Thinking about the Future of Complex Technological Systems: Which Technologies Should Shape Their Designs?

Jeffrey L. Funk

Abstract. The long lifetime of technological systems increases the importance of understanding those technologies that are experiencing rapid improvements. Ideally we would like to design our systems around these technologies so that we can benefit from the future benefits that these rapid improvements in component performance and cost can provide at a system level. This paper provides data on technologies that are experiencing rapid improvements and it uses transportation systems to demonstrate the impact of rates of improvement on system design issues.

1 Introduction

Many systems are expected to last decades if not centuries. This includes transportation, water and electricity distribution, housing, health care, information, communication, defense, and energy distribution and transportation. During this long life, improvements are expected to occur as new technologies emerge or as improvements to existing ones are made. This suggests that we should design systems around those technologies that are experiencing rapid improvements so that we can benefit at a systems level from these rapid improvements in component performance and cost.

But what are the technologies that are experiencing rapid improvements? We argue that this is not a non-trivial question and that few decision makers can actually answer it. For example, wind turbines are considered an important clean energy technology yet they have only experienced cost improvements of about 2% a year since the early 1980s (IPCC, 2013). Similarly, the energy storage density of Li-ion

Jeffrey L. Funk
National University of Singapore, Division of Engineering and Technology Management,
9 Engineering Drive 1, Singapore 117576
e-mail: etmfjl@nus.edu.sg

M.-A. Cardin et al. (eds.), *Complex Systems Design & Management Asia*,
DOI: 10.1007/978-3-319-12544-2_11

batteries, which impacts on the range and efficiency of electrical vehicles, has only risen at about 5% per year since the early 1990s (Tarascon, 2009). Contrast these rates of improvements with those of electronic components that are between 25 and 40% and one wonders why Li-ion batteries and wind turbines are considered important tools in the clean energy tool chest.

This paper provides data on technologies that are experiencing rapid improvements and the relevance of this data is demonstrated through examples of transportation systems. In doing this, we are not arguing that we have identified all of the technologies that are experiencing rapid improvements or all of their implications for transportation and other systems. We are merely arguing that understanding those technologies that are experiencing rapid improvements is important for designing systems and that better data is needed on rates of improvement in order to better design systems.

This paper first summarizes technologies that are experiencing improvements of greater than 10% per year. Second, the impacts of these rapid rates of improvement on transportation systems are then described. Third, the implications of these analysis for system design are summarized.

2 Technologies Experiencing Rapid Improvements

Table 1 summarizes technologies currently experiencing rapid rates of improvement. This data was found in *Science*, *Nature*, *IEEE*, and other science and engineering journals through extensive reading and searches. We characterize these improvements as annual rates of improvement since most of the time series data are straight lines on a logarithmic plot. We define "currently" as time series data that includes data from the last 10 years. Thus, although some of the time series shown in Table 1 include data from 30 years ago, the technology is included in Table 1 because the times series includes data from the last 10 years and the older parts of the time series data are retained for completeness. The relatively constant improvement rates for longer time periods suggest that these rates can be more reliably extrapolated into the future than can ones with shorter time periods.

The technologies are placed into several categories, which are consistent with characterizations of engineering systems (de Weck et al 2011). These categories include the transforming, storing, and transporting of energy, information, materials, and living organisms. Since a variety of performance measures are often relevant for a specific technology, data was collected on multiple dimensions some of which are represented in performance of basic functions per unit cost while others are in performance of functions per mass or per volume.

As expected, the rates of improvement for information transformation, storage and transmission are experiencing the most rapid rates of improvement. This includes well known components such as integrated circuits and magnetic disk drives and systems composed of them such as computers and mobile phone telecommunication systems. However, newer forms of information processing technologies such as MEMS-based sensors, organic transistors, single walled carbon nanotubes for transistors, and quantum computers are also experiencing rapid improvements and this suggests that there is no end in sight for Moore's Law and improvements in information systems.

Furthermore, many of the technologies classified under energy transformation are actually information technologies. For example, LEDs, OLEDs, GaAs lasers liquid crystal displays, and quantum dot displays transform electrical energy into light and thus are classified under energy transformation. However, unlike engines or motors, these technologies do not do work. Instead, they are used to display or transmit (e.g. lasers) information by transforming electrical energy into light. Even DNA sequencers can be defined as processors of information because they transform biological materials into information. Thus, most of the technologies that are experiencing rapid improvements are applicable to information systems.

The major exceptions are superconductors for energy transmission, carbon nanotubes and grapheme for structural applications, and cellulosic ethanol for energy. The small number of exceptions highlights the need to design systems around information more than other technologies because information technologies experience rapid improvements. Emphasizing information technologies in our design of systems will help us benefit at the system level from improvements in information technologies. We now demonstrate these ideas by looking at transportation systems.

3 Implications for Transportation Systems

The technology currently most discussed for transportation systems is electric vehicles that use batteries and electric motors in places of gasoline and internal combustion engines. The problem with electric vehicles is that the rates of improvement for batteries are very slow, only 5% per year and if these rates continue, the energy storage densities for batteries will not reach the 25 times higher levels found in gasoline for at least 60 years. Since energy storage densities have a large impact on the weight and range of the vehicle, it is very unlikely that battery-powered cars with the range of existing cars will appear for at least 60 years. Furthermore, low energy storage density can lead to a vicious cycle of heavier cars requiring more batteries and more batteries leading to heavier cars.

Of course some may argue that hybrid vehicles are sufficient or that these rates of improvement might increase as scientists and engineers create new materials that have higher energy and power storage densities; these are certainly a plausible future. We argue, however, that these are less plausible futures than the ones we describe below. For the former, users will always prefer a conventional vehicle over a hybrid vehicle since it is much cheaper. For the latter, other technologies are either experiencing more rapid rates than are batteries and/or other technologies are much closer to reaching their necessary levels of performance and cost than are batteries. Furthermore, batteries are not a new technology; they have been used in vehicles for more than 100 years so acceleration in the rate of improvement is unlikely.

Instead, we believe that technologies experiencing rapid improvements (See Table 1) or technologies experiencing moderate rates of improvements but are close to their necessary levels will probably have a larger impact on the effectiveness of transportation systems than will electric vehicles. This section summarizes scenarios that are more plausible than one of electric vehicles reaching the range and cost of conventional vehicles. First, improvements in ICs, sensors, computers, and mobile phones are rapidly improving the effectiveness and usability of public transportation. Specially designed computer systems are improving the capacity utilization of public transportation while improvements in mobile phone technologies and GPS are making it easier to find public transportation such as subway stations and buses. The increased use of GPS in buses will enable users to better monitor the timing of buses and to find the closest bus on their phone.

Second, improvements in cameras, MEMS, lasers, and wireless communication are making autonomous vehicles economically feasible. With annual improvements rates of 25% to 40% for many of the sensors, the cost of the controls for autonomous vehicles will probably drop by 90% in the next ten years thus making autonomous vehicles not much different from conventional vehicles. The largest benefits from automated vehicles will probably occur when roads are dedicated to them and thus tightly packed vehicles can travel at high speeds. Since fuel efficiencies drop as vehicle speeds drop, the use of dedicated roads for autonomous vehicles can have a dramatic impact on fuel efficiency and road capacity, two common problems in most urban and suburban settings. It is likely that autonomous vehicles will become economically feasible before the energy storage densities of current batteries are doubled, which will probably take as long at the last doubling occurred (15 years).

Third, most electrical utilities are combining the Internet, whose performance and cost are experiencing rapid improvements, with the electrical grid to create smart grids. One outcome of adding intelligence to our well established electrical grid can be the capability of vehicles to easily find and purchase electricity from a high density of charging stations in urban and suburban parts of developed countries. Since the cost of distributing electricity is much lower than that of gasoline, the cost of the charging stations is probably not as important as licensing large numbers of firms to sell electricity and thus overcoming the network effects associated with the number of charging stations and electric vehicles. Overcoming these network effects would enable electric vehicles to be charged while a vehicle is parked in a parking garage or along a street in the future (Huber, 2011). This would enable the vehicle to have far smaller storage capacities than are ordinarily thought and thus not depend on improvements in energy storage density.

Fourth, the implementation of densely packed systems of rapid charging stations are also facilitated by the improvements in energy transmission performance that are coming from improvements in superconductors. Superconductors are widely used in magnetic resonance imaging and are beginning to be used in transformers, cables, fault current limiters, motors, generators, and energy storage. We can envision these superconducting transmission lines providing extensive charging points throughout urban and suburban areas.

Fifth, gradual improvements in the performance and cost of power electronics are enabling the "electrification" of automobiles, which reduces the weight and thus the necessary battery capacity of vehicles. This replacement of mechanical controls and drive trains with electrical ones has already occurred in aircraft and heavy trucks and is now occurring in automobiles as the cost of power electronics gradually falls. While the rate of improvement is fairly slow (about 4% per year), announcements by automobile manufacturers suggest that the electrification of vehicles will be largely finished within the next five to ten years (CESA, 2013) and this will reduce the need for large storage capacity in batteries.

Sixth, two alternatives to batteries, capacitors and flywheels, experienced faster rates of improvement in energy storage density than did batteries until 2004 (10% for flywheels and 17% for capacitors) (Koh and Magee, 2006) but more recent data is not available and thus they are not shown in Table 1. This suggests that one of them will eventually have higher densities than do batteries for electric vehicles. Although capacitors have experienced faster rates of improvement than have flywheels, flywheels are currently ahead of capacitors and they are widely used in Formula 1 vehicles, partly because they have higher power densities than do batteries. One of the reasons for the rapid improvements in the densities for flywheels is the replacement of steel and glass with carbon fibers. Carbon fibers have higher strength to weight ratios than do steel or glass and thus can rotate faster than can steel or glass-based ones. Rotational velocity is important because the energy storage density of flywheels is a function of rotation velocity squared. Carbon nanotubes (CNT) have even higher strength-to weight ratios than do carbon fibers and thus CNT-based flywheels can potentially have even higher energy storage densities than do carbon-fiber based ones. Some estimates place the strength-to weight ratios of CNTs at ten times higher than those of carbon fiber. This suggests CNT-based flywheels can have an energy storage density that is ten times higher than that of carbon fiber based flywheels and thus batteries (Krack, Secanell and Mertiny, 2011).

4 Discussion

To the extent possible, systems should be designed around technologies that are experiencing rapid improvements. This paper provides information on technologies that are experiencing rapid improvements and it demonstrated how rates of improvement can impact on one types of system, transportation systems. Transportation systems are expected to be used for decades and it is unlikely that transportation systems designed around electric vehicles will become economically feasible in the near future without considering the low rates of improvement that Li-ion batteries are experiencing. Without considering these low rates of improvement, it is doubtful that electric vehicles with the range and acceleration of existing vehicles will emerge for at least 60 years.

Nevertheless, more data on rates of improvement are needed. There are many types of technologies and many types of systems that can be designed around these technologies. More data will improve our understanding of the tradeoffs between various systems and will thus help us design better systems. We look forward to working with other scholars on better databases of rates of improvement for various technologies and on their impact on various systems.

Table 1 Technologies with Recent Rapid Rates of Improvement

Technology Domain	Sub-Technology	Dimensions of measure	Time Period	Improvement Rate Per Year
Energy Transformation	Light Emitting Diodes (LEDs)	Luminosity per Watt, red	1965-2005	16.8%
		Lumens per Dollar, white	2000-2010	40.5%
	Organic LEDs	Luminosity/Watt, green	1987-2005	29%
	GaAs Lasers	Power density	1987-2007	30%
		Cost/Watt	1987-2007	31%
	Liquid Crystal Displays	Square meters per dollar	2001-2011	11.0%
	Quantum Dot Displays	External Efficiency, red	1998-2009	36.0%
	Solar Cells	Peak Watt Per Dollar	1977-2013	13.7%
		Efficiency, Organic	2001-2012	11.4%
		Efficiency, Quantum Dot	2010-2013	42.1%
		Efficiency, Perovskite	2009-2013	46.5%
Energy Transmission	Super-conductors	Current-length per dollar	2004-2010	115%
		Current x length - BSSCO	1987-2008	32.5%
		Current x length - YBCO	2002-2011	53.3%
Information Trans-formation	Microprocessor Integrated Circuits	Number of transistors per chip/die	1971-2011	38%
	Power ICs	Current Density	1993-2012	16.1%
	Camera chips	Pixels per dollar	1983-2013	48.7%
		Light sensitivity	1986-2008	18%
	MEMS for Artificial Eye	Number of Electrodes	2002-2013	45.6%
	MEMS Printing	Drops per second	1985-2009	61%
	Organic Transistors	Mobility	1984-2007	94%

Table 1 (*continued*)

	Sub-Technology	Dimensions of measure	Time Period	Improvement Rate Per Year
Information Trans-formation	Single Walled Carbon Nano-tube Tran-sistors	1/Purity	1999-2011	32.1%
		Density	2006-2011	357%
	Super-conducting Jo-sephson Junc-tions	1/Clock period	1990-2010	20.3%
		1/Bit energy	1990-2010	19.8%
		Qubit Lifetimes	1999-2012	142%
		Number of bits/Qubit lifetime	2005-2013	137%
	Photonics	Data Capacity per Chip	1983-2011	39.0%
	Computers	Instructions per unit time	1947-2009	36%
		Instructions per kw-hour	1947-2009	52%
	Quantum Comput-ers	Number of Qubits	2002-2012	107%
Information Storage	Magnetic Storage	Recording density of disks	1956-2007	36.5%
		Recording density of tape	1993-2011	32.1%
		Cost per bit of disks	1956-2007	38.5%
	Flash Memory	Storage Capacity	2001-2013	47%
	Resistive RAM	Storage Capacity	2006-2013	272%
	Ferro-electric RAM	Storage Capacity	2001-2009	37%
	Magneto RAM	Storage Capacity	2002-2011	58%
	Phase Change RAM	Storage Capacity	2004-2012	63%

Table 1 (*continued*)

	Sub-Technology	Dimensions of measure	Time Period	Improvement Rate Per Year
Information Transmission	Last Mile Wireline	Bits per second	1982-2010	48.7%
	Wireless, 100 meters	Bits per second	1996-2013	79.1%
	Wireless, 10 meters		1995-2010	58.4%
	Wireless, 1 meter (USB)		1996-2008	77.8%
Materials Trans-formation	Carbon Nanotubes	1/Minimum Theoretical Energy for Production	1999-2008	86.3%
	Graphene	Cost per square cm	2009-2013	216%
Biological Trans-formation	DNA	Sequencing per unit cost	2001-2013	146%
		Synthesizing per unit cost	2002-2010	84.3%
	Cellulosic Ethanol	Output per cost	2001-2012	13.9%

RAM: random access memory; MEMS: microelectronic mechanical systems. Sources: Adapted from (Funk and Magee, 2014)

References

CESA (2013), http://cesa-automotive-electronics.blogspot.sg/2012/09/dual-voltage-power-supply-system-with.html

de Weck, O., Roos, D., Magee, C.: Engineering Systems. MIT Press, Cambridge (2011); Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change, IPCC 2013. Cambridge University Press (2013)

Funk, J., Magee, C.: Exponential Change: What drives it? What does it tell us about the future (2014)

Huber, P.: Broadband Electricity and the Free-Market Path to Electric Cars, ManhattanInstitute for Policy Research (2011)

Krack, M., Secanell, M., Mertiny, P.: Rotor Design for High-Speed Flywheel Energy Storage Systems. In: Carbone, R., Tarascon, J. (eds.) Energy Storage in the Emerging Era of Smart Grids. Batteries for Transportation Now and in the Future, presented at Energy 2050, Stockholm, Sweden, October 19-20 (2011)