AC 2011-1245: A BALANCED VIEW OF NEW TECHNOLOGIES

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A Balanced View of New Technology Evolution

Abstract

Emerging technologies are essential contributors to the future energy and economic roadmap. Although their technology and associated engineering are well-represented in academic programs, the factors that can promote or hinder widespread adoption are invariably given less emphasis. A quantitative process has been developed to demonstrate progress of alternative energy sources towards market maturity. It has been tested in a number of courses and the paper provides guidance on its use, pitfalls, typical results and options for development. The cases covered are batteries and portable fuel cells with non-volatile memory used as a consumer product benchmark.

Educational rationale

The principles, materials and design of alternative energy sources can now be found in most engineering and technology degree programs. However, the stages of evolution they will have to pass through to achieve the desired market adoption have traditionally been given less emphasis. There are three principal reasons:

- Technologies have evolved slowly. The process typically took the greater part of a professional working life so it could be learned on the job.
- Emerging technologies are often covered in senior or masters-level courses. The content aligns well with faculty research interests but the treatment is rarely set in the general economic context of market requirements.
- All technologies are multi-disciplinary, especially as they reach the revenue-generating stages of maturity. Discipline-based academic units find it difficult to manage the implied breadth as well as depth in courses.

The need to break out of the status quo is now being driven partly by the speed with which new technologies can be brought to maturity and also because of the economic pressure to do so. Bringing alternative energy sources from a niche role into widespread use is one of the most pressing grand challenges. The underlying science and engineering principles are well established but for a commodity like energy, widespread adoption depends on delivering lower costs and matching loads both in time and location. These are extremely difficult performance goals for but the rewards for success are high with a global market waiting eagerly.

The rationale for making space to cover the path to technology maturity in an already overcrowded curriculum is that it defines many future engineering jobs. The solar cells, batteries and fuel cells can be manufactured today but can they beat the international competition to deliver the tough commodity performance metrics? High-level roadmaps for alternative energies have been formulated [1] but the goals remain stubbornly distant [2]. That emphasizes the need to recruit and prepare quality graduates equipped with the skills and tools to fully understand the scope of the challenge and to contribute solutions. One great advantage available to academic practitioners is that the process from concept to maturity is common for almost all product families and technologies so the experience of one sector can be exploited to show opportunities in another.

Project scope

Hardly a week passes without some new product or material being touted as the miracle solution that will drive the next wave of high-tech development [3]. Good students read these news reports and see them as pointers for their own career development. The reality is much less clear-cut. The advocates obviously dwell on the strengths of the new technology and sometimes their enthusiasm can drift into unrealistic hype. Few of their claims will be realized in the form predicted. Even the developments that eventually succeed will have a tortuous and demanding evolution path. The goal of the project reported in this paper was to integrate wide-scope technical analysis and cases studies into a degree program to explain the steps to technology maturity for new energy sources.

Technology evolution is based on the interaction of engineering, economics and market opportunities. This makes it difficult to compile the balanced view of the strengths and deficiencies of any emerging energy technology that is essential for long term planning. Maturity is defined by the ability of a class of products to generate enough market revenue to sustain evolution and growth without subsidies or preferential trade conditions. At that stage of development, market growth is often determined more by constraints than by new applications or performance features. These constraints are opportunities for those who recognize them.

Many parties have an interest in making objective assessments of the possible success of emerging technologies - from venture capital investors to students pondering their career direction. To make the task more tractable, the process described in this paper is directed towards generic new energy technologies rather than individual projects or products that use them. This avoids the minefield of research project funding, venture capital and peer-reviewed publications. The goal is to determine the maturity state and intrinsic merits of an emerging technology rather than measure the capacity of an individual or group to make it a success.

Constraints on evolution

For any new technology to be a success it must pass three competitive tests.

1. There must be enough customers to sustain a business. If the innovation is radical, it can be seen as meeting only a niche market and a self-limiting process of investment and development follows.

2. If the new technology is a replacement for an existing product, for example a new portable electrical energy source, there is a cost target to be met, in this case the cost of batteries. Until the new technology can approach the market cost-per-

function, benchmark comparisons will be poor [4] and there will be a natural reluctance to move away from the familiar technology. The commodity market is the hardest for any emerging technology to penetrate. Energy is a commodity.

3. International standards relating to quality, safety, environment, ethical applications and warranty have to evolve *and be met*. It can be a slow process but if standards are not met, the evolution of the technology will be curtailed [5].

These three constraints are a formidable 'catch-22' that is rarely featured in technical papers and even less in degree programs. However, most of today's high-impact technologies had to overcome similar challenges [6] and future economic success will go to those with viable solutions.

The simplest and perhaps aptly-named model for technology evolution is called 'The Valley of Death' and is represented in figure 1 [7]. It shows two types of funding for technology development. The x-axis is a non-linear time scale to encompass the stages of evolution of the technology from the original concept through combinations of research, development and production to end-of-life (EOL). The curve with a peak denoted by A aggregates all the sources of research funding (mostly from the federal government). The curve with a peak at B is derived from earnings retained in the business from open-market sales. The gap between A and B is the Valley of Death. With the loss of industry contributors such as Bell Labs, the gap is getting wider. However, if an embryonic product or new technology can cross the Valley of Death, that becomes an important early indicator for further success.

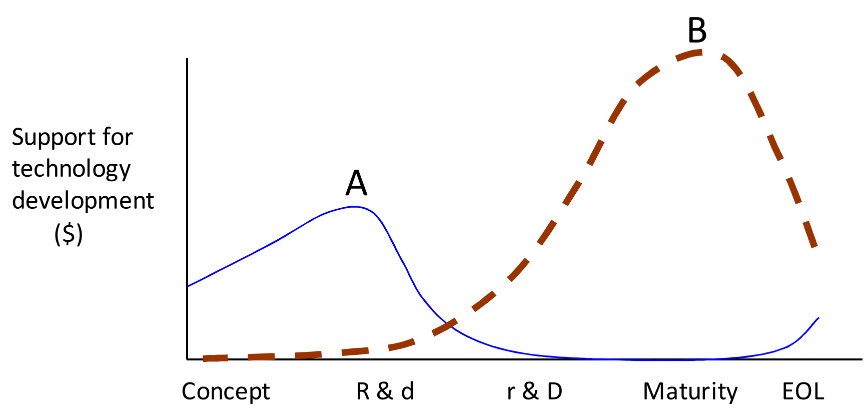

Figure 1. The Valley of Death

Two further general observations can be made:

- Since figure 1 refers to technology maturity, many companies and institutions are involved. There is a spread between leaders and followers but they are all on a similar evolutionary path.
- With hindsight, participants at A are too optimistic about the prospects for their progress to B while the successful technologists at B admit that there was a lot more they should have understood at A.

Measures of maturity

The concept of an all-embracing metric to measure performance or maturity is well known. The Technology Readiness Index or Level (TRI or TRL) was developed by NASA more than 20 years ago [8]. It is widely used by the defense industry. There are 9 levels with brief descriptions shown in figure 2.

	Level	Features
Explore	1	Basic principles observed & reported
	2	Concepts or applications formulated
	3	Lab studies to validate concepts
Examine	4	Components or sub-systems in lab form
	5	Show components in relevant environment
	6	Prototype product in relevant environment
Exploit	7	System prototype in operational environment
	8	System technology qualified
	9	Technology has successful mission operations

Figure 2. Technology Readiness Levels

The TRI is important because it is well-accepted for risk identification and analysis. The levels are defined in detail in the federal government literature [9, 10] but they can also be summarized concisely and usefully as shown in figure 2. The limitation of the TRI is that it was designed to assess components and cannot handle the much greater diversity of concepts, criteria and expectations involved in determining the maturity of a whole new technology. However, it is a good starting point for more extensive measures.

The goal for this project was to create a tool that will give a numerical measure of the maturity of a technology. The first step was to compile an extended list of the factors that must be present for any technology to be accepted and widely used. The current list is shown in figure 3. The list evolved to this state through many empirical trials [11]. Many technology cases were explored both in graduate classes and in short training courses in risk management for industry executives. The general evolution path is that in its early stages, a new technology borrows heavily from existing (successful) technologies. Then as it matures and gains acceptance, the parameters become more specific. Examples are unique tools, standards and regulations. For the more cynical, the first big patent litigation is a sure measure that positions are being taken seriously.

	Measure	Scope
1	Technology application	NASA metric from lab to trusted in the field
2	Validity of the science base	What's understood and well-validated
3	Intellectual property	Patents and trade secrets
4	Dedicated tools and processes	Tools for design. production, support and EOL
5	Supplier readiness	Location and number
6	Manufacturability	Crafted to capable
7	Qualification procedures	Ad hoc to universally accepted
8	Standards	Local, company, national, global
9	Failure and security	Discovery, known, design variable
10	Environment, safety and liability	Specific rules, tested in court
11	Market readiness	Early adopters to obsolete
12	Functional competitors	Number in the market
13	Price expectations	Determined by cost to commodity
14	Synergistic potential	Hybridize with other technologies
15	Sources of investment	Gov, VC, retained earnings
16	International locations	Measure globalization of the technology
17	A capable workforce	Self-taught, adapt, career path
18	Public awareness	Whispers, experts, hype, tech, politicains

Figure 3. Maturity parameter list

For each of the 18 parameters, independent data can be sought about its status. Evidence can be found from a very diverse range of sources. As well as the usual technical press, easily available sources such as trade magazines, blogs, lawsuits, legislation, advertising and news items provide a full 360^{o} view of the status. The resulting data is diverse and often has intrinsic conflicts but that has to be accepted and managed if the full capabilities of web searches are to be exploited.

Maturity is measured on a linear scale from 1 to 10 for each of the 18 parameters. The generic features for each value are listed in figure 4.

Score	Rubric
1	Concept exists, no other attributes
2	Topic is defined by originator(s)
3	Local conditions are adapted to fit
4	External interest, some 'buzz'
5	Serious external scrutiny, some hostile
6	Significant speculative growth
7	Self-sustaining from revenue earned
8	Full competition in all major markets
9	Mature technology cash cow
10	End of life management

Figure 4. General grading rubrics.

The tool is an Excel spreadsheet with a mouse-over comment that explains the scoring criteria for that parameter and level. A section is shown in figure 5.

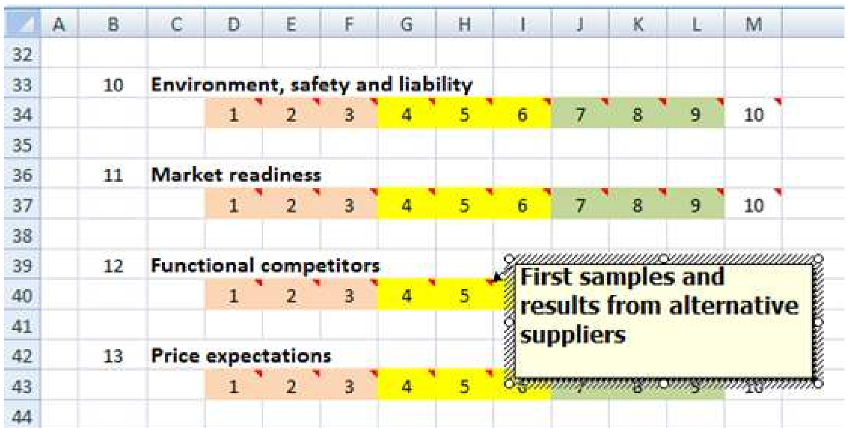

Figure 5. Section of scoreboard spreadsheet.

It is impractical to list all 180 rubrics. However, they all escalate in the sequence shown in figure 4. It is likely that other criteria will be added or some of those listed could be sub-divided. Fortunately, this does not require the consistency and rigor of an investment tool so the scope can be adapted to meet individual course needs.

Application within educational programs

The maturity assessment tool has been used in four educational contexts:

- A junior-level course at ASU on the tools for engineering management of technology development.
- A senior course at OIT on batteries and portable energy sources.
- A senior course at ASU on “Systems on silicon”.
- Short training courses for Chief Engineers in the aerospace and communications sectors.

Results from the first three are presented here. The conclusions from the industry groups are substantially the same but participants were able to use their broad experience and rely less on searching for evidence so the whole evaluation could be done much faster.

The assessment process is best treated as a class project. The rules are simple. The maturity index number must be supported by at least three independent items of evidence. As usual, the first recourse of students is to launch a web search. In this case, it works well since there are no restrictions on the sources of information and the goal is to get an overview of the evidence. The decision on what evidence to select is ultimately subjective but it is important that students learn how to make credible subjective decisions. The counterbalance is that such decisions have to be defended. If two or three students tackle each criterion, their conclusions (and evidence) have to be reconciled into a single number. That leads to a great deal of discussion as each quasi-informed position is defended and then adjusted. It usually requires only light oversight from the professor and the most useful learning outcomes come from this discussion. By having different student combinations for each criterion, a reasonable balance can be achieved. The final activity is to have a summary presentation of the outcome for each conclusion to the whole class.

Ratings are presented in figure 6 for three cases:

- Small rechargeable batteries for portable electronics
- Direct methanol fuel cells for portable applications
- Phase-change memory as a benchmark from another consumer market.

In all cases, the underlying technology is well-understood and has been in small-scale applications for decades. Mass markets, however, present other problems – all associated with cost. Phase change memory will only displace today's ubiquitous flash memory when it achieves price parity to complement its better performance. Portable fuel cells face the same challenges to displace the battery alternatives.

	Measure	Battery	Portable FC	PC memory
1	Technology application	9	5	7
2	Validity of the science base	9	7	7
3	Intellectual property	9	7	8
4	Dedicated tools and processes	8	7	7
5	Supplier readiness	8	5	8
6	Manufacturability	8	6	7
7	Qualification procedures	10	2	7
8	Standards	9	4	7
9	Failure and security	9	4	7
10	Environment, safety and liability	7	10	8
11	Market readiness	10	5	7
12	Functional competitors	10	6	7
13	Price expectations	9	6	7
14	Synergistic potential	9	8	8
15	Sources of investment	7	5	7
16	International locations	8	4	7
17	A capable workforce	6	4	8
18	Public awareness	9	6	7

Figure 6. Class scores for technology assessment.

The maturity assessment shows that the way forward for the two 'upstart' technologies is very different. The PCM technology gains through being able to use many of the same tools, materials, design and distribution channels that are available for mainstream semiconductor production [12]. As a result, its ratings are all at a similar level and put the technology on the verge of mass-market penetration. Portable fuel cells have less synergy of this kind so the maturity ratings show a much wider range of values. The leading companies still have a lot to do to build the technology infrastructure needed for volume production. The comparison between different levels of maturity and across different markets brings home the diversity and scale of the task to use technology and innovation to remain competitive in a global economy [13].

From the student perspective, the first surprise is usually that their common search technique (the first page of a Google query) does not work well. To find evidence, the context has to be understood and many more pages and query formats have to be checked. That requires understanding so a lot of self-directed learning has to be applied during the process of searching. This is the adult learning paradigm. Concept roadblocks uncovered in the search process lead to many requests for explanations. They are usually provided on demand as small *ad hoc* tutorials. The same issues arise again and again in all the parameter search teams. Student response to the search process is also a good discriminator of personal maturity.

It is impossible to show any numerical maturity ratings (figure 6) without generating controversy. That is a large part of its educational purpose. A class may passively accept a theoretical or technology description but defending a number for each parameter requires personal commitment. The supporting evidence for any rating depends on its source and the search methodology used. Students quickly realize that their conclusions will be challenged and their conclusions will survive better if their search questions had anticipated the likely challenges. They learn to distinguish between superficially attractive solutions which may deliver short-term technical results from those which can sustain market growth and at the same time offer a better value proposition than the established technology.

Conclusions

The educational value to students comes from directed research to find corroborating data, filter out hype and analyze where there is enough synergy to justify a sustainable business trend in an emerging technology. Invariably, this requires balance across the technology maturity parameters so there are important learning outcomes to compare the relative contributions of strong versus debilitating technology features. The evidence is often indirect and frequently contradictory so students have to develop their own criteria to aggregate it into a single rating that can withstand critical review. The concepts have been tested in senior BS and MS academic courses in two universities and in industry short courses for engineering executives.

One of the most important outcomes from any application of the assessment tool is the emphasis it gives to the development time domain. All too often, technology development is viewed as an obvious and automatic process that just happens at its own pace. Many factors (in this case 18) have to evolve in parallel and a weakness in any one can significantly delay the progress of a new technology to revenue generation.
A sound appreciation of the interaction of the technology maturity parameters can assist career planning and develop the soft skills students should seek to acquire through their

degree program. The assessment tool provides an easy-to-use map for technology development as well as a simple way to quantify what has to be done and how it can be measured. It can be applied both to incremental technology and to the most novel concepts.

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