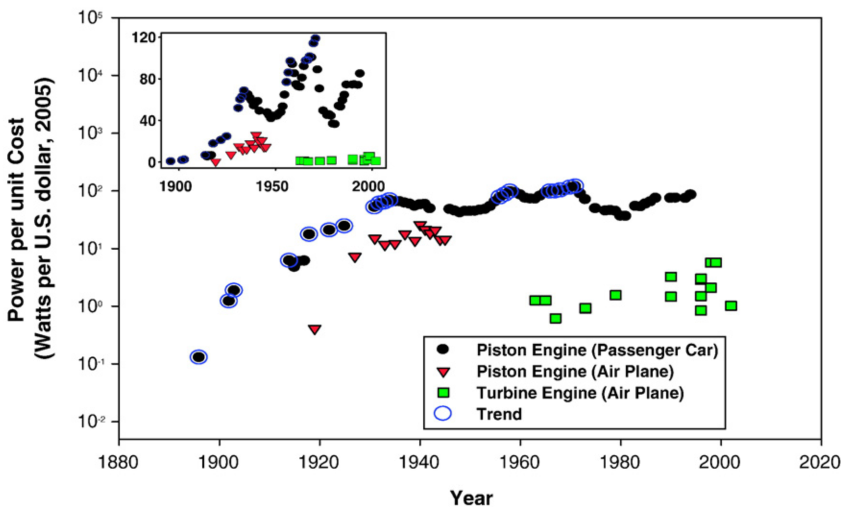


Fig. 5. Historical progresses in energy transformation by power per unit cost (2005) in logarithmic scale.

Table 3
Technological progress in energy technology

| Functional performance metric | | | | |
|---|---|---|---|---|
| Operation | Name | Linear | Exponential | |
| | | [a]$R^2$ | [a]$R^2$ | [b]Annual progress |
| Storage | Energy storage density | 0.67 | 0.94 | 2.8±0.4% |
| | Stored specific energy | 0.55 | 0.95 | 3.7±0.4% |
| | Stored energy per unit cost | 0.55 | 0.77 | 3.1±1.3% |
| Transportation | Powered distance | 0.18 | 0.93 | 13.2±2.2% |
| | Powered distance per unit cost | 0.28 | 0.78 | 4.3±2.2% |
| Transformation | Power density | 0.68 | 0.88 | 5.3±0.9% |
| | Specific power | 0.45 | 0.98 | 4.6±0.3% |
| | Power per unit cost | 0.64 | 0.74 | 6.4±2.2% |

[a] $R^2$ is rounded off to the second decimal place.
[b] The annual progress and error were estimated in 95% confidence interval.

We examine whether exponential fits of the data (as found for information technology [1]) are appropriate for these results. Table 3 gives the results of exponential and linear[5] fits to the trend points (these are the highest FPM values for given time periods) shown in Fig. 1 through 5. The exponential fits are substantially better than the linear fits and the linear only appear competitive for FPMs with very little progress.[6] Thus, the statistical results are consistent with the intuitive look of the linear insets as compared to the logarithmic graphs. Because of their clear superiority, we will use the progress rates determined from the exponential fit in all further discussion.

The results in Fig. 1 through 5 along with those in Table 3 indicate that the FPMs exhibit their strongest variability within the transportation functional category. Supplemental material [45] Table A4.1 gives some statistical support for this conclusion showing statistically significant differences among FPMs only in the transportation functional category. For information technology, the result of T tests showed [1] that substantial statistical significance exists for the differences between progress between different functional categories (storage < transportation < transformation) but often not for progress in FPMs in a given functional category. For the results in this paper, T tests show that statistically significant differences exist when comparing *some* different functional categories (Table A4.2) and when comparing *some* FPMs within given functional categories (Table A4.1) [45].

## 5. Discussion

### *5.1. Quantitative comparison of energy and information technological progress rates*

In this section, we will focus upon the quantitative differences between what we previously found relative to information technologies and what this paper establishes for energy technologies over long time periods. Table 4 shows a summary of the progress rates for energy and information technologies as found in this paper

[5] The linear equations are constrained to have FPM > 0 at $t = 1850$ to avoid having meaningless fits that only follow more recent data points.
[6] Comparing these fits is problematic because of different equation forms but does broadly agree with the visual conclusions.

Table 4
Progress rates for energy and information technologies

| Operation | Functional performance metric | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Information | | | | Energy | | | |
| | Name | Period | [a]$R^2$ | [b]Annual progress (%) | Name | Period | [a]$R^2$ | [b]Annual progress (%) |
| Storage | Stored specific information | 1880–2004 | 0.92 | 20.8±1.6% | Energy storage density | 1884–2005 | 0.94 | 2.8±0.4% |
| | | | | | Stored specific energy | 1884–2004 | 0.95 | 3.7±0.4% |
| | Stored specific information per unit cost | 1920–2004 | 0.94 | 26.2±3.1% | Stored energy per unit cost | 1950–2005 | 0.77 | 3.1±1.3% |
| Transportation | Bandwidth | 1850–2004 | 0.88 | 18.9±2.7% | Powered distance | 1889–2005 | 0.93 | 13.2±2.2% |
| | Bandwidth per cable length per unit cost | 1850–2004 | 0.88 | 19.1±2.8% | Powered distance per unit cost | 1889–2005 | 0.78 | 4.3±2.2% |
| Transformation | Calculations per second | 1890–2004 | 0.94 | 36.8±2.7% | Power density | 1881–2002 | 0.88 | 5.3±0.9% |
| | | | | | Specific power | 1881–2002 | 0.98 | 4.6±0.3% |
| | Calculations per second per unit cost | 1890–2004 | 0.95 | 30.9±2.5% | Power per unit cost | 1896–2002 | 0.74 | 6.4±2.2% |

[a] $R^2$ is rounded off to the second decimal place.
[b] The annual progress and error were estimated in 95% confidence interval.

and reference [1] over the period from the late 19th century to early in the 21st. The first (and surprising to very few people) observation is that for each comparable function, information technology shows a substantially higher rate of progress (1.5–4× faster for transport, 6–7× faster for storage and for transformation). A second difference apparent in Table 4 is that the ranking of the rate of progress in the three functional categories is different when energy rather than information is the operand. For information technology, the rate of progress is greatest for transformation and least for transportation whereas for energy (averaging the varying FPM progress rates) the rate of progress is greatest for transportation.

A third quantitative difference is that within a functional category the differentiation among competing technical approaches in rate of progress (and in absolute level of the FPM) is greater for energy than for information technologies. Table 5 shows some details of progress rates for *different energy forms* in the three functional categories of energy technology. Thus, Table 5 shows that even for a given FPM, energy technologies can show different progress rates depending upon the energy form studied. While we believe that generalization of these results must be approached cautiously, Table 5 indicates that progress has been most rapid for technologies involving only the electrical form of energy. These differences among technologies in the same functional category—in all three categories and in the efficiency trends—are substantially greater than for any differences found previously for information technology within a given functional category [1].

### 5.2. Qualitative aspects of technological progress in energy and information technologies

An observation that is semi-quantitative and significant is that for both information and energy operands, continuous exponential progress is found. For two of the energy technology functional

Table 5
Technological progress in energy technology for differing energy types

| Operation | Functional performance metric | | | |
|---|---|---|---|---|
| | Name | Energy type | [a]$R^2$ | [b]Annual progress (%) |
| Storage | Energy storage density | Chemical to electric | 0.94 | 2.8±0.4% |
| | | Mechanical to electrical | 0.99 | 11.1±1.6% |
| | | Electrical to electrical | 0.98 | 14.8±1.8% |
| | Stored specific energy | Chemical to electrical | 0.95 | 3.7±0.4% |
| | | Electrical to electrical | 0.97 | 21.5±1.9% |
| | Stored energy per unit cost | Chemical to electrical | 0.77 | 3.1±1.3% |
| | | Electrical to electrical | 0.82 | 18.3±10.0% |
| Transportation | Powered distance | Mechanical | 0.81 | 0.7±0.5% |
| | | Electrical | 0.93 | 13.2±2.2% |
| | Powered distance per unit cost | Electrical | 0.78 | 4.3±2.2% |
| Transformation | Specific power | Chemical to mechanical | 0.81 | 5.6±1.2% |
| | | Electrical to mechanical | 0.95 | 2.6±0.3% |
| | Power density | Chemical to mechanical | 0.98 | 4.5±0.2% |
| | | Electrical to mechanical | 0.95 | 2.6±0.2% |
| | Power per unit cost | Chemical to mechanical | 0.74 | 6.4±2.2% |
| Efficiency | Energy transformation efficiency | Chemical to light | 0.85 | 3.6±0.8% |
| | | Chemical to mechanical | 0.95 | 1.3±0.1% |

[a] $R^2$ is rounded off to the second decimal place.
[b] The annual progress and error were estimated in 95% confidence interval.

categories, there is—as for IT—no sign of saturation; technological progress continues unabated over these relatively long time periods. In the third functional category (transformation), there is some indication of reduced progress in later periods but not of stoppage of all progress. Certain technical approaches in functional categories with energy as the operand (for example AC power transmission) shows evidence of saturation in capability[7] but newer technical approaches (for example HVDC power transmission) are seen to continue progress in the functional category. The continuation of progress with new approaches (with little discontinuity) was often found when information is the operand. This observation indicates that the long-term functional category approach works for energy technologies as it did for information technology providing a meaningful and stable means of assessing long-term technological progress. However, we noted earlier that the variation of progress rates among FPMs and among energy forms in a given functional category is greater for energy than for information. This indicates that the functional distinction central to our approach is not as useful for energy as it is for information since in this case one progress rate cannot be denoted as characteristic of a functional category.

The final observation in this section is a qualitative dissimilarity between energy and information technology. We found that the data and measures of progress are less readily available for energy

[7] Our results cannot distinguish whether the apparent saturation precedes or follows the emergence of the newer technical approach and thus cannot be used to establish a direction of causation. It appears possible that the emergence of the new approach leads to *apparent* saturation of the existing approach or that technical saturation of the existing approach helps initiate the newer approach.

technology than we found them to be for information technology. While this is generally true, it is perhaps most easily noted for transportation where explicit metrics for assessing this function for energy have not previously been published (at least to our ability to find them).

### 5.3. Energy and information progress similarities and differences

We assert that the first quantitative observation—the fact that information technology improves at significantly faster rates of progress than do energy technologies—is the most fundamental of the quantitative differences noted in Sections 5.1 and 5.2. For example, it seems reasonable that the lack of metrics in energy technology (and indeed less attention to progress) is a natural consequence of this large difference in rates of progress as change does not need to be accounted for as carefully. Among the qualitative similarities, the *continuity* of *exponential* progress over the same long time periods is also particularly significant. Thus, we will focus in this section on possible explanations for these two observations.

The continuous exponential progress is consistent with the concept of new technology building cumulatively on past knowledge. Such a concept has been fairly widely noted [71–74]. Before considering this idea further, it is appropriate to discuss another possibility—noted by several authors (for example [75]) implicitly arguing that the effects are an example of a Self-fulfilling Prophecy as defined by Merton as [76]

> *The self-fulfilling prophecy is, in the beginning, a* ***false*** *definition of the situation evoking a new behavior which makes the original false conception come* ***true****.*

In our case, a belief that a certain progress rate is appropriate can lead to behavior that assures that the progress rate is met. Such effects seem possible for Moore's Law which has become the basis for inter-industry group (SEMATECH) technology planning [77,78]. However, such an explanation seems not to be able to account for the fact that Moore's Law appears to be an extension of a relationship[8] active for much prior time [1,72,79]. In a similar way, the recently named Kryder's Law [80] is only a small part of the exponential progress shown in reference [1] for information storage. A weaker version of the self-fulfilling prophecy explanation is that engineers and others develop an "awareness" of a given progress rate and this then is fulfilled by working toward it. Of course, there is then no pretense of a prophecy and thus the explanation is inactive. Overall, our core finding-exponential progress (at various rates of progress) occurs over long-term horizons in a *wide variety of functional categories in energy and information technology*—is strong refutation of a self-fulfilling prophecy hypothesis as a general explanation for continuous exponential technological progress. To assert that the *previously unrecognized* continuous exponential trends uncovered in this research arose from *prior prophecy* of progress rates seems particularly untenable.

The cumulative knowledge hypothesis arrives at exponential progress because the constantly growing stock of techniques, methods, technologies, frameworks, laws principles etc. form the basis for the current technological capability as well as the potential for the next increment of improvement.[9] Thus, each improvement in technology starts with all prior knowledge (practical and scientific) and larger improvement—indeed constant % per unit time improvement which leads to exponential behavior—is

[8] As is widely appreciated, Moore made forecasts relative to IC chip density that are closely related to the MIPS/$ FPM that is continuous (Fig. 3 in [1]) to periods long before Moore's forecast.

[9] This assumes that the active "knowledge stock" is the same for the past approach as well as for a new approach. If this is not true, then discontinuities of progress rates might be expected with new approaches.

expected from a simple cumulative technological knowledge model. To assert that this simple but reasonable model explains our observations requires some further and more arguable assumptions. One has to assume not just that more is known over time but that the required engineering and entrepreneurial effort is made to develop and implement the improved artifact or process made possible by the enhancement of existing knowledge. This further assumption is reasonable if the FPM improvement can be translated into increased application (market share or new revenue) because then competition-driven continued economic incentive (if the political economic system allows such incentives) can be expected to result in the engineering effort to achieve improvement. The trade-off style of metrics employed in this work was chosen because progress in such metrics *does* provide the potential for new products of increased economic value. Thus, the simplest model that can be expected to apply to technological capability results in exponential progress. S curves have become well established for *diffusion* of specific technological artifacts, innovations or systems and have become (appropriately) firmly embedded in thinking about social and business implications of technology progress. However, carrying this concept (as seems to often happen) over into thinking about technological *capability* appears totally inconsistent with our relatively extensive results. It is therefore important to stress that continuous exponential progress is consistent with a simple but reasonable model for progress in technical capability and is now firmly grounded empirically for a variety of energy and information technological capabilities for more than 100 years.

The results in this paper and our previous paper [1] show for the past 100–150 years that information technologies have outpaced energy technology in progress rates by a factor of 1.5 to 7 with neither type of technology showing strong saturation effects. First we should note that the existence of the progress rate differential is not surprising to people familiar with technology progress. However, our longer term studies tend to eliminate one popular explanation — that the (arguable) earlier origination of energy technologies has led to saturation whereas information technology is more immature and able to grow faster. It has long been recognized that information transformation (and transport) requires at least minimal energy expenditure [17]. It has been argued that these energy needs will eventually cause a fall in the progress rate for information technology. However, past progress that has occurred even with such energy needs tends to support those who argue that technological progress in information technology can and will find ways to keep progressing for many decades despite the practical fact of energy consumption and its involvement in information processing [71,72].

From a fundamental perspective, the connection of information to entropy links the two operands in thermodynamic considerations [16]. Indeed, Shannon in his 1948 paper compared the encoder in information transportation (communication) to the need for a transformer in power transmission. However, the second law of thermodynamics which dictates that energy processing always occurs with some loss of energy does not apply to information processing as Shannon showed this can occur with no information loss. An important limit in energy transportation of any kind is energy loss and technology improvements in this area have concentrated on diminishing this loss so as to allow further progress. For information, Shannon showed in the 1940s [16] that zero loss of information was compatible with information transport. Thus, for information technology improvements have focused on moving the zero loss transport to higher and higher rates.

In a similar way, the second law constraints on energy have important well-known effects on energy transformation processes. Fig. 6 shows overall progress in efficiency in transforming energy from one form to another. It shows that the efficiency for steam turbines has increased from less than 1% in 1700 to about 40% in 2000. Gas turbines (with their much later introduction) matched the steam engine efficiency in the 1980s. Fig. 6 also shows that for lighting systems the efficiency is progressing much more rapidly (see Table 5 for quantitative results) but that even for modern lighting systems only about 10% of the energy is converted to light. Overall, there are two key points relative to Fig. 6. First, even with great improvement in efficiency of conversion, substantial losses in energy are apparent in all of these processes consistent with the dictates of the second law of thermodynamics relative to energy technologies. However, the second point is that the difference in progress rates between information and energy FPMs is not *directly* explained by the fact that energy processing is more strongly constrained by the second law of thermodynamics than is information. Indeed, one might argue that the efficiency improvements seen in Fig. 6 could be an *additional* contribution to progress in energy transformation capability that is not applicable to information transformation.

In an attempt to understand the substantial progress rate differential for energy and information technologies, we consider a further important influence of these fundamental differences on informational and energy-based artifacts and systems. Simon pointed out in 1962 with his simple watch-maker parable that more complexity and efficiency of development was possible in systems that can be decomposed [81]. Baldwin and Clark [82] extended this argument to point to a role of decomposability (they use the term modularity) in fostering rapid technological development. They argue that modularity allows independent development and does not require the high coordination costs of simultaneous development. For a non-modular artifact or system, extensive rework and learning must occur as the various subsystems are improved (changed) because of the interrelated nature of the subsystems. This forced iteration greatly raises the necessary work to develop a new artifact. For our purposes, it is important to realize that increased engineering effort to achieve an improved system may not be as important as the increased time (even with increased effort) involved with developing an improved non-modular system. From quantitative evolutionary theory, this is similar to increases in the set of possible alternatives considered. Baldwin and Clark support their hypothesis by consideration of integrated circuits and the technical developments that make modularity particularly significant for such technologies.

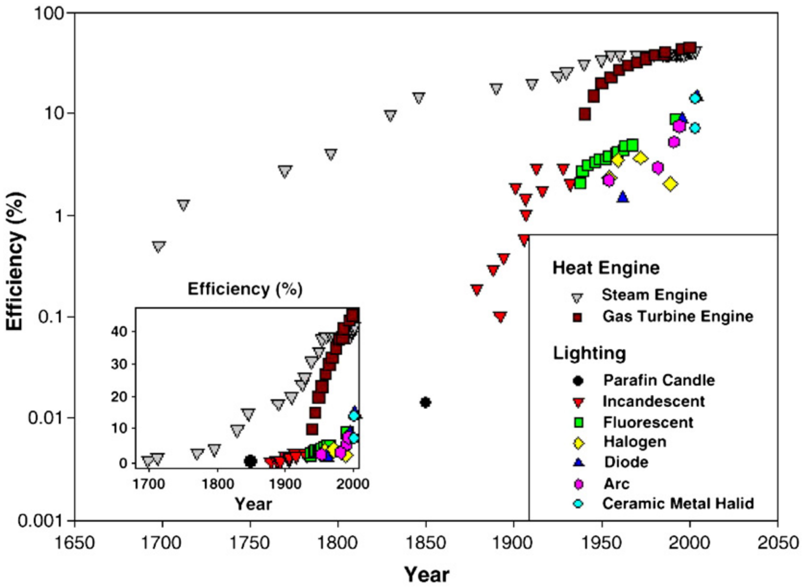


Fig. 6. Progress of energy efficiency for heat engines and luminous devices.

A possible explanation for the faster rate of progress for information technology than energy technology is thus increased modularity for information technology. However, for this explanation to be plausible for explaining the *long-term and widespread* progress rate differentials we have observed, a reason for energy and information technology to be *fundamentally different in modularity* is needed. Whitney [83] has not only observed the greater modularity of information technology systems but has pointed out that the fundamental differences of energy and information lead to the lower modularity in energy technology systems. He argues that lower (and higher) modularity is not just the result of a design approach choice for energy/power (vs. information) technology but instead is a direct consequence of the possibility of ignoring impedance matching at low power which promotes modularity. Conversely, the more important “side effects” associated with high power operations as compared to information processing lead to reduced decomposability/modularity. The side effects make developing or designing modular energy technology systems less effective than for systems that have no side effects (for example information technologies). The side effects (energy losses, need for impedance matching to minimize losses, need to control deleterious effects of energy coupling) pointed to by Whitney at high power arise from the fundamental differences between energy and information technologies discussed in the preceding paragraphs. Such side effects or impedance mismatches are not only larger for energy (in all forms) relative to information but can be argued to be variable within a functional category so that an elaboration of our argument might well explain the variation in progress rates within and between functional categories for energy technologies. For example, lower impedance mismatches for electrical than for mechanical technologies [83] is consistent with the higher rate of progress in energy transport compared to the other functional categories for energy. In a similar vein, the lack of variation in progress rates within each category for information technology is consistent with the lack of side effects and error free processing shown by Shannon [16].

In the preceding paragraphs, we have outlined a possible explanation for the substantial and persistent difference in improvement rate for energy and information technologies. However, other possible explanations—such as differing user impacts and other reasons for fundamental differences in the demand for the technologies—have not been eliminated. Explanations which are period dependent are not applicable because the results show that the progress rate differences exist for all time periods where data has been found.

### *5.4. Implications of results for theories of social change*

The preceding section has offered an explanation for the more rapid rates of progress in information technology as compared to energy technology that is consistent with the empirical observations concerning technological capability changes in the past 150 years. The explanation and observations indicate that these differences have predated the “Information Age”. The explanation relies upon fundamental differences between information and energy and not on saturation effects that rely on energy technology being an earlier mode of technological development. Indeed, we also argued in the preceding section that a simple reasonable model of progress in technological capability results in continuous exponential improvement which is consistent with our observations. In this section, we will consider the implications of the findings of this and the preceding paper [1] on theories of social change. We start by noting that the quantitative study of technological capability such as undertaken in this work cannot be sufficient by itself to understand the impact of technological development on social and cultural aspects of human life [14]. Technological capability is important to but not equivalent to the economic impact of technological change. Similarly, economic impact is important to but not equivalent to social and cultural impact. Thus, we agree with others who note that more holistic analysis will not be replaced by the quantitative study of technological capability in the study of social and cultural changes due to technological change [13,14]. Nonetheless, we believe that technological capability trends over time can inform interpretations of the drivers and the nature of technological change and thus are important to consider when developing theories of technological impacts on society. Thus we next outline some thoughts toward integrating such quantitative empirical results into historical and social studies of technological change. We then discuss the possible implications of exponential change on perceptions of change and the generally accepted idea that information technology is new relative to energy technology. We will close the discussion with consideration of what our results indicate relative to linking of different kinds of technology with different historical eras.

As a start to considering integration of quantitative technological capability into broader analyses, we note that the technological capability increases reflected in our FPMs should not be thought of as exogenous to the economic and social impact. If no economic or social impact of increasing capability is operative, reduced engineering effort and thus reduced progress in capability seems inevitable because the progress is indeed due to *intentional* activities of humans and not to some autonomous force. Because of this, the existence of progress in capability is evidence that the progress matters at least to some extent economically and socially. Indeed, since our FPMs are chosen to reflect key design tradeoffs, progress in such metrics reflects opportunities for designing artifacts and systems of higher economic value. Nonetheless, a one-to-one matching between economic impact and FPM progress is *not* expected for a variety of institutional reasons included in the technological diffusion problem [14,84]. A further consideration of importance is to recognize that linking the functional capabilities studied here to broad “constellations of technologies” [85] sometimes associated with major eras is not trivial. Although the FPMs do reflect key tradeoffs in the technologies in the “constellations”, they are not the only tradeoffs that could be important in designing technological artifacts or systems. In addition, the results considered have not covered all of Table 1 and we do not propose that Table 1 fully covers all technical functions of importance. Despite these caveats, we believe that the results thus far are worth considering in light of the importance of the six functional categories studied and because the FPMs do reflect a first approximation to increases in the value of technological artifacts.

One finding is that progress rates for both information technologies and energy technologies have increased exponentially over the 100–150 year period studied. Although exponential change gives a constant % increase in functional capability per year, the absolute amount of change is consistently increasing. The fact that this change per year is greater now than in the past can be quantified in that over a lifetime the amount of functional capability improvement per year can increase by as much as an order of magnitude even for more slowly improving energy technologies. Thus, the common perception of faster rates of change might be considered to be consistent with the quantitative results of this study.

Moreover, this acceleration of change [72] was in operation before the more recent realization of fast rates of change in information technology. Indeed, faster rates of change for information technology date to at least the 1850s (telegraph transmission capability) [1] so the idea that such rates of change only date to the Moore’s Law era (past 40 years) is clearly in error. The consistency of the rates of progress in the different functional categories over time might make us hesitate in accepting theories that hypothesize clear breaks in technological eras associated with different kinds of operands. The continuous nature of the progress rate improvements over many decades in both energy and information technology appears inconsistent with the idea of distinct revolutionary periods for either or both types of technologies. Even before the period that we have been able to quantitatively study, information technologies (for example, language, the alphabet, the printing press, accounting methods, the abacus etc.) contributed enormously to technological and social change [86]. In the last 150 years but before the middle of the 20th century (an often used boundary for when information technology began to dominate), many other important information technological developments such as telegraphy, radio, television, photography, movies, sound recording, telephones etc. occurred. It is therefore not reasonable to imply that all information technology change is of recent origin. The quantitative changes empirically established in the current work also indicate that there seems to be little factual basis for associating only the recent era with rapid improvements in information technology or for thinking that *all* technological progress now occurring is due to progress in information technology. A similar flaw is apparent in the broad conceptual idea that materials technology preceded energy and information technology in an evolutionary time frame [7,8]. Although stone tools did precede fire which may have preceded language, this does not establish a fundamental principle. Indeed, it is apparent that changes in materials technology are still extremely important in improving both energy (for example photovoltaic materials and materials for heat engines) and information (for example silicon and fiber optics) technological capability.

However, we believe it would be seriously incorrect to use the results of our work to argue against the association of recent cultural changes with information technology. In the first case, increasing awareness of information technology improvements can logically arise because they have recently begun to significantly improve upon earlier information technology developments. In this regard we note the point made in [1] that the 80 year exponential improvement in information storage by mechanical and electronic means had only recently (~1990) surpassed printing on paper as to information storage per unit cost. A second and more important point is that even though the progress trends have been consistent over time, the rate of progress for information technology has been *consistently significantly greater* than the rate of progress for energy technology. The consistent long-term progress rate difference has accumulated in a higher state of information technology capability that is *continuously increasing* relative to energy technology. The accumulating difference is important where information technology and energy technologies represent alternating approaches to fulfill a human need and assures that over time information technology will continue to supplant energy technology. The accumulating difference in technological capability also assures that as time progresses, more of the new generally noticed applications (IPOD, the Internet, etc.) will be more closely associated with information technologies. Thus, more of the artifacts and systems in current technological "constellations" will be informational in character justifying the association of the current changes (predominantly) with information technology. The accumulated difference in technological capability will also lead to transitions in economic sectors away from pre-existing technology constellations towards constellations dominated by information technology. Thus, the current dominance of information technology is not due to its recent emergence but instead to its long-term (fundamentally based) superiority of progress. It should also be noted that in an age where more of the technological changes are associated with rapidly improving information technology, the perceived overall rate of technological change is also accelerated.

The present quantitative results do not imply distinct "revolutions" at particular time periods during the past 250 years. Whatever hesitations and changes in direction have occurred, there is no evidence for long stases separated by rapid change in the quantitative technological capability record of the past 150 years but instead continuous progress (even if at different rates) in a wide variety of functional categories. It would appear that the entire period at least since 1750 might best be viewed as a period of rapid—if somewhat uneven in impact—progress. Perhaps "punctuated equilibrium" [87] and its general applicability to evolutionary processes suggests an eventual stasis but if "punctuated equilibrium" is applicable to technology development, it appears to act either on a much longer time scale than that used by most historians of technological development or at a higher level of abstraction than technological capability. Indeed, it is entirely feasible that relatively continuous increases in technological capability result in uneven or highly variable rates of economic and social impacts of technology perhaps due to lags in progress of social technology [84] or institutional change [88].

## 6. Conclusions

Quantitative analysis of the change in technological capability for energy and information technology over the past 150 years show that both types of technologies have continuously progressed exponentially but with information technologies progressing at significantly faster rates over the entire period. The observations are consistent with the idea that the progress rate differential is due to *fundamental differences* that allow information technological artifacts to be more decomposable than energy technology artifacts. On a practical engineering and business level, knowledge about such trends can be valuable in product and process planning, problem solving and research planning.

The observations (and the explanation) appear inconsistent with interpretations of social change due to technology being *cleanly* separated into eras where one and then the other of these types of technologies have dominated. However, the long-term, consistent superiority of information technology progress rate does mean that as time goes on, information technologies will become more and more important relative to energy technologies in the technological "constellations" of greatest economic and social significance. The fact that information technology is seen to be of particular importance in the current era is thus not due to its newness but instead is the result of the accumulation of a consistent long-term progress rate advantage over slower progressing technologies like energy technology.

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