Defining Sustainability: Critical Factors in Sustainable Material Selection

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Abstract

The designer is faced often with questions of material selection. To answer these, functional requirements must always be met, and second the cost constraints of the project must not be exceeded, and preferably they are minimized. Sadly, once the functional requirements are met, and the costs minimized, the selection process usually ends. By taking a life cycle analysis approach, the environmental impacts of a particular material can be assessed properly. If this were the third criterion, one could expect that environmental impacts like carbon emissions, energy requirements, and toxic emissions would all be minimized. But will these efforts result in sustainable material use? In this article we postulate that the additional question of whether a material can be recycled repeatedly without degradation, or cycled at a sustainable rate through nature (for example, by composting), is the most significant question to ask when assessing the sustainability of a particular material. Because economic considerations are often held paramount, it is common to select non-recyclable materials that are eventually discarded. These non-recyclable materials must be acquired as primary resources, and all the technologies required to obtain, process, and use these materials must be developed. When finally scarcity renders it economically prohibitive to extract, the effort and energy put into developing its use will have been wasted. This paper considers the long term life cycle cost of non-recyclable and recyclable materials. The results suggest that future designers avoid the use of non-recyclable materials in order to minimize environmental and economic cost over the long term.

Keywords:

Life Cycle Analysis; Material Selection; Recycling; Sustainability

1 INTRODUCTION

Everyday designers are faced with questions of material selection. Some of these decisions seem predetermined simply because a particular material is traditionally used for a given application. In other instances it is the client or customer who requires a specific material. But when the decision is left to the designer, how do they choose?

The first thoughts are likely to be of the functional requirements. Does this material have the ability to be shaped as needed? Will it have the necessary strength and resilience to survive the environment in which it will be used? Is it light enough? When there is enough flexibility in the design it is often the case that several possibilities satisfy the functional requirements, and then costs begin to factor into the equation. Which materials are the least costly, both initially and also once the cost of manufacturing is included. Figure 1 illustrates these.

If the functional requirements are met and the costs of both the material and manufacturing are minimized, the process of material selection often ends. It is essential that the selection process not end here because ultimately material choices affect sustainability. And, it can be argued that the state of our current and future energy supplies suggest the need for a rapid transition to a sustainable existence. The materials we choose require energy to extract, process, and manufacture.

In 2010, approximately 12,717 million tonnes of oil equivalent, (Mtoe), or 148PWh of energy was produced by humans and used in the world. This figure is the total primary energy supply (TPES) as determined by the International Energy Agency (IEA). In the same year the total final consumption (TFC) was approximately 8,677 Mtoe. The difference between these two numbers is a result of the energy consumed in the production of fossil fuels. That is "backflows from the petrochemical industry are not included in final consumption." [1] And so only about 68% of the energy supply was consumed for the reason the energy was collected in the first place. In 1973 the TPES was 6,107 Mtoe, and the TFC was 4,672 Mtoe, which results in 76% of the energy arriving at its end use. Apparently, our energy supply is getting less efficient despite advances in technology, and this is due in no small part to the increased difficulty of extracting fossil fuels that require more refining, from locations that are more difficult to access. As of 2010, over 81% of our energy supply worldwide was fossil fuel based [1]. We are already using almost one third of our energy supply in an effort to provide energy. The strain will only be greater in the future.

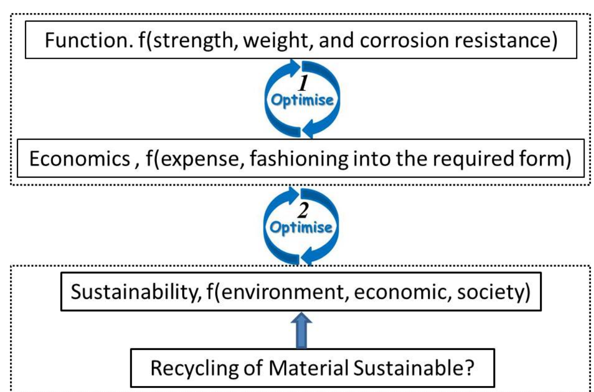

Figure 1: Product optimization process.

Similarly, materials like copper require greater efforts to extract when it can only be found at lower concentrations than in the past. Transitioning from a scarce material to one that is entirely recyclable, or in the case of copper simply ensuring we can recycle it instead of needing to extract it, will require effort and energy. According to some research it will be disruptive to make changes to material use if it requires more than about 3.5% of the global energy supply [2]. With the need to transition our energy supply to sources other than fossil fuels, and the need at some point to transition each and every material that cannot be sustainably used to those that can, those 3.5% of global energy supply will be quickly used. It is therefore vital that we make these changes as soon as possible.

If designers use materials that are sustainable, there will be greater need and demand for them. The infrastructure needed to provide larger quantities will be built and the technology surrounding these materials will be developed. Not only will environmental impacts be reduced in the short term, but paying the overall cost of the inevitable transition should be less disruptive because it occurs at a time when energy is available.

2 SUSTAINABILITY

In modern society, a primary concern of must be *sustainability*. The definition for sustainability is derived from the one published in the 1987 United Nations study headed by Brundtland [3], where the word *design* is substituted for *development*: "Design that meets the needs of the present without compromising the ability of future generations to meet their own needs". This includes the *three pillars of sustainability* and the interaction of Environment, Economics and Society. The three pillars are illustrated in figure 2.

2.1 Environment

The environmental pillar includes: maintaining diverse ecological systems, renewable energy, reducing fossil fuel consumption and emissions, sustainable agriculture and fishing, organic farming, tree planting and reducing deforestation, recycling, and better waste management.

2.2 Society

The pillar for a sustainable society is controversial and is discussed by Kates [4]. They find peace, freedom, development, and the environment to be prominent issues and aspirations. The foregoing now include: peace, social justice, reducing poverty, and ideals that promote social equity as listed in figure2.

Some companies [5] have taken this further by placing an emphasis upon the following:

- Decent/ Fair Wages Health & Safety
- Working Conditions
- Standard of Living
- Security and Stability
- Empowerment
- Community Cohesion
- Human Capital
- Diversity and Gender Equality
- Health & Well-Being
- Cultural Heritage

2.3 Economic

The basis of economics is consumption and collaboration; hence this pillar includes a managed, sustainable economic model that ensures fair distribution and efficient allocation of our resources for purposes of consumption. This pillar ensures that economic growth maintains a healthy balance with ecosystems. Can free enterprise operate sustainably? Yes it can with the proper ground rules in place, which take the foregoing two pillars into account.

2.4 Products

Products are not limited to engineered products as envisioned in CIRP [6]. The first notion of sustainability came from agriculture and biology with the book by Rachel Carson [7]. Products range from agricultural, to biological, to chemical, to mechanical, to electrical, etc. In fact, any product has some element of sustainability associated with it.

Buildings are also products and every building product has environmental, economic, and social impacts. These impacts occur at all life-cycle stages in multiple ways and on local, regional, and global scales. Building products now have their own ASTM standards [8], based upon ISO 14040: "Sustainable development is a scientific and technological endeavor that seeks to enhance the contribution of knowledge to environmentally sustainable human development". An example of materials is cement, which is an important building material and is recognized as a major carbon emitter in energy in production [9]. It accounts for around 5% of global carbon dioxide (CO_2) emissions [10] and is the second most consumed product globally, after water.

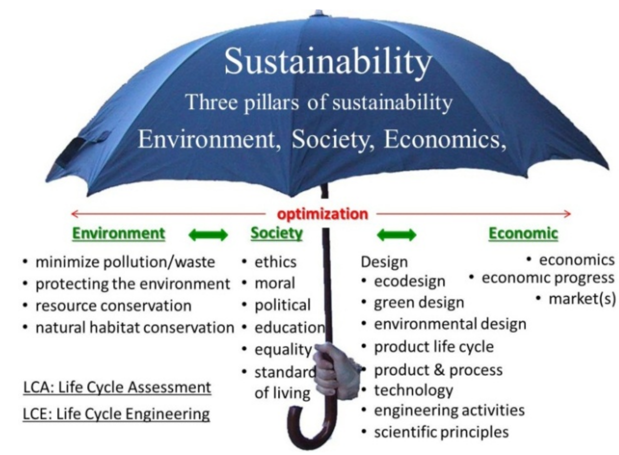

Figure 2: The Sustainability Umbrella, with the three pillars of sustainability.

Important product impacts include material use and energy consumption. Use is concerned with material scarcity, product EOL, recycling, energy and the three stressors: solids, fluids and gasses. The six main air pollutants (non-global warming effects), called "criteria pollutants" are: ozone, particulate matter, carbon monoxide, lead, nitrogen oxide and sulphur dioxide (affects lungs and is in acid rain). Effects are [10]: ozone (damage to lungs), particulate matter (PM affects heart and lungs), carbon monoxide (organs and brain), lead (nervous system, kidneys, immune system), nitrogen oxide (lungs and associated with PM and ozone) and sulphur dioxide (affects lungs and is in acid rain). Some of these are also contribute to global warming.

2.5 Defining Sustainability of Materials

The following definitions are needed for clarification. Many books [11, 12], reports and papers talk about product, the environment and impacts without giving a clear definition of the environment. Even SETAC in its definition of Life Cycle Assessment [13] talks about the environment without defining it. Documents such as the EU Directive 2011/92/EU on environmental impact assessment also do not have a definition.

A broad definition is: the natural environment, encompassing all living and nonliving things occurring naturally on earth. However, this is too general and because this paper deals with resources and a wide range of potential impacts, reference is made to a study which had a major impact upon development of a one million square kilometre area in 2004 [14].

Environment

We define the environment as follows: the components of the Earth including (a) land, water and air, including all layers of the atmosphere; (b) all organic and inorganic matter and living organisms; and (c) the interacting natural systems that include components referred to in paragraphs (a) and (b) [14].

Impact Upon the Environment

Any effect on land, water, air or any other component of the environment, as well as on wildlife harvesting, and includes any effect on the social and cultural environment or on heritage resources [14].

The following are areas of physical and chemical effects:

- Ground water.
- Surface water.
- Noise.
- Land.
- Nonrenewable natural resources; including resource depletion.
- Air/Climate/Atmosphere.
- Vegetation.
- Wildlife and Fish
- Habitat and communities
- Social and economic.
- Cultural and heritage.

Environmental Impact

Environmental impact is usually framed in terms of sustainability, which can have many interpretations. Even the EU Directive 2011/92/EU on environmental impact assessment does not have a definition of environmental impact. The business directory [15] gives the following definition: possible adverse effects caused by development, industrial or infrastructural projects or by release of a substance.

Environmental Impact Assessment [16] is the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development prior to major decisions being taken and commitments made.

Irreversible Processes

Many materials are obtained via extraction of a resource from our environment. In the case of fossil fuels it involves extraction, refining into a form that we can use, and then burning of that fuel to use the energy contained within it. The last process is irreversible, and makes fossil fuels a non-sustainable source of energy. That is to say that at some point it will no longer be feasible to extract fossil fuels in order to supply energy.

Dispersion

Fertilizer use is a prime example of a mineral dispersion system deployed at the global scale. Phosphorus in particular is mined in a number of locations around the world where it occurs in concentrations that make mining economically feasible. It is then transported everywhere there is agriculture, and it is spread about to nourish crops. Unfortunately, the phosphorus is not recovered. It is instead dispersed in the soils, waterways, and surrounds. This process cannot continue as it will result in the eventual dispersion of all the available phosphorus deposits and we will no longer be able to collect and utilize what is an abundant mineral for modern agriculture.

These are the cases one would aim to avoid. Using materials in a manner that makes it impossible to recover them for future use either by chemically changing them or by dispersing them is not sustainable. Therefore sustainable material use is to utilize while ensuring it can be infinitely recycled without degradation or irrecoverable dispersion. This is the ideal. It may not be achievable in all circumstances, but especially for some metals it seems at least theoretically possible to have nearly 100% recycling rates. [17]

3 MATERIAL SELECTION METHODOLOGY

It is suggested that when selecting materials, three requirements are fulfilled and optimized. These are:

1. Function: strength, weight, food-safety, corrosion, etc;
2. Sustainability;
3. Cost Minimization.

The first and last items are nearly always considered. It is the second that we will observe.

3.1 Life Cycle Assessment

Life cycle assessment is commonly applied with a temporal scope, including only the life of the product. The environmental impacts of mining, manufacturing, transporting, using, and recycling/disposing of that product are calculated and reported. Whether the materials that comprise the product are recyclable or not, will impact the analysis, but it will not guarantee sustainability. It is proposed that sustainable material choices will yield the lowest environmental impact in the long run.

By extending the term of a life cycle analysis to include the impacts of choosing materials that will in the future have to be replaced, we can show that the environmental cost is greater than choosing a material that can be used in perpetuity.

Resource depletion is an obvious consequence. The depletion will occur faster without recycling. If there were 100% recycling then resource depletion would stop.

This is an obvious consequence of either action or inaction. However, there are unknowns, such as discovery of new deposits through geologic exploration. A case in point is the discovery of chromite in the “ring of fire” in Northern Ontario [18]. With this discovery, the supply of chromium changed. Overnight, Canada suddenly had an estimated 10% of the world’s chromium supply. Discoveries such as this one are obvious “game changers” in terms of raw material supply availability.

No mines have been started at the foregoing location, but questions posed earlier in this paper are raised. For instance, considerations include the three sustainability issues of environment, economics, and society: 1) first is the energy needed to extract these resources (transportation, equipment operation, road or rail); 2) economic (is it viable?); 3) environment (how destructive will it be, how widespread will it be and can the end result be a renewed landscape with negligible impact?); 4) Will there be an employment benefit to society? 5) will aboriginal peoples claims to land use and the associated opportunities be respected? (society); 6) can the mined chromium be recycled for future use?

3.2 Materials, Cost, Complexity, Consumption, Environment, Energy

The challenge in design is to connect, optimally, product complexity (no. of parts), materials, cost, consumption (product & energy), carbon emissions, manufacturing, and environment. It is an optimization process.

Product complexity is important and economists define it as: an assessment about the number of components in a product [19]. In this paper it is proposed that a more extensive definition includes: material, number of parts, shape, size and energy needed to produce a part or product.

Since the industrial revolution the number of parts in a product often increases dramatically with time, as can be seen in figure 1. Once introduced, and accepted by markets, product complexity increases, with the number of parts in a product increasing exponentially in most cases. This is one factor in product complexity; however other factors also play a role.

As a product becomes more complex, materials often change. This can mean increased energy needs where the shape and size will also contribute to the amount of energy expended. Additionally, as a product becomes more complex the value added will increase. If energy needs increase, costs will also increase. Design for assembly considerations also come into play, with a goal being optimization, including the reduction in the number of parts, thereby reducing costs and hopefully energy consumption and emissions [20,21]. Often the foregoing is all optimized with one goal, to maximize profitability.

Product complexity plays a major role in determining if a product is worth disassembling (recycling) [22], especially with respect to reuse of part or all of a product, including materials. Usually it is the financial worth of the material content that is attractive. Ultimately, the financial benefit in disassembling and reusing, and/or recycling all or part of a product and its materials, will determine the EOL strategy for that product.

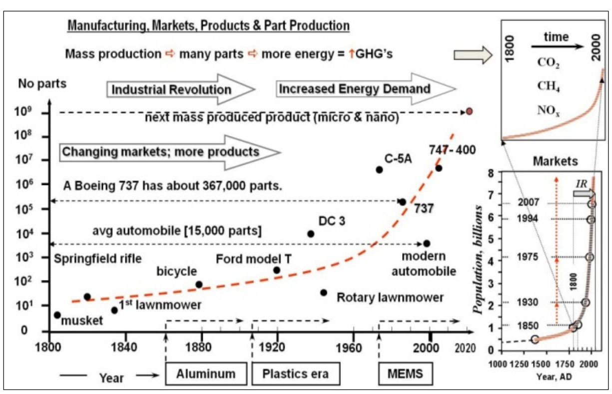

Figure 3: Increasing product complexity, as defined by the number of parts per product.

Products have become increasingly complex since the industrial revolution, as shown in figure 3. Energy supplies have changed, manufacturing is more complicated and automation has enabled mass production with increased efficiency and increasing energy needs and emissions. It is obvious that as a part is made, repeatedly, the energy consumption increases and the carbon emissions (carbon footprint) from manufacturing that part or product becomes an important factor. There will be increased carbon emissions, and water use which is also becoming a concern.

Economics is important in complexity: if it is not economical to produce a product because of complexity, it will not be manufactured. Hence marketing and customer requirements are important factors. Production cost will also have a major effect upon producing a product economically.

3.3 Examples of Products, Materials and Energy needs

The following looks at how products have material requirements where there is a potential to for materials to become scarce. In the following computer chip technology, Lithium batteries and photovoltaics (PV) are considered.

Computer Chip Technology

Computer chips are an example of new products coming to market. Figure 4 shows Moore's Law [23]. Silicon is the base material for computer chips, hence there is not a shortage in sight. Small amounts of gold are also used, but it too will be available in the foreseeable future, although expensive. The trend shown is linear.

The life cycle of Intel chips is shown in figure 5, indicating an increase in the production of units with time. So although material needs can be supplied, production energy is increasing.

Although there is not any concern with material supply, there is concern with energy needs for production and energy use [24][Low-tech, 2012]. As with any process, energy is required to produce pure silicon for computer chips. The energy used in producing nine or ten computers is enough to produce one automobile [22], which is 973 GJ per average sedan [25], or 97.3 GJ per computer, for which a major portion is for silicon production. 43% of the pure silicon crystal used in the process becomes part of the chip [22], hence approximately 41.8 GJ. If used for 12 hours per day, every day, for five years, a laptop using an average of 50W would require 1,095kWh or 4 GJ of energy over its lifetime. Corkish [26] shows the energy consumption to produce electronic grade silicon is in the range of 200 kWh/kg to 50 kWh/kg. It can be seen that although energy needs to produce electric grade silicon are decreasing, the production quantity is going up, increasing the total energy requirements.

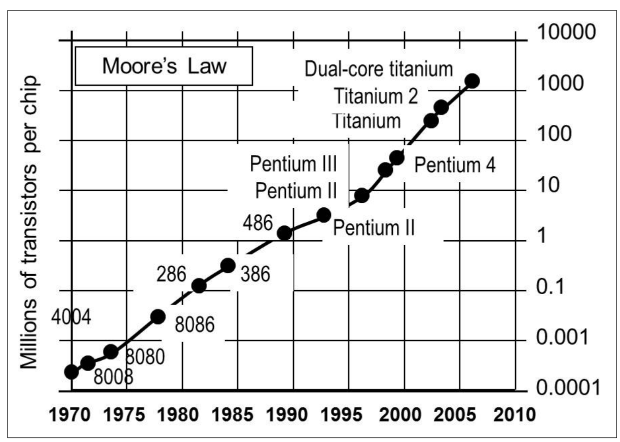

Figure 4: Moore's Law [23]

Waste in production goes to either PV cells or is recycled. As indicated in source [22] there are four stages to silicon chip manufacture: Raw Material Extraction; Material Production; Part Production; Assembly. 1) Raw Material Extraction: inputs, outputs and processes required to produce a supply of energy and silicon, including mining of materials. 2) Material Production: inputs, outputs and processes to produce crystalline silicon, including the crystallization of purified liquid silicon. 3) Part Production: inputs, outputs and processes to manufacture a chip, including etching circuits on a silicon wafer. 4) Assembly: inputs, outputs and processes to produce the final packaged chip, including the plastic or ceramic case with metal pins that encases the chip.

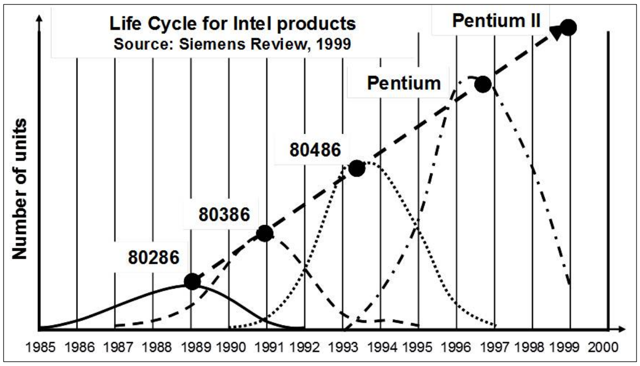

Figure 5: Life Cycle of Intel Processors [37].

Lithium Ion Batteries

Batteries have changed dramatically over time. The development of the modern battery coincides with the start of the industrial revolution, with the original batteries consisting of a galvanic cell made of zinc, copper and brine in the first iteration [27]. Over time, materials have changed, making them more efficient and smaller, ending up in 1949, with compact, portable alkaline batteries which are now ubiquitous. It is interesting to note the first solar cell in 1954, called a battery, is an offshoot of battery development [28]; this is discussed later. The materials used in batteries, up to that time, were commonplace and not thought of as scarce or strategic (materials critical to a supply chain). Material changes include: zinc-carbon, nickel-cadmium, nickel-metal hydride, iron-phospate, aluminum, cobalt oxide, etc [29].

Lithium carbonate reserves, 2008, million tonnes				Production
Lithium carbonate reserves, 2008, million tonnes				2010
Country	Brine	Mineral	Mixed	Tonnes
Argentina	1.86			2,200
Australia		1.17		4,400
Bolivia	28.74			
Brazil		4.84		
Canada		1.92		
Chile	15.97			7,400
China			5.86	2,300
Zimbabwe		0.14		

Table 1: Li Reserves, 2008 [38].

A change came about with the introduction of Lithium, because of its lightness and ability to deliver high current densities. Lithium is now an important battery material. Lithium alloys can store the greatest electrical energy per unit volume of any rechargeable battery technology [30]. They have long discharge-charge cycle lives, for longer times and give higher current densities when needed.

It is used in a variety of other products. It powers around 90% of laptop computers [30] and it is predicted that the demand for lithium will increase as shown in figure 6 [23].

In 1976 it was estimated there were 10.6 million tonnes of elemental lithium. Twelve years later, in 2008, estimates had changed to 28.4 million tonnes Li equivalent and to more than 150.0 million tonnes of lithium carbonate of which nearly 14.0 million tonnes lithium (about 74.0 million tonnes of carbonate) are at active or proposed operations [27]. Table 1 shows estimated Lithium reserves as of 2008. A third source, hectorite clays, has been identified but production methods have not been proven [31].

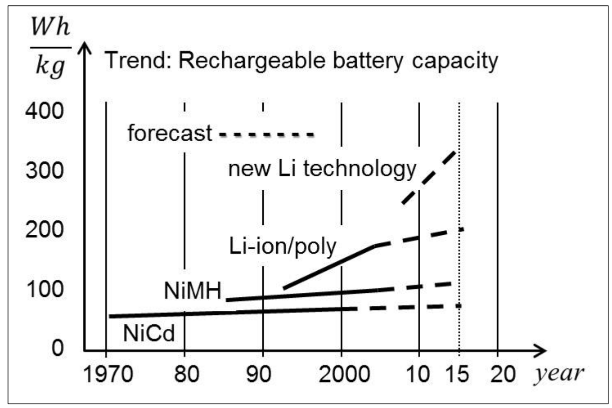

Figure 6*:* Predicted changes for lithium batteries [23].

Lithium has an embodied energy of 853 MJ/kg and carbon emissions of 5.3 kg CO2/GJ [32].The energy needed to mine Lithium depends upon whether it is brine or mineral. Because brine is like a combination of sand and liquid, it is easy to see that it is much simpler and more economical to use as a source [31]. The major energy component is in pumping the brine to solar pounds where evaporation yields Lithium carbonate and Lithium hydroxide. Note that up to 50% of the lithium in used batteries may be recycled in the future.

Photovoltaic Materials and Increasing Efficiency

There is competition to develop the most efficient PV solar cell, as shown in figure 7. Materials that play a role in the PV cells are:

- Silicon, Si, semiconductor;
- Gallium Arsenide, GaAs, semiconductor, gallium and arsenic;
- Cadmium Telluride, CdTe, thin film solar cells, 12% efficiency in 2012 [33]. Cd is a known toxic heavy metal [34];
- Ternary chalcopyrite, Cu(In, Ga)Se_2, thin film solar cells, 11.4% efficiency in 2011 [35]. CdTe systems have the smallest carbon footprint of any PV technology.

None of these materials is in danger of becoming scarce, however, there are other potential problems. Gases like nitrogen trifluoride, or NF3, is a greenhouse gas 17,000 times more potent than carbon dioxide. NF3 is commonly used in the manufacture of electronics and some solar panels [29]. In 2009 it was found NF3 levels were increasing at 11 percent each year, although the cause is unclear. Production of some other panels involves another gas called sulfur hexafluoride — the most potent greenhouse gas known to science.

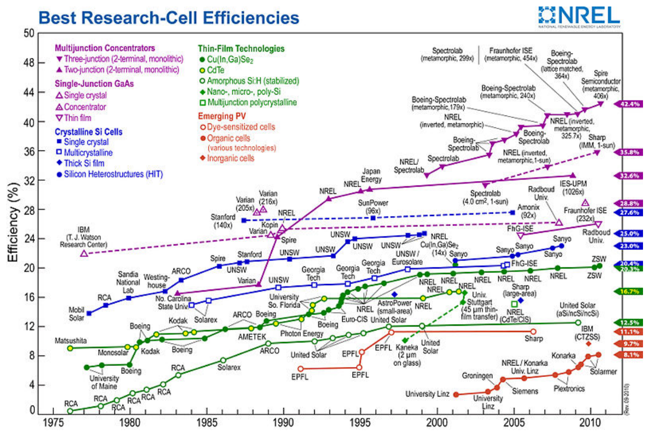

Figure 7: Changes in efficiency for PV cells [39].

3.4 Predicting Future Shortages

Predicting the future is risky at the best of times. Farmer and Trancik [36] conducted an extensive study in predicting trends for modern technology, using financial data. In the case of new technologies, where there is no historical data to extrapolate, forecasting the future is likely to be less certain, than technologies with track records of steady improvement, such as the Ford model T.

For the foregoing cases, one for PV cells and the other for Lithium use, trends indicate PV cells are likely to become more efficient, and in the case of batteries, Lithium use is likely to increase [23]. Hence, the materials necessary to manufacture PV cells, silicon and its doping materials, and Lithium to make batteries will become more necessary. In the one case, PV cells, there is not a potential shortage of material sources, but the process is toxic and requires considerable quantities of energy for manufacturing. Recycling may be a necessary alternative to keep energy needs lower.

However, Lithium is another case altogether. Energy needed to mine brine deposits and to produce commercial quantities is minimal. However, sources of Lithium brine are in finite supply, therefore a different approach is required. For reasons of potential scarcity it may be necessary to embark upon recycling Lithium.
So recycling is necessary for two different reasons, one to decrease energy use, and control toxic elements, the other for reasons of potential scarcity.

4 GENERAL DISCUSSION

Materials have generally been abundant since the industrial revolution. However, since the industrial revolution circumstances have changed considerably with much larger populations, increased complexity of products and more intensive use of resources, and with the advent of increased consumption there is a potential of depleting resources that contribute to environmental impacts and but are also important to decreasing environmental impacts. For instance, Lithium, whose alloys can store the greatest electrical energy per unit volume of any rechargeable battery technology [27] for longer times and give higher current densities.

Therefore choosing materials for a design has become much more complicated. To decrease the future impacts a designer must do a Risk Assessment and conduct a Due Diligence with respect to the goal of sustainability:"Design that meets the needs of the present without compromising the ability of future generations to meet their own needs". This includes choosing materials, the potential future scarcity of materials, toxicity in production and the energy expended in extracting those materials.

A list of concerns from Risk Assessment (RA) includes:

Scarcity

- Has resource consumption been optimized?
- Are closed loops being used?
- Is a material continuously recyclable?
- Is there a finite supply of a critical material such as Lithium? Potential scarcity requires an assessment of economic supply, and what will happen if economically attainable Lithium is depleted.
- Does the design include few, simple, recycled, unblended materials?
- Does the design include: recycling, and proper labelling; modules and breakpoints, and understandable and thoroughly explicit manuals?

Environment

- What is the trade-off between scarcity, pollution and toxicity?
- Is the material being considered a toxic substance as defined by the local legal jurisdiction? Although exposure to toxic materials is controlled locally, it becomes a moral/ethical question if requirements are less stringent in areas such as developing countries. Or if it concerns an area in a developed country where the remote possibility of jobs overrules local objections due to unemployment. This is a risk assessment problem. What is a population willing to risk to have full employment?
- Has material durability been designed into products which have significant environmental impacts, outside the use phase?
- Does the design include structural features and higher quality materials, to minimize weight, without interfering with the product: flexibility, impact strength or functional properties?
- Does the design use better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear?
- What are energy requirements for recycling a material?

Non Material Specific Questions Include

- Does the design use the minimum joining elements possible, and use screws, adhesives, welding, snap fits, geometric locking, etc. according to DFMA guidelines.
- Is minimization of packaging implemented?
- Have social implications been considered?
- Has energy consumption been optimized in production and transportation?
- Have energy and resource consumption been minimized in the use phase; especially for products having significant environmental impacts in use?
- Have easy repair, maintenance and upgrading been implemented?

Scarcity and energy waste are the two factors discussed in this paper. It has been shown that trying to predict material scarcity and price are difficult to ascertain. Material price is subject to market forces which can only be observed.

In order to be informed about potential scarcity problems and the risks involved, access to an inexpensive database with a few very simple indicators is needed.

5 CONCLUSIONS

Choosing materials in the design phase, their potential scarcity, and the energy wasted in not recycling a material, in place of using virgin materials has been discussed.

Predicting which materials can potentially become scarce has become critical given the rate of consumption in our modern society. It is paramount to use potentially scarce materials judiciously and at the same time reduce emissions. How this is addressed needs to be determined.

Two cases concerning potential material scarcity, one for PV cells and the other Lithium batteries have been considered. Lithium brine deposits are scarce and their supply needs to be nursed until appropriate recycling technology is in place. This is because Lithium-ion cells are being viewed as a solution to storing energy from renewable sources. PV cells have adequate supplies of materials, but energy needs are high and toxic elements are present in manufacturing. Both energy and toxicity are important.

Although predicting the future in the case of new technologies is risky, it is an important endeavour in modern society where there is a potential for scarcity and increased emissions.

6 REFERENCES

[1] International Energy Agency, Key World Energy Statistics 2012, 9 Rue de la Federation, 75739 Paris Cedex 15. Accessed 27 August 2012 http://www.iea.org/publications/freepublications/publication/kwes.pdf

[2] Igor Lubomirsky and David Cahen (2012). Energy limitations on materials availability. MRS Bulletin,37, pp 412-416

[3] Brundtland, G. 1987. World Commission on Environment and Development (WCED), *Our Common Future* (New York: Oxford University Press, 1987).

[4] Kates, R.W., Parris, T.M, and Leiserowitz, A.A. “What is sustainable development? Goals, indicators, values and practice”. Environment: Science and Policy for Sustainable Development, 2005, Volume 47, Number 3, pages 8–21.

[5] Puma, 2012. http://about.puma.com/wpcontent/themes/aboutPUMA_theme/media/pdf/2011/en/PRESS_KIT_E_P&L.pdf; accessed 7 Feb 2012.

[6] CIRP. College International pour la Recherche en Productique (The International Academy for Production Engineering); http://www.cirp.net/. 2012.

[7] Carson, 1962. Rachel Carson. Silent Spring © 1962 Rachel Carson.

[8] ASTM E2432; ISO 14040.

[9] Rubenstein, M. Emissions from the Cement Industry. Accessed 1 September 2012. http://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/.

[10] USEPA air quality website; accessed Sept 2012; http://www.airnow.gov/.

[11] Graedel, T.E. Streamlined Life-Cycle Assessment © 1998, Bell Laboratories, Lucent Technologies.

[12] Graedel, T.E. and Allenby, B.R. Industrial Ecology. © 2003 by AT&T, published by Prentice Hall, New Jersey.

[13] SETAC, Society of Environmental Toxicology and Chemistry; Pensacola, Florida, USA; http://www.setac.org/. 2012.

[14] MacKenzie, 2004. MacKenzie Valley Environmental Impact Review Board: Environmental Impact Assessment Guidelines March 2004; (accessed 1 september 2012; http://www.reviewboard.ca/upload/ref_library/MVE%20EIA%20Guidelines_1195078754.pdf.

[15] Business Directory, 2012. Business Directory.com. http://www.businessdictionary.com/definition/environmental-impact.html; accessed 1 Sept 2012.

[16] IEA, 2012. Institute of Environmental Assessment, Welton House, Limekiln Way, Lincoln, LINCS LN2 4US, UK. Accessed 1 September 2012. http://www.iaia.org/publicdocuments/special-publications/Principles%20of%20IA_web.pdf.

[17] Graedel, Erdmann T.E. Graedel and Lorenz Erdmann (2012). Will metal scarcity impede routine industrial use?. MRS Bulletin,37, pp 325-331.

[18] Gordon, J, Bhaswati, M. “Risk and Reward Beckon in Canada’s Ring of Fire”. Reuters May 24, 2012.

[19] Financial Terms, 2012.http://www.finance-lib.com/financial-term-product. complexity.html; 29 June 2012.

[20] Boothroyd, Dewhurst and Knight. Product Design for Manufacture and Assembly. © 1994 Marcel Dekker, NY.

[21] Boothroyd G. and Alting, L. Design for assembly and disassembly, Annals of CIRP, 41/2/1992; 625.

[22] ELC, 2008. Environmental Literacy Council, 2008. http://www.enviroliteracy.org/article.php/1275.html. 1 July 2012.

[23] The Economist 2008. Technology Quarterly: Case history. In search of the perfect battery. Mar 6th 2008.

[24] Low-tech, 2009. Low-tech Magazine The monster footprint of digital technology; http://www.low techmagazine.com/2009/06/embodied-energy-of-digital-technology.html; accessed July 2010.

[25] Sullivan, J.L., Williams, R.L., Yester, S., Cobas-Flores, E., Chubbs, S.T., Hentges, S.G., Pomper, S.D. “Life Cycle Inventory of a Generic US Family Sedan Overview of Results, USCAR AMP, 1998, SAE paper 982160.

[26] Corkish, R. “Can Solar Cells Ever Recapture the Energy Invested in their Manufacture?”. Solar Progress, vol. 18, No. 2, pp. 16-17 (1997).

[27] Evans, R.K. Lithium abundance – World lithium reserve. Accessed 1 September 2012. http://lithiumabundance.blogspot.ca/.

[28] Bellis, M. "History timeline of the Battery". Accessed 1 September 2012. http://inventors.about.com/od/bstartinventions/a/History-Of-The-Battery.htm.

[29] Parkinson, J. Feb 16, 2009. Voice of San Diego. http://www.voiceofsandiego.org/science/article_37811382-9d69-5936-adeb-5db1395225e3.html; 1 June 2009.

[30] Dahn, J., Jiang, J., Moshurchak, L., Buhrmester, C., Wang, R.L. "The Drugstore Li-Ion Cell". The Electrochemical Society Interface, Winter 2005, pp 27 – 31.

[31] Rodinia, 2012. Rodinia Lithium. http://rodinialithium.com/lithium/lithium_mining/; July1, 2012.

[32] Hammond, G.P. and Jones, C. Inventory of Carbon and Energy, ICE. Version 1.6 a. 2008. University of Bath.

[33] Bush, S. "Thin film CdTe solar cells to be 12% efficent in 2012 - First Solar". 25 July 2008, Electronics Weekly.com. Accessed June 1, 2012.

[34] Johri, N., Jacquillet, G, Unwin, R. "Heavy metal poisoning: the effects of cadmium on the kidney". Biometals, 2010 Oct;23(5):783-92.

[35] Gladyshev, P.P. "Thin film solar cells based on CdTe and Cu(In,Ga)Se_2 (CIGS) compounds." J of Physics, Conference series, vol 291, no 1.

[36] Farmer, J.D, and Trancik, J. (2007). J. Dynamics of technological development in the energy sector. (http://tuvalu.santafe.edu/~jdf/papers/DynamTechDev.pdf).

[37] Siemens, 1999. Life Cycle of Intel chips; Siemens Review, 1999.

[38] Greeniacs.com.http://www.greeniacs.com/GreeniacsArticles/Energy/Lithium-Mining.html; 2 July 2012.

[39] NewEnergyNews, 2011. http://newenergynews.blogspot.com/2011/03/germans-push-pvs-efficiency-limit.html; accessed March 30, 2011.