ENGN2226 SYSTEMS ANALYSIS PORTFOLIO
ANALYSIS ON THE BATTERY OF A TYPICAL SMARTPHONE

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Executive Summary

The aim of this portfolio is to analyse smartphone battery's performance and usage, and then provide recommendations to smartphone users and designers on how to improve performance from various perspectives. Table 1 summarises key finding and outcome from each section.

Table 1 - Section summary

1.0 Background Information (Page 2)
This section first defines portfolio scope, followed by a brief introduction to three alternatives – Lithium ion graphite, nickel-cadmium, and Lithium ion titanium dioxide batteries.
2.0 Human Factors (Page 2)
The study of human factors is carried out from hand anthropometrics and thermo ergonomics. From the results, it is recommended smartphone battery thickness to be around 5-7 mm. Lead acid battery is highly unsuitable due to lots of heat dissipation whereas Li-on and NiCd batteries are better candidates.
3.0 Materials Analysis (Page 5)
Advantages and disadvantages of the three types of battery can be identified by comparing embodied energy, life span, charging time, power density etc. The outcome is in favour of Li-on titanium battery due to a variety of reasons, and results from this section will also be used in subsequent sections of energy, time and cost analyses. Furthermore, mobile phone companies are advised to standardise smartphone battery and make it replaceable and compatible with other devices; this is to increase reusability for Li-on titanium battery and prepare what is to come in the near future.
4.0 Energy Analysis (Page 8)
Impact of CO_2 emission can be assessed at by employing I=PAT equation. The results show that in the long term, Li-on titanium produces the lowest amount of CO_2. Additionally, the Sankey diagram of energy flow helps identify a large mount is energy is lost as heat or consumed by GSM. Improving GSM power efficiency and decreasing battery internal resistance will significantly slow down power depletion.
5.0 Time Analysis (Page 10)
By analysing a typical charging cycle of the most widely used Li-on graphite battery, it is clear that a long charging period forces majority of users to charge overnight, accelerating battery degradation. In contrast, Li-on titanium battery's short charging time can dramatically improve this situation.
6.0 Cost Analysis (Page 11)
Of all three batteries, Li-on titanium battery has the largest capital costs in energy and money. However, due to lower operating cost and long life span, it has an economic payback period of around 4 years and an energy payback period of only 2 years.
7.0 Optimisation and Reliability (Page 13)
Software optimisation using the Pareto principle enables us to see what software activities consume most power. Auto-update on Wi-Fi and 3G and social apps are very resource demanding. Developers are recommended to make an option available – 'auto-update only when plugged in'. The efficiencies of Wi-Fi transmitter and GSM need also to be improved. Additionally, by inspecting the Bathtub Curve, it is clear that Li-on titanium battery can provide long term reliability.

8.0 Recommendations (Page 15)
Final recommendations are given to smartphone users, smartphone designers as well as software developers.

1.0 Background Information

The development of commercial smartphones has been concentrated on increasing the computing power, integrating more advanced sensors and creating a user friendly interface. As smartphones become faster and carry more sensors and functionality, they also inadvertently become more power hungry. Phone users are often forced to either bring chargers and plug in during the day, or limit their usage to save battery power. This has a very negative impact on the phone usage experience, greatly decreases the usefulness of smartphones. Therefore, this portfolio is dedicated to analysing the battery of a typical smartphone in various dimensions, namely, human factors, time, energy, material, reliability and cost. The aim is to provide solutions to the current situation facing smartphone users and designers.

1.1 Defining the Portfolio Scope

The analysis of the smartphone battery system and its performance will be carried out from a systems engineering perspective for different alternatives. In particular, the subjects that will be focused on are human factors, time, energy, materials, reliability and cost. In doing so, we can explore trade-offs for different types of batteries, speculate the future trend, and then provide recommendations to smartphone users as well as designers about how battery performance can be improved for the present and in the future.

1.2 Rechargeable Battery for Smartphones

Nowadays smartphone companies ubiquitously and almost exclusively implement traditional lithium-ion (Li-on) battery for their products. These Li-on batteries use graphite as electrolyte that produces relatively low internal resistance and high energy density, comparing with classical nickel-cadmium battery that has existed for more than a century.

The material advantages and disadvantages of Li-on battery are compared against other types of batteries in 3.0 Materials Analysis. Several existing alternatives for smartphone battery are nickel-cadmium (NiCd) battery and Lithium polymer battery (Buchmann, 2014). Recently, new research also brings up the possibility of Li-on battery that uses titanium dioxide as electrolyte, which claims to charge 70% in less than 2 minutes and will last more than 20 years (NTU, 2014). This can potentially achieve very promising results. Therefore, this portfolio will focus on three types – widely adopted Li-on graphite battery, newly emerged Li-on titanium battery, and lastly classic, mature NiCd battery that has been in the world for a long time. Sometimes other types such as lead acid battery may also be compared to further support analysis and results.

2.0 Human Factors

2.1 Introduction

This section studies the human factors involved in battery design of a typical smartphone, using methods of hand anthropometrics and thermal ergonomics. More specifically, we will be considering two parameters - battery thickness and battery thermal comfort.

2.1 HAND ANTHROPOMETRICS

The purpose of hand anthropometrics is to find out a suitable range battery thickness for a smartphone such that people can grip the phone in their hands comfortably. If the phone is too thick, then it would cause discomfort as the user tries to hold it; if the phone is too thin, then the user would be forced to hold it very tightly to prevent the phone from slipping away. The battery thickness, on most occasion, is about 50% of that of the phone. For Lumia 525, the battery is measured to be 5mm thick while the phone is 10mm thick. Further, the majority of people also use protective covers, which add another 2mm thickness and brings the total thickness to 12mm.

In order to understand whether this thickness is appropriate, we will analyse based on the statistical data of human hand. Figure 7 shows the anatomy of a human hand. As we grip a phone in our hand, different areas of fingers are responsible for different tasks. The palm and proximal phalanx remain flat to provide a platform. The middle phalanx curls upward to accommodate the thickness of the phone, and the distal phalanx hooks around the edge of the phone to prevent slipping. Therefore, the thickness of a phone and the thickness of the battery should be determined by primarily considering the length of the middle phalanx.

Since the length of the middle phalanx is roughly the same for the index, middle and ring fingers, we will focus our attention to the index finger. Appendix I provides important data of hand anthropometrics. The length of the index finger from 5th to 95th percentile population is between 64-79 mm for males, 60-74 mm for females. Therefore, by covering the range from 64mm-79mm, we are likely to provide coverage for at least 90% of the population, which is a general guideline in anthropometric design (NASA, 1995).

The average length of the middle phalanx is about 31% of the length of the entire index finger (Buryanov & Kotiuk, 2010). From this, we know that middle phalanx length of the general population is between 19.8-24.5mm, which, after subtracting the thickness of the finger i.e. about half according to (Komandur, et al., n.d.), would fall into the range of 10-12.5mm.

As we have discussed before, a typical smartphone like Lumia 525 has a thickness of 10mm without cover and a thickness of 12mm with cover. This shows that the thickness of a typical smartphone and the thickness of the battery inside the phone are appropriate for the majority population. Furthermore, it is notable that some new (but not so common) smartphone models with ultra-thin features (i.e. usually 5-8mm) may not feel as comfortable as a typical thicker smartphone.

From the anthropometric analysis, it is clear that the thickness of a smartphone, which is usually limited to half the thickness of a phone due to hardware, is generally appropriate in the range from 5-7mm. This approach looks at the thickness alone, assuming that other factors such as battery life stay the same. However, users may also gladly sacrifice battery comfort and have thick battery for extended battery life, as in the case of a super battery that is bulky but has much more power. Here, we look at different thickness assuming that other variables are the same. The final holistic recommendation in 8.0 will be given with consideration of this result as well as other perspective such as time, energy, materials etc.

2.2 ERGONOMICS AND HUMAN COMFORT

Human comfort concerning the design of a smartphone battery is mainly affected by the heat dissipated by the battery when the phone is being used. This kind of comfort concerning human interaction with heat sources is called thermo comfort (University of Ottawa, 2013). More specifically, if too much heat is given out by a battery, the energy will be then transferred through conduction to the hand that holds the phone. At this point, the user will feel uncomfortable as his/her hand becomes hotter and thus unable to thermodynamically maintain at human body temperature of 37.5°C. Heat is also produced from other electronic components such as screen, but they can be effectively ignored due to the fact that the battery produces heat at significantly higher level. The energy dissipation of a smartphone will be extensively looked at in 4.0 Energy Analysis. For now, we will see if lithium ion battery can satisfy thermo comfort for doing different smartphone tasks. A total of ten people are interviewed, and the qualitative results from the interview are shown in Table 2.

Table 2 - Qualitative results about thermo comfort of using a lithium-ion powered smartphone

Task	Response (No. people)		
	Completely comfortable (much below 37°C)	Okay, only slightly uncomfortable (around 35-40°C)	Very uncomfortable (much higher than 37°C)
Reading Email/msg	10	0	0
Browsing internet	7	3	0
Power gaming	1	3	6
Playing video	3	6	1
Making calls	7	2	1

The qualitative response given here, such as ‘slightly uncomfortable’, can help understand thermo comfort at a more personal level. Each person may have a different definition for ‘comfort’, and what the survey tries to understand is how acceptable people think of the temperature when performing different tasks. The obvious error here is the bias and perception. As an example, one person considers comfortable to play games with a very warm phone while others think that there is slightly or very discomfort. Despite of the subjectivity of the qualitative measurement, the general pattern is quite clear – most people think reading emails/messages, browsing internet and making calls are thermo comfortable whereas power gaming and playing videos are not.

Heat production is directly associated to the internal resistance of electrolyte inside the battery (Energizer, 2005). The lower the cell’s internal resistance, the less heat will be lost, and more comfortable the user will be. An additional benefit of low internal resistance is more efficiency per unit mass and thus longer battery life (See 3.0 Materials Analysis). The following results are available in Table 3.

Table 3 – Internal resistance comparison between rechargeable batteries (Woodbank Communications, 2005)

Type	Lithium Ion (Li-on)	Lead Acid	Nickel–cadmium (NiCd)
Internal Resistance	0.1-0.2Ω	1.8Ω	0.2Ω

Low internal resistance can be found in Li-on and NiCd batteries. They are equally competent in terms of giving better thermo comfort. In 3.0 Materials Analysis, other characteristics will also be compared. Measured data in Table 3 involves a number of sources of errors such as temperature, number of cycles etc. Hence, from the thermal comfort perspective, Li-on and NiCd batteries are suggestive whereas lead acid battery is not.

2.3 Recommendations/Conclusion

After conducting human factor analysis, it is clear that the typical battery thickness (5mm) and phone thickness (10mm) are largely suitable as they allow the phone to be anthropometrically fit into the majority of human hands. By considering the thermo ergonomics, Li-on and NiCd batteries will be good candidates because they will produce the lowest amount of heat. On the other hand, lead acid battery is considered very unfit because it dissipates much greater amount of heat and causes greater discomfort due to a much higher internal resistance.

3.0 Materials Analysis

3.1 Introduction

Previously we have concluded lead-acid battery highly unsuitable for smartphones due to the fact that it produces great amount of heat that would cause great human discomfort. In this section, the analysis will be carried on into the materials domain, where we will extensively compare the materials between the most suitable candidates - lithium ion battery and nickel-cadmium battery. Lithium ion battery diverges into two types, which may use either graphite or titanium dioxide as electrolyte. The perspectives provided are broad and multidimensional, involving many parameters and trade-offs such as embodied energy, energy density, cycle life, charging efficiency etc. The data and results drawn from materials analysis will also form important bases for the subsequent analyses of energy, time and cost.

3.2 Materials Audit - Embodied Energy and Other Properties

The materials audit is conducted to compare lithium ion battery and nickel-cadmium battery in terms of embodied energy, cycle life and other performance parameters. Table 4 breaks down the embodied energy of batteries into energies of manufacturing and material acquisition of electronics, electrolyte and protective shell.

Table 4 - Materials audit for embodied energy (Synthesis Studios, 2009)

Component	Material	Required Quantity (g)	Embodied Energy (MJ)
Li-on graphite battery (5.3Wh)			
Electronics	N/A	1	50
Electrolyte	Lithium Manganese Oxide, graphite	19	1.11
Protective case	Plastic	4	0.4
Manufacturing	N/A	N/A	40
		Total	**91.5 MJ**
Nickel-cadmium battery (5.3Wh)			
Electronics	N/A	1	50
Electrolyte	Nickel oxide, cadmium, graphite	20	4.0
Protective case	Plastic	4	0.4
Manufacturing	N/A	N/A	*40
		Total	**94.0 MJ**

Note*: Where there is no available data, estimated values are used and marked by asterisk (*).

As we can see, the main cost of embodied energy comes from electronic components and manufacturing, while the electrolytes on which the battery performance depends do not significantly contribute to the total embodied energy. Nickel-cadmium battery appears to use slightly more production energy, but this means very little as there are a few sources of error presented in the embodied energy data. Firstly, materials acquisition methods with different level of technologies will give different embodied energies. Additionally, the actual measurements may likely involve different standards and some forms of estimation. Furthermore, we have assumed that the manufacturing energy of NiCd battery is the same as that of Ni-on battery, which is not necessarily the case. Therefore, on a grand scale, they appear to be evenly matched in total embodied energy.

While embodied energy serves an important indicator for environmental impact, other factors that should also be considered include battery's performance and degradation characteristics.

Table 5 - Performance and characteristics comparisons between Li-on and NiCd battery (Cleveland & Morris, 2013)

Properties	Li-on graphite battery	Nickel-cadmium battery
Cycle life	1000cycles	500-800 cycles
Nominal voltage	3.7V	1.2V
Power density	150-370W/kg	150-300W/kg
Self-discharge per day	0.1-0.3%	0.2-0.6%
Production cost per unit (See 6.0 Cost Analysis)	$13.25	$3.71

The comparison made in Table 5 provides a useful insight into the strengths and weaknesses of the two batteries. Lithium ion battery promises more cycles, and that translates to a longer life span. It also provides higher voltage, slightly higher power density and a low self-discharge rate. In terms of performance, lithium ion battery has the upper hand in every department. The only major drawback is the much more expensive production cost.

Before the commercialisation of Li-on battery in 1991, majority of rechargeable devices used NiCd battery (invented in 1899) or lead acid battery (Buchmann, 2014). Since then, the vast nickel powered fleet has been gradually replaced by Li-on, which presents lower toxicity and higher energy density.

While NiCd becomes more and more obsolete, the research and development in Li-on battery are still on-going and seems promising. A recent breakthrough claims to use titanium dioxide and extend the Li-on battery cycle to above 10,000 while reducing the charging time per cycle to less than three minutes (NTU, 2014). Although no relevant specifications have been released, we can still conduct analysis from Table 6 based on what we know, and then use materials, time, and cost analyses in later sections to predict how well this potentially promising technology can be adopted in smartphone industry.

Table 6 - Comparison of graphite and titanium dioxide lithium ion batteries (Cleveland & Morris, 2013)

Characteristics	Lithium ion (with graphite) battery	Lithium ion (with titanium dioxide) battery
Cycle life	1,000cycles	10,000+ cycles
Charging time	120 mins	3 mins
Life span	2 years	20+ years
Embodied Energy	91.5MJ	150MJ
Cost	$13.25	~$28

The embodied energy of titanium dioxide (TiO_2) in Table 6 is derived from the application of paint, in which the embodied energy of TiO_2 is around 60MJ/kg (Greenspec, 2014), and assuming that there is 19g of titanium dioxide. The result is that Li-on titanium battery would have nearly twice the embodied energy. However, this new generation of lithium battery has the advantage of having more than ten times greater the life span and about 40 times faster charging rate than the graphite counterpart.

In the future, adoption of Li-on titanium battery will likely drop the cost and production energy to a similar level of the current Li-on graphite battery as technology and manufacturing methods progress.

3.3 End-of-life Issues

Due to the fast pace in development, new generations of smartphone arrive every one or two years (e.g. iPhone). It is not reasonable to expect users to use same phone for a period of 20 years to match the life span of Li-on titanium battery. After every three or four years, when a new phone becomes an old one and is thrown aside to collect dust, it would be very wasteful to not reuse the Li-on titanium battery inside, which has been designed to last for another 16 years or more. In fact, this would be worse for environment because Li-on titanium battery has much more embodied energy than a normal Li-on battery.

Therefore, there must be enough incentive for users to reuse their smartphone battery, and one can easily create such incentive by simply separating the purchase of phone and battery. More specifically, if phone buyers get new phones without getting new batteries, then it encourages them to reuse batteries from their previous phones, as otherwise extra expense would incur for buying new ones. The major barrier for this scheme is the standardisation of smartphone battery. Some brands, such as Apple, are also reluctant to allow users to open up phone case, and this increases the difficulty of implementing reusable, standardised Li-on titanium battery. Should such system be successfully implemented in the future, the overall environmental impact of smartphone batteries (and possibly batteries of many other technologies such as laptops, tablets, GPS etc.) can be greatly reduced. More analysis on long-term embodied energy benefit of Li-on titanium battery is provided in 6.2 Payback Period.

3.4 Recommendations/Conclusion

From the materials analysis, we can clearly see the positive and negative sides of the contenders. They are summarised in Table 7 below.

Table 7 - Advantage and disadvantage of Li-on graphite, Li-on titanium and nickel-cadmium batteries

Battery	Advantage	Disadvantage
Lithium ion (graphite)	• High voltage • Low self-discharge • Relatively cheaper than Li-on titanium battery • Lower embodied energy	• Expensive • Degrades at high temperature • Short life span
Lithium ion (titanium dioxide)	• High voltage • Low self-discharge • Very long life span • Very short charging time	• Expensive • High embodied energy
Nickel-cadmium	• High efficiency charge • High mechanical strength • Very cheap • Lower embodied energy	• Low energy • Toxicity • Low energy density • Short life span

It is at this stage inconclusive which type of battery is most appropriate for the role. The trade-offs between these characteristics are complex, but slight favour is given to lithium ion titanium dioxide battery due to its extraordinarily short charging time and long life span. However, further analyses from energy, time and cost will be needed to show if this hypothesis is indeed right and make the recommendations at the end of the portfolio more solid.

4.0 Energy Analysis

4.1 Introduction

Environmental impact, apart from using embodied energy, can also be assessed by estimating life-cycle CO_2 emission using I=PAT equation. This section will also look at the energy flow of a typical smartphone from a Sankey Diagram to identify major sources of energy losses.

4.2 I=PAT and Life-Cycle Environmental Impact

The overall environmental impacts of the three batteries can be analysed by using I=PAT equation. Here, we measure the carbon dioxide emission as an indicator of environmental impact. As shown in Table 8, the term 'T' (technology) is the amount of CO2 emitted per unit during a full life cycle. The affluence, or 'A', is the number of batteries that a person consumes in a span of 40 years. With no available data, the CO_2 emission for the future Li-on titanium battery is predicted to be 0.80 kg CO_2/unit - slightly higher than Li-on graphite battery.

Table 8 - Life-cycle CO_2 emission (Hawkins, et al., 2011)

Battery Type	CO2 emission per unit	Consumption per person in 40 years	Approximate Impact (per person)
Lithium ion (graphite)	~0.56 kg	20 units	11.2 kg CO_2
Lithium ion (titanium)	~0.80 kg	2 units	1.6 kg CO_2
Nickel-cadmium	~1.40 kg	32 units	44.8 kg CO_2

The population 'p' would become redundant when we try to establish a relative scale on environmental impacts of the three types. In a long term, Li-on titanium battery is clearly advantageous as it has much longer service life. On the other hand, NiCd battery produces greatest amount of CO_2 because it has the shortest life span and requires greatest amount of energy (i.e. therefore CO_2) to manufacture. When we look at the total impact of smartphones in the world, the population factor needs to be considered. By the current exponential growth in population, the life-cycle carbon emission and consumption will have to decrease at the same rate in order to keep the environmental impact at the same level.

The I=PAT equation is very simplistic because it makes many assumptions. Firstly, it assumes that battery technology and manufacturing methods stay the same in the future. Then, users assume to use the battery for the full duration of its life span, which may not be the case. For example, some smartphones such as iPhone have non-removable battery that simply cannot be removed and refit when users decide to get a new phone. In addition, this model also assumes the three variables – population, affluence and technology, have linear relationships to the impact, which is not the case in real world. The halving of battery emission per unit may not bring the total impact down, because, the decrease in emission translates to lower environmental impact per unit, which can destroy the population's incentive to reuse and recycle them, hence the impact may be reduced to half of the original. For the purpose of this paper however, we can still rely on the results obtained from I=PAT equation because it allows us to estimate the environmental impacts caused by implementing different types of batteries.

4.3 Energy Flow and Sankey Diagram

As have discussed in 2.0 Human Factors, chemical energy stored in a cell is converted to electrical energy with waste heat as by-product. This waste heat is contributed by the internal resistance of electrolyte in an electro-chemical reaction. For a typical Li-on battery, about 20% of the total chemical energy is dissipated as heat, and 80% is converted to electrical power to supply various electronic components of a smartphone (Buchmann, 2014). Table 9 shows a typical energy balance of the battery under regular usage pattern is shown in detail. The regular usage pattern in one charge cycle is to have 30min SMS, 60min audio, 30min phone call, 15min web browsing, 15min email and the rest in sleep mode (Carroll, 2014).

Table 9 – Energy loss per charge cycle of a typical smartphone under regular usage (Carroll, 2014)

Energy Loss	Component	Energy loss (percentage)	Energy loss (J)
Heat		20 %	3818
Electrical power	GSM	35%	6720
	CPU	11%	2138
	RAM	3%	611
	Graphics	11%	2138
	LCD	3%	611
	Backlight	6%	1069
	Rest	11%	1985

A graphical way to understand the energy flow is a Sankey diagram as shown in Figure 1 in page 9. From the figure and table, GSM unit consumes largest amount of energy, followed by passive heat loss, CPU, and graphics. It becomes evident that, in order to improve the overall power consumption, these components as well as heat loss should be made as power efficient as possible. To clarify it further, the internal resistance of electrolyte of battery can be decreased to reduce heat production; GSM unit can also be made more power efficient in a development project, with one possibility of

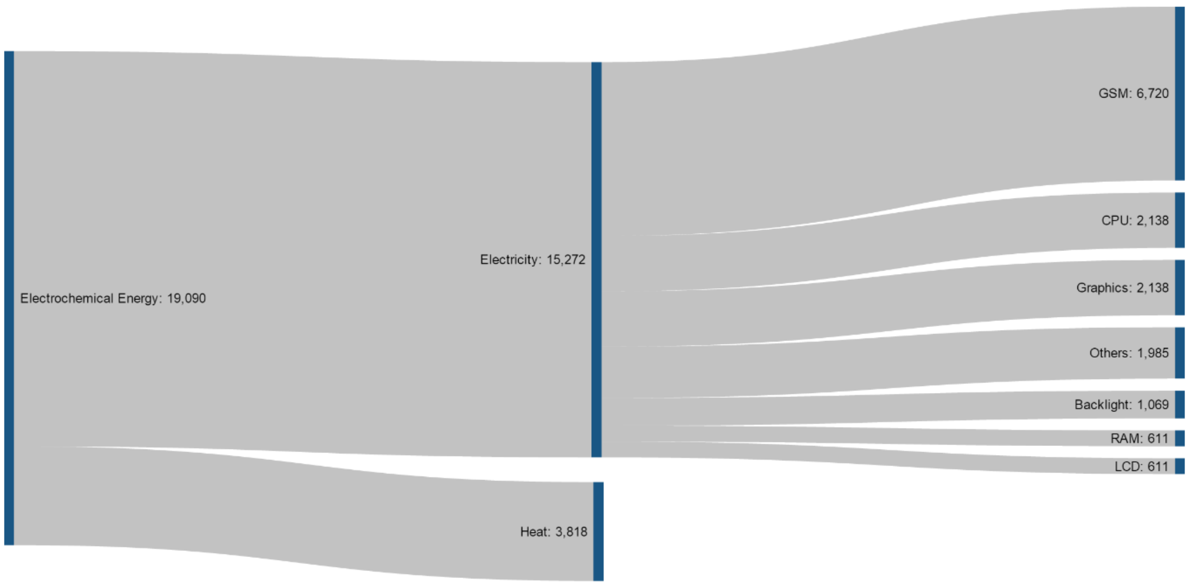

Figure 1 - Sankey diagram of the energy flow in a single charge cycle (unit: Joule)

turning GSM receiver on and putting other components into sleep mode when not in use. This will involve complicated research that is outside the scope of this paper.

As opposed to what is commonly believed, improving the power efficiency of components like LCD screen and backlight will relatively achieve less significant result. Although they also represent some portion of total energy flow, research and development should primarily focus on increasing the power efficiency of GSM unit as well as reducing internal resistance of battery.

4.4 Recommendations/Conclusion

Li-on titanium battery will produce much less carbon dioxide than others, provided that it is reused for the duration of full life span. In order to do so, it is essential to first standardise smartphone battery across different phone brands and platforms, and then sell phones and batteries separately. Further analysis on energy flow shows that the most significant amount of energy is either lost as heat or consumed by GSM unit. Improvement can be made by further reducing internal resistance of battery and by making GSM unit more power efficient.

5.0 Time Analysis

5.1 Introduction

Time analysis will be conducted from a perspective of duty cycle that aims to understand the pattern of how people charge their phones in a typical day and then find out whether or not a shorter charging time is much better.

5.2 Duty Cycle

Understanding the behaviour of how people charge their phones is critical to maximising battery efficiency. To that end, we have conducted qualitative interviews that asks people to describe how they charge their phones during weekdays. The results are coded and categorised by the time pattern, as shown in Table 10 below.

Table 10 - Categorising different charging pattern from interviews

Category	Code	Frequency (no. of people)
Charging during the night	AT NIGHT SLEEP	7
No fixed charging pattern	AS NEEDED LOW BATTERY POWER RUNS OUT	2
Charge whenever possible (even when it's 100%)	ALWAYS PLUGGED IN	1

Majority of people prefer to plug in and charge before sleep and then unplug in the next morning. We will therefore analyse this scenario from a duty cycle perspective. Suppose that one cycle is 24 hours and that a phone is charged from 10pm-6am, we then assume the following model – the phone charges and discharges at constant rates, with charging time of 120 minutes and battery life of 1 day (1440 minutes). The graph of battery capacity over 2 days can be produced in Figure 2.

With this pattern, the charging time per cycle is about 8 hours. Although most lithium ion batteries have adopted 'overcharge protection' that reduces the effect of overcharging, it is still recommended by battery experts to preserve optimum battery performance by not overcharging for too long, even better if it is always kept between 40-80% (Buchmann, 2014).

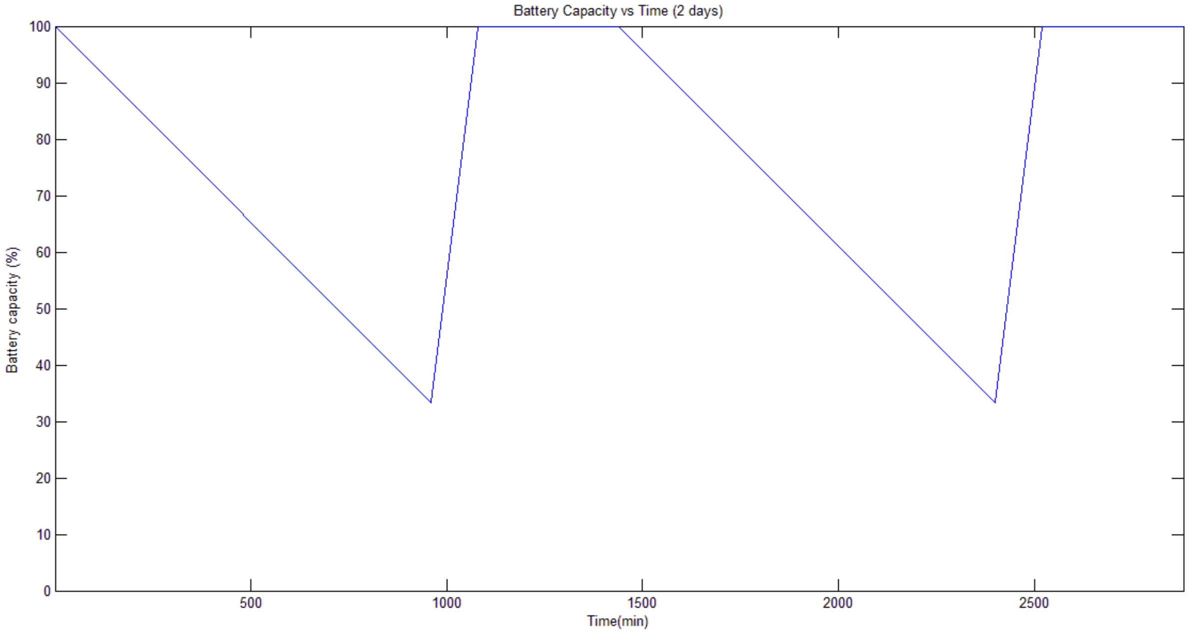

Figure 2 - Duty cycle for charging overnight

The behaviour of users influences how products are designed, and likewise product design also renders the way people use them. The 2-hour charging time of current Li-on battery forces people to only charge at night because they don't want to spend time waiting during the day.

On the other hand, Li-on titanium battery's 3 minute charging time makes it possible to conveniently charge at other times because users don't have to wait for a long time. In fact, people also discussed in the interview about Li-on titanium battery's 3-minute charging time, in which everyone thinks that they can simply charge whenever they need to, even possible at places like shopping centre or train station. This, apart from saving people's trouble of worrying about charging battery all the time, also helps slow down battery degradation by avoiding 'overcharging', which at the moment is a problem for most people.

5.3 Recommendations/Conclusions

The behaviour pattern of the majority of people has been identified to be night charging, that is, charging phones when they sleep. From the duty cycle analysis, it becomes apparent that this charging pattern is likely due to the long waiting time of Li-on graphite battery. This causes the issue of overcharging that degrades batteries gradually over time. The implementation of Li-on titanium battery will dramatically improve the situation as people don't have to wait for a long period, and this, in turn, also helps retain battery performance by preventing from overcharging.

6.0 Cost Analysis

6.1 Introduction

In cost analysis, the subject being studied is about economic and energy costs. More specifically, the concept of payback is used to compare both costs across the three candidates. The goal is to identify payback periods of money and energy for the three batteries and then make recommendations based on the results.

6.2 Payback Periods

The identification of payback periods requires the parameters, which are given in Table 11. For Li-on titanium, the charge cycle cost is predicted to be slightly lower than graphite counterpart.

Table 11 - Cost analysis on Li-on and NiCd batteries (Cleveland & Morris, 2013)

	Li-on graphite	Li-on titanium	NiCd
Economic			
Capital cost	$13.25 ($2500/kWh)	~$28	$3.71 ($700/kWh)
Charge cycle cost	0.024 cents/cycle	0.020 cents/cycle	0.027 cents/cycle
Operation cost	$0.72/months	$0.72/months	$1.08/months
Life span	24 months	240 months	18 months
Energy			
Embodied energy	91.5MJ	150MJ	94.0MJ
Operational energy consumption	0.57MJ/month	0.57MJ/month	0.86MJ/month

The plot of monetary cost over time of the three types is given in Figure 4 in page 13.

It is shown clearly that, while the costs of having Li-on graphite battery and nickel-cadmium battery are very much the same, the cost of having Li-on titanium battery that has nearly twice the capital cost is clearly less after four years. And in a long term, it is the cheapest option.

The plot of energy cost over time given in Figure 3 has similar patterns. Li-on titanium has 50MJ higher capital cost in energy, but a lower operation cost and much longer service time make Li-on titanium battery more energy efficient than the others after only 2-3 years. Additionally, it can be seen that nickel-cadmium battery uses more energy than Li-on graphite battery, and this energy difference increases linearly with time.

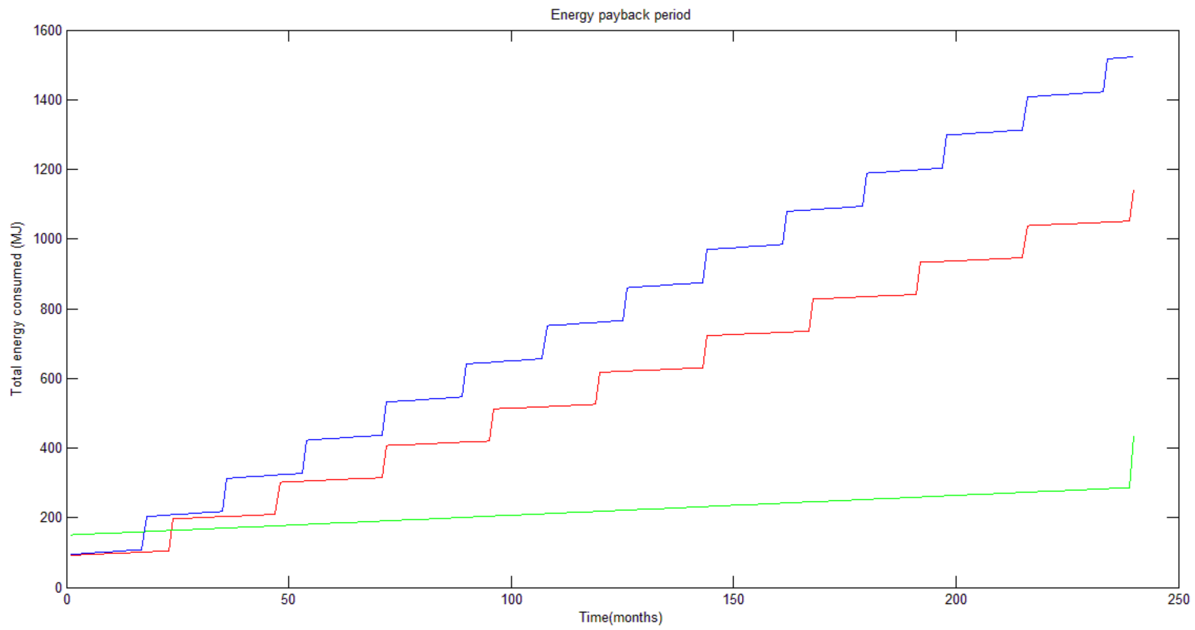

Figure 3 - Energy payback period (Li-on graphite: red; Li-on titanium: green; NiCd: blue)

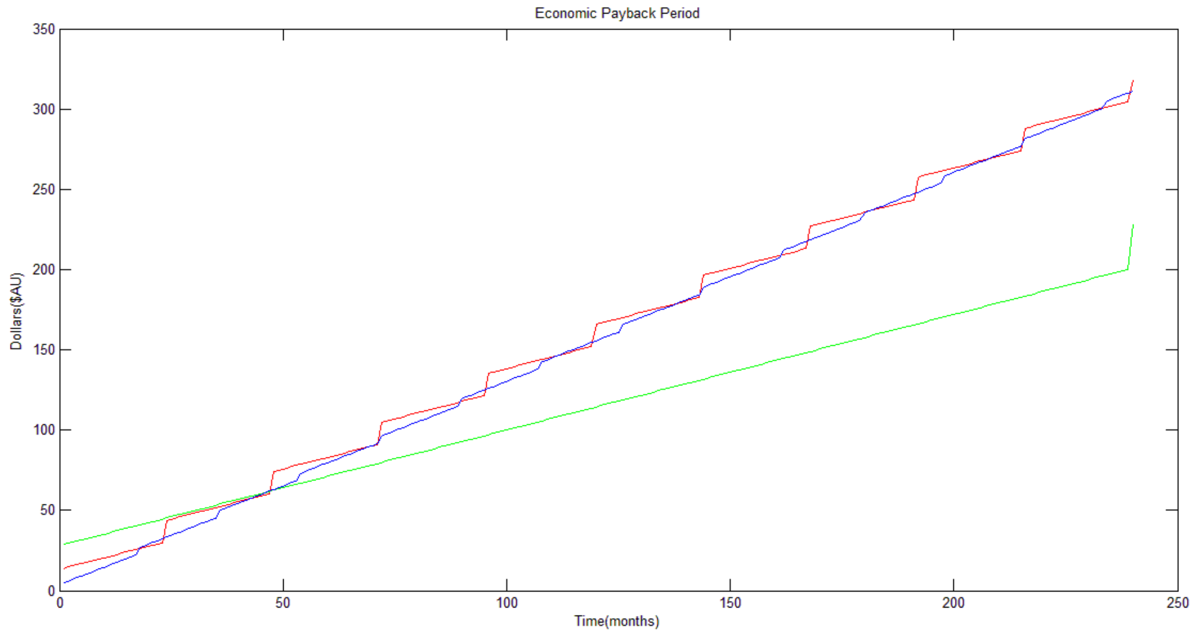

Figure 4 - Economic payback period (Li-on graphite: red; Li-on titanium: green; NiCd: blue)

Overall, Li-on titanium battery has the energy advantage after 2-3 years and the economic advantage after 4 years.

6.3 Recommendations/Conclusion

After applying cost analysis on economic and energy payback periods, it becomes clear that Li-on titanium is the cheapest and most energy efficient solution in a long run (i.e. after 4 years). Furthermore, Li-on graphite battery and nickel-cadmium battery have similar economic cost, but Li-on graphite has the upper hand in energy efficiency to nickel-cadmium.

7.0 Optimisation and Reliability

7.1 Introduction

In 4.0 Energy Analysis, we have looked at energy flow from a hardware dimension. In a similar fashion, software energy usage will be analysed in this section using Pareto approach in the hope of identifying best battery-saving strategies. Additionally we will use Bathtub Curve to briefly investigate the reliabilities of the three types of battery.

7.2 Software Optimisation

Apps and mobile operating system (OS) use different components and sensors to perform all kinds of tasks. The Pareto Principle, which states that 80% of effects are due to 20% of causes, is also true in battery usage of software. In order to find out the software activities that use most battery power, Lumia 525 has been tested. The power consumption of different activities in a typical day can be found out by using the in-built Battery Monitor app (Figure 5). For example, the rate of battery consumption when auto updates are turned on is about three times as high as the rate at which system is at standby without auto-update, and hence 2/3 power is used by auto-update and 1/3 is used by the OS.

The activities that consume majority of battery are auto-update and social apps/SMS, and we should seek to cut down battery usage from them. Firstly, auto-update may be completely or partially turned off, depending on what information users want to receive. A good strategy is to only turn on updates

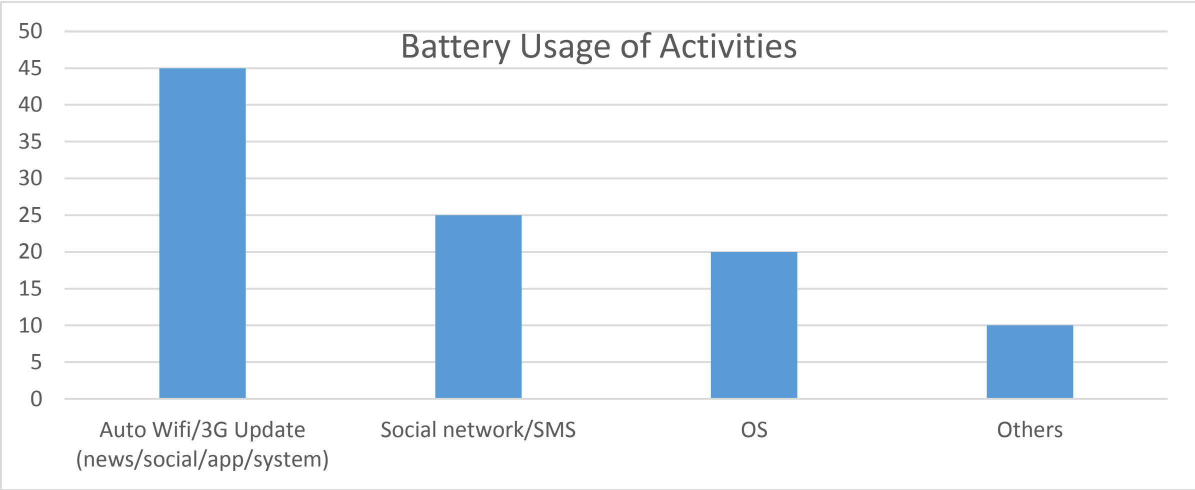

Figure 5 - Battery usage of different activities

for system, apps or other news feeds when phone is being charged. This can effectively save unnecessary battery usage when users are on the move. Hence, software developers may consider to create an option - 'Only auto-update when plugged in', as presently major mobile phone systems (i.e. iPhone, Android, windows phone) lack this feature. On the other hand, social apps and SMS are essential functions of smartphone that cannot be refrained from using. The improvement on them would again take a hardware approach, by improving efficiency of GSM and Wi-Fi transmitter. Of course, different users will have different graphs for battery usage. In general, things such like games, phone calls, GPS, Wi-Fi or 3G related activities will cost significant amount of power (SONY, 2014).

7.3 The Bathtub Curve

It is useful to look at the reliability of battery over the life span. For Li-on titanium battery, the likelihood of failure may be high in the beginning because of technological immaturity. On the contrary, Li-on graphite and nickel-cadmium batteries are not likely to fail in the beginning, but they tend to fail much more quickly with shorter life spans. And in general, Li-on battery is more robust than nickel-cadmium battery. The bathtub curve of likelihood of failure is shown in Figure 6. Notably Li-on graphite and nickel-cadmium have only the latter half of the curves because of already mature technology and manufacturing precision.

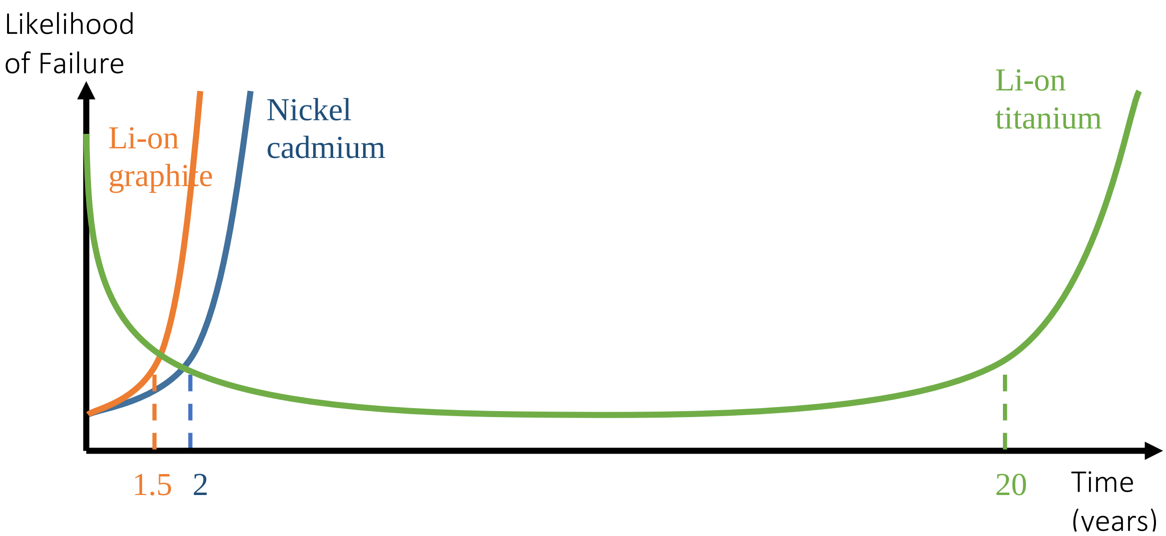

Figure 6 - The bathtub curves of three batteries plotted on the same graph

Both Li-on graphite and nickel-cadmium batteries are expected to have a more stable performance in the beginning, but failure rapidly rises after 2-3 years. Li-on titanium battery will have high failure rate in the beginning, followed by a low failure rate for a long time. One important thing here is that Li-on titanium is still in the very early stage of diffusions of innovations. However, as manufacturing methods and technology improve in the future, the high failure rate at the start will rapidly decrease or disappear, and by that point, Li-on titanium battery will be clearly a superior option.

7.3 Recommendations/Conclusion

Software developers, especially OS designers, are recommended to allow an option of auto-update only when phones are plugged in. Hardware improvement can be made on power efficiencies of GSM unit and Wi-Fi transmitter. Reliability of three batteries is also compared, and it is clear that over a span of 20 years, Li-on titanium battery has the greatest stability. Even though it is still immature and can have higher rate of early failures, Li-on titanium will become progressively better as technology and manufacturing methods improve.

8.0 Recommendations

In summary, the following recommendations can be made to smartphone companies, users and software developers regarding possible improvements on performance of smartphone battery.

8.1 Smartphone Companies

- New generations of smartphones in development should adopt Li-on titanium dioxide battery due to long life span and short charging time.
- There is a need for battery standardisation across different smartphone devices. Battery should be made removable to increase reusability.
- A typical thickness of 5-7mm is appropriate. Although it is also possible to increase thickness for greater capacity, it will be unnecessary for most users after the introduction of Li-on titanium battery.
- As Li-on titanium battery is not yet available, Li-on graphite battery should continue to be used. Nickel-cadmium and lead acid batteries are considered unsuitable.
- Further R&D can focus on reducing internal resistance of battery and improving power efficiency of GSM unit and Wi-Fi transmitter.

8.2 Users

- Smartphone users can give serious consideration to Li-on titanium powered phones when they come out. They should make sure batteries on those phones are removable and reusable.
- Auto-update option can be turned off to save a significant amount of power. Excessive usage of social apps and SMS should be avoided when battery is low. Users should also use battery saver app to tailor their own usage.
- Heat can cause serious battery degradation and should be avoided.

8.3 Mobile OS Developers

- Mobile phone OS can be designed to update system, apps, news only when phones are plugged in; alternatively options can be given to users for what and when to update.
- More efficient algorithm can be developed for most commonly used apps such as Facebook, twitter or camera to reduce CPU usage.

Appendix I

The table below summarises the anthropometry of human hand (Georgia Tech Research Institute, 2008).

Table 12 - Hand Anthropometry of Non-disabled Individuals

Dimension	Gender	5th percentile (mm)	50th percentile (mm)	95th percentile (mm)
Hand length	Male	173-175	178-189	205-209
	Female	159-160	167-174	189-191
Palm length	Male	98	107	116
	Female	89	97	105
Thumb length	Male	44	51	58
	Female	40	47	53
Thumb breadth	Male	11-12	23	26-27
	Female	10-14	20-21	24
Index finger length	Male	64	72	79
	Female	60	67	74
Hand breadth	Male	78	87	95
	Female	69	76	83-85

Appendix II

The following picture depicts the anatomy of human hand. The parts that are concerned in the report in 2.1 Hand Anthropometrics are middle phalanx of the index finger.

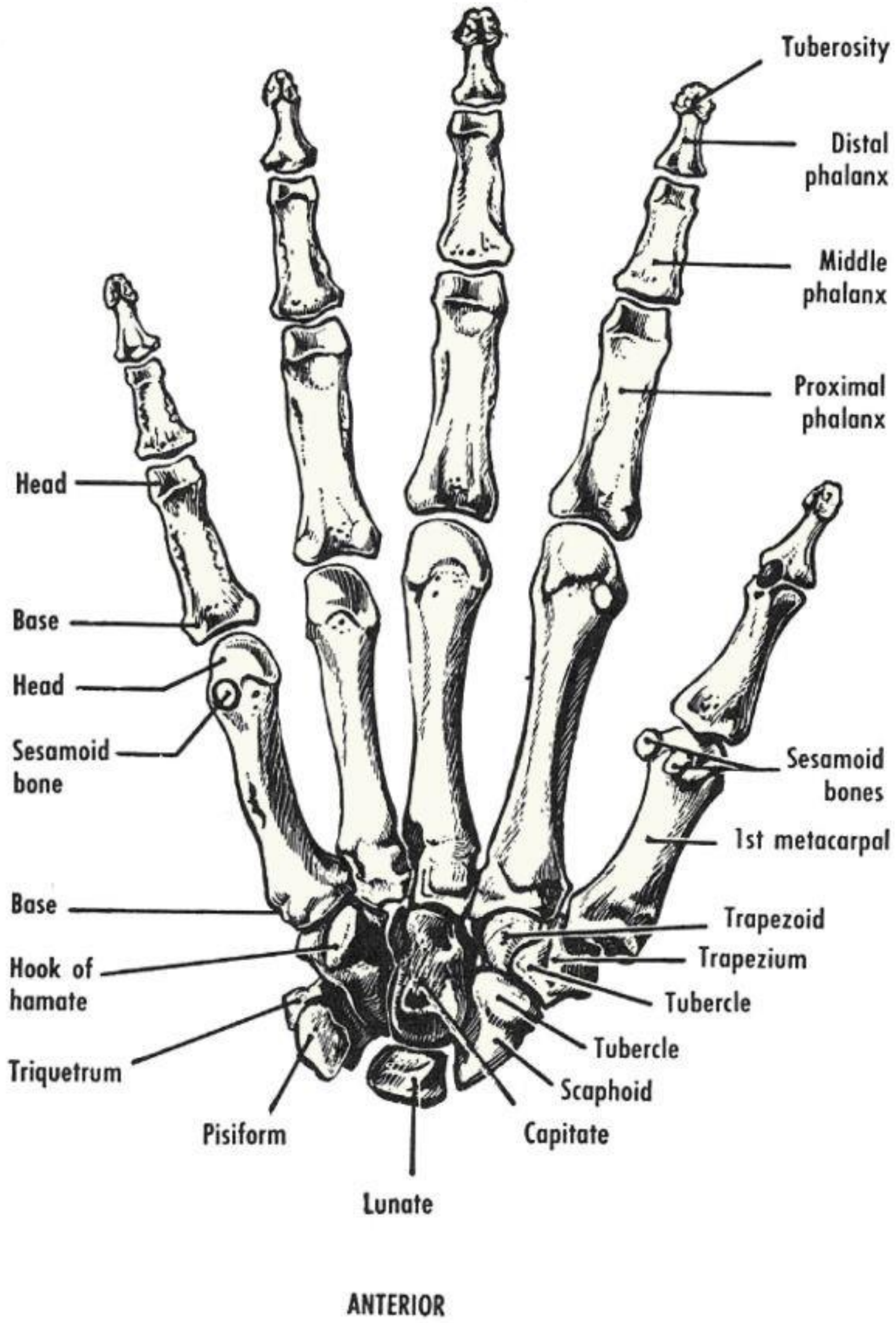

Figure 7 - Anatomy of human hand

References

Buchmann, I., 2014. *Battery University.* [Online] Available at: http://batteryuniversity.com/ [Accessed 13 October 2014].

Buryanov, A. & Kotiuk, V., 2010. *Proportions of Hand Segments,* Kiev: International Journal of Morphology.

Carroll, A., 2014. *An Analysis of Power Consumption in a Smartphone*, s.l.: NICTA and University of New South Wales.

Cleveland, C. & Morris, C., 2013. *Handbook of Energy: Diagrams, Charts, and Tables.* s.l.:Newnes.

Energizer, 2005. *Battery Internal Resistance,* s.l.: Energizer Holdings.

Georgia Tech Research Institute, 2008. *Hand Anthropometry.* [Online] Available at: http://usability.gtri.gatech.edu/eou_info/hand_anthro.php [Accessed 6 October 2014].

Greenspec, 2014. *The impact of paint on the environment.* [Online] Available at: http://www.greenspec.co.uk/building-design/paint/ [Accessed 16 Octorber 2014].

Hawkins, T., Strømman, A. & Majeau-Bettez, G., 2011. *Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries,* Trondheim: American Chemical Society.

Komandur, S., Johnson, P., Storch, R. & Yost, M., n.d. *Relation between Index Finger Width and Hand Width Anthropometric Measures,* s.l.: s.n.

NASA, 1995. *ANTHROPOMETRY AND BIOMECHANICS.* [Online] Available at: http://msis.jsc.nasa.gov/sections/section03.htm#_3.2_GENERAL_ANTHROPOMETRICS [Accessed 14 September 2014].

NTU, 2014. *NTU develops ultra-fast charging batteries that last 20 years.* [Online] Available at: http://media.ntu.edu.sg/NewsReleases/Pages/newsdetail.aspx?news=809fbb2f-95f0-4995-b5c0-10ae4c50c934 [Accessed 16 October 2014].

SONY, 2014. *Optimise battery performance.* [Online] Available at: http://www.sonymobile.com/au/support/discover-more/optimise-battery-performance/ [Accessed 22 October 2014].

Synthesis Studios, 2009. *Embodied Energy Database.* [Online] Available at: http://legacy.wattzon.com/stuff [Accessed 11 September 2014].

University of Ottawa, 2013. *Thermo Ergonomics Laboratory.* [Online] Available at: http://www.health.uottawa.ca/ojay/ [Accessed 12 October 2014].

Woodbank Communications, 2005. *Battery and Energy Technologies - Thermal Management.* [Online] Available at: http://www.mpoweruk.com/thermal.htm [Accessed 17 September 2014].