Benefits of Direct Current Electricity Supply for Domestic Application

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Abstract

Although, the use of DC in the home has a long history, AC is presently used almost exclusively in all domestic electricity supply with DC limited only to niche applications such as motorised caravans/mobile homes and other leisure craft. In recent years there has been growing interest in the use of DC in the home partly because many modern home appliances use DC voltages and most renewable energy sources generate DC power. Continued use of AC therefore seems wasteful, as the energy has to be converted using an inverter from DC to AC and then using an AC to DC converter back to DC with consequent energy losses. Elimination of this multiple stage energy conversion saves energy, and CO_2 emissions. Most of the previous works undertaken to assess the feasibility of DC in the home have concluded that it is not practical for technical and cost reasons. This research re-examines the methodologies and assumptions used in previous work on DC.

In contrast to previous work whose goal was to determine if DC voltage could substitute AC voltage in home applications, the primary objective of this research was to assess whether DC voltage could be used in the home avoiding any constraints imposed by how electricity is used today. A novel bottom-up approach is proposed starting with real DC loads that are found on the open market. These DC loads are apportioned to different zones, power sockets and cable spurs to determine the DC voltage peak power that directly correlates with real DC loads. Even given the constraints of voltage drops along the cables, this approach allows for the use of $4mm^2$ cables in the design and enables micromanagement of the loads. Previous works have suggested much bigger cable gauges.

Different design implementations/scenarios are investigated from which it has been shown that low power DC voltage can be practically and economically implemented with cables of an acceptable gauge. Some of the indirect economic and socioeconomic benefits that widespread use of DC in the home provides are discussed. These include Energy Independence with Energy Security, reduced pressure to import fossil fuels, the advantages of decentralised energy generation, and the increase in the quality of life and Gross Domestic Product of developing nations. It is concluded however, that a full implementation of a DC system will only become possible within the context of Smart House Technology.

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Declaration

No portion of the work referred to in this thesis has been submitted in support of any application for another degree or qualification of this or any other university or other Institute of learning.

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Copyright Statement

Chapter 1

Introduction

Summary

This chapter puts this research into its historical context and sets out the underlying reasons for the need to rethink the way energy is used in the home. Then to determine if, how and what advantages there are to change from the conventional electrical supply of alternating current (AC) to direct current (DC). The direct phenomena that affect the amount of energy used in the home are discussed. Also discussed are the wider affects the proliferation of the DC house will have on society beyond that which are manifest in the home. These are termed the 'global objective' and are the drivers pushing the debate. An overview of this thesis is also given.

1.1.0 Historical Background

1.1.1 History of direct current electricity

With the partnership of Swan and Edison in 1879 began the beginning of modern electrification of the home [1Page 15]. In the United Kingdom, from the 1st of October 1881 Godalming, became the first town to supply electricity for public and private use. At the same time in New York saw the setting up by Edison of the Pearl Street generators in downtown Manhattan. "*At three o'clock on September 4, 1882 the current began to flow from the Pearl Street, generators*" [2]. Initially, all the current provided was DC. DC voltage presented the problem of voltage drops (See Sections 3.2.0 and 3.2.5 for further discussion about voltage drop along cables), which was circumvented by Edison, by placing the electrical generators close to the buildings he was going to supply with DC electricity. As the electrical network expanded, the distance between the generators and the end user began to grow. It became apparent that over long distances direct current was not a practical solution. Westinghouse, together with

Tesla believed that AC current was the best and only way forward especially for long transmission lines.

The development of the transformer, which allowed for easy step up or down of AC voltage without large voltage drops, took place between 1878 and 1887 and sealed the fate of DC for transmission purposes. The controversy, as to the merits or otherwise of using alternate current or direct current, raged between the late 1870s to the late 1890s. However by the time AC had been taken up as the way forward, most of downtown Manhattan as well as parts of Queens had been fully equipped and running with direct Current.

The controversy did not destroy Edison, as once the infrastructure was in place supplying electrical energy to thousands of customers the only thing that could be done was to generate the electrical power using AC and then convert the energy to DC. This was done in 1898 [2, Page 113]. Although the way of generating and delivering electrical power has been for over a century using alternating current, throughout this time many electrical systems and household appliances worked on DC. Besides the electric lights, the Edison Company produced DC appliances to be used in the buildings that the company supplied with DC electricity. Therefore the concept of a home appliance that only works on DC voltage is not new, but in fact goes back at least to the beginning of the electrification of the home itself. In parts of Manhattan until as late as the second half of the 1950s and early 1960s in some apartment blocks every apartment had dual DC and AC electrical supply. It was not until 14th November 2007 that the last section of DC power was turned off by the ConEdisson Electric Company in Manhattan [3]. However there were still customers using DC so they were provided with on-site AC to DC converters.

Historically the main phenomenon that was against DC voltage was the I^2R/power losses which cause the voltage to drop along a transmission line. However for use in the home at very short cable lengths, coupled with the advent of low powered electronic home appliances that take advantage of integrated circuit power-electronic components, DC voltage in the home has now come of age.

1.1.2 Development of Power electronics

The invention of the bipolar transistor in 1947 [4] saw the beginning of what is now known as the modern power electronics industry. Power electronic components need DC voltage to operate, and have therefore needed an AC to DC converter to provide the necessary DC voltage. Over the years, the amount of gadgetry employing power electronics has increased, while the size of the components has gradually shrunk, with the resultant reduction in energy consumption. It has now come to the point that many gadgets that are using inefficient AC to DC converters, that according to the Building Research Establishment (see Section 1.2.1) and Natural Resources Defence Council NRDC (see Section 6.2.2) operate at less than 50% efficiency will consume less power than their AC to DC converter. Therefore now is the time to take a hard look at the way DC voltage gadgetry is powered. The question is, to continue to find different ways of reducing power consumption by for example manufacturing state-of-the-art switch mode AC to DC converters, or is it time to eliminate the AC to DC converter altogether, by having a full DC electric home?

1.1.3 DC for leisure, boats and satellites

For many years there has been a thriving niche market for DC only appliances. Different gadgets on leisure craft like, cars, boats, yachts, caravans etc have for a long time had their electricity supplied via batteries. A small industry has built up that provides a limited amount of basic electrical goods that operate on DC. Some autonomous systems running on solar power, for example satellites, run completely on DC voltage.

Although the amount of different DC gadgetry is small compared to that for AC, there is no engineering reason why AC gadgetry cannot be easily reengineered to work on DC. However, where a large power is required the extra low voltage DC home will place restrictions on the upper limit on the maximum power that the system can provide. This may place a limit to the usability but not functionality of some of these appliances, the best example of this is an electric kettle (see Section 3.5.5 for further discussion). Huge advances have been made in DC motor technology for use in DC appliances. Some state-of-the-art extraction fans have recently been made to run on 12 V DC. Therefore trying to implement a DC voltage home is not a complete new concept, much of the groundwork for DC appliances already exists. All that is required is further work to see how more AC appliances can be reengineered to work on DC.

1.1.4 Renewable micro energy generation using DC

The most widespread micro energy generators are solar and wind, both of which provide DC voltage output. However in almost all cases the DC electrical energy is feeding into an AC house, which requires an inverter to provide the AC mains electricity. Then, each appliance requires either an internal or an external AC to DC converter, so that it can operate at its correct DC voltage. Therefore the technology for two of the three stages of the electrical system already exists. There are the DC energy generators on the supply side and the DC loads on the demand side, all that is missing is the middle stage, the DC distribution network in the house.

1.2.0 Some advantages of the DC house

1.2.1 Saves energy by eliminating the inverter AC to DC converters

The all DC house if powered from generators that produce DC voltage will not need an inverter. The electricity provided at the sockets in most buildings is 230V AC, but many if not all electrical appliances, actually run on a much lower voltage. One has to just look around any home or office to see the ubiquitous power adapters/ AC to DC converters, needed to run a large array of appliances. These power adapters are transformers, which besides using up energy and resources to manufacture, also use up energy as long as they are connected to the electricity supply, even if the appliance is in standby mode. This is manifested in the heating up of the adapter.

For the internal power supply the energy dissipated as heat, heats up the internal electronics of the whole appliance. The hotter it gets the higher the probability of its mean time to failure being shorter. Once a power supply, fails in most cases, this is catastrophic enough for the need to replace the whole appliance. Therefore without the AC to DC converter, not only are electrical energy and raw materials being saved but the mean time to failure for the whole appliance is greatly increased, and the need to replace it becomes diminished. (See extracts from Vent-Axia Section 6.4)

Some lights, especially many halogen lights used today need a transformer to operate. These are usually hidden in the ceiling or in the light fitting. Many appliances, including computers, in fact operate at much lower voltage than the mains, and employ a Universal Power Supply (UPS) inside their casing that incorporates a step down transformer. Therefore what is the real voltage and power level at which each appliance works? It can be stated with great certainty that it is less than the mains supply of 230V. All electrical goods have their electrical ratings printed, embossed to attaches to them, in the main, their DC voltage is below 25V.

To comprehend the phenomenal potential energy and raw material saved from the elimination of the AC to DC converter, an estimate for their usage, based on work carried out at the Lawrence Berkeley National Laboratory is quoted verbatim from the Executive Summary of a Natural Resources Defence Council (NRDC) report dated 2002. [5] *"Nearly 2.5 billion electrical products containing power supplies are currently in use in the United States, and about 400 to 500 million new power supplies (linear and switching) are sold in the U.S. each year. The total amount of electricity that flows through these power supplies is more than 207 billion kWh/year, or about 6% of the national electric bill. More efficient designs could save an expected 15 to 20% of that energy. Savings of 32 billion kWh/year would cut the annual national energy bill by $2.5 billion, displace the power output of seven large nuclear or coal-fired power plants, and reduce carbon dioxide emissions by more than 24 million tons per year."* This savings is obtained by using a more efficient power supply, a much higher saving can be made by eliminating the AC to DC converter altogether. If this is only for the United States how much energy can be saved through worldwide adoption of the DC house? Or for new installations in the third world, how much less energy or smaller renewable energy generators will be needed to operate the equivalent amount of DC appliances?

It is appreciated that in an all DC electrical system there will be a need for the use of DC to DC converters. A mobile phone has two chargers one for the house

230 AC mains and a 12 V DC one for the car. If one opens them both up and looks at the materials used in their manufacture, it is apparent that the AC version uses more raw materials than the DC one, (See pictures in Appendix 3). Future work will need to be carried out to see what energy savings can be achieved by eliminating the AC to DC converters and where appropriate exchanging them for DC to DC converters.

1.2.2 CO_2 emissions and fossil fuels

Not only is energy generation throughout the world mostly via the burning of fossil fuels, but many raw materials, for example brass, copper, aluminium and glass, need huge amounts of energy to be transformed into everyday household goods. In these processes tonnes of CO_2 gas are produced. The low powered DC house with its low powered appliances and wiring network, offers a great opportunity to reduce the amount of raw materials that will be needed. This in turn will reduce the amount of fossil fuels that will be needed to produce the energy to manufacture all these hopefully redundant components. This in turn will have a large positive impact on the environment.

1.2.3 Direct economic advantages

The DC house offers the opportunity to save on the capital outlays for the energy generating system as the expensive DC to AC inverter is not needed. The elimination of the conventional 230V AC to DC converters for each appliance when replaced with a sub 50 Volt on-board mass produced integrated circuit DC to DC converter, specifically designed for that gadget should bring down their cost. By decreasing the energy consumed by multiple voltage conversions, it should be possible to either reduce the size of the micro generator or given a defined budget, increase its size with the same budget.

1.3.0 The DC house as part of the Global Objectives

1.3.1 Introduction – Indirect Economic advantages

So far this thesis has looked at the direct advantages to the electrical system and energy usage in the house of changing from AC to DC. However there are also the indirect socioeconomic affects the DC house will have on the people living in it, as well as the positive economic ramifications to society in general and on national energy policy in particular. The drivers pushing the energy debate are; (1) the finite availability of fossil fuels, (2) the need to reduce CO_2 emissions, (3) the need for a degree of energy independence with security and (4) should electricity be provided by either a centralised or decentralised electrical energy system or hybrid? The '**global objectives**' of this research are that the DC home should be part of the means to attaining (i) a degree of energy independence, (ii) a degree of energy security (iii) through a decentralised electricity system, and (iv) a reduction in the carbon footprint of the home.

1.3.2 Reliance on fossil fuels for electrical energy

At the present time electrical energy generation relies heavily on fossil fuels. Although the debate still rages, many analysts have been predicting for many decades that the fossil fuels used in energy production are finite and fast running out. In the world today the availability and the way fossil fuels and electricity are consumed is that which makes the difference between a developed world standard of living and a developing world standard of living. The dependence the Western World has on the use of fossil fuels and electricity is so great that, were this to suddenly stop, not only would much of the developed world be reduced to developing world living standards, but in many situations the living standards could be reduced to an inhuman and unbearable standard. Living in a city, a modern concrete jungle, and all of a sudden having no fuel for transport and no electricity, the human suffering that this would cause is incalculable.

War and siege cause terrible suffering in themselves, but the lack of fuel and electricity exacerbate it manifold. Two examples of this are, the siege of Sarajevo in the 1990s, and the war in Iraq where the people in cities like Basra suffered throughout the summer of 2003. Another example was the loss of electricity in the eastern United States of America in the summer of 2006 which caused untold misery by not having electricity in the sweltering heat. These power outages were not indefinite, however in the situation where a country does not have the fossil fuels needed to generate electricity what is it to do? Not having the fuel for transport or manufacturing not only reduces the standard of living but can also lead to total societal breakdown.

The human instincts for survival and self interest are a great motivator and as such, nations feel the need to take steps to secure for the future, strategic supplies of fossil fuels and water. This has led to some regional conflicts and may lead to more. In recent years countries that are rich in natural resources but economically poor, have forged direct political and economic alliances with a specific country that is willing to inject massive amounts of capital into the country to boost its economy. Long-term contracts are signed that guarantee the importing country the necessary fuel and raw materials needed to keep their economy stable.

A country that is a producer and the net exporter of fossil fuels, knowing that this resource is finite, naturally seek to reduce production and exports. However since the global village is so interdependent, these countries cannot just simply cease exports, they have to find other ways to hold on to their natural resources. One way is to increase the price, which if done as a single nation will be totally ineffective, therefore countries forge alliances in order to create a cartel that has the power to control the price of commodities.

For countries that are net importers of energy and raw materials and do not have economic might, these types of alliances are seen as a threat to their long-term stability. Europe and the United Kingdom have had an adversarial relationship with Russia for many years. Russia announced on 21st of October 2008 that together with Iran and Qatar, who together control about 60% of the world's gas reserves, they intend forming an OPEC style gas cartel [6]. Unfortunately Eastern European nations of the former Soviet bloc have found their independence under threat due to their reliant on imports of Russian energy. Western Europe is directly dependent and the United Kingdom is indirectly dependent, for around 44% [7] of its natural gas imports, from Russia. In 2007 41% of UK electricity generated was from gas (Digest of UK Energy Statistics 2008 Table 5.1).

The UK is projected to get about 1% of its gas from Russia in 2010 and this dependence is projected to rise to 15.6% by 2025 [8]. Twice in the last few years a crisis occurred between Ukraine and Russia and natural gas piped to many eastern European countries via Ukraine was temporarily stopped. Although Russia has claimed it has no political agenda and that this crisis was purely economic, due to monies owed to it by Ukraine, the knock-on effect to Western

Europe and its dependence on Russian energy leaves it very vulnerable. As an aftermath of the second incident between the Ukraine and Russia, in January 2009, Energy Ministers across Europe began thinking about what the European Community can do on a pan European level to reduce its reliance on Russian natural gas.

Energy and fossil fuels are commodities and as such are subject to market forces. By August 2008 futures dealers had forced up the NYMEX Crude Oil Futures price for a barrel of crude oil to a record price of over $140 a barrel. At $140 a barrel many economies were badly hit and people saw prices of food and basic commodities going up due to the increase in the price of crude oil. By February 2009 the economic downturn had caused a world recession and some say that this was partly fuelled by the high price of oil throughout the 2007/2008. Although due to recession, the demand for oil dropped and the price in February 2009 was about $40 a barrel, by the economics of supply and demand, some say that in the future the price of a barrel of crude oil will go back up to the $200 barrel mark [9], with some analysts saying it could even be double that in the future.

This event has shown how fragile the global economy can be and how easy it is for economies to be adversely affected due to the price of fuel. This has opened up the eyes of some governments who have realised that their dependence on foreign energy leaves them vulnerable to external economic and political influences. Many countries have now started looking at ways to reduce this dependency and increase their own energy independence. President Barrack Obama of the USA, pledged $50 billion to be used in renewable energy schemes to reduce the United States of America’s reliance on imported fuels.

1.3.3 Energy independence and energy security

This research defines Energy Security as “The ability of a nation or a person to procure the raw materials to generate enough energy to be able to keep themselves in their accustomed lifestyle”. This is a strategic policy, and as conventional energy generators rely on fossil fuels which are finite in any given country, governments will have to rely on their economic or military might to keep the raw materials flowing. However, as they are still relying on imports to provide the energy, such a nation or person cannot be labelled “energy independent”. A definition of Energy Independence can be “The ability of a nation or a person to have the energy needed to be able to live a normal accustomed lifestyle without being dependent on another nation or person to provide this energy”. When both of these definitions come together, the implication is that a government can provide energy independence for its people by being able to secure the raw materials or energy generators to provide the required energy without having to rely on others.

For most countries that do not possess their required supply of fossil fuels, the goal of energy independence with security may seem impossible. However a way forward in the long term, that may provide a high degree of energy independence and energy security, will be through the use of decentralised renewable energy generators feeding low powered DC homes, as well as centralised nuclear power plants.

1.3.4 Future trends in electricity demand

As the twenty first century progresses and perhaps the availability of fossil fuels diminish, is the projected UK electricity demand set to increase or decrease? Only time will tell what will happen in fifty years from now, however in some instances, present government policy is leading to an increase in the energy required in the home over the next ten to twenty years.

An example of an active policy is the TV digital changeover. “*By 2012, all UK households will need a digital television adaptor if they are to continue to watch television*”. By June 2007 “*18 million digital adapters were in use in the United Kingdom*”. “*This is estimated to increase to a worst case scenario of 80 million by the year 2020*” [10]. “*The total anticipated peak additional power consumption in the UK as a direct result of the digital switchover is expected to be around 31MWh per day. Over time, as older equipment is naturally replaced and technology becomes more power efficient, our model predicts that this will trend towards zero*” [11]. What it does not say is how long it will take for the net increase to “*trend toward zero*”. The daily increase of 31MWh may only be 0.003% of the total UK energy consumption, however this still adds up to 11,315MWh per year which equates a carbon footprint (1kWh = 0.493824 kg

CO^2) of 5,587,618 kg of CO_2 emissions per year (this excludes the carbon footprint of any new energy generators). What is apparent from the Energy Savings Trust is that, at least until 2020, the effects of digital TV changeover on the increase in energy consumption will be felt.

What is also new, is that in mid 2009 there has been talk of digitising the radio signals so that everyone will need a digital radio as well as a digital TV receiver. The futuristic outlook is to have one integrated digital computer, TV, radio and telephone all receiving their signals via the internet. Everything else being the same such a scenario will definitely initially lead to an increase in the overall energy consumption in the UK.

This packaging together of these services, all powered from a centralised electricity system, and needing in each house an independent electrical supply for the internet router/set top box/cable modem and telephone handsets, increases the UK's vulnerability if an interruption occurs in times of emergency [12]. Once the electricity supply in the home is interrupted the homeowner will not be able to operate the computer/mobile/telephone/TV to communicate to anyone outside the house especially if there is also a widespread blackout and mobile phone masts lose power. In an all digital system with a prolonged widespread blackout how will government and emergency services be able to communicate with the people? A decentralised energy generating system, a pivotal part of which is the DC home, will surly mitigate this scenario.

New UK government initiatives also include the electrification of some diesel railways and putting high on the agenda the development of the electric car with a network of battery charge stations. From Chart 4.1 [13] even the base case shows an increase in Peak Demand from just over 60 GW to just over 65 GW by 2023. This thesis envisages that the DC house will help to decrease the peak demand for electricity.

1.3.5 Centralised generation Vis-à-vis decentralized microgeneration

Can a centralised energy system provide energy independence with security? Before one can determine what it means in reality that a nation has energy independence one has to look at how at the present time the nation is providing the energy necessary to run its economy properly.

In the United Kingdom there is a mix of fossil fuel powered electrical generators and nuclear powered reactors as well as a growing amount of renewable energy generators, which by 2009 have a generating capacity of about 4.9% of national demand [14]. The United Kingdom Energy Policy still relies mostly on centralised electricity distribution via the national grid, which without radical upgrades to its infrastructure may not be fit for purpose. The estimated cost to upgrade just the grid, to accommodate 34 GW of wind energy is £4.7bn, [15, Section 1.4]. The future use of “smart grid” technology is still seen as the way forward in centralised energy distribution [16]. The UK also has an under-sea cable in the North Sea providing a direct electrical connection for imported electricity.

The UK could build many nuclear power stations and feel that it is able to produce enough electricity by itself without the need to import fossil fuels for electrical generation. However nuclear-power stations need uranium, which at this time must be imported. Therefore even nuclear power stations will not provide electrical energy independence as there will still be the reliance on foreign production of uranium as a fuel for the power stations. Even though it is estimated that worldwide the supply of Uranium is enough for the next 160 years at today’s rate of consumption [17], in the future it cannot be known how secure the supply chain will be.

Having national energy independence with a centralised distribution system alone is not enough, it must come with energy security for the ordinary citizens. In America in June 2006 and in Iraq 2003, the centralised electrical delivery system did not offer the man on the street, energy security. On the contrary, failures in the centralised system meant that the whole city or county was without electricity. The other modern disadvantage of centralised energy generation and distribution is its vulnerability to attack by terrorists or foreign government agents.

There has been much research and talk in the last few years about decentralised electricity generation and micro-grid distribution. This has been seen as a way of increasing the nation’s energy security by decreasing the nation's vulnerability to attacks on the centralised electricity generation infrastructure. While decentralised electrical generation does increase energy security, small-scale electrical generation employing micro-grid distribution does not go far enough.

1.3.6 How the DC house fits into UK Government Energy Policy

This thesis proposes that each building, whether it is a private dwelling, office, or industrial complex should have the ability to generate its own electrical energy needs, thus becoming totally independent from anyone else. Using only DC is seen as a way of reducing the overall size of the renewable energy generating system and will help in their proliferation. This type of generation and distribution of energy in a single building can be called an “electrical nano-grid”.

Such a level of energy independence will increase the nation's security vis-à-vis the rest of the world, if the energy generators will be renewable energy generators. This should reduce the nation's needs to import fossil fuels to power the centralised electrical generators. To decide exactly which type of energy generators will be used in the home is beyond this research, however each building could have a combination of at least, solar and hydrogen generators/fuel cell and perhaps also some small types of wind powered generators. Unless the UK can become a manufacturer of renewable energy generators, and associated DC systems, it will still have a dependence on imported spare parts even if a 100% of it electrical energy is home produced.

The argument given by the antagonists to decentralised energy generation is its cost to implement. If it costs in the UK upwards of £14,000 per household for a PV system and many more times this amount for offices and industrial buildings who will foot the bill? For those homeowners who can invest in such a system, is this the best way to use their money? Will they get more out of their money if they invest it elsewhere and pay the equivalent value out over a number of years in their electric bills? For the vast majority who can’t afford it, such a system is beyond reach and therefore for decentralised generation to proliferate a helping hand will be needed.

For the last decade the reduction in carbon emissions has been top of the agenda. A large percentage of electrical energy generated in the UK is produced by burning fossil fuels. The main emphasis has been on the reduction on fossil fuel dependence as a way of meeting the 2012 Kyoto CO_2 emission targets, of the reduction in the overall emissions by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012 [18]. There are many motivating factors in the decision-making process as to which different schemes should be used. The UK government made a policy decision that for renewable energy generation schemes that a greater emphasis will be put on onshore and offshore wind than that of solar and hydrogen [19]. This approach is a centralised top down approach that mainly emphasises the generation of electricity with less emphasises on energy consumption. Work on standby energy consumption does not look at reengineering the appliances so that standby losses are reduced to insignificance, but rather to set a low limit using the same basic electrical design. This strategy mainly emphasises the reduction in CO_2 emissions in energy generation, however in the DC house with the elimination of the AC to DC conversion stage it will be possible to make further reductions in energy consumption and CO_2 emissions.

Grants of £2500 are available to private individuals for solar panels on their homes. However the cost for a 2.72 kWp system has been quoted at £14,355, going up to £19,850 for a large 4.08 kWp system (See Appendix 3 for quote). By the end of 2007 the number of installed PV units for electricity generation across the whole UK was 2,993 [20] compared to over 100,000 installed systems in Germany. The DC house will reduce the overall cost of the PV system which should result in an increase in installed units (See Sections 6.2.1 & 6.2.3).

In the next ten years some of the power plants in the UK will have to close down. (ensg report URN 09D717 Table 2.6 page 36) If new power stations do not come on line quickly to plug the gap between generating capacity and demand, electric shortages may occur. On the 5th of February 2009 the UK government gave the go-ahead for the building of three new coal fired power stations, as long as carbon sequestration and depositing it in underground geological formations can be achieved. This thesis postulates that if the money estimated for the upgrade of the national grid and for cost of new power generators was diverted to the DC house, the UK could gain a high degree of energy independence with security and reduce its overall carbon footprint.

1.4.0 The component objectives for this research

1.4.0.1 To analyse previous work and see to see how the research could be advanced.

1.4.0.2 To develop a methodology for approaching the design problems.

1.4.0.3 To understand the parameters of the electrical system in the home, including optimum voltage, cable size and to develop a methodology to calculate peak power and power usage per year.

1.4.0.4 To identify a list of DC appliances to be used in the ‘research home’, which together would provide a good level of living standard.

1.4.0.5 To provide the physical layout of the DC home and apportion the DC appliances to different zones.

1.4.0.6 To identify and compare technical, energy savings and economic aspects of AC and DC.

1.4.0.7 To look at different alternative implementations of the DC home.

1.4.0.8 To research the affects the DC house will have on the ‘global objectives’

1.4.1 Building on previous work

The most important objective of this research was to ascertain if a home, exclusively supplied by direct current voltage, was implementable and economic, for widespread usage. However it was noticed that the main criterion of the previous work cited in the beginning of Chapter 2 below, was not the same, but was rather to emulate the usage of AC with DC, which unfortunately imposed some restrictive criteria to their work. Their use of the underlying system mathematics was somewhat lacking and therefore made it difficult to reproduce their results. They were also not looking at the bigger picture which brings out the advantages the use DC voltage provides to the householder and to the nation. This research looked to identify what the bigger picture was and thus came up with the ‘global objectives’. Their conclusions were negative and not encouraging. However this research started off with the premise that, if a different approach was taken, would a positive conclusion be reachable?

1.4.2 General methodology for approaching the design problems

There are three parts to any domestic electrical system, (1) the energy supply, (2) the mains distribution network in the house and (3) the loads that will be connected to the mains. There are two approaches to researching the practicalities of the electrical system for the all DC house. The first is the conventional approach which is to start with the energy supply and work toward the loads, this is called the top-down approach. The approach of this research is to work in the opposite direction, starting at the loads and working towards the energy supply. This is called the bottom-up approach.

The top-down approach is essentially the methodology used by all previous work in this field. They start with statistics to come up with a value for the mean daily peak power consumption of the house, this is used to choose the appropriate size of energy generators. Then together with a chosen voltage and current the appropriate gauge of cable is used to implement the electrical distribution network.

The approach of this research is novel in that it starts by working backwards from the loads. In an ideal world the best scenario would be to be able to examine all appliances and determine what would be the lowest DC voltage at which they will be able to operate efficiently. However at this time this is not possible. Many small appliances use AC toque motors and would have to be converted to DC, which would change their power characteristics. Also many DC voltage appliances work off the AC voltage via AC to DC power adapters and to determine their actual DC voltage power ratings, some re-engineering will be needed.

1.4.3 Stages in the design process

- To understand the underlying mathematical framework that describes the system parameters, the British standard documents BS 7671:2008 entitled “Requirements for Electrical Installations IEE Wiring Regulations Seventeenth Edition”, which lays down all the necessary information regarding choosing the correct cable gauge and all associated parameters, was used.

- A cross-section of DC appliances was chosen from what was available at the moment on the open market. Using their power ratings values for different system parameters for each individual appliance was calculated.

- The size of the floor area was chosen from the value given in the "40% house" report from the Environmental Exchange Institute. The set of appliances was apportioned to different zones in the house, connecting them to specific power sockets. Then sets of power sockets were connected to their respective cable spurs to make up the whole electrical mains system for the house.

- Once the affect that each individual appliance has on the system parameters was calculated, it was possible to calculate the parameters for each individual cable and then the whole house. From this, the peak power drawn and the power consumption for the whole house was calculated.

- From the analysis it was possible to build a picture of different scenarios for the DC electrical mains design and implementation.

- When a decision has to be made as to the merits or otherwise of DC, the first questions that need to be answered are, if AC has served as a good system for so long why change? Can it be practically implemented? And will DC be economical?. Therefore identifying and comparing technical, energy savings and economic aspects of AC and DC needed to be carried out.

- Once the practicalities of DC have been established the next stage is to assess its impacts. It was postulated that the impacts would be, a reduction in energy used, reduction in costs for the DC system and a reduction in CO_2 emissions, all of which would help towards energy independence with security. In other words to see what affects the DC house will have on the 'global objectives'

1.5.0 Achievements

1.5.1 A thorough understanding of all the parameters that affect the DC house has been gained. Quantitative analysis by way of a calculated example has been carried out that shows how the different parameters affect the electrical system. With a result that shows that with a relative small gauge of $4mm^2$ the electrical cables can be implemented. And an implementable detailed design for the electrical mains of the all DC house has been found.

1.5.2 One of the outcomes of the mathematical analysis has been the understanding gained about relationships between the system parameters and the tradeoffs between them. Different graphs showing these relationships were generated.

1.5.3 All the analysis was done with power ratings from DC appliances without the need for any AC data. As AC and DC appliances are not directly comparable, an understanding that values taken from AC measurements, statistical or otherwise, cannot be used to determine the DC design parameters, was achieved. In a DC appliance, besides the elimination of the AC to DC converter, there are the unknown quantities of the other components including what type of DC to DC conversion that will be needed. Further work including direct measurements of comparable AC and DC appliances will have to be carried out under controlled conditions.

1.5.4 Analysing the energy used in the home was done load by load and not as a lump sum from statistics. This approach to the research therefore enables the micro-design of the electrical system and the ability to add, or move any appliance around the house and see how it would affect the electrical integrity of the system.

1.5.5 A peak daily energy and energy usage per year was calculated, which can be used to size the renewable energy generators.

1.5.6 It has been possible to work out some energy and financial gains of changing from AC to DC but the results lack the detailed controlled measurements which are beyond this project.

1.5.7 The discussion of the merits that the DC house can have on the ‘global objectives’ has been developed, and the importance for these objectives to be implemented has been established.

1.5.8 It has been possible to identify what further research is needed.

1.6.0 Conclusions

1.6.1 The thesis puts forward the hypothesis that, if the end use for the energy is a low power appliance then even the low efficient solar cells that exist today and even in temperate climates where the energy from the sun is weak, society should still be able to take advantage of solar energy and create a society where everyone can have some degree of energy independence. There will also be positive consequences for, CO_2 emissions, the global economy, and perhaps more global peace.

1.6.2 By setting out to establish the foundations of the DC house using the bottom-up approach, a better understanding of the fundamental laws governing the electrical system will be established which will help in the implementation of the DC home for different scenarios.

1.6.3 The UK government has moved forward in legislating and coercing business and private individuals to change the way energy is used and as a result, CO_2 emissions are being affected. What is now needed is a radical approach to tackle the way electrical energy is used in the home and workplace that will produce long term changes to the distribution and usage of electrical energy, the second and third stage of our electrical system.

1.6.4 Understanding the effects the DC house has on energy policy puts it in a greater context than just the argument between AC and DC voltage. This adds a new dimension to its importance to today's society.

1.7.0 Thesis Organisation

1.7.1 Chapter 1- Introduction

This chapter puts this research into its historical context and sets out the underlying reasons for the need to rethink the way energy is used in the home. Then to determine if, how and what advantages there are to change from the conventional electrical supply of alternating current (AC) to direct current (DC). The direct phenomena that affect the amount of energy used in the home are discussed. Also discussed are the wider affects the proliferation of the DC house will have on society beyond that which are manifest in the home. These are termed the 'global objective' and are the drivers pushing the debate.

1.7.2 Chapter 2 - Literary Review:

This chapter reviews the work carried out so far and compares the different papers. It is set up conceptually and goes through the parameters that affect the DC house comparing and contrasting their work and that of this research. It evaluates their work to establish a framework on which this research could build. Some critical analysis is given and how this research differs in approach and analysis is discussed

1.7.3 Chapter 3: Methodology

This chapter looks at the different system parameters and uses the different equations to analyses how each effects the design process of the extra low voltage DC electrical system. A set of DC appliances is chosen and the equations are used to work out voltage drop (V_{Cal}) and maximum length of cable (L_{Max}) for each appliance. A set of example calculations using a 24V slow cooker is shown. Using these equations a set of data over a range of load currents at different voltages was compiled and is presented in graphical form

1.7.4 Chapter 4 - The Design of the DC house

By way of example using a set of 24 V DC appliances all the parameters are calculated and the details for the DC electrical design worked out. The economic ramifications are also discussed. The electrical integrity of the design is investigated and values for daily peak power and yearly power usage are worked out. Then to contrast the results with previous work a critical analysis of their work was carried out.

1.7.5 Chapter 5 - Scenario Analysis

Different scenarios for the DC voltage and layout of the electrical system are discussed. The drivers behind the decision making process, some technical and implementation options, and some extracts from previous work are also discussed. An attempt is made to answer the universal question, what would be the optimum DC voltage for an extra-low voltage DC home? Having an optimal voltage would obviously narrow down the scenario possibilities

1.7.6 Chapter 6 - The economics and socioeconomics of the DC home

This chapter considers the economic effects of the DC house in a wider context than those normally directly associated with changing from AC to DC. Firstly the direct economics of the different elements that make the DC house different from the AC house are considered. This is followed by the indirect, environmental and socioeconomic effects of the DC house and its ramifications on energy independence with security. Some example comparisons are made between AC and DC systems.

1.7.7 Chapter 7- Conclusions and further work

In this chapter the conclusions and recommendations that have evolved out of this research are brought together. From the many different possibilities a single scenario is chosen. The label "Smart House" is employed. This research concludes that the information, used to decide if the low powered DC voltage smart home is practical and economic, must include its indirect and socioeconomic ramifications on society. More research will be needed on some aspects of the design, implementation and pathways to market. The further work is split into three categories, (1) The architecture of the electrical system, (2) the economic advantages of a decentralised electrical generating system and (3) the wider socioeconomic effects of the decentralised low powered DC voltage smart house.

1.7.8 **Appendix 1**: Tables from British Standard document BS 7671:2008

1.7.9 **Appendix 2**: Graphical Tools with the data are shown in a representation of the different parameters in the electrical system.

1.7.10 **Appendix 3**: Datasheets and other documentation.

Chapter 2

Literature Review and Analysis

Summary

This chapter reviews the work carried out so far and compares the different papers. It is set up conceptually and goes through the parameters that affect the DC house comparing and contrasting their work and that of this research. It evaluates their work to establish a framework on which this research could build. Some critical analysis is given and how this research differs in approach and analysis is discussed.

2.1.0 Gathered literature

A literature search was carried out, however in many cases, the only information available was non academic and as such the statements given are not backed up by quantitative analysis, and while informative are not academic research. However, with the absence of quantitative analysis, statements made from these sources come with the caveat that further work to prove these statements will have to be carried out.

It was also found that for many years PV arrays and PV wind systems have been used in off grid situations to power stand alone water pumps, lighting or refrigeration [21][22] (NASA's Glenn Research Centre, did about 57 such projects all around the world up to 1977 after which the Department of Energy was created and took over from NASA the work on terrestrial photovoltaic systems.). In many cases the end usage of the DC generated electricity was AC voltage loads [23]. In the Standard for space stations [24], satellites [25] and as part of the electrical subsystems on war ships [26], DC voltage is also used. Further work should be carried out to see if any of this DC technology is transferable to be used in the DC home.

Listed below are the main papers that have looked at the possibility of using DC for the home. Many of the other citations are looking specifically at different aspects of how electricity is used and the specifics of different AC and DC applications.

- Pellis [27]
- Friedeman[28]
- BRE (Building Research Establishment for the DTI) [29]
- Postiglione [30]
- BS 7671:2008 [31]

2.2.0 Different Aims and Objectives

2.2.1 Replacing AC or implementing DC?

The main papers cited are all looking into how DC can be used in the home or the office, each one has their own angle, with slightly different objectives. However they all concur in trying to see if the conventional AC electrical system can be replaced by a DC system. The optimum description is 'replaced' as they are looking to emulate the modern Western style consumption, with its heavy reliance on electricity through AC devices, with a DC system. The goal of this research was not to determine how DC could replace AC in a straight comparison. Rather it was to ascertain if a DC house could be practical in the first instance and how would it be implementable in its own right. Then afterwards to assess to what extent it would replace AC now and in the future and what advantages DC could offer over AC.

Their main goals were restricted by only looking to see if DC would save energy and be more economical in a Western lifestyle scenario. While this research was carried out as part of a larger goal to see how the basic and then the sophisticated DC house will affect Energy Independence with Energy Security, CO_2 emissions and the finite availability of fossil fuels. As such, it was not restricted to the constraints that the energy requirements of a Western lifestyle put on the research. It tries to ascertain what basic lifestyle DC could provide, and what would be needed to improve it to a more Western lifestyle.

2.2.2 For the home or the office?

BRE and Postiglione start by looking at the home and reject it as being impractical or uneconomic and then look at the office. Pellis and this research are only concerned about what the basic parameters that affect the electrical system are and to create a framework for the implementation of the DC system. What is not so important is if it is implemented in the office or the home, as long as a framework exists, then it can be used to design and implement different DC scenarios.

2.2.3 Operating voltage and cable gauge

The most important goals for the practicalities of DC are what voltage and cable gauge to use. Everyone was looking for a single ‘optimum’ voltage value with which to do their mathematical analysis. This research differed in that it was not looking to constrain its analysis by any single or set of voltage values, but was rather looking to see how different voltages would affect the parameters of a DC electrical system. (See Section 3.7.0 where the Graphical Tools are used to choose a DC voltage, and Section 5.2.0 for further discussion about ‘optimum’ voltage.) Postiglione looks at a retrofit, thus keeping to the conventional cable gauge and is therefore limited by the voltage that can be used in the DC home. Conventional very long AC ring main cables are impractical for DC due to the voltage drop along the cable. Pellis, Friedman and BRE, are looking to see if an optimum cable gauge for the home can be found without being constraint by the cable gauge now in use, and all use a star or spur for the cable configuration as opposed to a ring main, this research builds on their design.

2.2.4 Only direct or also indirect economic factors?

As the goal of the other researches was to make a direct comparison between AC and DC, the goal of their economic analysis was to ascertain if there was a direct economic advantage in the implementation of a DC system over AC in the Western world. Their analysis therefore only took into consideration direct economic values. However as this research is very much interested in how the DC home can affect society, especially in the developing world, its indirect economic and socioeconomic effects, and its effects on long term government energy policy are very important and are therefore central to the economic discussions.

2.2.5 DC feeds a DC or AC system?

The project by Ortlepp [26] is a standalone house not connected to the electric grid which is powered by a wind turbine and some Solar Photovoltaic panels. This house is part of "The Advanced Houses" program "*with the goal of building houses that incorporate energy efficiencies and renewable energy sources to exceed previous house performance standards based on the R2000 program*". The design used DC power that is passed through an inverter to provide a 110V AC powered electrical mains system. As the goal of this research is a house that works on extra low voltage, a voltage below 50V, and uses direct current for its power, the design of this AC house is not so pertinent to this project. However the conclusions are most interesting (See Section 5.6.0).

2.3.0 Methodologies and Results

2.3.1 The use of simulation software

As part of the process to implement the DC home, simulation software was used by BER, Postiglione, Pellis and Friedman, as well as straight forward mathematics. This research only employs mathematical analysis using Microsoft Excel and found no need for any simulation software.

2.3.2 Top Down approach using statistics

These citations use the top down method when approaching this problem and look at the whole system from a more hands off generalised viewpoint. They look at the whole system, the energy generators and the backup systems as well as the internal electric systems. However the finer points of how the energy is used in general and specifically by the DC loads are not considered. Heavy emphasis is placed on generalised, lumped or estimated values that are based on statistical analysis and/or assumptions, rather than on detailed values that are ether given by a manufacturer or measured. Therefore although the role of statistics in any design process cannot be underestimated sometimes its use can be out of context, misleading or lead to erroneous conclusions.

2.3.3 Using AC statistics to work out peak power and power consumption

The most important underlying number for the designer of the low voltage DC home is the value of the peak daily power. This value is needed to quantify the size of the renewable energy generators and is most important to the values that will be chosen for voltage and current. This in turn affects the size of cabling to be used and the maximum possible size of the home. The next important value is the amount of energy used per year and is given in kWh/year. So how are these values derived?

There are two approaches to this question, the first and most widely used is the top-down approach, whereby the number is derived from statistics. Pellis's data (Section 4.1.2) for household electricity consumption is derived from a report on the AC electricity consumption for households in the Netherlands (Caps BEK 95). "*The average electricity consumption per household in the Netherlands in 1995 was 3259 kWh. This average consumption was calculated using the consumption of many different kinds of households. Households with a shop or a small company with large energy consumption, are also included in this calculation. Therefore the average consumption of a 'standard household' living in a single-family dwelling might be smaller than 3259 kWh. Monitoring the electricity consumption of households in Amsterdam by Energie Noord West resulted in an average electricity consumption of 2600 kWh."*

BER (Section 6.1) uses the 'decade data' [32] to derive the annual energy profile. "*The energy consumption for the average house can be determined by simply dividing the gross energy use by the number of houses."* They start with the average house's annual consumption of the Electrical Association house, which is 3608 kWh. This value was reduced by a factor that reflected the use of efficient equipment rather than 'average' equipment. From this the energy consumption for the 'model' house was derived as 3088 kWh (Section 7.1). Then by adding in the future predictions from the Market Transformation Program they use the Best Practice assumptions to reduce the annual consumption even further to 1865 kWh (section 7.2). All this was consumption analysis for AC. They then go on in Page 31 to use the Best Practice model to reduce the annual consumption to 1424 kWh/year, then using a DC voltage model to further reduce the power consumption to 1247 kWh/annum. BRE uses this five stage statistical analysis, each stage based on multiple assumptions which themselves are based on AC power usage, in the design process for their DC home.

This research differs in that it does not use substantive statistics or layers of assumptions, nor does it take data derived from AC usage and transpose it onto the DC system, (See Section 2.3.7 for further discussion). It relies on printed manufacturer's data of current and voltage ratings of real DC appliances and the statistical data given in Appendix 2 of the BRE report about the average daily time appliances are used, to derive the peak power and yearly power consumption values (See Section 4.5.0). These values are as close to a real DC house scenario as possible, without extrapolating data from AC statistics.

One of the main reasons for following this route was the detailed analysis given in the discussion of the efficiency of AC to DC power adapters. BRE (chapter 3), Pellis (chapter 4) and the NRDC report [6]. The efficiency of AC to DC converters will depend on the topology of it design, Linear or Switch Mode, on its load factor and on the specific design of the manufacturer. This all adds up to a question of "is my converter a worst case of 40% efficient or a best case of 95% efficient?" Given a statistical value for the energy consumption of the average AC home, what percentage of energy is used to run the loads, the value of which can be transposed onto the DC home and what amount is used up by the AC to DC conversion process? Therefore if the energy values used are derived from statistical AC consumption data, what if any, is their correlation with DC consumption, to enable them to be used in the design of the DC house?

Another reason that makes it hard to compare AC and DC efficiency values is the possibility of misinterpretation. Efficiency is a percentage, and like all percentages the question is of what? Unfortunately it is easy to fall into the trap of comparing efficiencies rather than real energy loss values, which may be done if the data for real values does not exist. Pellis (Section 4.2.2) uses the quote below to conclude that DC does not necessarily reduce energy losses. He states "*Manufacturer data on converters (from Mascot, Vicor, EA and Kniel) makes it clear that typical efficiencies of DCIDC and AC to DC converters lie between 80% and 90%. The obtained data does not show a clear difference between the efficiency of DCIDC and ACIDC converters.*" However in a comparable scenario is the actual energy lost, measured in Watts, by a DC to DC converter over a given period of time more or less than that of an AC to DC converter? Does it make a difference if the AC is 230V or 110V? And how comparable is total energy used in the same AC and DC appliance if the design and therefore the amounts of the components used to provide the same operation differ?

As the methodology of a straight comparison between AC and DC creates great uncertainty in any results, it was decided to build up the peak power and consumption levels from DC only. There are disadvantages to this in that the pool of DC only appliances is limited and that until further research is carried out, it is not known if their electrical and electronic design has been properly optimised for the best energy efficiency under DC operation. However this approach is still preferred and is the essence of the bottom up approach.

2.3.4 The use of the system mathematics

Where this research differs, is that others chose a voltage and then used it for their mathematical analysis, while this research did the mathematical analysis and then looked at which voltage to use for the DC home. They constrain themselves to identifying an optimum voltage that is governed by external phenomena and then based their conclusions only on the mathematical analysis associated with their chosen voltage values. While this research was not looking for an optimum voltage it was trying to ascertain through mathematical analysis if an optimum voltage or a range of optimum voltages for different circumstances exists. Their methodologies lead them to a negative conclusion while this research found a positive solution.

BRE (Section 5.3) chose 18V for the home as 16V to 18V "*is the natural environment for electronics*". Pellis (Chapter 4) chose 24V as this is the output of solar panels and 120V as this is the European regulatory ceiling for not needing electrical protection. Postiglione (Section 2.3.3) chose to work with 48V 120V 230V and 326V. Each has a good reason why it was chosen and each has its own merit. However such methodology can only come from the top down approach, as a voltage is needed before the design process can continue, this research however used the design process to look for a usable voltage.

Once the mathematics for the design framework was accomplished this research needed to verify the design process and to show that a DC house can be practically implemented, given the constraints imposed by voltage drop. At this stage it was therefore necessary to choose a particular voltage for the mathematical analysis. Since the only available real DC appliances were 12V or 24V, by way of example the values for the 24V appliances were used in the mathematical analysis. However this was not an attempt to provide a solution for the best or optimum voltage for the DC home. In fact the results from the mathematics showed that there would always be a trade off between the size of the house, i.e. the length of cable, and the amount of current any single cable could draw. This is shown by way of a graphical presentation that gives a clear picture of the trade-offs between the many different system parameters (See section 3.7.0). The 24V analysis was therefore only used as a proof of concept.

2.3.5 Building a scenario only using DC loads

The methodology for this research used the bottom up approach which starts by looking at the DC loads. In order to able to derive meaningful values for peak power, and power used per year, a list of real DC loads was built up and the design for the house was made around them. It is believed that this method is novel and new, and does not rely on statistics, but rather on real DC values. From these real values for this specific home, the design for the amount and size of cabling was derived. This gave a single scenario picture. However as the peak power and the physical electrical layout of the house are built up from the derived values of real loads, it is easy to move around the power sockets and loads to create different scenarios and add more loads, while still having the ability to understand how each change will affect the total electrical integrity of the system. No other research has so far been found that uses this detail of analysis, which is based on the understanding of the way the loads affect the system and allows micromanagement of the design. This research therefore showed the fundamental framework upon which further work in developing the concept of the DC home rests.

2.3.6 Voltage drops

The most important practical hurdle to overcome in the transporting of extra low DC voltage is the phenomenon called ‘voltage drop’. Pellis (Table 6.2 in section

6.3.2) sets out the results to his calculations and shows the correlation between the different parameters affecting the electrical DC system. These results are then used to justify his need for 6mm^2 cable for a 24V DC system and 4 mm^2 cable for a 120V system. By stipulating a maximum power drawn that is a percentage of the cables' capacity a working electrical system was designed. As Postiglione (Chapter 4) is only trying to retrofit an AC system, she shows in her results that voltage drop disallows the use of 24V DC for her system. BRE although mentioning voltage drop, does not show any calculations.

Using the bottom up approach helps to identify and understand how each individual DC appliance would affect the voltage drop in the cables and therefore the usability of the electrical system. These affects cannot be identified using the top down approach.

2.3.7 Do DC appliances use up less energy?

This research postulates and there seems to be a consensus, including statements from manufacturers, that DC appliances should use up less power without the power conversion hardware than AC appliances. However, without identifying a framework that will make it scientifically acceptable to actually identify that the AC and DC appliances being compared were identical in some way, it cannot be scientifically stated that DC appliances use less energy than AC appliances. Although Pellis (Section 4.5.2) concurs that this research is required, he stated in section 4.3 "*There is no reason to expect a much lower power demand for DC household appliances*", why not? Surly if conventional AC to DC converters, which are between 40% and 95% efficient have been eliminated and replaced by an integrated on-board specifically designed DC to DC converter DC appliances should use up less power. However these statements can only be scientifically accepted through rigorous testing. As the work so far has not provided the opportunity to actually do any quantitative analysis on real appliances, datasheets and mathematical analysis will have to be relied on. It is imperative, that further work to actually verify quantitatively that DC appliances use up less power than AC appliances, be carried out.

2.4.0 Conclusions

Many times, conclusions will depend on the initial premise. Pellis, and this research, only look at the domestic household, while BER and Postiglione look at the home and the office environments. All the other work seeks to find a specific solution for a house with a Western lifestyle. Although it is agreed that on an electrical integrity level, the DC house can work, they all agree that due to either the practicality or economics or both, that the DC house is unviable. However they do not ask the question, is there a wider picture in which if the initial premises are changed, are there circumstances in which the DC house can be practical? This research has done just that. It has taken the bottom up approach and also looked at wider economic and socioeconomic effects.

As part of their argument BRE (Section 3.3 under the heading Storage) concluded that a PV system would be better suited for the office environment where the daytime load curve is closer to that of the daytime intensity of the sun then that of the house, as "*Most households are heavy energy users in the morning and evening*." This statement is perfectly true for the average Western family especially if the occupants are out during the day. However the retired, a sector of the UK population that is growing every year, the unemployed or sick and mothers at home looking after children are in fact more likely to do washing, cooking and generally be heavy users of electricity during the day. This is also true for many in the developing world who do not have access to electricity, all their household chores are most likely to be performed in the daylight hours. For these reasons this research has concentrated on the home and not the office.

In the economic analysis and conclusions BER confine themselves to the distribution system in the home, and thus come up with a conclusion that the cost for DC is about two to four times that of the AC. What they leave out of a their analysis, even though they mention it in their report, is the economic benefits of the elimination of the inverter, and all the energy-consuming AC to DC converters, with the consequential economic savings from the need for less square metres of solar panels. It is possible that in their DC house, as it is connected to the grid, this advantage is not available and an inverter will always be needed as the grid is AC, but what about the power losses saved from the elimination of the AC to DC converters in the appliances?, (for further discussion see Section 6.2.2). Pellis, Friedeman, and this research are all looking at an off grid DC home. Ortlepp states that to connect her house to the Canadian grid will cost C$20,000, for the UK, the London estimate is around £4,000. If this cost together with that of the inverter and energy saved by eliminating AC to DC converters is saved, the balance is tipped in favour of the DC home.

The values given in the BRE design were inputted to the equations in this thesis. With 18V and 65A passing through 10mm^2 cables the maximum length of cable at which a 5% voltage drop occurs will be 3.15m, which is a very impractical length, (See Section 4.9.3 for calculations). In general, in all the citations found, there has been a lack of the mathematical analysis that is in British Standard 7671. As a consequence this research found it very necessary to start from the basic equations in order to understand the underlying phenomena that affect the DC house and prove the integrity of its design.

What this research seeks to do is to take this in two separate steps. Firstly to look at the practicalities of using DC in a home, then once the practicalities have been established, putting aside the economics, the lifestyle of the occupants can therefore be established. As the DC home is itself the goal and not as a means to different ends, like the reduction of CO_2 and energy usage, coming up against practical, or economic problems is part of the challenge, and are looked at as surmountable. Unfortunately as many of the other researchers have a narrow goal, as they encountered bottlenecks in the work, they concluded that the DC home given their criteria was not practical, with the caveat that more research needs to be done. All the eight Net Zero Carbon Houses at the BRE Innovations Park [33] are all powered by DC renewable energy generators yet all internally use AC voltage. It is not known if, the reason that none of them use DC voltage is a consequence of the BRE report cited here or not.

What researchers have so far accomplished is to rely as the basis for their argument on statistical values for AC in order to justify their DC design. However without measuring AC and DC appliances to see how their power usage correlates, then conclusions about power, which impact on the size of the mains cables, must surely be questionable. What has to be established is what percentage of AC voltage energy is saved by using DC. Although manufacturers claim that DC appliances use less energy than AC this so far has not been backed up by independent quantitative analysis.

2.5.0 The inadequacies of the work so far

BRE are very informative but show little quantitative analysis to help the reader understand their numbers, they use the % mark very often but do not give real numbers. All their work was carried out many years ago and since then the power electronics, battery and renewable energy generator industries have made huge technical and efficiency advancements. This makes it the right time to re-examine the numbers.

This research has only looked at the electrical integrity of the DC home and not at backup systems and the type of energy generators. All the results rely on mathematics, and some lack the type of quantitative analysis gained from making laboratory controlled measurements. This research is the first stage of the bottom up approach, to bringing the DC home to fruition.

This research has achieved the goal of proving that within the given constraints the DC house is possible. However this is only a piece of the whole jigsaw. To convince governments and industry that the DC home should be part of the strategy to bring closer Energy Independence with Security, to reduce CO_2 emissions and to deal with the finite availability of fossil fuels, some more pieces of the jigsaw will be needed.

Chapter 3

Methodology

Summary

This chapter looks at identifying and understanding the different parameters of the electrical system and the equations by which they are governed, and analyses how each effects the design process of the extra low voltage DC electrical system. A set of DC appliances is chosen for the house and the equations are used to work out voltage drop (V_{Cal}) and maximum length of cable (L_{Max}) for each appliance. A set of example calculations using a 24V slow cooker is shown. Using these equations a set of data over a range of load currents at different voltages was compiled and is presented in graphical form.

3.1.0 Introduction

After substantial research into previous work on the use of low voltage DC for the home, it became apparent that the previous work did not show in any depth the underlying electrical equations, laws and regulations that govern the basic phenomena of the electrical system in the house. As a consequence this research started from the basics, in order to understand these underlying phenomena. The underlying equations were then used to assess how appliances or groups of appliances would affect the integrity of the electrical system if different cable gauges were used.

The British Standard document BS 7671:2008 entitled “Requirements for Electrical Installations IEE Wiring Regulations Seventeenth Edition”, lays down all the necessary information regarding choosing the correct cable gauge and all associated parameters. Chapter 52 deals with selecting cables and together with Appendix 4 provides the necessary equations and tabulated information with regard to choosing the right cable for a given current and gives values for voltage drops along cables. The data quoted in this chapter will be from the Tables in the Appendices and Sections in this British Standard document. (see Appendix 2 below for some of the Tables)

The definition given in the Standard (Page 31) for a DC voltage below 120 V is "Extra-low" Voltage. In this thesis, the terminology extra low and very low are interchangeable and will always imply a DC voltage below 50 V DC.

The main barrier to using DC power at this very low voltage is the high current needed to supply the power to correctly operate many appliances. Any length of copper cable has a resistance, which causes energy to be lost as the electrons move along the cable, as Ohms' Law applies. Resistance is proportional to length and inversely proportional to cross-sectional area of a cable and is the cause for the voltage to drop along a cable. The longer the cable or the smaller the gauge, the larger the voltage drop will be at the load. Temperature also affects the resistance of the cable, the lower the temperature, the smaller the resistance, and the smaller the actual voltage drop along the cable.

The temperature under consideration is the operating temperature of the actual wire in the cable, which in turn is affected by other parameters. The ambient temperature surrounding the cable, the method used to install the cable and the amount of current being drawn through the cable by the load. Also specified, is the maximum permissible operating temperature which is given as either 70°C or 90°C, depending on the type of insulation surrounding the copper wire.

The operating temperature in turn is a parameter that affects the current carrying capacity of the cable. Therefore, as the operating temperature itself is dependent on other parameters, the value given for the current carrying capacity of a cable in the manufacturer's specification will only be given for a specific operating scenario of that cable.

The four main system parameters are (1) voltage drop per amp per metre, (2) the current carrying capacity for the cable, (3) cross sectional area of the cable and (4) its length, as well as others that are mentioned in SB 7671, are all discussed in more detail below.

3.2.0 The system parameters

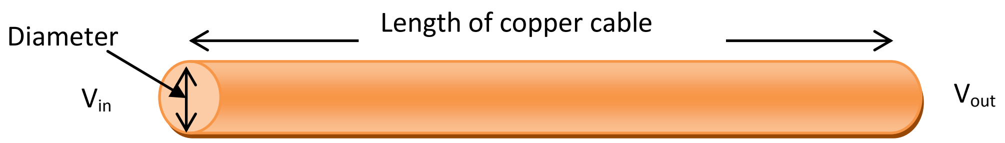


Diagram 1 The physical attributes of copper cable that affect voltage drop

A length of cable has some obvious physical characteristics, as illustrated in Diagram 1, which will usually affect its electrical characteristics. The most obvious is the cable gauge and its length. When an extra low DC voltage load is connected to the cable, this will draw a current, as the physical copper cause's energy to be lost along the cable there will be a resultant voltage drop at the load, therefore V_{out} will never equal to V_{in}.

3.2.1 The Cables

A cable could be either single-core or multicore, with the cross sectional area of its core being specified as specific sizes, which are given in column 1 of Tables 4D1A to 4G2A. For the purpose of this research four gauges will be discussed, 2.5 mm^2, 4 mm^2, 6 mm^2 and 10 mm^2. Depending on the material surrounding the core, the cable will have a maximum allowed operating temperature of either 70°C, which is BS 6004 or 90°C, which is BS 7211.

There are two choices for the cable, either a twin core insulated and sheathed cable, the data for which is given in tables 4D2A & 4D2B, or two single core insulated cables, (with or without a sheath), data for which is given in tables 4D1A & 4D1B. In order to minimise the installation costs one cable should be cheaper to install than two, therefore a multicore cable was chosen for the cables in the house. (As the house will be rated with a voltage below 120V earth bonding is not required. (See the Standard Section 411.3.2.2 Note1)

3.2.2 Temperature

For all cables installed in the home that are not subterranean, the reference ambient temperature is given as 30°C. Where the ambient temperature differs from the reference ambient temperature a rating factor is given in Table 4B1. Grouping cables together in a bunch, and the method used to install them, also affect temperature and therefore the voltage drop. For rating factors see Tables 4C1.

3.2.3 Methods of Installation

Table 4A2 provides a schedule of installation methods, with example diagrams for 77 different ways of installing cables. In section 7.1, the Standard specifies seven specific Reference Methods of installation, designated A to G, for all of which the current carrying capacity has been determined by test or calculation. Each of the 77 different ways of installing cables, shown in Table 4A2, has been designated a Reference Method to be used to determine the current carrying capacity of that installation method.

3.2.4 Tabulated current carrying capacity (V_{tab})

The tabulated current carrying capacity for different types of copper cables of specified cross-sectional area and with different Reference Methods of installation, are given in Tables 4D1A to 4G2A. These values are given under the specific temperature conditions of ambient temperature at 30°C and maximum allowed conductor operating temperature of either 70°C, which is BS 6004 or 90°C, which is BS 7211.

3.2.5 Voltage drop

Tables, 4D1B to 4G1B provides values for the tabulated voltage drop per amp per metre for copper cables with the given specified cross-sectional area. These values are given under the specific conditions of ambient temperature and conductor operating temperature and at 100% ‘Load Factor’. This means that the value given for the voltage drop is only true when the current going through the cable is equal to the current carrying capacity of that cable.

When designing an electrical system it is imperative that the cables have the capacity to provide the needed power for the load to operate without compromising safety and the usability of the load. Section 525.2 leaves the safe operation voltage of loads to that of the manufacturer’s specification. This means that if the appliance is rated 24V but the manufacturer gives a tolerance of ± 20%, which means that it can safely operate with a voltage of 19.23V, this implies that a voltage drop of 20% is acceptable. However when designing a DC low voltage system with many appliances that operate with different tolerances, or with unknown tolerances, the Standard specifies in Appendix 12 a best practice value of 5% voltage drop at the load. Or in other words, the voltage at the load should not be less than 95% of the operating voltage of the load

All other research as well as this research use the best practice value of 5% as the limit for voltage drop at the load. This research is about formulating a framework for the electrical design of the DC house. Appliance tolerances are not part of this framework and will have to be analysed by future work, if and when quantitative analysis comparing energy usage and best practice design between AC and DC appliances is carried out.

3.2.6 Maximum Length of Cable (L_{Max})

Whatever the system voltage is, the maximum limit of the allowed voltage drop occurs somewhere along the length of a cable. At this point the voltage drop is so large that connecting a load beyond this point, the correct and safe operation of the load is compromised. The length of cable where the voltage drop reaches this limit is called the 'Maximum Length of Cable'.

3.2.7 Correction Factors

Many of the parameters are given under specific operating conditions. Different scaling factors will have to be worked out, which will change the Tabulated Values given in these tables to a more accurate Calculated Values.

3.3.0 The equations

The voltage drop along a cable is a measure of how much the voltage decreases depending on the amount of current flowing in the cable and its length and is measured in millivolts per amp per metre (mV/A/m). The total voltage drop over a given length of cable and with a given current is given in Equation (1).

$$V_{TotDrop} = V_{tab} * I * L \quad (1)$$

Where

$V_{TotDrop}$	The total voltage drop over a given length of cable (V)
V_{tab}	The tabulated voltage drop in millivolts per amp per metre (mV/A/m)
I	The current (capacity) in Amperes (A)
L	The length of the cable in metres (m)

Therefore for any given cable when 1A flows through 1m of wire $V_{TotDrop}$ is equal to V_{tab}. For best practice operation at full load, $V_{TotDrop}$ must not exceed 5% of the required operating voltage for the load. Therefore $V_{TotDrop}$ will be fixed by the voltage chosen for the system. By way of example Table 1 shows the total voltage drop at the load for four example voltages.

Voltage rating for system	24 V	36 V	42 V	48 V
Total voltage drop of 5%	1.2 V	1.8V	2.1V	2.4V

Table 1 Maximum best practice voltage drop as measured at the load with 100% load factor

At domestic AC voltage the voltage drop in the cables is not usually an issue. However in the all DC voltage house, the voltage will be below 50V and perhaps as low as 24V. At these low system voltages the voltage drop in the cables will have a dramatic affect and impose severe constraints upon the electrical design. What is therefore very important and most useful to work out, is the maximum length of cable (L_{Max}), that can be used, given the power ratings of the known loads. Therefore rearranging Equation (1) above, gives Equation (2).

$$L_{Max} = \frac{V_{TotDrop}}{V_{tab} * I} \qquad (2)$$

The values for the tabulated voltage drop along a cable are given in Appendix 4. However, as stated, these values are given for the specific scenario, of a 100% load factor at maximum current rating and operating at maximum temperature for each cable of specific cross-sectional area. In reality for most of the time in the domestic arena the loads connected to the electrical supply cable will be below the maximum rating for that cable. This can easily be seen in the nonlinear shape of a usual domestic daily load profile. It is only for a relatively small period in every twenty four hours that peak load power is drawn, the rest of the time the system is operating with excess capacity.

When the load current is below the maximum current rating of the mains cable, two things will be affected. (i) the maximum temperature that the cable will reach will be below the maximum rated temperature for that cable, (usually for domestic application the maximum operating temperature is given as 70°C) and (ii) as temperature affects the resistance of the cable, the lower the temperature, the smaller the resistance, and the actual voltage drop along the cable will be less than the tabulated voltage drop given in the tables of Appendix 4. Therefore, in reality, Equation (2) is only a rough guide to work out maximum length of cable.

In his book entitled "Electrical Installation Calculations", a companion book to the 16th edition of the British Standard 7671, DB Jenkins on page 39, introduces a method to calculate cable temperature when it is operating below its full current carrying capacity. This method can be used to calculate the effect this will have on the voltage drop per amp per metre.

To calculate the actual operating temperature of the cable Equation (3) is used.

$$t_{op} = t_a + \frac{I_b^2}{I_{ta}^2}\left(\mathrm{t_p} - \mathrm{t_{amb}}\right)^{\circ}\mathrm{C} \qquad (3)$$

Where

t_{op}	Actual operating temperature for the cable
t_a	Actual ambient temperature
I_b	Current rating of appliance
I_{ta}	Actual tabulated current carrying capacity of the cable
t_p	Maximum permitted conductor operating temperature
t_{amb}	Rated ambient temperature

[Notes: (1) DB Jenkins uses the notation t_1 for the actual conductor operating temperature, while here t_{op} is used. (2) On page 39 he uses Equation (3) to determine a design voltage drop per amp per metre, in an equation which is based on the approximate temperature coefficient of resistance of copper and aluminium of 0.004per°C at 20°C. However in this thesis equation (4) will be used to calculate this.]

To calculate the actual voltage drop per amp per metre when the loads connected to the cable are below the cable's maximum current rating, a correction factor will have to be worked out. The equation to work out this correction factor is found in Section 6.1 of the British Standard and is given as Equation (4).

$$C_t = \frac{230 + t_p - \left(C_a^2 * C_g^2 - \frac{I_b^2}{I_t^2}\right)(t_p - 30)}{230 + t_p} \qquad (4)$$

Where

C_t Correction factor

t_p Maximum permitted conductor operating temperature

I_b Operating current of load and cable run

I_t Tabulated maximum current carrying capacity of cable

C_a Rating factor for an ambient temperature

C_g Group weighting factor

[Note: For the ‘Tabulated maximum current carrying capacity of cable’ the British Standard uses the notation I_t while DB Jenkins uses a slightly different notation of I_{ta}.]

The actual voltage drop along the cable, designated V_{cal} (calculated voltage drop per amp per metre), is worked out using Equation (5).

$$V_{cal} = V_{tab} * C_t \qquad (5)$$

3.4.0 Different approaches to the design process

3.4.1 The Conventional approach

There are three parts to any domestic electrical system, (1) the energy supply, (2) the mains distribution network in the building and (3) the loads that will be connected to the mains. In trying to form an opinion as to where to start in the decision making process as to the appropriate ratings of the electrical system for the all DC house, the convectional approach is as follows. They start with AC voltage statistics to come up with a value for the mean daily peak power consumption of the house. This is then used to choose an appropriate size of energy sources which could be a combination of, Grid, PVs or wind. Then using the value for peak power consumption, combined with a chosen DC voltage the system current and the appropriate gauge of cable to implement the electrical distribution network is chosen. This top down approach is essentially the conventional methodology used by previous work in this field. They do not take into consideration the individual DC loads that will be used in the house as part of the electrical design process.

3.4.2 The approach of this research

In determining an appropriate electrical rating system for the house the approach of this research is opposite from the standard convention and is to work backwards from the loads by first looking at the individual voltage, current and power ratings of household appliances. In an ideal world the best scenario would be to be able to examine all appliances and determine what would be the lowest DC voltage at which they will be able to work efficiently. However at this time this is not possible. Many small appliances use AC toque motors and would have to be converted to DC, which would change their power characteristics. Also many DC voltage appliances operate using AC voltage via AC-to-DC power adapters and to determine their actual DC power consumption some re-engineering is needed. However, there are a small number of appliances that work directly off DC voltage.

A list of DC voltage appliances allows for the identification as to where in a house they will be used. Then a picture can be built of what sort of power ratings will be needed in each room. This would then allow the apportioning of the house into zones, each with its own power ratings. Then the gauge of cable that would be needed for each zone can be determined. One of the criteria for determining the voltage drop along a cable is the length of the cable. Therefore for any given set of appliances their usability will be determined by how big the house is and the layout of the rooms. In other words, for the same group of appliances connected to a single cable, a larger gauge will be needed the further they are situated from the power source.

The cross-section of DC appliances that will be used in the design of the DC house was determined by what was available at the moment in the open market. This helps to focus the analysis and build a picture of a possible scenario for the low-power all DC house. 24V was chosen for the analysis only by way of example as this is the voltage of many of the DC appliances. However this is not a definitive value, as DC appliances can be made to operate at higher or lower voltages and new innovations in power electronics will in the future help reduce their power consumption. Also, appliances that only come as AC voltage examples could one day be re-engineered as DC appliances. However, there is no reason why with some re-engineering every possible appliance, cannot be converted to, or manufactured to work with DC voltage. Finally, using data for the average daily time appliances are in use, a peak power and a power consumption profile can be built up.

The type of power source to power the home is beyond the scope of this thesis. It was decided not to do the analysis with regard to the lighting system as it is expected that the future DC home will be powered by very low power LED or similar lighting, which can easily be implemented.

3.5.0 Building a list of DC voltage household appliances

3.5.1 Introduction

There are three main groups of DC voltage appliances. The first group of appliances that was examined were those that operate using AC to DC power adapters and do not use batteries. The second also uses AC to DC power adapters but they are only as a means of charging a battery and are termed cordless appliances, the larger of which are power tools and garden equipment. The third was household appliances that are sold for the leisure industry and have been manufactured or modified to work directly off a DC voltage power supply, such as a car battery or solar panel system.

3.5.2 First group of appliances that use AC mains power adapters

Each AC to DC power adapter has its voltage and current ratings printed or embossed on it. Therefore it was easy to populate Table 2 below. The appliances in Table 2 must be continually connected to the mains via the AC to DC power adapter. Table 2 shows that the voltage range was between 5V and 14V, the current range varied from 0.15A to a maximum of 1.5A with a power range from 1 to 21 Watts. In theory the low currents should allow this group of appliances to operate on long cable runs. The values in column 3 and 4 were read off the power adapters and those in column 5 were worked out by calculation. The ‘home phone’ itself is powered using rechargeable batteries, but it is usual that the base-station is plugged in twenty four hours a day that is why it is in this group.

What charger is for	Manufacturer	Voltage (V)	Current (A)	Power (W)
(1)	(2)	(3)	(4)	(5)
Home phone	BT	5.5	0.15	0.83
Music keyboard	Casio	9	0.85	7.65
CD player & radio	Tesco	12	1	12.00
Cable modem	ntl	10	1.2	12.00
Door entry phone system		14V	1.5	21.00
External USB Hard drive	Freecom	5	?	0.00

Table 2 Ratings for appliances powered via AC-to-DC power converters

3.5.3 Second group of appliances that use batteries

Table 3a is a list of cordless appliances that the current ratings have been obtained from the manufactures like Grey Technology [34], or by reading it off the power adapter.

Table 3b is taken from the Argos catalogue summer 2008, which is a list of tools and garden machinery that all operate with batteries. However the data available gives only their voltage ratings. As the Argos catalogue gives many models of the same appliance the range of voltages has been recorded. As many of these appliances have variable speed control the current drawn over the period of their use will change. The voltage range is between 3.6V and 24V. At this time their maximum current ratings are not known, however it is believed that they will not be above 2A. If the power adapters were to hand, the current ratings would be on the battery on charge. (An attempt was made to go to B&Q to read off the information on the battery chargers, however all boxes for cordless equipment were sealed.)

Appliance Type	Information from	Voltage	Current	Power
Mobile phone	Motorola	5.9	0.375	2.21
Digital camera	advent	6.0	0.6	3.60
Mobile phone	Nokia	5.0	0.89	4.45
Pocket PC	iPAQ	5.0	2	10.00
Laptop computer	Samsung	19.5	3.16	61.62
Lady shaver		1.5	0.065	0.09
Lawn mower rotary	Grey Technology	12.0	0.600	7.20
Hedge trimmer	Grey Technology	15.0	0.160	2.40
Lawn trimmer & edger	Grey Technology	17.0	0.600	10.2
Jigsaw	Performance	18.0	1.3	23.40
Drill	JCB	18.0	1.9	34.20
Hedge trimmer	Bosch	14.4	0.4	5.60

Table 3a Voltage ratings for cordless equipment whose rating are available

Appliance Type	Information from	Manufacturer	Voltage
Staple gun	Argos catalogue	Bosch	3.6
Reciprocating saw	Argos catalogue	Black & Decker	6.0
Carpet cleaner	Grey Technology	Gtech	7.2
Air compressors	Argos catalogue	Challenge	12.0
Details Sander	Argos catalogue	Challenge	14.4
Chainsaw	Argos catalogue	Black & Decker	18.0
Tree lopper	Argos catalogue	Black & Decker	18.0
Microwave	Argos catalogue	various	12 - 24
Lawn strimmer	Argos catalogue	various	14.4 - 18
Hedge trimmer	Argos catalogue	various	14.4 - 24
Screwdriver	Argos catalogue	various	3.6 - 4.8
Drill	Argos catalogue	various	9.6 - 18

Table 3b Voltage ratings for cordless equipment where the current is not known

3.5.4 Third group of appliances that work directly off a DC voltage supply

For many years, the leisure industry has used DC power, provided from (car) batteries, to power 12 and 24 V DC appliances. These appliances are mostly used in the mobile-home/camping and marine leisure industry. There are many retail suppliers of DC appliances advertising through the Internet, for this analysis the appliances were chosen from the catalogue of a supplier called RoadPro [35]. These appliances are rated at 12V or 24V. (See Appendix 3 below)

These values are not specific to the operational needs of the appliances. Rather due to the historic fact that car batteries and the spare battery which is called the 'leisure battery' are rated at 12V. The manufactures of these appliances have implemented the correct engineering design by matching their voltage rating to the battery supply, (This saves on DC-DC conversion). For higher powered goods 24V was chosen as this is the standard voltage for solar panels found on many modern leisure vehicles. Therefore those appliances that are 12V could easily be manufactured to work with a 24V system. There is a large lobby in the motor industry that wants the power mains for cars to be put up to 42V. At this time there are electronic appliance manufacturers that are working towards producing 42V DC appliances (BRE section 5.3). The voltage standard for the telecommunications industry is 48V and as such there are those that would like to see this voltage standard as that for the home and office.

For very good technical reasons, an appliance will have a specific voltage-current combination, however for any given fixed value of power an appliance can be designed such that many values of voltage-current combination can successfully be used in its operation. Many of the chosen appliances operate on 12 V, which is too low for the DC house, as the power losses along the cables are intolerable. Therefore for some of the appliances it was necessary to improvise by doubling the voltage and halving the current, while keeping the power the same, so that all the appliances operate at 24 V.

With reference to Table 4 below, the computer is an Inveneo [36] 12V DC powered computer. Twenty four more DC appliances were identified from the RoadPro catalogue. For some of the appliances it gives full information while for other appliances only voltage and power consumption. Some of the appliances have models that have a voltage rating of either 12V or 24V and some appliances have both 12V and 24V models. For those that have only 12 volt models, the data for a 24 volt model had been derived and is given in bold italics in column 4 and 5 with the power rating the same as for the 12 volt model.

		12 Volt Appliances			24 Volt Appliances		
No	Appliances	Voltage (V)	DC current (A)	power (W)	Voltage (V)	DC current (A)	power (W)
		(1)	(2)	(3)	(4)	(5)	(6)
1	Spot light	12	0.21	2.5	***24***	***0.10***	***2.5***
2	Reading lamp	12	0.83	10	***24***	***0.42***	***10***
3	Fan	12	1.50	18	24	0.75	18
4	Fridge	12	1.58	19	24	0.79	19
5	Freezer	12	1.67	20	24	0.83	20
6	Computer	12	2.00	24	***24***	***1.00***	***24***
7	Satellite receiver	12	2.00	24	***24***	***1.00***	***24***
8	Fridge & freezer combo	12	2.75	33	24	1.38	33
9	TV 19" flat screen DVD & freeview (D0517)	12	3.00	36	***24***	**1.5**	**36**
10	Alden Netmaster Satellite TV & Internet receiver	12	2.25	27	***24***	***1.13***	***27***
11	Freeview receiver	12	3.50	42	24	2.00	48
12	Heated blanket	12	4.00	48	***24***	***2.00***	***48***
13	Toasted sandwich maker	12	4.00	48	***24***	***2.00***	***48***
14	Slow cooker	12	7.00	84	***24***	***3.50***	***84***
15	Dry/wet vacuum cleaner	12	10.00	120	***24***	***5.00***	***120***
16	Frying pan	12	12.50	150	***24***	***6.25***	***150***
17	Saucepan & popcorn maker	12	12.50	150	***24***	***6.25***	***150***
18	Hair dryer	12	15.00	180	***24***	***7.5***	***180***
19	Kettle (C1205) &(C1206)	12	14.00	168	24	10.00	240
20	Air conditioner Airco 4400RM	12	25.00	300	24	12.50	300
21	Air conditioner Airco 9000RM	12	39.00	470	24	19.50	470
22	Air conditioner split unit Airco 8500				24	20.00	490
23	Microwave oven	12	65.00	780	24	40.00	960
24	TV 15" flat screen DVD & freeview (D0469)	12	2.00	24	***24***	***1***	***24***
25	Security camera system (CAMOS)	12			24		

Table 4 DC appliances From the RoadPro catalogue

3.5.5 Conclusion about the DC appliances

Table 4 shows that all the 24 volt appliances, except the microwave oven, air conditioners and a kettle have a maximum power of less than 180 Watts, with most of them including a fridge freezer and the 19 inch TV operating at less than 100 Watts. This value and the fact that the current drawn by these appliances is small, implies that the maximum lengths of cable should be long enough to allow a reasonably sized house.

So far approximately fifty four appliances that have a voltage range of 3.6V to 24V and a current rating from 0.15A to 20A have been examined. Excluding the 24V microwave oven that is rated at 24V 40A. The selection of DC appliances, both fixed-wire and cordless could provide enough appliances for a household to have a reasonable standard of living, depending on the lifestyle of the occupants.

It is appreciated that the usability of some of these DC appliances will not be equitable with AC appliances. This is why it is recognised that extensive work needs to be carried out to re-engineer AC appliances for DC use. An example of this is the kettle. A 3 kW AC kettle will boil a litre of water many times faster than the 24V DC kettle can boil 2 cups. However this research is not about ousting AC with an equivalent DC system, but it is about seeking the usability of DC in the home, which in the final analysis may only be suitable in a developing world environment or as part of a duel electrical system in a grid connected house. Friedeman (section 4.1.1) used an inverter to provide AC for the highest powered loads. Ortlepp (section 3.1) used Propane gas for cooking, hot water and backup heating. These are seen as interim measures to provide a Western lifestyle. For the all electric DC house these forms of energy are not deemed appropriate.

3.6.0 Example calculations

3.6.1 Introduction and methodology

Starting with the premise that a reasonable length of cable in a family house is 30 metres, (Pellis page 35 & BRE section 5.4), the equations were inputted into Excel spread sheets. The voltage and current ratings for each of the 25 appliances, was inputted into the equations individually to see what effect, each one would have individually on the system parameters. Sets of data were generated for all the four possible cable gauges.

To show an example set of calculations in this thesis, a 24V 3.5A DC slow cooker, which is appliance 14 in Table 4 was chosen. This particular item was chosen as it draws the highest current of 3.5A in the sub 100 Watt power range. If this appliance can operate on a reasonable length of cable without the voltage drop being too large then all of the other sub 100 Watt appliances will also operate on a good maximum length of cable.

3.6.2 Equation for the maximum length of cable L_{Max}

Equation (2) above, (Section 3.4.1) is a starting point and gives a good indication as to the approximate maximum length of cable where the best practice 5% voltage drop occurs. The conventional cable size for the ring main in an ordinary domestic house is 2.5mm^2 for the power sockets and 1.5mm^2 for the lighting. However using equation (2) this calculation was carried out for all five wire gauges at both 12V and 24V and the results are shown in Table 5 below.

Cable Cross-section area (mm^2)	Rated current (A)	Rated current (A)	Voltage drop per Amp per metre at 70°C (mV/A/m)	Maximum Power (W)		Maximum Length of cable (L_{Max}) (m)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	12 V	**24 V**		**12 V**	**24 V**	**12 V**	**24 V**
1.5	7	3.5	29	84	84	2.96	11.82
2.5	7	3.5	18	84	84	4.76	19.05
4	7	3.5	11	84	84	7.79	31.17
6	7	3.5	7.3	84	84	11.74	46.97
10	7	3.5	4.4	84	84	19.48	77.92

Table 5 Two models of a slow cooker

This slow cooker is a 12V model which has been changed into 24V by halving its current and doubling the voltage. The consequence of this is that, as the voltage drop along a cable depends directly on the current through it, as the current has been halved and the voltage doubled the maximum length of the cable has quadrupled in length. This can be seen by comparing the values in column 8 to those in column 7.

What is apparent from column 7 is that the maximum length of cable at which a 5% voltage drop will occur for a 12 volt appliance will be so small as to render

12V unusable for a target length of 30m. Even with a huge investment in $10mm^2$ cables and associated electrical connectors, the length of cable will only be two thirds of the target. Therefore having a voltage of at least 24V is important. It is also obvious from column 8 that at 24V the voltage drop will be too large with a cable size of less than 4 mm^2. Therefore, for these sample calculations a $4mm^2$ cable was used.

Example calculations:

The total voltage drop under best practice conditions of 5% is 1.2 V for a 24V system. V_{tab} for a $4mm^2$ cable is given in table 4D2B as 11mV/A/m, and L_{Max} is calculated in equation (6) using Equation (2) above.

$$L_{Max} = (1.2)/(0.011*3.5) = 31.17m \qquad (6)$$

These calculations used the value of the tabulated voltage drop along the cable V_{tab} from the tables given in Appendix 4. However these values for voltage drop are stated for full load at maximum current and maximum operating temperature. For a $4mm^2$ cable the rated maximum current is given in Table 4D2A as 25A, the 24V slow cooker is rated at a fraction of this at 3.5A. This will therefore change the value for the voltage drop per amp per metre (mv/A/m), which is calculated for a maximum load factor. Therefore the calculated value for the voltage drop along the cable will have to be worked out for each appliance. This means that in reality, as all the appliances have individual currents that are below the current carrying capacity of the $4mm^2$ cable, the actual calculated voltage drop will be smaller then V_{tab} and therefore the maximum length of cable will be larger.

3.6.3 A more accurate calculated value for the voltage drop along a cable

Table 4D2B provides a tabulated value for the voltage drop V_{tab} along a specific type of conductor, for each standard cross-sectional area of cable. The conductor is a multicore cable, manufactured with thermoplastic insulation and thermoplastic sheathed. The values given in column 2 are dependent on many variables and are specific to certain conditions. So for example, a 4 mm^2 cross-sectional cable will have an 11 mV per amp per metre voltage drop when the cable is operating under full current carrying capacity of 25A at a maximum conductor operating temperature of 70°C in an ambient temperature of 30°C. These values may change by the simple fact that the cable has different insulation or sheathing.

In an electrical conductor the resistance is proportional to the temperature of the conductor, therefore if the equilibrium temperature of the conductor is below 70°C, due to the fact that the load has a current below the maximum current carrying capacity, the value given for the voltage drop per amp per metre will therefore be less than the tabulated value which is given as 11 mV/A/m. So by operating with loads that have a current below the current carrying capacity for the given cross-sectional area, the maximum length of the cable at which the voltage drop equals 5% of the rated voltage of the appliance will be much longer.

3.6.4 Equilibrium operating temperature

Temperature effects electrical resistance and therefore the voltage drop along the cable. DB Jenkins [37] has shown with Equation (3) that by analysing the equilibrium operating temperature that the conductor reaches it can be seen that the voltage drop per amp per metre will be below that given in the Tables in the British Standard document.

The actual equilibrium operating temperature, for appliance 14 the slow cooker, that has a load current below that of the maximum rated current for 4mm^2 cable, was calculated using Equation (3) above.

The values used in equation (7) below are as follows

t_{op}	This value has to be worked out
t_a	Assumed the same as rated ambient temperature, 30°C
I_b	3.5A (this is given by the Manufacturer)
I_{ta}	25A (this is given in Table 4D2A)
t_p	70°C (given in heading of Table 4D2A)
t_{amb}	at 30°C this is 1(this is given in Table 4B1 page 267)

$$t_{op} = 30 + \frac{3.5^2}{25^2}(70-30)℃ \quad = 30.8°C \quad (7)$$

This calculation shows that for this slow cooker, the equilibrium temperature reached by the cable when the slow cooker is operating at its maximum power rating is nominally only approximately the ambient temperature. This implies that the voltage drop per amp per metre will be much lower than that given in table 4D2B. This also implies that the maximum length of cable will therefore be much longer. To calculate the actual voltage drop per amp per metre a correction factor will have to be worked out.

3.6.5 Working out the calculated voltage drop per metre V_{cal}

As the current of 3.5A is much smaller than the current carrying capacity of 25A for a 4 mm² cable, a correction factor (C_t) will have to be worked out in order to find the value for the calculated voltage drop per amp per metre V_{Cal}. Equation (4) is used to work out C_t and together with Equation (5) the calculated voltage drop per Amp per metre V_{Cal} was worked out in equation (8).

The values used in equation (8) below are as follows

C_t	This value has to be worked out
t_p	70°C (given in heading of table 4D2A)
I_b	3.5A (this is given by the manufacturer)
I_t	25V (this is given in table 4D2A)
C_a	at 30°C this is 1(this is given in table 4B1)
C_g	For one cable this is 1 (this is given in table 4C1)

$$C_t = \frac{230+70-\left(1*1-\frac{3.5^2}{25^2}\right)(70-30)}{230+70} = 0.86928 \qquad (8)$$

Now that C_t has been worked out V_{cal} can be calculated using equation (5)

$$V_{cal} = V_{tab} * C_t = 0.86928 * 11 = 9.562 \text{ mV per amp per metre.} \quad (10)$$

Using equation (2) a more accurate value for L_{max} can now be worked out.

As this is a 24Volt system, the best practice total voltage drop voltage is 1.2V. See Table 1 above.

$$L_{max} = \frac{1.2}{0.00956 * 3.5} = 35.8\text{m} \quad (11)$$

This is an increase in the length of approximately 15% from 31.17 m, as worked out in equation (6) to this value of 35.85M or in real terms the distance between the power source and the load has increased by 4.68 m. Table 6 below shows the same approximate 15% increase in L_{max} for all appliances.

Using equations (4) and (2) a set of correction factors and new maximum length was worked out for all the DC appliances and is shown in Table 6. The parameters used were; 70°C 4mm^2 cable which has a V_{tab} of 0.0011V/A/m for all appliances except the 40A microwave which uses 10mm^2 cable and has a V_{tab} 0.0044V/A/m.

No	Description	DC current Ib (A)	correction factor	V_{Cal} calculated voltage drop per amp per metre (V/A/m)	L_{max} maximum length with V_{tab} (m)	L_{max} maximum length with V_{Cal} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	Spot light	0.10	0.8666688	0.009533	1090.90	1258.74
2	Reading lamp	0.42	0.8667043	0.009534	259.74	299.68
3	Fan	0.75	0.8667867	0.009535	145.45	167.81
4	Fridge	0.79	0.8667998	0.009535	138.09	159.31
5	Freezer	0.83	0.8668136	0.009535	131.43	151.63
6	Computer	1.00	0.8668800	0.009536	109.09	125.84
7	Satellite receiver	1.00	0.8668800	0.009536	109.09	125.84
8	Fridge & freezer combo	1.38	0.8670729	0.009538	79.05	91.17
9	TV 19" flat screen DVD & freeview	1.50	0.8671467	0.009539	72.73	83.87
10	Alden Netmaster Satellite TV & Internet receiver	1.13	0.8669391	0.009539	96.54	111.32
11	Freeview receiver	2.00	0.8675200	0.009543	54.54	62.87
12	Heated blanket	2.00	0.8675200	0.009543	54.54	62.87
13	Toasted sandwich maker	2.00	0.8675200	0.009543	54.54	62.87
14	Slow cooker	3.50	0.8692800	0.009562	31.17	35.86
15	Dry/wet vacuum cleaner	5.00	0.8720000	0.009592	21.82	25.02
16	Frying pan	6.25	0.8750000	0.009625	17.45	19.95
17	Saucepan & popcorn maker	6.25	0.8750000	0.009625	17.45	19.95
18	Hair dryer	7.50	0.8786667	0.009665	14.54	16.55
19	Kettle	10.00	0.8880000	0.009768	10.91	12.28
20	Air conditioner Airco 4400RM	12.50	0.9000000	0.009900	8.65	9.70
21	Air conditioner Airco 9000RM	19.50	0.9478000	0.014257	5.55	5.90
22	Air conditioner split unit Airco 8500	20.00	0.9520000	0.010472	5.41	5.73
23	Microwave oven	40.00	0.9820443	0.004321	6.82	6.94
24	TV 15" flat screen DVD & freeview	1.00	0.8668800	0.009536	109.09	125.84
25	Security camera system ***	not known	not known	not known	not known	not known

Table 6 Shows the maximum length for each individual 24 Volt appliance

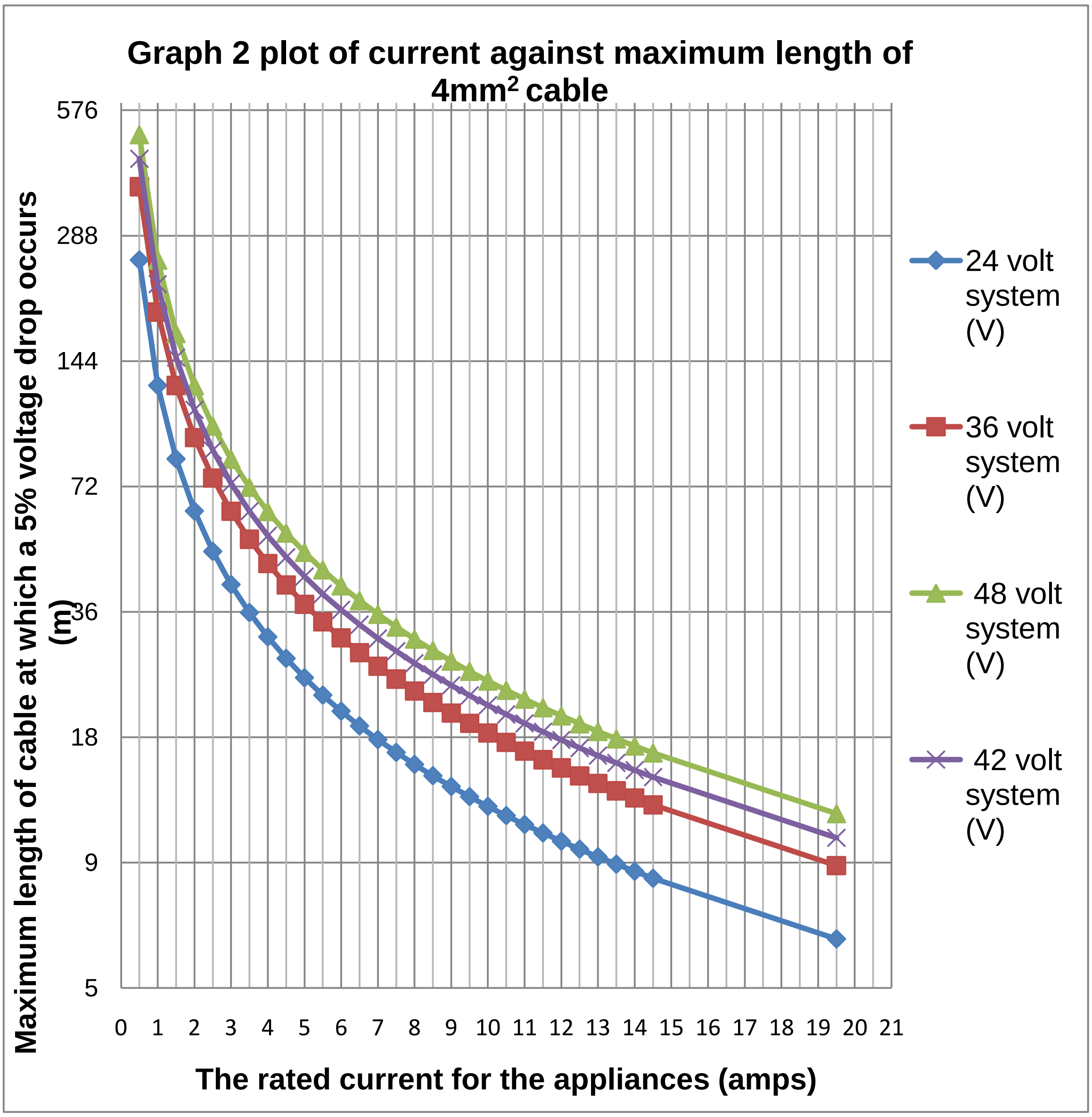
*** Appliance 25 is a complete DC system that can use different cameras and different screens, therefore as a system the value for the current is not known. However if it is compared to a small screen and a digital camera, the current should be less than 2A.

From column 7 it is obvious that the premise that 30m is a target length for the cable run for a domestic dwelling may have been over ambitious, as all the appliances from number 15 and up will not comply at 30m to the best practice of a 5% voltage drop. The most noticeable thing from Table 6 is that, the most important parameter in this low voltage system is the current, the larger the current the larger the voltage drop and the shorter the maximum length of cable will be.

3.7.0 Graphical tools

From the above analysis of an example 24 volt system, it is obvious that there is a simple trade off between current and L_{max}. However the above analysis is quite cumbersome and only represents a 24 volt system using a limited number of DC appliances. These calculations represent a multi-variable and complex system. What the designer of DC appliances and the DC house needs, is a way of easily finding out how the different design parameters will impact the design. However with at least 4 parameters, manual calculations can be very time consuming. One of the easiest ways of presenting a complex system with multiple variables is graphically. To help the designer get a quick perspective of the different cable gauges and lengths of the cable runs, voltages and currents that make up the system parameters, a set of graphical tools were developed. These graphs offer a full range of current and cable lengths. For very low currents the cable lengths can be one hundred times longer than that for a current very close to the current carrying capacity of the cable therefore a logarithmic scale was used for L_{Max}.

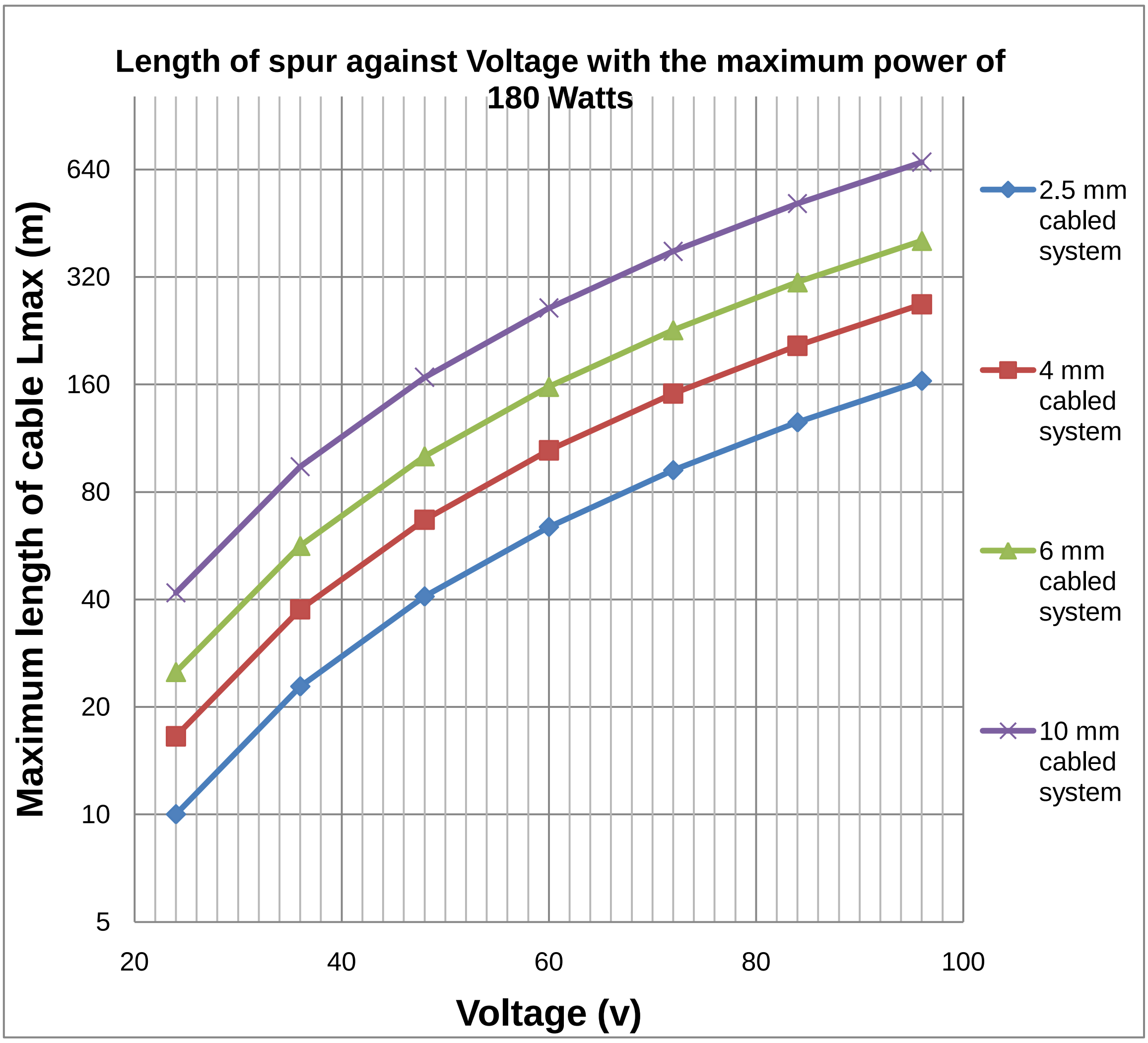
Using Microsoft Excel, tables similar to Table 6 were made. The calculations were made for a range of currents form 0.5A to 15A DC and the voltages chosen were 24V, 36V, 42V, and 48V. For each gauge cable, a complete date set was produced and graphs plotted for each voltage.



Graph 1 Plot of L_{Max} against current for different voltage systems

With a set of graphs to hand it is easy to see that if the cable length is 18 m then the maximum drawn current can be between 7A and 13A depending if the mains dc voltage is between 12V and 48V. For the data sets and the graphs for all four cable gauges see Appendix 1 below (pages 135 -142)

In Graph 1 the fixed parameter is the cable gauge. However if the designer wants to compare which cable to use for a range of different voltages and maximum lengths of cable for a given fixed load power then Graph 2 below should be used.



Graph 2 Plot of L_{Max} against Voltage for different cable gauges

For example if the designer wants 180W maximum load per cable and has decided that 48V is the design voltage then he can either choose the maximum length which could be approximately 40m or 160m depending if the chosen cable is $4mm^2$ or $10mm^2$. These plots were done at 150W, 180W and 250W, and are shown in Appendix 1 below (Pages 143 - 145). All these plots are good tools to help in the design of the DC voltage house and in theory any number of plots can be produced to suit the needs of the designer.

What is clear from these graphs is that there are up to five variables all of which are floating. This will make it difficult to find an optimum voltage for the low powered DC home without deciding to fix some of the variables. It may be that fixing the variable will in itself be arbitrary and may depend on extraneous factors such as financial constraints, the availability of already existing renewable energy generators or the dc appliances. As with many electronic gadgets, it has been market forces rather than science that have set the Standard.

Chapter 4

The Electrical Design of the DC House

Summary

In Chapter 3 the first hurdle in the design process of the DC house was overcome. It showed that for the chosen set of DC appliances a 5% voltage drop along the cable will occur at a reasonable length of cable. This chapter uses the equations and appliance parameters shown in Chapter 3 to further the design process by applying the methodology as described below. The electrical integrity of the design is investigated and values for daily peak power and yearly power usage are worked out. A critical analysis of previous work is carried out.

4.1.0 Introduction – Electrical design methodology

A breakdown of the design presses is as follows:

1. To decide on the size and layout of the physical house.
2. To divide the house into different zones.
3. Apportion the DC appliances to each zone, by way of connecting them to a specific power socket.
4. Apportion groups of power sockets to a cable spur.
5. Work out peak power for each spur and for the whole house.
6. Use available statistics about the amount of time appliances are used in the home per day to work out kilowatt-hours used per day and per year.

4.2.0 The layout of the house

It was decided to work on a house that would be small but comfortable. A schematic of the proposed house is shown in Figure 1 below. It is a single story two bedroom open plan house, with the electricity control unit for all the power to the house sited at the black square which is in the roof above the kitchen. This idea is from the Friedman See [31]. This allows the shortest length of cable to the highest powered appliances which are in the kitchen and to the air conditioners which are roof mounted.

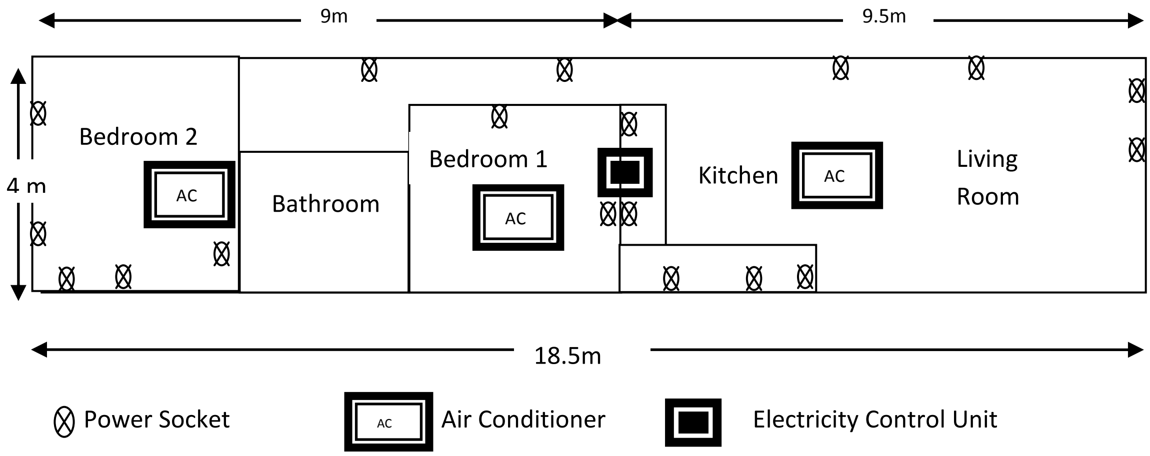


Figure 1 Schematic of the DC House

The floor area size was chosen to be that which has been stipulated as the “average living space of 74m^2 per dwelling...” in the United Kingdom for the year 2050 [38 Page 7]. The height of the rooms throughout the house is 3 m. This size takes into consideration the need to minimise the maximum length of any cable, while providing adequate voltage at the load. For a load at the furthermost distance from the electricity control unit the maximum length of cable will be approximately 2m + 9.5m +3m = 14.5m. For the calculations 15 m will be used which is a more practical value than the initial assumption of 30m. The shortest cable run, which will feed the power sockets in the kitchen, will be approximately two to three metres long.

It is assumed that just as in a conventional house there are many wall sockets not all of which are used at the same time, so too this house will have a good number of sockets around the house. However for this electrical system to work without being overloaded some guidelines will have to be laid down as to the way the householder uses electricity. More work will have to be carried out to implement the electrical hardware needed to uphold the integrity of these guidelines.

4.2.1 Guidelines and Assumptions

1) Assume for simplicity that the power supply, whatever form it takes, is available. (It could be from renewable energy generators like solar cells or

wind generators, or it could be from hydrogen/bio-fuelled fuel cells, or grid connected AC.)

2) Assume that the cable feed into the control unit is at least a 16mm^2 cable.
3) Fixed high powered appliances will be permanently connected to the mains
4) A mechanism must exist that will not allow appliances to operate if they will overload a circuit. This will restrict the number of appliances that can be in operation at any one time.
5) All the appliances are 24V models, or that they are adapted to work at 24V.

4.2.2 The zones

It can be seen from the data in Table 6 that with a target length of 15m it will be possible to have more than one appliance connected to a single cable. By apportioning different appliances to be used in different parts of the house, they will be able to be grouped together on the same cable spur thus reducing the complexity of the electrical cabling in the house.

This design was iterative and began by dividing the house up into different zones. The idea was to compartmentalise the house so that each zone could be fed with a minimal amount of cables. The zones given were, the living room, kitchen, bedroom one, hallway, bathroom and bedroom two

4.2.3 Apportioning appliances to each zone

It was decided where in the house each appliance would be used and each was designated to a power socket. Table 7 below sets out the house, according to the rooms/zones (column 1), electrical power sockets (column 2), and appliances used (columns 3 & 4). Consideration was given for the fact that some of the appliances will not be working at the same time as others. For example, in the kitchen socket 6 is apportioned to 4 different electrical appliances with the assumption that only one of them will be working at the same time. The total values given in bold in column 5 indicate the maximum current and power drawn by each zone. The question now is how many of the appliances will be able to properly operate at the same time on the same cable spur, before the voltage drop will be below the best practice value of 22.8V?

Zone	Power Socket #	Appliance from list in Table 6	Description of appliance	Maximum Current (A)	Maximum Power (W)	Maximum Length of 4 mm^2 Cable(m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
living	1	9	TV 19" flat screen DVD & freeview	1.50	36	83.87
living	2	21	air conditioner Airco 9000RM	19.50	470	5.90
living	3	15	dry/wet vacuum cleaner	5.00	120	25.02
living	4	2	reading lamp	0.42	11	299.69
living	5	6	computer	1.00	24	125.84
			Total values	**27.42**	**661**	
Kitchen	6	16	frying pan	6.25	150	19.95
Kitchen	6	14	slow cooker	3.50	84	35.86
Kitchen	6	13	toasted sandwich maker	2.00	48	62.87
Kitchen	6	17	saucepan & popcorn maker	6.25	150	19.95
Kitchen	7	19	kettle	10.00	240	12.29
Kitchen	8	8	fridge & freezer combo	1.38	33	62.88
Kitchen	9		recharge station *	2.00	48	125.84
			Total values	**31.40**	**753**	
Kitchen	10	23	microwave oven **	40.00	960	6.94
Hallway	11	15	dry/wet vacuum cleaner	5.00	120	25.02
Hallway	12	18	hair dryer	7.50	180	16.55
			Total values	**12.5**	**300**	
bed 1	13	9	TV 19" flat screen DVD & freeview	1.50	36	83.87
bed 1	14	20	air conditioner Airco 4400RM	12.5	300	9.70
bed 1	15	2	reading lamp	0.42	11	299.69
			Total values	**14.42**	**347**	
bed 2	16	9	TV 19" flat screen DVD & freeview	1.50	36	83.87
bed 2	17	20	air conditioner Airco 4400RM	12.5	300	9.70
bed 2	17	3	Fan	1.00	18	125.84
bed 2	18	12	heated blanket	2.00	48	62.87
bed 2	19	2	reading lamp	0.42	11	299.69
bed 2	20	6	computer	1.00	24	125.84
			Total values	**18.92**	**437**	

Table 7 Appliances apportioned to power sockets and zones

* The recharge station may have a few separate sockets each for a different appliance however it is not envisaged that more than a few appliances will be recharged at any one time.

** The Microwave is connected using 10mm^2 cable

4.3.0 The number of cable spurs

4.3.1 Design boundaries

As explained above in the calculations (Section 3.6.2), it was decided to use a 4mm^2 cable for the wiring in the house, except for the microwave, which uses 10mm^2. Using the graphical tools, it can be seen from Plot 1 above (Section 3.7.0) , that for a 15 m cable run, the maximum current will be somewhere above 7.5A. Doing the actual calculation at 24V the maximum current at which a best practice 5% voltage drop will occur at the load is 8.26A.

4.3.2 Methodology

The design so far consists of, the layout of the house with its power sockets, a set of 24 Volt DC appliances, and a possible scenario as to how the appliances could be apportioned to each zone in the house. The next stage is to apportion the power sockets with their attached loads to the cable spurs, in a way that does not overload any of them. By doing this the amount of cable spurs to supply all the loads will be established. In reality each socket will be a different distance from the control board, which implies that each is fed by different length of cable. As these cable lengths are an unknown quantity, it was decided to calculate for the worst case scenario, which is 15m. This means that all the loads on a spur, regardless as to where along its length the power socket is located, are lumped together and the voltage drop calculations are done as if they are all one appliance at a distance of 15m from the power board. The rationale behind this is that if the electrical integrity of the system is upheld in this situation it will definitely be true for shorter cables.

The air conditioners are roof mounted appliances that can, without any technical issues, be situated within 5m to 7m of the control board. Also their current ratings are above the 8.26A for 15m of $4mm^2$ cable. Therefore instead of using a cable run of 15m, the calculations were done for a 5m cable length to the living room, 3m for bedroom 1 and 7m for bedroom 2. The unit for the living room is a 10,000 BTU/h unit and those for the bedrooms are 4760 BTU/h units. As the current carrying capacity of the $4mm^2$ cable is 25A, this size cable will still be able to be used for these high current air conditioners, as the cable lengths are so small.

The value for maximum length of cable given in Table 7 Column 7 is when each appliance is connected to a cable without any other appliances. As more appliances are added to a cable spur the total current drawn increases and the maximum length of cable gets smaller. As the maximum current per zone has been calculated to be 8.26A, more than one $4mm^2$ cable spur will be needed when this current is surpassed.

4.3.3 How many $4mm^2$ cable spurs are needed?

Some latitude can be taken when working out how many cable spurs will be needed as some of the cable spurs will definitely be less than 15m. As such it was possible to introduce more power sockets for the same amount of cable spurs and to move others around. This is shown in Table 8, where now power socket 6 has only two appliances associated with it and the number of power sockets connected by $4mm^2$ cables has gone up from 19 to 22.

The maximum current for the living room appliances is 7.92A, which will suffice with one cable spur and the air conditioner will have its own spur. The kitchen has one $10mm^2$ cable for the microwave, and three spurs for all other appliances. Even though the kettle is 10A, it can still use a $4mm^2$ cable as long as the kettle is only used in the kitchen, where the cable spur is only a few metres long, however it will not be able to be used in the power sockets at the extremities of the house where the cable length is more than 12.9m from the control board. The hallway sockets will be on one spur. The maximum current for bedroom 1 is 14.42A this still allows for the use of only one spur as the air conditioner is less than 1.5m from the control panel. For bedroom 2, two spurs should suffice. The design for the power distribution network in this house will therefore consist of nine 4mm^2 cable spurs and one 10mm^2 cable spur.

Although the total possible current drawn through some of the cable spurs is on the high side, as explained above, since in reality many of the power sockets are much less than 15m from the power board, the electrical integrity of the system will still be upheld. The three air conditioners and the microwave will be permanently connected to the electricity supply, like a 30A AC electric cooker is connected up today, with a fused switch on the power socket.

4.3.4 Apportioning power sockets to cable spurs

The apportionment of the appliances will be according to the total current drawn by each group. In Table 8 the cable spurs (column 1) have been added and a set of power sockets has been apportioned for each spur (column 3).

No consideration has been given for the voltage drop in the cable that connects the appliance to the power socket, which in practice could be between one and three metres long. Further work could be to look into setting a practical maximum length of appliance flex which would become a Standard for home appliances. The peak power (Column 8) is when all the appliances are connected to the spur at the same time. In the case where more than one has been designated to the same socket the highest powered device is used.

Spur	Room	Power Socket Number	Appliance Number	Appliance Type	Current (A)	Max power (W)	Possible Peak Load Power (W)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	living	1	9	TV 19" flat screen DVD & freeview	1.5	36	
1	living	2	15	dry/wet vacuum cleaner	5	120	
1	living	3	2	reading lamp	0.42	11	
1	living	4	6	computer	1	24	191
2	living	5	19	air conditioner	19.5	470	470
3	Kitchen	6	16	frying pan	6.25	150	
3	Kitchen	6	17	saucepan & popcorn maker	6.25	150	
3	Kitchen	7		recharge station	2	48	198
4	Kitchen	8	14	slow cooker	3.5	84	
4	Kitchen	9	13	Toasted sandwich maker	2	48	
4	Kitchen	10	8	Fridge & freezer combo	1.38	33	165
5	Kitchen	11	20	Kettle	10	240	240
6	Hallway	12	15	dry/wet vacuum cleaner	5	120	
6	Hallway	13	18	hair dryer	7.5	180	300
7	bed 1	14	9	TV 19" flat screen DVD & freeview	1.5	36	
7	bed 1	15	19	Air conditioner Airco 4400RM	12.5	300	
7	bed 1	16	2	reading lamp	0.42	10	346
8	bed 2	17	9	TV 19" flat screen DVD & freeview	1.5	36	
8	bed 2	18	3	Fan	0.75	18	
8	bed 2	19	12	heated blanket	2	48	
8	bed 2	20	2	reading lamp	0.42	11	113
9	bed 2	21	6	computer	1	24	
9	bed 2	22	19	Air conditioner Airco 4400RM	12.5	300	324
				Peak Power (W)			**2347**

Table 8 A scenario for the connection of loads to sockets with 4mm^2 cable spurs

4.3.5 Notes on apportionment of power sockets to electrical spurs

(1) It is assumed that all four appliances will be connected to spur 1 at the same time, this implies that the peak power to run all these loads will be 191 W. If the rated voltage is 24V then the maximum drawn current should be 7.96A.

(2) It is, assumed that the air conditioner will be directly connected to its own dedicated fused spur, which has been designated spur 2.

(3) Spurs 3, 4 and 5 have been designated for use by the kitchen appliances. When apportioning appliances to power sockets, as shown in Table 7, the premise was to try and reduce the number of sockets. It was assumed that some appliances will not be needed to be used together, therefore four were lumped together to be used in power socket 6. However when looked at in more detail, it was decided for the convenience of the householder, to add more sockets so that power socket 6 is now only designated for two appliances. This allows spur 3 to power sockets 6 and 7

This design is very simplified and conservative as it was made under the constraints of a 15m cable with a maximum allowed current of 8.26A per spur. However If the maximum length of cable into the kitchen is only 5m, then the maximum current can be approximately 22A! This should allow for more power sockets which will allow for more appliances to be connected at the same time. However, at this time this analysis is for a cable length of 15m. Dynamic control of the electrical system, which is outside of this research, would allow for a more precise design and control of the whole electrical system.

(4) It is assumed that the wet/dry vacuum cleaner and the hairdryer will be used at the same time in the hallway connected to spur 6. If this happens their combined total current will be 12.5A. As the real length of spur 6 is less than the maximum length (L_{Max}) of 9 m of 4 mm^2 cable, when 12.5A is drawn, the electrical integrity of this spur will be upheld.

(5) The two sockets in bedroom 1 and the air conditioner will be fed from spur 7.

(6) All the sockets in bedroom 2 excluding that for the air conditioner are connected to spur 8. With the air conditioner and computer on spur 9.

(7) Missing in table 8 is the 10 mm^2 cable that will be used in the kitchen to supply power to the microwave oven, which has a current capacity of 40A. The maximum length of cable at which a 5% drop occurs when the 40A is drawn through a 10 mm^2 cable is 6.94m. This length is ample to supply power for the microwave which can be situated in the kitchen anywhere within 6.94m of the control board.

4.4.0 System integrity

In reality, each cable that goes from the control board to its designated zone in the house will be of different length. For the main calculations it was generally assumed that the cables have a maximum length of 15m, however it has been shown that most of the high current appliances are within 5m of the control board. What is needed is a mechanism to be able to automatically measure when the voltage at the socket becomes close to the best practice value of 5% of system voltage. Or regardless of the voltage drop, to identify if the voltage supplied at the socket is within the tolerance allowed by the manufacturers' specification, as per BS 7671:2008 Section 525.2. The mechanism missing at this time is the ability to dynamically control voltage and current on each cable spur and at each power socket.

With dynamic control of the whole electrical system, overloaded circuits will not occur, and interchanging appliances from one room to another, which implies connecting an appliance to different lengths of cable, will also be possible. It will allow a much more flexible and robust system.

Today, there exist many smart, dynamic control possibilities that with adaptations can be used in the DC home. The jargon used is "Smart House Technology", with "Mr Bill Gates's home on the shores of Lake Washington being full of such technology" [39]. However, these control mechanisms are not part of this project, and at this time will have to be adapted from state of the art technology some of which in itself is in its infancy. Future work will have to look at how to control the voltage and current at each socket from a centralised control unit using software and hardware.

It could be argued that if this design is for a minimalist house perhaps even in the developing world, the microwave oven and the three air conditioners are in fact a very big luxury and could therefore be left out from the design. However, the microwave has been included here, as no consideration has been given for an electric cooker in this scenario. The air conditioners show that this house has potential for use in the developed world, and that the electric integrity of the house still holds up with such high current appliances. Removing these appliances will drastically reduce the peak power and energy consumption of the home, but with the consequences of a possible reduction in the living standard of the occupants. Alternatively their removal could allow for the same energy to be used by many more smaller appliances which could in many cases increase the living standards of the occupants. There is therefore a direct correlation between what living standard is required and the number of appliances or power consumption that can be incorporated into the design.

4.5.0 Peak power, per spur and for the whole house

4.5.1 Introduction

The peak power value is usually used when sizing up for renewable energy generators. The conventional method is to use statistics to work out the peak power. This is worked out by using the total load profile provided by an energy supply company for a specific geographical area and then taking the amount of houses, work out an average daily peak power. Using this method one gets a statistical average peak power per house. This methodology has very little direct correlation to the actual appliances used in the different homes in that geographical area and suffers from the disadvantage that it is derived from AC energy usage and not DC. For this research the bottom up approach is employed and the actual DC appliances utilised in the design of the DC house are used to derive the peak power and power usage.

4.5.2 Peak power

The current rating for each appliance given in column 6 of Table 8 was multiplied by 24, the nominal voltage of the system, to give us the maximum power for each appliance, which is shown in column 7. The total possible power for each spur is given in column 8. This gives us a peak power of 2347 Watts. The microwave oven by itself uses 960 Watts. With the microwave the peak power becomes 2347 + 960 = 3307 Watts. As explained above, the microwave is perhaps a luxury and would not be desired in the minimalistic house. However what will the householder use to cook the food? Would the slow cooker be good enough?

In summary, if all appliances are in use, peak power is 3307W. Remove the air conditioners, peak power is reduced to 2237W and further remove the microwave oven the peak power is reduced to only 1277W. (For further discussion about this see section 4.6.0 below)

4.5.3 Daily and yearly peak power usage

People have different habits and different needs, and even with the same set of appliances, and the same size house and size family, one family may use more energy than the other. The goal is to build up a peak energy profile which would be realistic, but not definitive. The size of the model house, the number of sockets and electrical cable spurs, as well as a list of DC powered appliances have already been defined. What is now needed is how long each appliance is used each day? One way of finding this out is by physically measuring people's homes on a daily basis and deriving a statistical average from all measurements. However this is beyond the scope of this research, therefore the available national statistics was used to build up the daily usage profile.

BRE in Appendix 2 show Table 1 ‘Home’ Model’, which provides an electrical equipment inventory. This shows the energy usage in kilowatt-hours per annum and provides the amount of hours per day each appliance, on average is used. This data is at least seven years old and has been used as the baseline when designating the amount of hours per day the appliances will be used. By way of an example Table 9 shows the calculations of the power consumption in spur 1 which feeds power sockets 1 to 4 in the living room.

Socket Number	Appliance Number	Appliance	Current (A)	Power (W)	Amount of hours used per 24 hour period averaged over a year	Amount of kWh used per 24 hour period	Amount of kWh used per year
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	9	TV 19" flat screen DVD & freeview	1.5	36	4	0.144	52.56
2	15	dry/wet vacuum cleaner	5	120	0.05	0.006	2.19
3	2	reading lamp	0.42	10	2	0.022	8.03
4	6	computer	1	24	3	0.072	26.28
		Totals	7.92	190		0.244	89.06

Table 9 Example data for working out peak power and kWh in spur 1

The power given in column 5 is a multiplication of the current for the individual appliance and the mains voltage of 24V. Column 6 is the average time the appliance is said to be used per day taking the yearly usage for the appliance and dividing by 365 days of the year. Column 7 is the total power used by an appliance per day in kWh. For example for the TV that uses 36 Watts for 4 hours the total wattage used is 144Wh or 0.144kWh. From Table 9 it is apparent that 0.242kWh of electricity would be used per day by the appliances connected to spur 1, which equates to 88.33kWh per year. Note: it is beyond the scope of this research to use within these calculations the standby power usage.

Table 10 gives the power usage for the whole house, inclusive of the microwave oven. The daily peak power consumption is 3.307 kWh and the peak yearly power consumption 1390.29 kWh/year. This information can be used in the design of the system to be employed to power the house and to put a cost to the yearly electricity consumption.

Spur	Socket Number	Appliance	Current (A)	Power (W)	Amount of hours used per 24 hour period averaged over a year	Power consumption per 24 hour period (kWh)	Amount of kWh used per year
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	1	TV 19" flat screen DVD & freeview	1.5	36	4	0.144	52.560
1	2	dry/wet vacuum cleaner	5	120	0.05	0.006	2.190
1	3	reading lamp	0.42	11	2	0.022	8.030
1	4	computer	1	24	3	0.072	26.280
2	5	air conditioner	19.5	470	1.5	0.705	257.325
3	6	frying pan	6.25	150	0.4	0.060	21.900
3	6	saucepan & popcorn maker	6.25	150	1	0.150	54.750
3	7	recharge station	2	48	0.02	0.001	0.3650
4	8	slow cooker	3.5	84	2	0.168	61.320
4	9	Toasted sandwich maker	2	48	0.02	0.001	0.365
4	10	Fridge & freezer combo	1.38	33	24	0.792	289.080
5	11	Kettle	10	240	0.9	0.216	78.840
6	12	dry/wet vacuum cleaner	5	120	0.05	0.006	2.190
6	13	hair dryer	7.5	180	0.15	0.027	9.855
7	14	TV 19" flat screen DVD & freeview	1.5	36	2.7	0.097	35.405
7	16	air conditioner	12.5	300	1.5	0.450	164.250
7	16	reading lamp	0.42	10	2	0.020	7.300
8	17	TV 19" flat screen DVD & freeview	1.5	36	2	0.072	26.28
8	18	Fan	1	18	1	0.018	6.570
8	19	heated blanket	4	48	4	0.192	70.080
8	20	reading lamp	1	10	2	0.020	7.300
8	21	computer	1	24	1	0.024	8.760
9	22	air conditioner	12.5	300	1.5	0.450	164.250
10	23	microwave oven	40	960	0.1	0.096	35.040
		Total Power consumption per day (kWh)				3.809	
		Total kWh consumed per year					1390.290

Table 10 Total power used per year for the given scenario

4.6.0 Conclusions - General electrical reliability

At this stage, the extra-low voltage DC powered house is completely possible from the point of view of the internal cable mains using 4mm^2 cable at 24V DC. This cabling allows a very high peak power per day well beyond that shown by Pellis or BRE, a value that would make the DC house suitable for use even in the developed world. However what is not considered is how to power the home. With a peak power of over 3.307 kW the current drawn at 24V is 137.8A. It is not known if a domestic electrical system can practically and safely operate at this high current. The way to reduce this current level is to remove some of the high powered appliances or make a split power source which will halve this current. With the air conditioners removed the current drawn is still high at 93.3A. And without the microwave the current goes down further to a very manageable 53.3 A. Not having the air conditioners is a very likely option. (See Chapter 5 for different design scenarios)

This high current would makes a good case for increasing the voltage to 36V or 48V, which would reduce the maximum total current to 91.9A and 68.9A respectively and still allow the use of all the appliances. This would also greatly increase the maximum length of cable and possibly reduce the number of cable spurs. These results are obviously also limited by the fact that these calculations are restricted to the available DC appliances. However the electrical architecture of the power supplying the home is not part of this project and will need further work to see how it can be best implemented.

This design for the mains installation, incorporates a 24V system, using a maximum cable length of 15 m long 4 mm^2 cables configured as a star mains rather than ring mains. Such a design implies that all housing stock that at the moment are using 2.5 mm^2 cables would have to be rewired. Also, as the design is using a 40A microwave in the kitchen, it will have to also incorporate at least one 10 mm^2 cable. Also, with electronic dynamic control more accurate optimisations of the design can be implemented increasing the usability of the home.

4.7.0 Critical analysis of previous work - Introduction

From the BRE report and the thesis by Pellis, it became apparent that although comprehensive, both did not provide the basic knowledge that would help a researcher understand how appliances interact with the mains electricity and what effects they have on voltage drop and system integrity. They also brought to light many questions that needed answering. Therefore, as explained in the introduction to Chapter 3, this research found it necessary to start from the bottom up, starting with the system parameters and equations. After working through the calculations, the results of this research were different from that of the previous work. In order to compare and contrast this research with the previous work, an in-depth analysis of their work was carried out.

4.8.0 Data for Maximum length of cable Pellis

J.Pellis in Table 6.2 of his thesis shows the maximum lengths of cable (L_{max}) for a given cable and given power, at which the voltage drop is 5% of the rated voltage of the load. His Table 6.2 is reproduced here as Table 11 except for column (3), which was worked out by rearranging Equation (1) to obtain equation (11) and inputted the values for L, I and $V_{TotDrop}$ from his data.

$$V_{tab} = V_{cal} = \frac{V_{TotDrop}}{I * L} \quad (11)$$

Note: Although it has been explained that Equation 1 is a rough guide and that for an accurate calculation a correction factor must be worked out, here, as the values in column 2 are almost the same as the values for the current carrying capacity given in BS 7671 for the cables, the correction factor can be assumed to therefore be 1.

Cross-sectional area (mm^2)	Maximum Current (A)	Calculated Voltage Drop per metre per Amp at 70°C [V_{cal}] (mV/A/m)	Maximum Power (W)			Maximum Length (m)		
			24 V	120 V	220 V	24 V	120 V	220 V
(1)	(2)	**(3)**	(4)	(5)	(6)	(7)	(8)	(9)
1.5	14.0	**22.56**	336	1680	3080	3.8	19	34.8
2.5	19.2	**13.59**	460.8	2304	4224	4.6	23	42.2
4.0	25.6	**8.52**	614.4	3072	5632	5.5	27.5	50.4
6.0	32.8	**5.63**	787.2	3936	7216	6.5	32.5	59.6
10.0	45.6	**3.42**	1094.4	5472	10032	7.7	38.5	70.6

Table 11 Data from Pellis and the worked out values for V_{cal}

The values given for maximum current in Table 11 column 2 slightly differ from those given in BS 7671:2008. It was thought that perhaps the standard has changed since his thesis was written. However on looking up the 1991 sixteenth edition of BS 7671 no significant changes exist that equate to the values given by Pellis.

The values worked out in column (3) are far from those given in BS 7671 Table 4D1B for V_{tab}. This was expected because the values for the current capacity are also different. The values presented by Pellis were based on the data in Table 6.24-C1 and 52-E1 of the Dutch Standard document called NEN 1010, which is equivalent to the British Standard document and as the wiring regulation are understood to be pan-European it is expected that the data in each should be the same. Unfortunately this Dutch Standard was unavailable to look into to confirm his data.

4.8.1 Calculations for maximum length of cable using BS 7671

From the data given in Tables 4D2A and 4D2B column 2 in Appendix 4 of BS 7671 the maximum length of cable was worked out using equation (2). It was decided to use ‘Reference Method A’, as the values for maximum current capacity were as close to those of Pellis as possible.

Cross-sectional area (mm^2)	Maximum Current (A)	Tabulated voltage drop per metre per Amp at 70°C [V_{tab}] (mV/A/m)	Maximum Power (W)			Maximum Length L_{Max} (m)		
			24 V	120 V	220 V	24 V	120 V	220 V
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1.5	14.0	29	336	1680	3080	**2.96**	**14.78**	**27.09**
2.5	18.5	18	444	2220	4070	**3.60**	**18.02**	**33.03**
4	25.0	11	600	3000	5500	**4.36**	**21.82**	**40.00**
6	32.0	7.3	768	3840	7040	**5.14**	**25.68**	**47.09**
10	43.0	4.4	1032	5160	9460	**6.34**	**31.71**	**58.14**

Table 12 Maximum length of cable worked out using BS 7671

Columns 1 and 2 come from Table 4D2A (Page 276). Column 3 comes from Table 4D2B. The maximum powers in columns 4, 5, and 6 were worked out by multiplying the voltage by the maximum current given in column 2. To work out the maximum length of cable (L_{Max}), columns 7, 8, and 9, at which a 5% voltage drop occurs, Equation (2) was used, and the value for $V_{TotDrop}$ was found from Equation (1), see Section 3.3.0 above for equations.

4.8.2 Comparing and contrasting the two sets of data

Cross-sectional area (mm^2)	Current capacity BS 7671	Current capacity Pellis	V_{tab} BS 7671	V_{cal} Pellis	V_{diff}	% V_{diff}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1.5	14.0	14.0	29	22.56	6.44	22.22%
2.5	18.5	19.2	18.5	13.59	4.41	24.52%
4	25.0	25.6	11	8.52	2.48	22.52%
6	32.0	32.8	7.3	5.63	1.67	22.90%
10	43.0	45.6	4.4	3.42	0.98	22.33%

Table 13 Comparison of voltage drop and current capacity data with Pellis

What is noticeable is that the values calculated for V_{tab}, shown in Table 13 column (5) using the data given by Pellis, are lower than those given in any of the tables of BS 7671 Appendix 4, shown in column (4). As V_{tab} values are higher in the British Standards document the maximum length of cable for the given parameters is as expected less than that given in Pellis Table 6.2.

V_{diff} was defined as the difference between the values in columns 4 and 5 of Table 13. V_{diff} was divided by V_{tab} to see if perhaps Pellis had used a Correction

Factor, like C_t that gave him his values for the voltage drop along a cable. As there appears to be a pattern with an approximate 22% to 23% difference in the two sets of figures (other than for 2.5mm^2 cable?) perhaps there is a correction factor, however at the time of writing this paper it is not known. What is further not understood about his values for V_{tab} is that in explaining the data in Table 6.2 Pellis stated that "Table 6.2 gives Maximum..." which implies a 100% load factor with C_t = 1. Therefore what needs to be understood is why are the values from the Dutch Standard NEN 1010 different than those given in BS 7671 when these Standards should be the same as these are Pan European?

Is it possible that Pellis used a Correction Factor (C_t)? C_t depends on the ratio of the current being drawn by the load and the current capacity of the cable. From the data set (Table A1-2) in Appendix 1 below, for the range of load current of 0.5A to 19.5A for a 4mm^2 cable the correction factor is 0.8667 to 0.9478 respectively. This means that for a current of only 2% of the current capacity of 25A the voltage drop per amp per metre is reduced by only 13.3%. For a V_{diff} of 22.52 % the correction factor will have to be 0.7748, which is not possible. This can be seen from Equation (4). If the load current is very small let's say 0.01A going through a 4mm^2 cable of 25A capacity, then the ratio I_b^2/I_t^2 becomes so small that it does not affect C_t. For values of less than 1A, C_t to four decimal places can only get as small as 0.8667, which will only reduce V_{tab} by 13.3%. Therefore the values given by J. Pellis in Table 6.2 require further verification.

4.8.3 Comparing efficiency of AC/DC and DC/DC power converters

In section 4.2.2 Pellis makes a straight comparison between the percentage efficiency of an AC to DC converter and a DC to DC converter stating that typical converters have an efficiency of 80% to 90%. He then goes on to state that "*The obtained data does not show a clear difference between the efficiency of DC/DC converters and AC/DC converters*". He also makes the statement that the assumption that changing over to DC will save energy "...*is not necessarily true*...". From this and from his Table 4.5 he gives the impression that he is making a direct comparison between the efficiency of AC to DC converters and DC to DC converters.

The question is, can one make a direct comparison between AC to DC and DC to DC converters or are they complete different items? Is it an acceptable methodology to compare two items solely by their percentage efficiency? Can one presume that the power consumption of an 80% efficient conventional AC to DC converter used to step down from 230V AC to 3V DC will have the same power consumption as an 80% on-board integrated circuit DC to DC converter to step down from 24 or 48V DC to 3V DC? Therefore, while it is agreed the analysis needed to answer these questions is beyond the scope of this research, his statement that it "...*is not necessarily true.*" that changing from AC to DC will save energy, is questionable.

4.9.0 Calculations from the data given in the BRE report

It was apparent that BRE's conclusion, as to whether DC voltage is a way forward for the home, was based on their electrical specification. To see why the electrical specification of this research and therefore its conclusion was not in agreement with BRE's, it was felt that a thorough recalculation of their numbers had to be carried out.

4.9.1 Data given by BRE

BRE in section 7.4 states as follows, "*The power circuits for DC are assumed to be 10mm^2, double insulated and clipped directly into a wall or roof space, giving a current carrying capacity of 65A, capable of supplying 1170 Watts at 18V*". There are three points that need analysis. (1), the current carrying capacity of 65A is given for a 10mm^2 cable, (2) the description of the installation method for the cable being used is described as "… *clipped directly into a wall or roof space*." And (3) that the cable is "…*double insulated…".*

4.9.2 Contradictory ideas

Their design, as written down in the quotation above, is such that each electrical cable spur will have a current carrying capacity equal to the total current capacity of the whole house i.e. 65A, and therefore the size of the cable needed for the electrical installation is given as 10 mm^2. Also in Appendix 2.3 the schematics for their cable layout specifically state "*12 x spurs @ 10mm^2*", which again implies their design for each spur is for the total current capacity. This is not understood from an electrical engineering point of view, surely not all appliances will be connected to any one spur at the same time? Therefore logically each spur will only carry a fraction of the total current required for the whole house. It would make sense if BRE offered a single ring main solution, which would have to be designed to carry the full current capacity however, their design explicitly uses spurs and not a ring main.

Also it is stated that " *Assuming that no large electrical loads in excess of 500 Watt*", if this is to be accepted, then how can the current capacity of the house be 65A? For a 500 W load at 18V the maximum current has to be 27.78A, which would suffice with a 6mm^2 cable as per Table 4D2A column 2. Therefore the specification of this research of 4mm^2 cable is accepted above that of BRE's design for 10 mm^2 cables at 65A.

Furthermore BS 7671:2008 provides many scenarios for the installation of cables. The ability of a cable to lose heat to the ambient depends on the method of installation. The only value for the current carrying capacity of 65A in a 10mm^2 cable is that found in Table 4D1A in column (6) which is for 2 single core ordinary thermoplastic insulated cables, using the installation method of "clipped direct", which is Reference Method C. For a multicore cable the actual value is given as 63 A in Table 4D2A column (6).

From the point of view of domestic cable installation looking at Table 4A2 in Appendix 4 (page 261-264) the description given by BRE "clipped direct" is the fixing method given in number 20 and annotated Reference Method C which is for cables installed in open spaces. However in normal domestic applications, the cable will be cited in the ceiling/ floor or wall cavity and as such would come under number 40 or number 55 both of which are Reference Method B, as the ability for the cable to lose heat to the surroundings is restricted by the fact that it is enclosed in the wall or ceiling/floor.

The only 10mm^2 cable that has a current carrying capacity of 65A is found in Table 4D1A in column (6), which as described by BRE is for Reference Method C "clipped direct". However the data given in this table is for single core cable, which is usually also only single sheath insulated. This is in contention with their description of the wire being "…*double insulated…*". Presuming that they stick to using Reference Method C and use "double insulated" cable then the current carrying capacity for multi-core cable which is found in table 4D2A column (6), only gives a value of 63A and not 65A. This leaves us with the question can 65A be implemented with a 10mm^2 cable in a usual domestic setting?

Note: The use of the terminology "…*double insulated…"* is somewhat a misnomer. All installed electrical cables should have two types of protection, one must be for 'mechanical' protection of the conductor and one must be for 'electrical' insulation. The inner cover on the conductor is for electrical insulation and the outer cover is for mechanical protection. In a multi-core cable both protections come as part of the cable and could be mistaken as a double layer of insulation, while for a single–core cable the electrical insulation comes as part of the cable and the mechanical protection should be provided by some sort of conduit in which it is encased/covered.

4.9.3 Calculating Maximum Length of Cable (L_{Max}) for BRE system

It is a contention of this thesis that the current carrying capacity of 65A chosen by BRE is not suitable for normal domestic applications. To test this statement the above equations were used to find the maximum length of cable at which the voltage drop is 5%. Starting with their given specification shown in Row (1) of Table 14 shows that the maximum length of cable at 65A, 18V can only be 3.15 m~~!~~ .This value seems quite an inappropriate and impractical cable length when used with the maximum current rating of 65A.

They also state that "*Assuming that no large electrical loads in excess of 500 Watt*". When they chose the voltage of 18V it was because electrical equipment is between 16V to 18V. Let's presume that a voltage drop of 2V is permissible. By taking their maximum of 500W to its two extremities, there will be a maximum voltage with a minimum current or a minimum voltage with a maximum current and all possibilities in-between. This is either 18V at 27.77A or 16V at 31.25A.

Using the same methodologies above and fixing $V_{TotDrop}$ as 5% of rated voltage of 18V and accepting 65A as the current capacity of a 10mm^2 cable, the largest possible value for maximum length of cable is 8.27m, Row (2). When the load voltage is 16V, $V_{TotDrop}$ is allowed to drop by 12.5% to 2V and L_{max} becomes 16.21m, Row (3). These lengths of cable are too small for a single 500W load, when one considers that BRE is designing for long cable runs of between 30m and 40m.

	Cross-sectional area of cable (mm^2)	Voltage drop per metre per Amp at 70 deg (mV/A/m)	Maximum Current (A)	Voltage (V)	Maximum Power (W)	Length of cable L_{Max} (m)	Maximum allowed voltage drop at 5% (V)	Maximum allowed voltage drop at 12.25% (V)
(1)	10	4.4	65	18	1170	3.15	0.90	
(2)	10	4.4	27.77	18	499.86	8.27	0.90	
(3)	10	4.4	31.25	16	500	16.21		2.00

Table 14 Maximum lengths of cable for 500 Watt load with $10mm^2$ cable.

4.9.4 Comparative costs of different electrical systems

BRE, (Section 5.3) besides proposing an 18 Volt system they also propose an alternative of 340V, this is because *"most switch mode power supplies are peak voltage detecting devices".* They then go on to look at the new proposed 42V standard being lobbied for by the automotive industry. They then conclude *"... that it could be argued that DC houses should adapt 42 Volts to benefit from the availability of consumer goods that will run at that voltage." "The cost for the cabling for a 42 volt system could be about half of that for the 16-18 volt system".* In their conclusion they state that a DC 18V mains is twice the cost as ordinary AC, from this information can one imply that a 42V DC system would therefore have a cost roughly comparable to and AC system which would make a 42V DC house economically viable, yet they still used only 18V and concluded that it was too expensive.

4.10.0 Conclusions on previous work

The data given by Pellis in Table 6.2 needs further verification to be reconciled with values worked out using the data from BS 7671:2008 document, which is a pan European Specification.

The type of installation chosen by BRE 'Reference Method C' as described in their section 7.2 and Table 4A2 of BS7671 does not seem very appropriate, rather 'Reference Methods A or B' are more appropriate for their specification.

The combination of 18V 65A is an inappropriate rating for a DC domestic electrical mains specification due to many reasons, including the maximum practical length of cable when operating with 18V at the cable's current capacity of 65A. Therefore the design and conclusions of BRE that the DC house is not practical or economically feasible are highly disputed.

Chapter 5
Scenario Analysis

Summary

Scenario analysis implies by its very nature, different possibilities that result in the same, similar or quite diverse outcomes. This chapter looks at the drivers behind the decision making process, gives some technical and implementation options, and some extracts from previous work. An attempt is made to answer the universal question, what would be the optimum DC voltage for an extra-low voltage DC home? Having an optimal voltage would obviously narrow down the scenario possibilities.

5.1.0 Introduction

5.1.1 The drivers behind the decision to opt for a DC system

Scenario analysis implies by its very nature, different possibilities that result in the same, similar or quite diverse outcomes. There are many different and sometimes competing factors that make up the decision-making process as to choosing a DC system in the first place and what configuration or design it should have. The reasoning behind choosing a particular system in a developing world country that has access to high intensity sunlight, may be different than a developed world country that is in the temperate region of the world.

In much of the developing world, whether in Africa, South America, Asia or the Far East like Indonesia there are millions of people who do not yet have grid connected electricity. Many of these people live in very small dwellings that are equivalent to, or smaller than the research house (In Figure 1 Section 4.2.0). At this time their standard of living does not include many power hungry consumer gadgetry and as such it is envisaged that the peak power of the average house will be much lower than that of the research house. Therefore a DC house can offer a quick solution for a government to provide electricity to its citizens using decentralised microgeneration rather than centralised generation and distribution.

Each government or region will have its unique set of circumstances and therefore may require a unique solution. Each will have different reasons for opting for the DC home. These may be political, economic, socioeconomic (See

Chapter 6), carbon emissions reduction, energy security, and energy independence (See Chapter 1). There will inevitably be a combination of these factors in every decision.

The research house opts for air conditioners and a microwave oven. There is no technical reason why these can't be used in the developing world, however they may be very expensive and therefore may not be part of a solution. It can be envisaged, that in very arid parts of the world where wood has traditionally been the choice of fuel for cooking, that as this resource becomes ever more scares, the microwave oven or another electric cooking devise may be a best choice for survival. As the market for appliances in these emerging markets is so large they could set the Standard, and incentivise the appliance manufacturers who now build only 24 V appliances, to build multi voltage functionality into their products.

The main driver behind this research is the final goal of energy independence with security. The DC house in itself will not at this time provide full energy independence. The initial goal at this time is decentralised electricity generation. It should offer a level of energy independence that, were there to be a breakdown in the centralised electricity distribution then householder and small business, will have an independent energy supply that will provide enough energy for their basic needs. The stress at this time is to provide "basic needs" and not all the needs that a Western lifestyle presently provides. However these basic needs may be more than the present best lifestyle of poor people in the developing world, and with which their lifestyle can be greatly enhanced. The final goal of energy independence, with security has to be for the long-term. No country is capable of changing in one giant leap. Small steps will have to be taken on many different fronts to reach the goal of energy independence with security. This research is just one such step, that in itself is very significant, and over time as DC proliferation increases, its impact on the world will be enormously rewarding.

5.1.2 Other drivers

Once a decision has been made to opt for the DC system, the question now is what system configuration to have? There are technical and economic factors to take into consideration. The increase in costs for the larger gauge cables, and the need to retro fit the old housing stock, has to be balanced against the decrease in the capital cost of a DC system (see Chapter 6). The problems of voltage drop (see chapter 3) which restricts the maximum length of cable, and therefore the size of the house, the availability of only 24 V DC home Appliances and the overall restriction in the maximum current that the whole DC system can handle all have to be taken into consideration. The system voltage of 24 V used in this research was fixed by the availability of the appliances however, the question still remains, is this the best voltage for a domestic DC system? To overcome some of these hurdles, modifications to the design of the research house as described in Chapter 4 are set out below. However before this is undertaken choosing which system parameter to fix, especially voltage will be discussed.

5.2.0 Optimum DC voltage

5.2.1 The development of a Standard

There is an international quest in the engineering community to find the magic number, which could be called the ‘optimum’ DC voltage that will be used as the DC Standard in datacentres, offices and the home. What is very apparent from the graphical tools produced at the end of Chapter 3 is the complexity and amount of variables in the system. There is always a trade-off between the maximum length of cable, and the amount of current that can be drawn through that cable, therefore in a sense there is no optimum voltage for the DC house. It will depend on the balance in the variables that the designer chooses. Therefore, how does one choose a particular system voltage to create and official Standard? Will the Standard emerge due to market forces applied by the appliance industry, or the micro generator industry or through a Standing Committee of experts?

To answer this question one can look back in history. There are two examples in the electronics industry where different standards were created, not by any Standards body, but rather by the marketplace. These are the video (VHS against Betamax) and the DVD (MultiMedia Compact Disc against Super Density disc) Standards. There are many other situations in the emergence of new electronic gadgetry where the standard implemented by the biggest player in the market became the norm. This is what may happen with establishment of a Standard for the voltage of the DC home. To understand how this may happen, given below is some of the ideas discusses at a recent conference.

There was a conference in June 2009 in Anaheim California called the Green Builder Power Forum [40], which was dedicated to the use of low voltage DC power in datacentres, offices and the home. What emerged from that conference was that at this moment there are two camps. One is called the EMerge Alliance [41], which purports to be an open industry association. It has very strong backing from world leaders in industry, (see this page for association members [42]). As they are coming mainly from the point of view of lighting and control systems they have chosen 24 V for their DC system. In the United States of America, the regulatory authorities have stipulated that the voltage for DC lighting must not exceed 30 V. This is the main criteria for the EMerge Alliance and others using sub 30 V as their design benchmark. They stated that they intend to have in place, an official US Standard for lighting by the end of 2009.

The second group is more loosely associated and comes from a combination of those from the datacentre industry and from the telecommunications industry. This group is not looking to reinvent the wheel by looking into different voltages than that which they already use. They are using 48V as this has been a long-standing voltage that already has many applications and would like this to be the Standard for all datacentres and would be pleased if it were adapted as the Standard in the office and home. While those at Intel are using 400V DC for their applications and see 48V as having disadvantages.

At the conference were some academics that are doing research into the use of DC, or have already used DC as the preferred voltage in their projects. One academic, called Professor Dushan Boroyevich from the Centre for Power Electronics Systems at Virginia Polytechnic Institute and State University, has a design for a home using 48V and 380 V DC power supply. He is working together with Whirlpool to produce DC ‘white goods’. At the present time his project is only a laboratory appraisal, but he is, as stated working at 48 V as his extra low voltage DC. Professor Tsai-Fu Wu from the Department of Electrical engineering, National Chung Cheng University, Taiwan, is overseeing a student complex that will be all DC. He is using 360V DC to power the student accommodation.

What emerges is that those who are actually producing working models or real DC powered homes, are actually not only working at extra-low voltage DC, which is usually sub 50V, but are opting for a 360V to 400V DC bus for the high powered appliances. Their applications are geared specifically for a developed world living standard, where their goal is to reproduce the same comfort and usability of an ordinary AC home with DC. This may explain why they have opted for a 360V to 400V DC power mains. It is not clear how much research has gone into actually reengineering AC appliances to work on DC. What is also not apparent is the work that they have carried out on the power optimisation aspects of their designs. However, this research is focusing on the extent to which DC voltage can be used to power a home anywhere in the world.

5.2.2 The use of the graphical tools by a designer

At the end of Chapter 3 a set of graphical tools are shown that can be used to easily approximate the different parameters in a DC voltage system. These graphs are derived from the data sets calculated using the system equations found in the above chapter. The current ratings chosen for these graphs are not for the chosen set of DC appliances (Given in Table 4 above) but rather over a full linear range of currents for each size cable. They show a pictorial presentation of the correlation between maximum length of cable L_{max} and current for the possible scenarios. This was carried out for different sized cables at 24V, 36V, 42V and 48V. For the smaller cable sizes the maximum length of cable was worked out over a current range of 0.5A to 15A. For the 10 mm^2 cable the current was taken from 5A to 43A, this being the maximum rated current for the cable under the specific conditions of column 2 Table 4D2A. The data can be found in Tables, A1-1 to A1 -4 and the graphs can be found in Graphs 1 to 4 in Appendix 1 below.

As the graphical tools provide endless possibilities, the designer has to provide design characteristics that will limit the scope of possibilities. This is done by fixing some of the system parameters so that the design is characterised by one curve on the graphs, or by a point on a curve. Pellis and BRE have worked with a maximum length of cable of 30 m, which seems to be a sensible value for the present housing stock. The DC house in this research is a bungalow with a maximum length of cable of only 15 m. Therefore, for the scenario analysis the calculations will also be for a large two-storey dwelling with a maximum length of cable of 30m and 40m.

Table 15 shows the scenarios that a designer can choose from when three fixed lengths of cable with four different voltages, for each of the four cross-sectional area cables. In effect by choosing a voltage the designer has chosen one curve on the graph or for the fixed three lengths the rows in Table 15. Or by choosing a length of cable it is like drawing a horizontal line across the curves with the points of intersection being the maximum current allowed at each different voltage, this being the columns 3 , 4 and 5.

Using Very Large Scale integrated circuit manufacturing processes the implementation of the DC to DC converters can be as part of the design of the whole chipset which is designed for a specific gadget. Therefore for our sub 50V house from an electrical engineering point of view, the closer the mains voltage is to the actual operating voltage of the appliance, its implementation can be the easier, cheaper and with lower energy losses .However this has to be balanced against the maximum current drawn by the whole system, which may require a larger mains voltage than that necessary for the individual appliances.

cross-sectional area of cable (mm^2)	System voltage (V)	The maximum current (A) at which there is a voltage drop of 5% of rated voltage with the given lengths of cable		
(1)	(2)	(3)	(4)	(5)
		15m	30m	40m
2.5	24	5.07	2.50	1.95
2.5	36	7.50	3.80	2.95
2.5	42	8.70	4.54	3.35
2.5	48	9.83	5.07	3.81
4.0	24	8.26	4.18	3.13
4.0	36	12.15	6.23	4.70
4.0	42	14.04	7.25	5.50
4.0	48	15.85	8.26	6.25
6.0	24	12.40	6.29	4.85
6.0	36	18.25	9.40	7.10
6.0	42	20.80	10.88	8.22
6.0	48	23.40	12.40	9.37
10	24	20.30	10.40	7.85
10	36	29.40	15.45	11.68
10	42	33.58	17.90	13.56
10	48	37.55	20.29	15.44

Table 15 The maximum current for the given lengths of different cable

5.3.0 The settings for a scenario

5.3.1 Introduction

When looking at possible electrical scenarios, the environment in which the house will be situated will greatly affect the decision. The successes of any particular design for the DC house will be dependent on factors other than those that are purely technical. Some of these are;

- Is a single worldwide extra low DC voltage Standard optimal?
- Where in the world is the house to be situated?
- Is a full or partial DC electrical solution required/acceptable?
- What type of lifestyle is required?
- To what extent can renewable energy generators be used?
- Is there a desire to use fossil fuels and are they available?

There cannot be a one-size-fits-all solution and adaptations or compromises will have to be made. No attempt will be made here to provide a single solution with a set of fixed parameters. Every scenario will have to start with some prerequisites which will act to fix some of the system variables. Therefore what will be set out below is a range of design options/ modifications rather than completely different solutions.

5.3.2 The main scenario in this research – 24V system

So far one scenario, which is a 24 V system that uses 4 mm^2 cables in a single-storey two-bedroom house and only uses a fixed set of DC appliances, has been considered (Chapter 4). However, as explained above, this was only used to illustrate an example set of calculations. However there is no specific necessity compelling the use of a 24 V system as against a 36V, 42V or 48V or any other voltage for which there may or may not be available appliances. Not having the appliances does not and should not in any way cloud the decision-making process as to the best system voltage to choose. For many appliances by using some very small and relatively cheap components, there is no reason why they cannot be modified to work at any voltage below 50 V. There are today some electronic gadgetry that with the flick of a switch can be made to operate on either 230V or 110V, this voltage switch mechanism is a cheap component compared to the overall price of the gadget.

5.3.3 The possible scenarios with the available DC appliances

Line	Appliances	Peak Power (W)	voltage (V)	Peak Current (A)
(1)	All appliances	3307	24	137.79
(2)	All appliances	3307	36	91.86
(3)	All appliances	3307	42	78.74
(4)	All appliances	3307	48	68.90
(5)	less Air conditioners	2237	24	93.21
(6)	less Air conditioners	2237	36	62.14
(7)	less Air conditioners	2237	42	53.26
(8)	less Air conditioners	2237	48	46.60
(9)	less Air conditioners and microwave oven	1277	24	53.21
(10)	less Air conditioners and microwave oven	1277	36	35.47
(11)	less Air conditioners and microwave oven	1277	42	30.40
(12)	less Air conditioners and microwave oven	1277	48	26.60
(13)	Only microwave oven not used	2347	24	97.79
(14)	Only microwave oven not used	2347	36	65.19
(15)	Only microwave oven not used	2347	42	55.88
(16)	Only microwave oven not used	2347	48	48.90

Table 16 Peak system power and peak system current when using $4mm^2$ cables

From Table 16 it can be seen, that reducing the peak power in the research house and depending of the system voltage, what the affect will be on the total current drawn by all appliances. The largest charge controller that was found was the Apollo Solar T-100 MPPT Charge Controller, current capacity 100A, voltage and can operate at 12/24/36/48 Volts DC [43], however they can be stacked in parallel to provide enough current capacity.

5.4.0 Electrical design options

5.4.1 Option 1: Different cable gauge system

This scenario will have a fixed voltage but use different gauge cables. Table 17 shows the required current capacity, in column 1 for a fixed voltage of 24V and three fixed cable lengths columns 2, 3 & 4. Therefore in order to maximise the required current capacity of the system, as the distance from the distribution board increases, the cable gauge can also increase. For example, if the system requires a current capacity of 6A, the power sockets that are up to 15m from the distribution board can use $4mm^2$ cables, then from 15m up to 30m use $6mm^2$ cables and then from 30m to 40m use $10mm^2$ cables. This different gauge cable system is the same as some AC electrical systems, where different cable gauges are used for lighting, power sockets and heavy duty appliances like electric cookers.

The different possibilities are shown in Table 17. If the situation occurs where the designer needs a large spur current above where a $10mm^2$ cable can be used, then one option available is to increase the system voltage, or to consider the other scenarios below. For each system voltage a table similar to Table 17 can be produced.

Required **current capacity** (A) per spur up to	The **cable gauge** (mm^2) that can be used to supply the needed current in a 24 Volt system with an allowed 5% voltage drop		
(1)	(2)	(3)	(4)
	15 metres	**30 metres**	**40 metres**
1	2.5	2.5	2.5
2	2.5	2.5	4.0
3	2.5	4.0	4.0
4	2.5	4.0	6.0
5	2.5	6.0	10
6	4.0	6.0	10
7	4.0	10.0	10
8	4.0	10.0	
9	6.0	10.0	
10	6.0	10.0	
11	6.0		
12	6.0		
up to 20A	10.0		

Table 17 Cables to use for a fixed maximum spur current.

5.4.2 Option 2: Higher specification cable

All the calculations carried out in Chapters 3 and 4 above, were carried out using the data for a multicore thermoplastic insulated or sheathed cable with a maximum operating temperature of 70°C. Were the calculations carried out using a higher specification multicore thermosetting insulated cable with a maximum operating temperature of 90°C, L_{max} would have been be larger. Although for a 90°C cable the voltage drop per amp per metre is fractionally more, the current carrying capacity is much larger. Using BS7671 the data for 70°C cable from Table 4D2B it can be contrasted with that from Table 4E2B for 90°C cable. For example, a 2.5mm^2 cable the voltage drop goes from 18 to 19 mV/A/m and the current carrying capacity goes up from 18.5A to 25A. And for a 4mm^2 cable voltage drop goes from 11 to 12 mV/A/m and the current carrying capacity goes up from 25A to 33A. Further work will have to be carried out to see what affect changing the cables to 90°C will have on L_{max} and to the possible gauge of cable that can be successfully used.

5.4.3 Option 3: Multi voltage appliances and fixed size cables

To what extent an expensive DC to DC converter or only a simple voltage divider using simple components is needed is not known at this time and needs further investigation. However one can buy an off the shelf laptop computer and other devices that have a switch on the back to change their voltage rating from 230 to 110V. Therefore there is no reason why for a relative small increase in price, appliances could not be manufactured with the ability to operate at a range of different voltages. If this is possible then for under 42V the voltage ratings of the appliances will be independent from the value of the mains voltage. This means that a small dwelling with a 15m cable length could use 4mm^2 at 24V and a larger dwelling could use 4mm^2 at 36V or 48V all could use the same set of appliances but would have a manual or automatic switching mechanism to change their voltage ratings according to the voltage of the power mains. Further work will have to be carried out to verify if such appliances and different voltages is a practical solution.

5.4.4 Option 4: Split system

For a 2.5 kW peak power solar system in Manchester UK, a company quoted a requirement for 16 m² of solar panels. For this scenario, the ordinary 24 V system using 4mm^2 cable with a maximum cable length of 15m is used. An alternative solution would be to split the electrical system into two smaller systems, instead of one control panel and one radial set of cables feeding the power sockets. This solution however has the added cost of a second charge controller (A 60Amp Flexmax charge controller by Outback Power systems) which costs £627 [44]. The advantages are that the physical length of cable to the furthest power socket has been halved and the current capacity doubled. The layout for this house is shown in Figure 2 below, with one control board above the kitchen/living room area and the other above the bathroom. Alternatively with the same maximum current the floor size of the single story house could be doubled or a second floor could be added without the need for larger gauge cables.

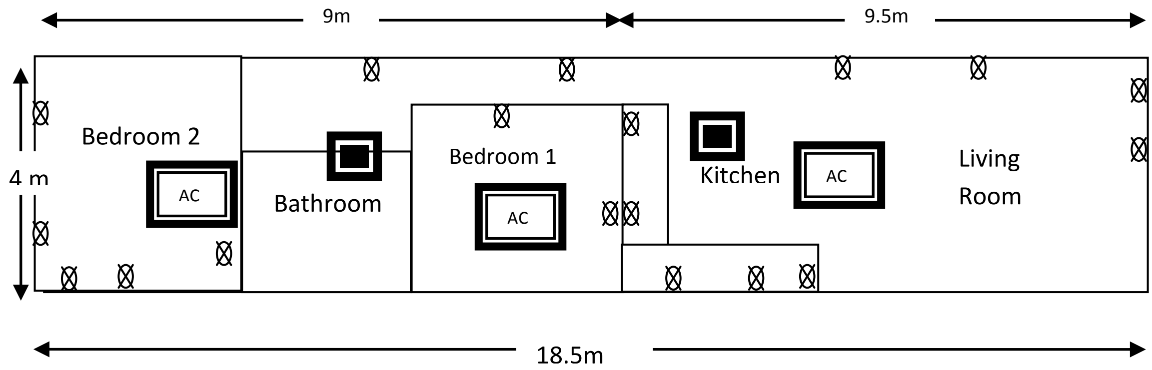


Figure 2 Scenario with two control boards where the cable length is halved and the current is doubled.

5.4.5 Option 5: Multi voltage & cable size system fixed voltage appliances

A conventional AC voltage electric house employs three cable gauges, one for lighting 1.5mm^2, one for the power sockets where appliances are plugged in 2.5mm^2 and 10mm^2 for the electric cooker which is wired directly into the mains. This scenario envisions using the same gauge cables but changing the voltage. For lights and plugged in appliances it could be 24V and for wired-in appliances like the microwave and air conditioners 48V. This scenario is ignoring large white goods that at this time do not operate on DC voltage. Perhaps for these appliances the cable gauge may have to go up to 10mm^2.

Wired-in appliances are inconvenient for the home owner who will have to employ a certified electrician when an appliance needs to be replaced. However with today's technology this may be the safest method of installation. There are different companies and researches at the conference, ([40] Presentation 6.1 by Anderson Power Products http://www.andersonpower.com/. Presentation 4.4 by NTT Facilities Inc. And Presentation 5.2 by Professor Dushan Boroyevich of the Centre for Power Electronics Systems, The Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, Virginia, USA), who are looking into ways of making safe plugs that will remove the dangerous phenomenon called arcing, which occurs when one tries to interrupt a large DC current. In the future it may be possible to use a safe plug in method for these large current appliances.

5.5.0 Pathways to Implement the DC house

A method of implementing the DC home for a grid connected AC house is a staged approach using a hybrid solution. This solution starts with full reliance on the national grid network and uses a transformer to provide the DC voltage for a selection of critical household appliances. This duel voltage stage is how many Manhattan apartments were electrified up to the early 1960s. Then over time each house will be fitted with photovoltaic panels to increase the amount of appliances using DC voltage. The final stage is a fully integrated DC home only powered from DC renewable energy generators, with a best case situation of 100% energy independence for both households and offices. This approach will seek to make continual improvements on the load side by reducing the power consumption of the average house, combined with micro energy generation using renewables.

By taking this approach, not only will the total electrical energy usage across the nation be reduced, but the need to build new centralised energy generators will be much reduced if not eliminated. The more photovoltaic panels installed, combined with the introduction of small wind turbines and later perhaps hydrogen fuel cells, the less energy will be needed from centralised generation.

The nation will still have to rely on centralised energy generation for many years to come, however with research into the reduction of the energy needed for appliances and the elimination of losses due to power conversion, eventually it must become possible, for each property or group of properties to be totally energy independent with its own electrical generation.

The use of the DC house in the developed world cannot at this stage of the research provide an equivalent lifestyle opportunity to that of a conventional AC home. However it can be used to reduce the total energy consumed and therefore the carbon footprint of the home. If it is part of a renewable energy generation system, as explained above, a smaller system will be required for the DC home as against the AC home. If critical appliances are DC powered by renewable energy generators then the energy security of the home will be increased. Having the lights, fridge, freezer, microwave alarm system, telephone, Internet and other critical appliances working off DC renewable generators, will mitigate the effects of power cuts by the National Grid, reduce the load on the grid, and increase personal energy security.

With more research, especially into the reengineering of AC appliances and with the use of a dynamic control to provide adequate voltage to the loads and stop system overloads, it is envisaged that the usefulness of the DC house to everyone will increase.

5.6.0 Other decision making processes

To get an insight into the decision making process involved in providing power for an off gird house Ortlepp in section 4.1.1 of her MSc thesis explains this very well and is therefore quoted here verbatim. *"Designing a solar power system that is cost effective for the homeowner means that the homeowner will have to make some choices about the household loads that are most important to him or her. While a solar power system is certainly capable of operating with any size of load, cost considerations require a compromise and a consciousness of energy usage on a day-to-day basis. For a homeowner, this means making a choice of household loads that will supply the essentials such as water and mechanical systems and then selecting the appliances and devices that are believed to be most important to a fulfilling lifestyle. A load analysis determines the amount of energy in kWh used by the chosen selection of household loads so that the appropriate size of solar and / or wind charging system can be designed for the* *climate conditions of the area. The experimental house was designed to operate the necessary mechanical systems for the house, such as a jet pump to pump water from a sandpoint well and a submersible septic pump, and also to operate the appliances and office and entertainment devices."* Unfortunately her house is 110V AC.

BRE in section 3.3 under the heading 'Storage' state the following "*Most PV arrays obviously deliver peak power at around midday, therefore their output compares well with an office's load profile. However, where PV is fitted to dwellings the opposite is true. Most households are heavy energy users in the morning and evening".* This argument is used by BRE against using DC in the domestic arena and for using it in an office environment. This may best describe a small household in the developed world, where for much of the day people are out of the house. However for housewives at home with children, and for many of the elderly who stay home for much of the day, even in the developed world, their power usage profile would not necessarily be distributed mainly in the morning and at night. In fact the main housework of washing the clothes and the dishes and cooking would show a more evenly distribution of energy consumption throughout the day. Also one must consider the lifestyle of millions of rural people in parts of the developing world that at this time do not have electricity. Their day to day living, where electricity will improve their standard of living, is carried out in day light hours. Very little daily chores would be done at night. Therefore PVs even without storage would give them a great increase in their standard of living in the daytime and storage would greatly increase their ability to use electricity at night.

5.7.0 Conclusion

There are two methods of designating the value for the voltage level in the low-power DC home. The first would be to let market forces decide. The second would be to do the research needed to reengineer appliances so that they work on the lowest possible DC power, and fix the voltage according to the specification of the appliances. A multi voltage system may be the best option. It must not be forgotten that there is a trade-off between the maximum length of cable at which the voltage drop adversely affects the functioning of the loads and a maximum current that can be drawn through the cable. However given a set of specific circumstances, whereby many of the system parameters can be fixed, a best voltage can be determined for those circumstances.

There is no one-size-fits-all solution for all possible situations where the DC house will be used. Many options exist that are suitable for different environments. It is broadly understood that a sub 50 V DC system will never offer the same usability as 240 V AC without reengineering of the appliances. It is possible that the voltage standard agreed-upon for lighting systems and appliances may be different, perhaps 24V for lights and low powered appliances and 48V for high powered appliances. This may imply that different sized mains cables for lighting, low powered appliances and high powered appliances will be used, with the distinction between high powered and low powered appliances, having different plugs or as per this research, the high powered ones will be permanently wired in to the mains.

Chapter 6
The economics and socioeconomics of the DC home

Summary

This chapter considers the economic effects of the DC house in a wider context than those normally directly associated with changing from AC to DC. Firstly the direct economics of the different elements that make the DC house different from the AC house are considered. This is followed by the indirect, environmental and socioeconomic effects of the DC house and its ramifications on energy independence with security. An extensive look at all appliances and their associated energy consumptions, and to work out a full and thorough quantitative comparisons between an AC and a DC system is beyond this research. However, some examples are given. Some analysis of the economic discussion of previous work is shown.

6.1.0 Introduction

In any decision making process the bottom line will always be how much will it cost, or how much will it save? Therefore, in the decision-making process, whether to change from conventional AC voltage mains to DC, some of the underlying questions that need to be answered will always be economic. Pellis and BRE seek a direct economic comparison between the cost of installing an AC and a DC system and seem to use their analysis as the make or break criteria as to the viability of the DC house. This research is concerned with how the DC house can be implemented as part of the means to fulfil the global objectives, which are energy independence with security, using sustainable microgenerators within a decentralised generating framework that reduces the carbon footprint of the home. The overarching economic analysis, inclusive of direct, indirect and socio economic effects are all looked into and a conclusion about the economic worthiness of the DC house is taken from the combined analysis. Making a direct economic comparison between the capital expenditure on AC and DC electrical systems like Pellis and BRE is important but as the two systems are not alike (See chapter 1) it is not pivotal to the debate.

6.2.0 Money saved by having an all DC electrical system in the home

6.2.1 The money saved by not having an inverter

In an all DC voltage house powered by a DC microgenerator an inverter is not needed. Depending on the set of hardware used in the whole microgeneration system and the peak power required, the inverter would have cost between £870 and £3,546 as advertised on the thePowerStore.co.uk website [45]. For a 2kW peak power system a Sunny Boy SB-2500 inverter will cost £1236 and for a 3kW load the SB-3000TL will cost £1469. Their efficiency is given as between 92% and 95%. As the general shape of efficiency curves indicate, the best efficiency occurs at full load, by not having the inverter there will be a minimum energy savings of 5-8%. However as in operation it is highly possible that full load conditions may not occur for much of the time, by not having an inverter the actual savings will be much more than 5-8%.

BRE section 2.5, "*In the early days of the German pilot, "1000 Solar Roofs" programme, the annual inverter failure rate was 25%. In general, inverters and power supply units are very complicated and add another element of 'something else to go wrong', therefore avoiding AC to DC and DC to AC converters the all DC system should prove to be more robust than a DC/AC/DC system*."

Pellis (Section 8.2) gives the cost for the DC cabling in Table 8.3. He then states that the cost of a typical AC installation is *f*3,500 and that for a DC installation it "*will probably be higher*", and the cost for the inverter is between *f*6,000 and *f*10,000. Yet he then states that "*It can be concluded that taking account of the extra installation materials (Table 8.3) the autonomous DC, low voltage house is more expensive than the autonomous AC house. These extra costs may however be compensated by the elimination of costs for a converter.*" For the extra cost of a DC installation to "*compensated*" it must equal the cost of the AC system of *f*3,500, plus that of the inverter, which implies a total cost for the DC system inclusive of the inverter of between *f*9,500 and *f*13,500 .This value seems rather high. Therefore his conclusion that on economic grounds the autonomous DC house is not economical compared to AC is also somewhat questionable.

There is a report out that suggests that the inverter industry was worth $3.4 Billion in 2009 and is set to grow to $4.8 Billion by 2014 [46]. What percentage of this value is specifically for homes is not known, but this shows a huge potential monetary and CO_2 savings by eliminating the inverter, and therefore shows what potential opportunity there is for this money to be spent towards more energy generators.

6.2.2 Money saved by eliminating AC to DC converters/adapters

In general there are two types of AC adapters, the first is the black boxes which are combined within the plugs attached to most electronic and some electrical gadgets. These are sometimes called external AC power supplies. The second is incorporated into the appliance, sometimes one can place one's hand, on certain parts of the casing of the appliance and that section feels warmer than the rest of the casing, behind this spot is the AC adapter. This is called the internal AC power supply. They inherently use up energy while they work and in most cases, even while the appliance is not operational as long as it is connected to the electricity supply, electricity is still flowing through the adapter and energy is still being consumed.

In the course of this research, no detailed research which shows the efficiency of different AC adapters was found. BRE in section 3.1 discuss adapter efficiency in general and some of what is written here is from there. Also the Natural Resources Defence Council (NRDC) report quoted in Chapter 1 is also very informative, but is also in general terms. Exactly how many internal and external AC adapters there are in the average house will depend on its' location and the affluence of the occupants. NRDC (page 7) mentions "*20 to 25 products per home*"

In the design of cheap AC adapters particularly for cheap electrical and electronic goods, very little care is taken to make sure that the conversion losses should be low and efficiency high. The goal of the manufacturer is to make a safe and efficient product at the lowest price, the consequential cost for the increase in electricity consumed is paid for by the consumer and goes completely unnoticed. In fact many times the appliance manufacturer will use oversized "power supplies to reduce any potential liability or performance troubles from overloading them".

Also "many external power supplies sold today in retail stores are capable of providing any of a number of different voltages, preventing them from being optimized for any one particular application" This "cause most power supplies to run under part load conditions most of the time, reducing efficiency" (NRDC page 16). The consequence is that when the appliance is operating at full load, its power is still less than that quoted for the rated full load power of the AC adapter, which implies a lower efficiency. BRE quotes a worst case efficiency of 40% while NRDC (page 4) states "*Typical efficiencies when a product is operating are about 25 to 60% for linear power supplies and about 50 to 90% for switching power supplies.*"

The switch mode power supplies, which are rather expensive compared to the cheap mass produced AC adapters, in essence do the same conversion process from AC to DC voltage, but with an efficiency of more than 90%. However switch mode power supplies are voltage detectors and therefore this efficiency is only at a voltage close to their design voltage. It is not known how widespread these switch mode AC power adapters are, but even using them at full load there will be a minimum power loss of between 8 and 10% per electrical/electronic appliance.

The 24 Volt DC home may have eliminated the AC to DC converters, however the DC appliances operate at voltages ranging from 1.5V to 24V. Therefore there will still be a need to use DC to DC converters. The question is, can a cheap 1% resister used in a voltage divider circuit be used or is a silicon based electronic DC to DC converter needed? Also if a DC to DC converter is needed does it use up more or less energy than an AC to DC converter?

It is beyond this research to compare and contrast the actual efficiency of and raw material used in, conventional AC to DC converters and low powered modern DC to DC converters. However AC to DC converters employ copper wound metal transformers and other electrical components, while modern DC to DC converters employ electronic components. It is therefore understood that less energy will be lost in a DC to DC conversion of 24V to 5V than an AC to DC conversion of 230V to 5V. It is also obvious that AC to DC converters use up more raw materials in their manufacture than the DC to DC converters. One just has to open up the two power adapters supplied with a mobile phone, to confirm that the one for the house uses up more materials than the one for the car. (See pictures in Appendix 3). Therefore from the point of view of CO_2 emissions the DC only home employing only DC to DC converters should use up less CO_2 to produce electrical and electronic gadgetry than an AC home supplied by DC voltage. However further quantitative analysis will have to be carried out to confirm this.

In summary eliminating AC to DC converters, will save energy, reduce the carbon footprint of the house and should reduce the cost of the appliances. Exactly how much money this will save the homeowner is not known.

6.2.3 The size of the photovoltaic array

For a peak power of 2kW in Manchester England and estimate of 12m^2 of PVs has been received. For a Suchuco SP-4 170Wp PV panel a price of £565 has been quoted,(see Appendix 3 page 157 for quote). Therefore for every 170 watts of peak power saved by eliminating the AC parts of the electrical system there will be a saving of one PV panel at £565. Or for a 2kW peak power system that would have used a Sunny Boy SB-2500 inverter that would have cost £1454 the PV array could be increased by two panels.

6.2.4 Cost of connection to the electricity grid

There is a very large cost associated with the connection of a home to the National Grid. It was found that a builder was quoted £4000 by a utility company for them to dig up the road and install a new 100A armoured cable to connect a house in London England to the mains electricity supply. Ortlepp in Table 4.10 shows this cost to be C$10,000 to connect their off grid home to the Canadian national grid. Depending on the location of the all DC voltage house, there will be a saving of the capital cost for the grid connection if it is made independent of the grid.

In the developing world when a government or utility company is looking to electrify a village or town for the first time, it has two options. The first option is to build a centralised power station and install all the infrastructure of the electricity distribution network to the homes, or to opt for a decentralised design with micro or nano grids to supply each house. Further work is needed to corroborate this, but it is hypothesised that with a DC only powered home, the amount of houses that can be provided electricity by opting for decentralised renewable energy generating systems, may in some incidence be more, for the same price of a centralised system. There is also the added benefit of increased energy security with decentralised energy generation.

6.3.0 AC motors versus DC motors

A good explanation about the advantages of DC motors was found on the Vent Axia website and is reproduced in full in Appendix 3. As DC motors do not at this time have the advantage of manufacture at economies of scale their present higher price is ignored as the more they proliferate the cheaper they will become. The advantages of the DC motors used in their DC fans over AC equivalent examples are given below and were extracted from the above cited Vent Axia write-up.

The advantages that DC motors offer over AC motors are, that they are;

- Faster
- More Efficient
- More accurate speed and position control
- Much quieter that the 60 Hz “hum,” of AC
- Smaller sized components therefore smaller sized fans
- Draw two to four times less current than equivalent AC unit
- More reliable and last longer therefore the mean time to failure longer
- With a more reliable motor the other components in the fan last longer
- Reduced service costs
- Should therefore have an economic advantage over their lifecycle

Vent Axia state that *“Across Europe, energy efficient fan systems could save almost 200 billion KWh a year of electricity*”

It should be noted that these advantages are at their best when the DC motor is operating at the low level of power that is applicable for many applications in domestic DC appliances. See Appendix 3 for the manufacturers' efficiency graph for the fan motor which compares AC to DC.

6.4.0 Comparing an AC freezer with a DC Freezer

This research when discussing peak daily power and power usage has previously stated that it is improper to directly compare AC to DC. It has also stated that AC and DC appliances are different items and cannot be directly compared. This is all true with regard to a direct energy comparison. However if the energy comparison is based on a parameter that is equal in both of them they can be compared. For example if an AC and a DC fan move the same volume of air per unit of time then they can be compared.

A comparison was made between an AC and DC freezer, with both of them having the same 100 litre volume, this being the parameter equivalent to both machines, which affords us the ability to make this comparison. The values given for the specification of the fridges are from the manufactures and what scientific criteria were used in the laboratory tests to get these numbers is not known. This introduces a great weakness to the comparison, however the workings are shown here just to show a potential for energy savings. The AC freezer chosen was a John Lewis JLUCFZW6002 under-the-counter freezer (See Appendix 3 for data sheet) [47]. It has a gross volume of 100 L and is given an energy consumption of 208 kWh/year. The 24 V DC freezer chosen was an indelB C2947, found in the RoadPro magazine. This also has 100 L capacity, with a given power drawn as 19 Watts. If this freezer is on for 24 hours a day for a whole year, its power consumption will be 166.44 kWh/year. This is a saving of 41.56 kWh/year, which is equivalent to 20.523kg of CO_2 . (This value has been worked out from Annex 3 of the Greenhouse Gas Conversion Factors updated September 2009 and found at [48]. As the conversion factors change every year due to the change in the mix of fuels used to generate the electricity inputted to the national grid, the average conversion factor for the eight years 2000 to 2007 was use. This is 0.493824 Kg CO2 per kWh of electricity. 0.493824 * 41.56 =20.52332 Kg CO2.) Extrapolated over the whole UK's 24.7 Million households, (2004 National census) [49] this is a savings of 1,026,532,000 kWh per year of electricity, or 506,918 Million tonnes of CO_2. The indelB freezer also has the advantages that its overall dimensions are smaller and it is much quieter than its AC equivalent. With laboratory bench-testing of AC and DC appliances proper scientific quantitative analysis can be undertaken.

6.5.0 Increases in costs for DC

So far the advantages both in terms of energy and money saved have been addressed. However as explained above, with an extra-low voltage system, the current drawn will cause voltage drops in the cables. The design specifies a best practice voltage drop of no more than 5% of system voltage. With dynamic control of the whole electrical system it would be possible to measure the power losses when appliances are connected. Without such measurement techniques it is a great challenge to work out mathematically the power losses only due to voltage drop in the cables and then translate this peak power loss into a value in kilo Watt hours. (This is because it is difficult to measure the physical length of each cable. Also there will be a need to know which appliance is working at which time and in which plug, as when more than one appliance is connected to a cable, the voltage drop along the cable will not be uniform.) However this research envisages that the monetary value of the energy lost will be very small compared to the money saved by eliminating the AC parts of the system.

The size of cables used in a conventional UK AC mains voltage system is 2.5 mm^2. The installation cost to cable up a two-bedroom single-storey house, has been quoted in summer 2009 at £1300 by a UK national house builder. The cost per metre for the different size cables, as of autumn 2009, was found on the Internet [50] and is given in Table 18 column 3. Previous analysis (Table 15) has shown that the use of 2.5 mm^2 cables is impractical when 24V is the designated DC mains voltage. Therefore, the comparison analysis was only carried out on the three practical cable gauges of $4mm^2$, $6mm^2$ and $10mm^2$, anything larger than this is again impractical for a house.

In order to contrast the increase in cost associated with a change of cable size. The difference between the cost per metre of $2.5mm^2$ cable and each of the other cables was worked out, and is shown in column 5. This shows that the increase in the cabling cost between using 2.5mm^2 cables and 4mm^2 cables is only £47.25.

Cable mm^2	Basic cost of installation	Cost of cable per metre	Increase in cost over 2.5 mm cable for 1 metre	Increase in cost of cables for 9, 15 metres spurs	Total cost of cables for 9, 15 metres spurs
(1)	(2)	(3)	(4)	(5)	(5)
2.5	£1,300.00	£0.30			£1,300.00
4	£1,300.00	£0.65	£0.35	£47.25	£1,347.25
6	£1,300.00	£0.80	£0.50	£67.50	£1,367.50
10	£1,300.00	£1.80	£1.50	£202.50	£1,502.50

Table 18 Cabling costs

6.6.0 BRE cable installation comparisons

BRE state in section 2.5 as follows “The *expectation is that with no investment in inverters and transformer/ rectifier/ voltage controller power supply units, the overall capital expenditure on electrical equipment will fall. However, this will be counteracted by increased price of the DC installation due to the need for cabling of greater current carrying capacity*." They then go on in section 7.4 to detail the costs associated with the increased size of the DC cabling system, which for their DC house costs only £791 more than cabling for AC . (This is very high as they are using 10mm^2 cables see Section 4.9.3 above). However they do not show the decrease in the PV system costs due to in the elimination of any of the capital equipment that they say is not necessarily in a DC system. The elimination of the inverter alone will save £870 for a 1.1kW peak system. The analysis carried out throughout this research finds the increase in costs for the DC cabling is much smaller than the amount of money saved through the elimination of the AC hardware. As the BRE house, regardless if it is an AC or DC system, will use a smart meter to sell electricity back to the grid, its price should not be taken into consideration. Their conclusion that the savings in the DC system are “*counteracted by increased price of the DC installation”* does not show the money saved, due to decreases in energy losses by not having an inverter and the reduction in the size of the PV array as well as others mentioned above. Surly therefore their conclusion against the use of DC on economic grounds is somewhat questionable.

6.7.0 Other economic considerations

6.7.1 Introduction

There is more to the economic discussion than that of capital expenditure. The DC house has made a reduction in the capital cost of a renewable energy generation system and should in the long run reduce the cost of appliances, the next big question now is who will pay for such a system? The poor, wherever they are in the world, can't afford the upfront capital cost and many in the developing world don't have the means to pay for the appliances! This is where the indirect economic advantages and the socioeconomic effects come into the discussion.

By looking at the problem, of providing everyone with the means to use electricity, in a much wider context than just direct monetary expenditure, the economic argument in favour of decentralised electrical energy generation using renewable energy generators feeding a DC system becomes very strong. There are many national economic ramifications to a decentralised system that provides a good level of energy independence with security that are not direct monetary values associated with the hardware system implementation. The total economics of the DC house can be broken down into three more possible categories. (1) The indirect monetary costs, (2) the economic value to the environment and (3) the value mankind places on maintaining an acceptable level of lifestyle. It is postulated that when all the economic benefits are added up, the arguments in favour of having a decentralised energy generation system is made stronger when it feeds a DC rather than an AC system.

6.7.2 Indirect monetary costs

In a review of economic analyses of using micro-renewable generators such as photovoltaics or small wind turbines, it was found that the focus is usually on the direct capital cost employed, the investment payback period and the kWh unit cost of electricity. The analyses tend to focus only on the cost of the renewable generating system against the value of the energy generated over its lifetime. This type of analysis leads to the conclusion that in the UK at today's costs a PV system will just about pay for itself over its full lifetime of 25 years [51]. (Note: the payback period changes according to the changes in the unit price of a kWh of electricity and the average sunlight in a particular area of the country.) However if the economic and CO_2 savings to society through the reduction of centralised electrical generation and the associated cost of fuel were taken into consideration it is postulated that the energy and investment payback period would be greatly reduced. This should not be dissimilar to placing a monetary value when trading Carbon credits.

What is often quoted is the price per kWh or MWh. Comparisons are made between the price for different types of electricity generators and usually the price worked out for PVs and wind is quoted as being much higher than fossil fuelled or nuclear power plants. The price per kWh is usually worked out from the total cost of the plant and fuels to produce that kWh of electricity. However if the indirect costs that are saved by the DC house and the value of the socioeconomic benefits were taken into consideration, it is postulated that the disparity in the cost per kWh between conventional generation and that for a decentralised system in many parts of the world would decrease to a point where, the DC house would become more economically viable.

The expenditure by government as part of their energy security policy to secure the continuation of the supply of the fuels needed to generate electricity, is another indirect cost that should be added to the price per MWh of conventional fossil fuel power stations. By doing this the disparity between the cost per kWh of conventional fossil fuel generated electricity and decentralised renewable energy generation will be reduced. Some of the expenditures are; (1) for warships to patrol the high seas especially in the Indian Ocean to guarantee safe passage of oil tankers, (2) to secure power plants against terrorism, especially through no-fly-zones, (3) as grants to the renewables and nuclear industries and (4) for the operation of facilities to store strategic quantities of different fuels. It is highly possible that there are other monies spent by governments by way of direct grants or in roundabout ways to secure their countries energy supply. How much is spent and if the expenditure is significant is not known and is left for further work. It is postulate that even if each individual expenditure may be perhaps insignificant when compared to the overall cost of energy generation, all the different expenditures added together may have significance, and only through further work will its impact be brought to light.

One of the main parts of the UK Energy Strategy is to increase the amount of energy generated from renewable sources. However the national grid transmission network needs upgrading. The total estimated cost of the proposed upgrade that would accommodate a further 45 GW of generation by 2020 is £4.7bn [15 Section 1.4]. A BERR proposal (Section 31 & 32 page 11) is for 3,000 5MW offshore wind generators and 4,000 3MW onshore wind generators to be installed by 2020 [52, p11]. 3000 5MW turbines at £1500 per kW installed= 3000 X 5 X 1000 X 1500 = £22.5 bn. And 4000 3MW turbines at £1000 per kW installed= 4000 X 3 X 1000 X 1000 = £12 bn. Therefore the total estimated capital cost of at summer 2009 prices will be £34.5bn. This excludes the cost of new nuclear power stations that will be commissioned before 2020. Together the total cost for generation and distribution adds up to £39.2bn at autumn 2009 prices. (However at 2011 prices, this value is estimated to be very much larger) If it is possible to deliver the same amount of GWh to the end user if this £39.2bn was spent on decentralised energy generation is not known. And how many low maintenance domestic PV systems could be installed into hybrid DC houses that are also grid connected for the same outlay is also not known. What is needed is a study to see what the impacts to energy policy there would be if this money was used for decentralised generation combined with the DC home.

What decentralised energy generation feeding DC domestic systems using renewable energy generators does, is to further reduce many of these indirect economic costs. Therefore these savings should be put into the calculations when working out total cost to the individual and society for a decentralised DC voltage system. Putting values to all aspects of these indirect costs is beyond this research and is left for further work.

6.7.3 Environmental costs

The most important environmental consequence of the conventional energy generation from fossil fuels is CO_2 emissions and according to many, its consequential effect on global warming. Most of the world agrees that CO_2 emissions must be reduced however the mainstream thinking in the UK is to spend billions of pounds on centralised solutions by increasing the amount of electricity produced from renewables and nuclear. This research postulates that decentralised energy generation especially when feeding the DC house will help to mitigate many environmental costs. The savings made should be taken away from the overall cost of the DC system, thus reducing the cost to produce each kWh of electricity.

One of the main drivers behind changes in the way the UK will in the future generate its electricity is how much CO_2 does the generation process produce? Billions of pounds of capital investment depend on this question. And when trying to compare the DC home using decentralised DC generated electricity to centrally generated electricity the arguments can become blurred.

The use of the labels, “zero carbon emissions”[53] “zero carbon electricity”[54] and “zero carbon technology”[55] cloud the CO_2 debate and how electricity should be generated. For example when looking at photovoltaic devices one would hear that they are “emissions free electricity” [56], “free electricity” they “save CO_2”. These labels may be true when only looking at the act of electricity generation, which as it is made by the power of the sun the energy expended to make it compared to using fossil fuels, is so negligible it that it can be labelled “zero”. However in reality the use of the word “zero” is somewhat misleading and perhaps disingenuous as at least until after the energy payback period there is an associated CO_2 ‘cost’.

In most instances encountered by this research, the CO_2 approach usually only looks at comparing the CO_2 savings brought about by a specific change in a specific action, but does not always look at life cycle analysis and none direct CO_2 expenditure, which is a great disadvantage. There are four stages of CO_2 emissions associated with the lifecycle of electricity generation. (1) that expended to manufacture and install the generators, (2) that used to produce the fuel for the generators, (3) that used to operate and maintain the generators and (4) that used to decommission them.

The process of gathering the fuels, including Uranium, and maintaining the generators (especially for wind farms) that all have an associated CO_2 cost are rarely discussed as part of the CO_2 debate, that is why the word “zero” is so readily used. In the calculations for the “energy payback period” the energy associated with the manufacturing and installing the generators is included, but is the energy to supply the Uranium or for running and maintaining the generator, or that expended in the 32 years of decommissioning? [57, Chart 2 p59]. When consumers are encouraged to replace older models of home appliances and perhaps even cars, will there be an overall reduction of CO_2 emissions or will "residual" CO_2 from the older appliance be wasted? What is important is not only the carbon footprint when in operation, but also the whole life-cycle carbon footprint.

For direct CO_2 emissions, the economic value of the electricity saved in the DC house can easily be quantified, using the monetary value given by the Carbon or Emissions Trading Scheme. However there are also indirect savings on CO_2 emissions that should be taken into consideration. Each year in the UK until 2050 the projected amount of new houses that will need to be built is 220,000 (*40% house report page 47)*. Besides expanding the housing stock this also includes new build to replace those that will need to be demolished. By installing PVs as part of the roof fabric, the savings for their aluminium frames and in high value CO_2 roof tiles can be offset against the CO_2 cost to manufacture the PVs. If a centralised solar or wind farm is used to generate the same amount of kilo Watt hours, the need for structures to hold the PVs and the new electrical infrastructure that will be needed to deliver the electricity will have a large CO_2 cost, which can be eliminated in a decentralised system. More work will have to be carried out to put some numbers to these CO_2 savings.

There is another environmental effect with its own economic cost that the DC home with its decentralised energy generation can help to mitigate. "*Human activities are the main cause of acid rain. Over the past few decades, humans have released so many different chemicals into the air that they have changed the mix of gases in the atmosphere. Power plants release the majority of sulphur dioxide and much of the nitrogen oxides when they burn fossil fuels such as coal, to produce electricity. In addition, the exhaust from cars, trucks, and buses releases nitrogen oxides and sulphur dioxide into the air, pollutants which cause acid rain*." [58] . Although in the developed world there are strict regulations for emissions, nonetheless until all old coal powered power plants and old cars are all replaced with the best technology the atmosphere will continue to receive pollutants with its associated environmental cost.

Can some of the money that will be spent by the international community to combat the global impact of CO_2 emissions and global worming be better spent on giving grants for decentralised energy generation to power the DC home?

6.7.4 How electricity affects people's Lifestyle

From the point of view of businesses, in the last few years, Google [13], Microsoft, Coca Cola and many international companies have placed huge amounts of PVs on their roofs to supply key company buildings with electricity. BRE (section 2.4), gives an estimate that the blackouts in California in 2001, cost businesses at least £50m per day. Although not privy to the decision making process of the above companies, these projects are seen as the companies doing their bit for the environment. The question is, given the blackouts of 2001 was there any element of security of supply in the decision process? Whatever their motives, using historical data from different parts of the world, it is possible to work out a monetary value to businesses for the loss of productivity and earnings associated with the loss of energy supply. The potential money saved by energy independence, can be used as a balance against the direct capital expenditure of a microgeneration system and thus bring the cost per kWh down.

It has been show by Yang [59] and by Marimoto & Hope [60] that there is a correlation between, the availability of electricity in a country and its Gross Domestic Product and economic growth. Therefore one can put an economic figure when comparing the economic advantage to a country of waiting many years to build large scale centralised generators, with being able to start now with a decentralised DC system. For a developing country that does not have access to the huge funds (can be Billions of US dollars) needed to finance a capital intensive centralised generating and distributing system, but has the opportunity to gradually invest in a decentralised DC system according to its means, this system will start the economic engine now and begin to increase the GDP and economic welfare of the nation much sooner. Similarly for the hundreds of millions of rural people in developing nation that although there has been a centralised system for decades, the government cannot afford to connect them to the grid, they would benefit now from a gradual proliferation of a decentralised DC electrical system. This analysis will also help to measure the different economic impacts on energy security, GDP and the economic welfare, of the nation from a breakdown in the centralised generators between a country that has no decentralised capacity to a country that has a high degree of decentralised capacity.

The above research was on a countrywide basis. However this research envisages that the direct economic cost to a person in his home that is sitting in a power cut, cannot so easily be worked out. How does one put a monetary value to comfort and lifestyle? Perhaps work could be carried out in the future through market research etc, to put an economic value to the individual, of the loss of electrical and/or gas energy to the home. It is possible that in the developed world, this monetary value could be quite high. For example rich South Africans, having suffered rolling blackouts in late 2007 and in 2008, have invested heavily in diesel generators and PV's just to secure a continuous supply of electricity to their homes and businesses. People pay this premium for their personal security, especially the rich, who rely on electric fences and alarm systems which they feel vulnerable without. More work should be carried out into what is spent globally on energy security, and what is the cost to insurance companies per year from power cuts. This economic premium for personal energy security and all the other indirect cost mentioned above should be included in the cost per kWh of AC electricity as the DC home which provides that same level of energy security will cost more per kWh, thus narrowing the gap between the cost per kWh of AC and DC.

6.8.0 Conclusions

6.8.1 Direct economic factors

In this chapter the direct economic factors have been looked at, some of them can now be quantified while others will need further research before a realistic economic value can be worked out. For a 2kW peak power if two solar panels and the inverter can be eliminated a capital saving of £2584 will be made. It is concluded that; the energy saved by eliminating the multiple AC to DC conversions used in a conventional AC home, the savings in raw materials to produce appliances and their decrease in mean time to failure, and their consequential reduction in CO_2 emissions, far outweighs the extra cost for the larger sized cables and energy loss due to the associate voltage drop.

6.8.2 Indirect economic factors

In the long-term economic stability is important for any country. Volatility in energy prices isn't good for anyone. Reducing the demand for the fossil fuels used in energy generation, whether it is coal, gas or crude oil can only be a good thing. By decentralising the energy generation, the production of electricity and the demand for fossil fuels can be affected straight away without the need to wait many years to build a new nuclear power plant. Therefore the money saved, through not needing to build new power plants, through stability in the price of fossil fuels, and from the budget that would be used to maintain the level of energy security in the country, all can be factored in as the economic advantages of the DC home.

What economic value can one put on energy Independence with Security? This economic value is possibly very high. Therefore if nothing is done to increase the energy independence, both on a personal level and on a national level, the present cost to the economy of the increases and volatility in the price of fossil fuels, the money needed for energy security and some sort of energy independence will keep going up. In the long run only those countries, that take the steps now to increase their energy security with energy independence, will see a good level of economic stability far into the future.

Were all these monetary outlays to be taken into consideration, together with the value which people would give to keep their present standard of living, the direct monetary cost to implement the low voltage DC home and office would be small compared to the present and future direct and indirect economic cost of securing energy independence from other nations. The only question is who has to pay for it the consumer or the government? If it is left to the consumer it is believed that equality for all mankind in the level of energy independence will not be the same, it will only be with the willing participation and involvement of governments that a more level playing field will evolve.

Chapter 7

Conclusions, Recommendations & Further Work

Summary

In this chapter the conclusions, recommendations and further work that have evolved out of this research are brought together. From the many different possibilities a single scenario is chosen. The label "Smart House" is employed. This research concludes that the information used to decide if the low powered DC voltage smart home is practical and economic, must also include its indirect and socioeconomic ramifications on society.

7.1.0 General Conclusions

7.1.1 The cited previous work have concluded that the DC house is either impractical, uneconomic or both (Section 4.7.0 & 4.8.0). However this research concludes that it is both practical and economic and must be implemented (section 6.8.0).

7.1.2 It is concluded that the reason this research was able to reach a positive outcome was mainly due to its initial goal. This goal was to ascertain if an all DC house was implementable in practice, a goal that was not constraints by any initial scenarios into which it was to operate. This was in contrast to the other researchers who were looking to see if DC voltage was able to practically supersede the use of AC voltage in the home, which involved the constraints of modern AC systems and loads. (Section 2.2.1).

7.1.3 It is concluded that the results obtained by this research are more realistic as they are based on the power consumption of real DC appliances whereas the other researchers have based their results on AC statistical power usage obtained from power companies.

7.1.4 Approaching the design process by beginning with the loads had enabled the micro-design of the electrical system and provides the ability to add more appliances, or move any of them around the house and easily see how the change would affect the electrical integrity of the system. This is the innovative novelty the bottom-up design approach gives to the design process for the DC house.

7.1.5 With the evolvement within this research, for the need for dynamic control of the voltage and current throughout the house, which implies a need for what is now termed “Smart House Technology”, the label given to this house is now “The Low Powered DC Voltage Smart House” (Section 4.4.0).

7.1.6 The system parameters show that the practicalities for the design of the electrical mains rely on a complex multi variable system and tradeoffs exist between parameters. (Section 3.7.0). The designer is forced to therefore fix some of the variables to narrow down a design. This research fixes voltage and maximum length of cable (Section 5.4.5).

7.1.7 The question is; should society continue on its journey down the route that takes the top-down approach, looking to solve their energy policy conundrums by concentrating on the energy supply side - the infrastructure side (See Section 1.3.0). Or should it look into a radical change of direction and concentrate on the bottom-up approach, radically changing the way energy is used by reengineering the appliances and machinery that are using up this energy – the load side? This research concludes that not only is the bottom up approach preferable, from the point of view of designing the DC house, but the positive affects it has on the ’global objectives’ also provides a solution to the goals of those using the top down approach

7.2.0 Electrical reliability and architecture

7.2.1 The model research 24 Volt home can be implemented using reasonable gauge cables, with nine 4mm^2 cables and one 10mm^2 cable being sufficient. (Section 4.3.3).

7.2.2 The layout of the cables was chosen as per BRE and Pellis to be in a star/spur configuration.

7.2.3 When the total system current demand is over 100 Amps a split system will be necessary. (Section 5.4.4)

7.3.0 Economic advantaged of DC over AC for domestic usage

7.3.1 The overall economic savings of the DC home far outweigh the increase in capital cost for the installation of the electrical mains system.

7.3.2 It is concluded that DC saves energy: The elimination of the inverter and the AC to DC converters in the home will reduce the total energy consumed and reduce its carbon footprint. The consequence of this is the reduction in the size of the renewable energy generators needed to power the home.

7.3.3 It is concluded that for a successful and swift implementation before 2020, there will have to be a concerted effort by the government by way of policy/Law and financial assistance.

7.3.4 It is concluded that the DC house will increase people's quality of life and prosperity: It has been shown that for Sri Lanka there was a direct relationship between Gross Domestic Product and electricity consumption. As the DC house reduces the energy losses it will allow for a cheaper microgeneration system than an AC voltage system. Therefore it can be used by governments in developing countries as a tool to increase the quality of life and prosperity of their citizens quicker than by waiting to build a centralised generation and distribution network. (Section 6.7.4)

7.3.5 If the end use for the electrical energy is low power DC appliances then even the low efficient solar cells that exist today and even in temperate climates where the energy from the sun is weak, society should still be able to take advantage of solar energy and create a society where everyone can have some degree of energy independence. There will also be positive consequences for, CO_2 emissions, the global economy, and more global peace.

7.3.6 It is concluded that as computers, mobiles, telephones, television and perhaps radio are all digitised and therefore need independent electrical supplies, for the benefit of society a decentralised electrical system must be implemented. (section 1.3.4)

7.3.7 The low powered smart DC voltage house will help towards fulfilling the global objectives of this research, which are; energy independence with security, using sustainable microgenerators within a decentralised generating framework that reduces the carbon footprint of the home, with all the subsequent socioeconomic benefits this brings to society. (Section 1.3.0)

7.4.0 Recommendations

7.4.1 Implementation of the Low Powered DC Voltage Smart House

- This research recommends Option 5 (section 5.4.5), which is a multi voltage and multi cable size system with fixed voltage appliances. Like a conventional AC voltage electric house, three cable gauges should be used. The cable for low powered and LED lighting is 2.5mm^2. The one for the power sockets where appliances are plugged in is 4 mm^2 and for the high powered appliances that are wired directly into the mains 10mm^2. For the low powered and LED lighting the recommended voltage should if possible be 12V, for the power sockets for plugged-in appliances and high powered lighting the recommended voltage should be 24V and for wired-in appliances like the microwave and air conditioners it should be 48V.

- For a 24 Volt system employing 4mm^2 cable for lengths up to 15m, when the distance between the control panel and the power socket is between 15m and 30m 6mm^2 cables should be used and between 30m to 40m 10mm^2 should be used. (Section 5.4.1)

- The best method of immediately taking up the advantages of the DC home, for a grid connected AC house is a staged approach using a hybrid solution. This is especially pertinent now when the availability of DC appliances is limited. This solution starts with full reliance on the national grid network and uses a transformer to provide the DC voltage for a selection of critical DC household appliances. Then over time each house will be fitted with photovoltaic panels to decrease its reliance on the grid and on a continual basis increasing the amount of the available DC voltage appliances. The final stage is a fully integrated DC home only powered from DC renewable energy generators, with a best case situation of 100% energy independence for both households and offices. This approach will seek to make continual improvements on the load side by reducing the power consumption of the average house, combined with micro energy generation using renewables.

7.4.2 Electrical Standards for the Low Powered DC Voltage Smart House

The full set of Regulations pertaining to the extra-low voltage DC electrical system are not brought together as a set of regulations directly explaining this type of system. This DC system is somewhat different than those described in BS 7671:2008 Part 7 and especially Section 721 regarding caravans and motor caravans. The regulations in Part 4 Protection for Safety, especially when dealing with electrical separation and earth protection, are not brought together clearly for the low powered domestic DC systems. It is therefore recommended that a new IET working (sub)committee look at redefining the electrical installation requirements for a fixed extra low voltage DC domestic electrical installation.

7.5.0 Further Work

7.5.1 Introduction to further work

There are three areas of further research each of which will be needed to provide a fuller solution to the implementation of the DC house. They are; (1) The architecture of the electrical system, (2) the economic advantages of a decentralised electrical generating system and (3) the wider socioeconomic effects of the decentralised low powered DC voltage smart house.

7.6.0 The architecture of the electrical system of the smart DC house

7.6.1 A practical dynamic control mechanism will have to be researched and defined. This dynamic control system will use a combination of software and hardware and build on what is known as Smart House Technology. With electronic dynamic control more accurate optimisations of the design can be implemented increasing the usability of the home. Overloaded circuits will not occur, and interchanging appliances from one room to another, which implies connecting an appliance to different lengths of cable, will also be possible. It will allow for a much more flexible and robust system.

7.6.2 Further work will have to be carried out to see what affect changing the cables to ones that can operate up to 90°C will have on L_{max}, the possible gauge of cable that can be used, the number of spurs that will be needed and the maximum drawn current per spur that can be successfully used.

7.6.3 In a DC appliance, besides the elimination of the AC to DC converter, there are the unknown quantities of the other components including what type of DC to DC conversion that will be needed. Therefore research into the re-engineering of AC appliances to operate on DC will have to be carried out.

7.6.4 Work needs to be carried out to see what will be an optimal DC voltage for each appliance. This may help to define the most appropriate system voltage. The length of flex connecting an appliance to the power socket will also have a voltage drop in it. A practical maximum length of appliance flex which would become a Standard for home appliances will have to be looked into.

7.6.5 Quantitative analysis has to be carried out to verify, via laboratory controlled measurements, that DC appliances use up less energy than equivalent AC appliances.

7.6.6 Work should be carried out to see what energy and CO_2 burden the Smart House Technology itself places on the power usage of the AC and DC electrical system and whether Smart House Technology uses up less energy when part of a DC house as opposed to an AC home.

7.6.7 Work will have to be carried out to see if the phenomenon called electrical arcing is a concern at the envisaged voltages and currents, and to see if there will be a need special and perhaps expensive switches and power sockets.

7.6.8 The electrical architecture of the power supplying the home and different energy storage possibilities including hydrogen, compressed air, and heat storage will need further work to see how they can be implemented.

7.7.0 Further work into the practicalities of decentralised energy generation

7.7.1 If all internal and external AC to DC converters are eliminated what amount of raw materials and therefore CO_2 has been saved in an average house by changing from AC to DC?

7.7.2 Quantify the total cost of a PV system installed into new houses as against retrofitting the system to old houses. What effect will incorporating renewable energy generators into newly built homes have on their proliferation and on the total cost of the house? What effect will this have on energy security and energy independence?

7.7.3 To do the cost benefit analysis, for both the economic and the carbon footprint, of generating the same amount of electricity using different centralised power plants to generate the equivalent energy capacity from domestically installed renewable energy generation systems.

7.7.4 A study into the vulnerability of the procurement chain for the fuels used for the UK's centralised electrical generators and to determine what impact the DC house will have on any conclusions reached.

7.8.0 Socioeconomic effects and new emerging markets

7.8.1 How will the low powered DC voltage smart house reduce the carbon footprint of the home? How will the reduction in the carbon footprint affect government targets for "net-zero carbon homes" in the UK and of reducing it up to 60% by 2050, otherwise known as the "the 40% house" policy?

7.8.2 To answer the following questions and to see how decentralised energy generation will affect them. How much money do nations pay for their warships to patrol the high seas especially in the Indian Ocean to guarantee safe passage of oil tankers? How much money is paid out to secure power plants against terrorism? How much money is given out by way of grants to the nuclear industry? How much is spent on facilities to store strategic quantities of different fuels? What other monies are spent by governments by way of direct grants or in roundabout ways to secure their countries energy supply? Quantify where possible, these costs and see how decentralised energy generation using renewable energy generators affect these outlays.

7.8.3 With the implementation of the DC home in emerging markets, what size will the new market for DC appliances be? How can this influence or/and convince appliance manufactures to invest in research and development to produce low powered DC appliances?

7.8.4 To ascertain what would companies and rich individuals pay for a degree of energy independence with security? And to see how this can be incorporated into the calculations used to determine price per kWh of electricity.

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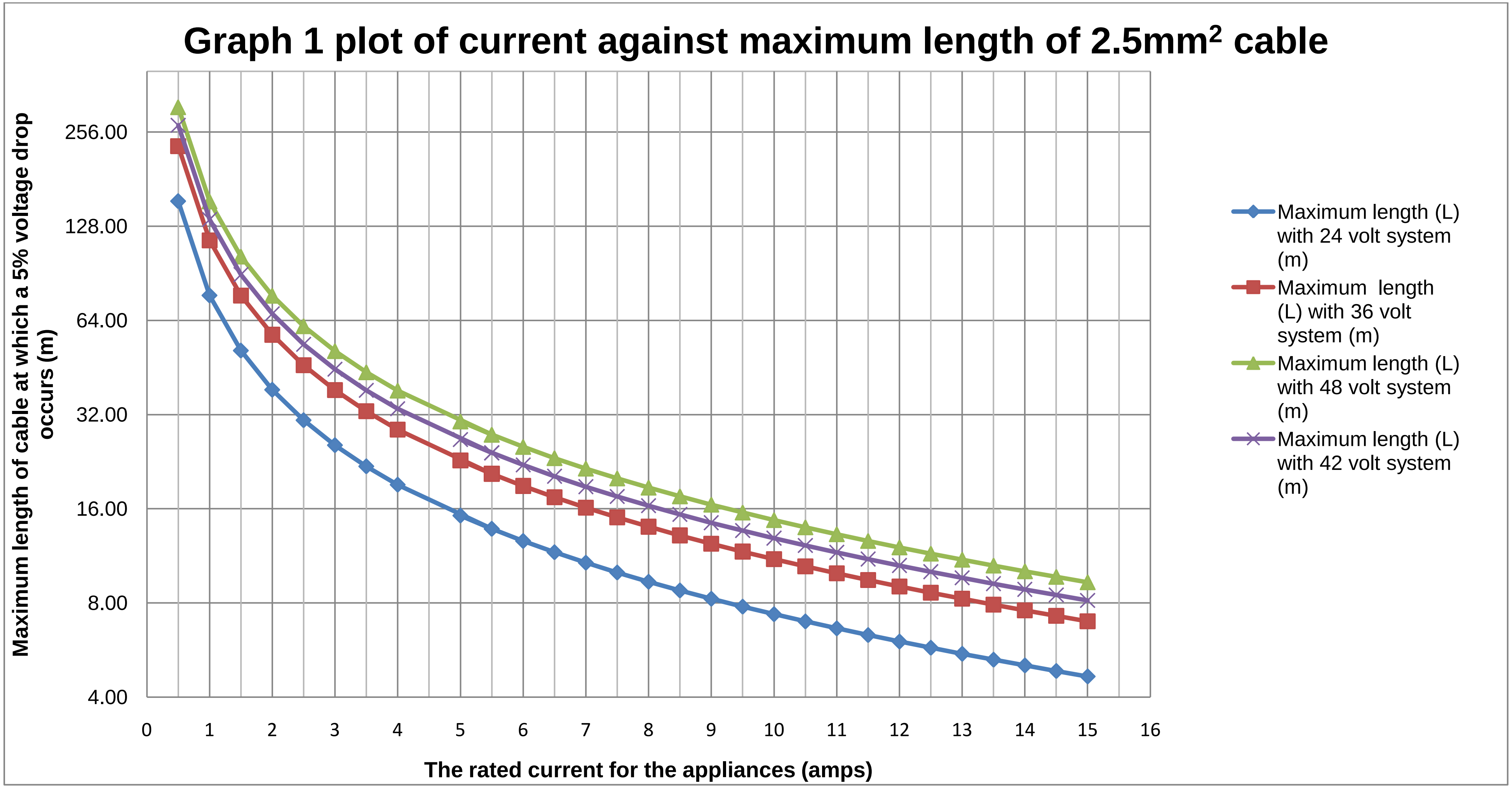
Appendix 1 Graphical Tools, Data and Graphs

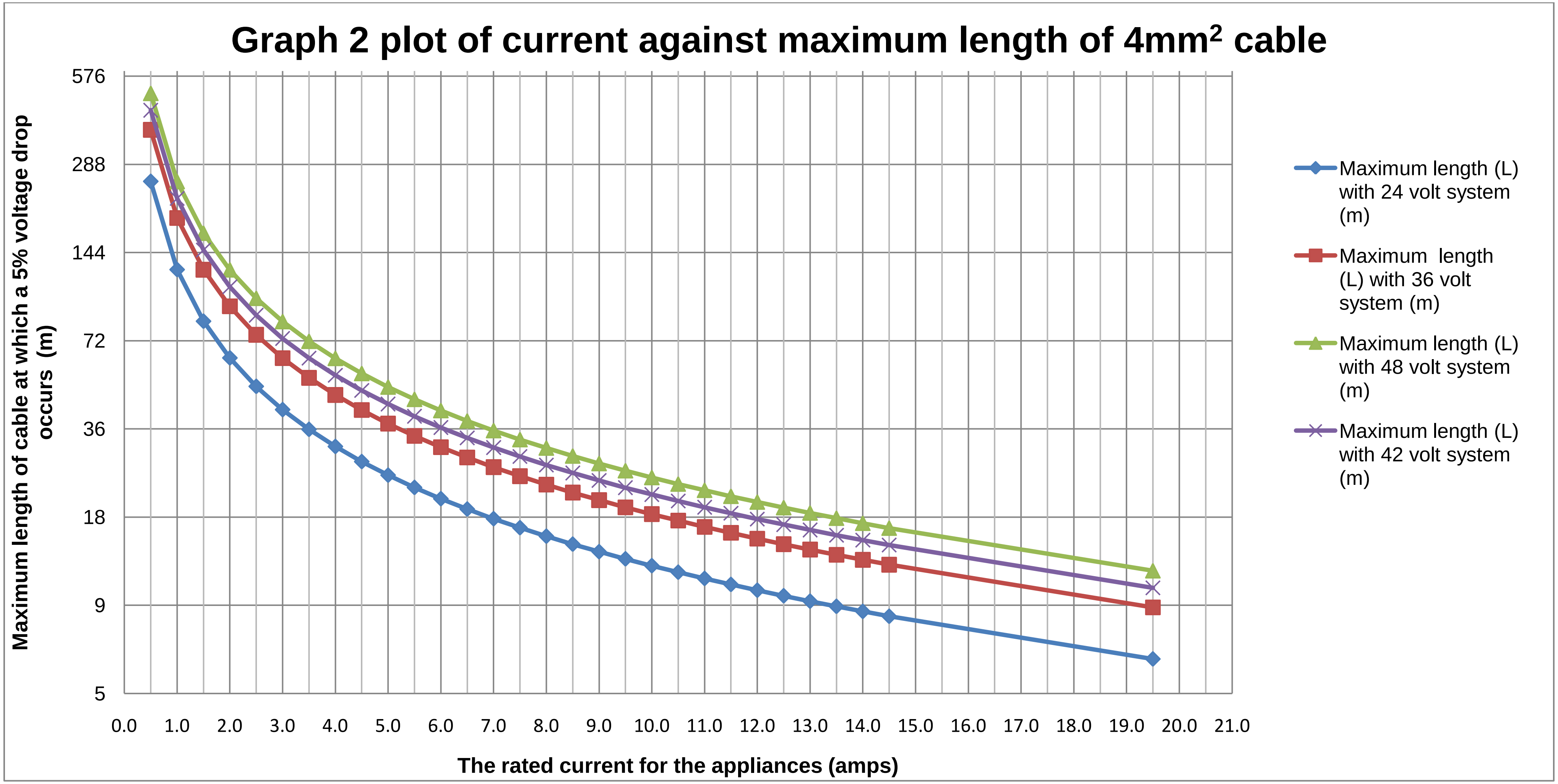
DC current - Ib (A)	tp	230+tp	Correction factor	Tabulated Voltage drop mV/A/m	Calculated Voltage drop mV/A/m	Maximum length (L) with 24 volt system (m)	Maximum length (L) with 36 volt system (m)	Maximum length (L) with 42 volt system (m)	Maximum length (L) with 48 volt system (m)
0.50	70	300	0.8668	18	15.6018	153.83	230.74	269.20	307.66
1.00	70	300	0.8671	18	15.6070	76.89	115.33	134.55	153.78
1.50	70	300	0.8675	18	15.6158	51.23	76.85	89.65	102.46
2.00	70	300	0.8682	18	15.6280	38.39	57.59	67.19	76.79
2.50	70	300	0.8691	18	15.6438	30.68	46.02	53.70	61.37
3.00	70	300	0.8702	18	15.6631	25.54	38.31	44.69	51.08
3.50	70	300	0.8714	18	15.6859	21.86	32.79	38.25	43.72
4.00	70	300	0.8729	18	15.7122	19.09	28.64	33.41	38.19
5.50	70	300	0.8785	18	15.8121	13.80	20.70	24.15	27.60
5.00	70	300	0.8764	18	15.7753	15.21	22.82	26.62	30.43
5.50	70	300	0.8785	18	15.8121	13.80	20.70	24.15	27.60
6.00	70	300	0.8807	18	15.8524	12.62	18.92	22.08	25.23
6.50	70	300	0.8831	18	15.8963	11.61	17.42	20.32	23.23
7.00	70	300	0.8858	18	15.9436	10.75	16.13	18.82	21.50
7.50	70	300	0.8886	18	15.9944	10.00	15.01	17.51	20.01
8.00	70	300	0.8916	18	16.0488	9.35	14.02	16.36	18.69
8.50	70	300	0.8948	18	16.1066	8.77	13.15	15.34	17.53
9.00	70	300	0.8982	18	16.1680	8.25	12.37	14.43	16.49
9.50	70	300	0.9018	18	16.2329	7.78	11.67	13.62	15.56
10.00	70	300	0.9056	18	16.3012	7.36	11.04	12.88	14.72
10.50	70	300	0.9096	18	16.3731	6.98	10.47	12.22	13.96
11.00	70	300	0.9138	18	16.4485	6.63	9.95	11.61	13.26
11.50	70	300	0.9182	18	16.5274	6.31	9.47	11.05	12.63
12.00	70	300	0.9228	18	16.6098	6.02	9.03	10.54	12.04
12.50	70	300	0.9275	18	16.6957	5.75	8.62	10.06	11.50
13.00	70	300	0.9325	18	16.7851	5.50	8.25	9.62	11.00
13.50	70	300	0.9377	18	16.8780	5.27	7.90	9.22	10.53
14.00	70	300	0.9430	18	16.9744	5.05	7.57	8.84	10.10
14.50	70	300	0.9486	18	17.0744	4.85	7.27	8.48	9.69
15.00	70	300	0.9543	18	17.1778	4.66	6.99	8.15	9.31

Table A1-1 Voltage loss and maximum length for **2.5mm^2** cable operating at different voltage


Graph 1 plot of current against maximum length of 2.5mm² cable
Maximum length of cable at which a 5% voltage drop occurs (m)
256.00
128.00
64.00
32.00
16.00
8.00
4.00
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
The rated current for the appliances (amps)
Maximum length (L) with 24 volt system (m)
Maximum length (L) with 36 volt system (m)
Maximum length (L) with 48 volt system (m)
Maximum length (L) with 42 volt system (m)

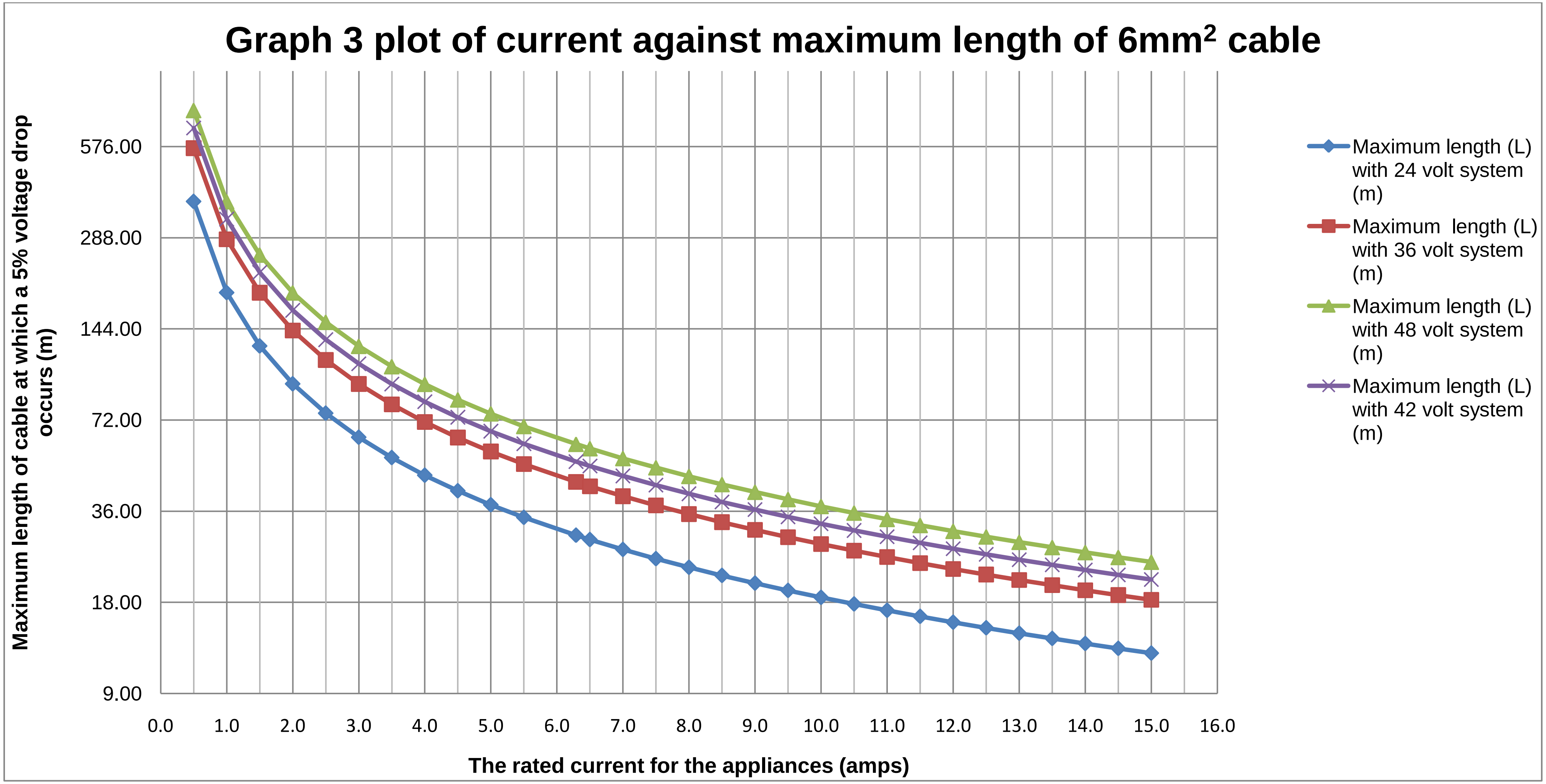
DC current - Ib (A)	tp	230+tp	Correction factor	Tabulated Voltage drop mV/A/m	Calculated Voltage drop mV/A/m	Maximum length (L) with 24 volt system (m)	Maximum length (L) with 36 volt system (m)	Maximum length (L) with 42 volt system (m)	Maximum length (L) with 48 volt system (m)
0.50	70	300	0.8667	11	9.5339	251.73	377.60	440.53	503.47
1.00	70	300	0.8669	11	9.5357	125.84	188.76	220.23	251.69
1.50	70	300	0.8671	11	9.5386	83.87	125.80	146.77	167.74
2.00	70	300	0.8675	11	9.5427	62.88	94.31	110.03	125.75
2.50	70	300	0.8680	11	9.5480	50.27	75.41	87.98	100.54
3.00	70	300	0.8686	11	9.5545	41.87	62.80	73.26	83.73
3.50	70	300	0.8693	11	9.5621	35.86	53.78	62.75	71.71
4.00	70	300	0.8701	11	9.5709	31.35	47.02	54.85	62.69
4.50	70	300	0.8710	11	9.5809	27.83	41.75	48.71	55.67
5.00	70	300	0.8720	11	9.5920	25.02	37.53	43.79	50.04
5.50	70	300	0.8731	11	9.6043	22.72	34.08	39.75	45.43
6.00	70	300	0.8743	11	9.6178	20.79	31.19	36.39	41.59
6.50	70	300	0.8757	11	9.6325	19.17	28.75	33.54	38.33
7.00	70	300	0.8771	11	9.6483	17.77	26.65	31.09	35.54
7.50	70	300	0.8787	11	9.6653	16.55	24.83	28.97	33.11
8.00	70	300	0.8803	11	9.6835	15.49	23.24	27.11	30.98
8.50	70	300	0.8821	11	9.7029	14.55	21.82	25.46	29.10
9.00	70	300	0.8839	11	9.7234	13.71	20.57	24.00	27.43
9.50	70	300	0.8859	11	9.7451	12.96	19.44	22.68	25.92
10.00	70	300	0.8880	11	9.7680	12.29	18.43	21.50	24.57
10.50	70	300	0.8902	11	9.7921	11.67	17.51	20.42	23.34
11.00	70	300	0.8925	11	9.8173	11.11	16.67	19.45	22.22
11.50	70	300	0.8949	11	9.8437	10.60	15.90	18.55	21.20
12.00	70	300	0.8974	11	9.8713	10.13	15.20	17.73	20.26
12.50	70	300	0.9000	11	9.9000	9.70	14.55	16.97	19.39
13.00	70	300	0.9027	11	9.9299	9.30	13.94	16.27	18.59
13.50	70	300	0.9055	11	9.9610	8.92	13.39	15.62	17.85
14.00	70	300	0.9085	11	9.9933	8.58	12.87	15.01	17.15
14.50	70	300	0.9115	11	10.0267	8.25	12.38	14.44	16.51
19.50	70	300	0.9478	11	10.4257	5.90	8.85	10.33	11.81

Table A1-2 Voltage loss and maximum length for 24mm^2 cable operating at different voltage


Graph 2 plot of current against maximum length of 4mm² cable
576
288
144
72
36
18
9
5
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0 21.0
Maximum length of cable at which a 5% voltage drop occurs (m)
The rated current for the appliances (amps)
Maximum length (L) with 24 volt system (m)
Maximum length (L) with 36 volt system (m)
Maximum length (L) with 48 volt system (m)
Maximum length (L) with 42 volt system (m)

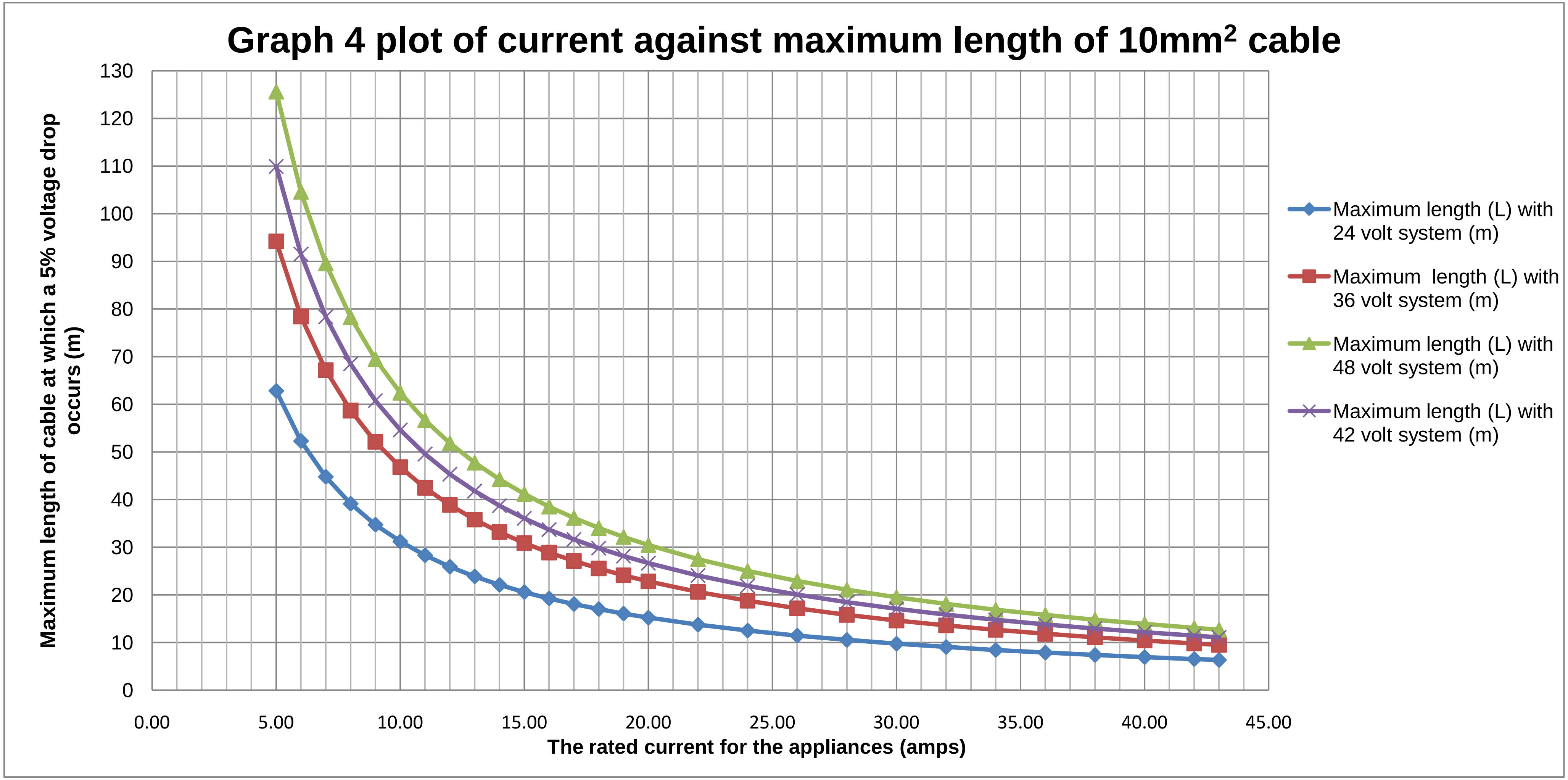
DC current - Ib (A)	tp	230+tp	Correction factor	Tabulated Voltage drop mV/A/m	Calculated Voltage drop mV/A/m	Maximum length (L) with 24 volt system (m)	Maximum length (L) with 36 volt system (m)	Maximum length (L) with 42 volt system (m)	Maximum length (L) with 48 volt system (m)
0.50	70	300	0.8667	7.3	6.3269	379.33	569.00	663.83	758.66
1.00	70	300	0.8668	7.3	6.3276	189.64	284.47	331.88	379.29
1.50	70	300	0.8670	7.3	6.3288	126.41	189.61	221.21	252.81
2.00	70	300	0.8672	7.3	6.3305	94.78	142.17	165.86	189.56
2.50	70	300	0.8675	7.3	6.3326	75.80	113.70	132.65	151.60
3.00	70	300	0.8678	7.3	6.3352	63.14	94.71	110.49	126.28
3.50	70	300	0.8683	7.3	6.3383	54.09	81.14	94.66	108.19
4.00	70	300	0.8688	7.3	6.3419	47.30	70.96	82.78	94.61
4.50	70	300	0.8693	7.3	6.3459	42.02	63.03	73.54	84.04
5.00	70	300	0.8699	7.3	6.3504	37.79	56.69	66.14	75.59
5.50	70	300	0.8706	7.3	6.3554	34.33	51.50	60.08	68.66
6.29	70	300	0.8718	7.3	6.3643	29.98	44.96	52.46	59.95
6.50	70	300	0.8722	7.3	6.3668	29.00	43.49	50.74	57.99
7.00	70	300	0.8730	7.3	6.3732	26.90	40.35	47.07	53.80
7.50	70	300	0.8740	7.3	6.3801	25.08	37.62	43.89	50.16
8.00	70	300	0.8750	7.3	6.3875	23.48	35.23	41.10	46.97
8.50	70	300	0.8761	7.3	6.3953	22.07	33.11	38.63	44.15
9.00	70	300	0.8772	7.3	6.4037	20.82	31.23	36.44	41.64
9.50	70	300	0.8784	7.3	6.4125	19.70	29.55	34.47	39.40
10.00	70	300	0.8797	7.3	6.4217	18.69	28.03	32.70	37.37
10.50	70	300	0.8810	7.3	6.4315	17.77	26.65	31.10	35.54
11.00	70	300	0.8824	7.3	6.4417	16.94	25.40	29.64	33.87
11.50	70	300	0.8839	7.3	6.4524	16.17	24.26	28.30	32.34
12.00	70	300	0.8854	7.3	6.4635	15.47	23.21	27.07	30.94
12.50	70	300	0.8870	7.3	6.4752	14.83	22.24	25.95	29.65
13.00	70	300	0.8887	7.3	6.4873	14.23	21.34	24.90	28.46
13.50	70	300	0.8904	7.3	6.4999	13.68	20.51	23.93	27.35
14.00	70	300	0.8922	7.3	6.5130	13.16	19.74	23.03	26.32
14.50	70	300	0.8940	7.3	6.5265	12.68	19.02	22.19	25.36
15.00	70	300	0.8960	7.3	6.5405	12.23	18.35	21.40	24.46

Table A1-3 Voltage loss and maximum length for **6mm^2** cable operating at different voltage


Graph 3 plot of current against maximum length of 6mm² cable
Maximum length of cable at which a 5% voltage drop occurs (m)
576.00
288.00
144.00
72.00
36.00
18.00
9.00
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
The rated current for the appliances (amps)
Maximum length (L) with 24 volt system (m)
Maximum length (L) with 36 volt system (m)
Maximum length (L) with 48 volt system (m)
Maximum length (L) with 42 volt system (m)

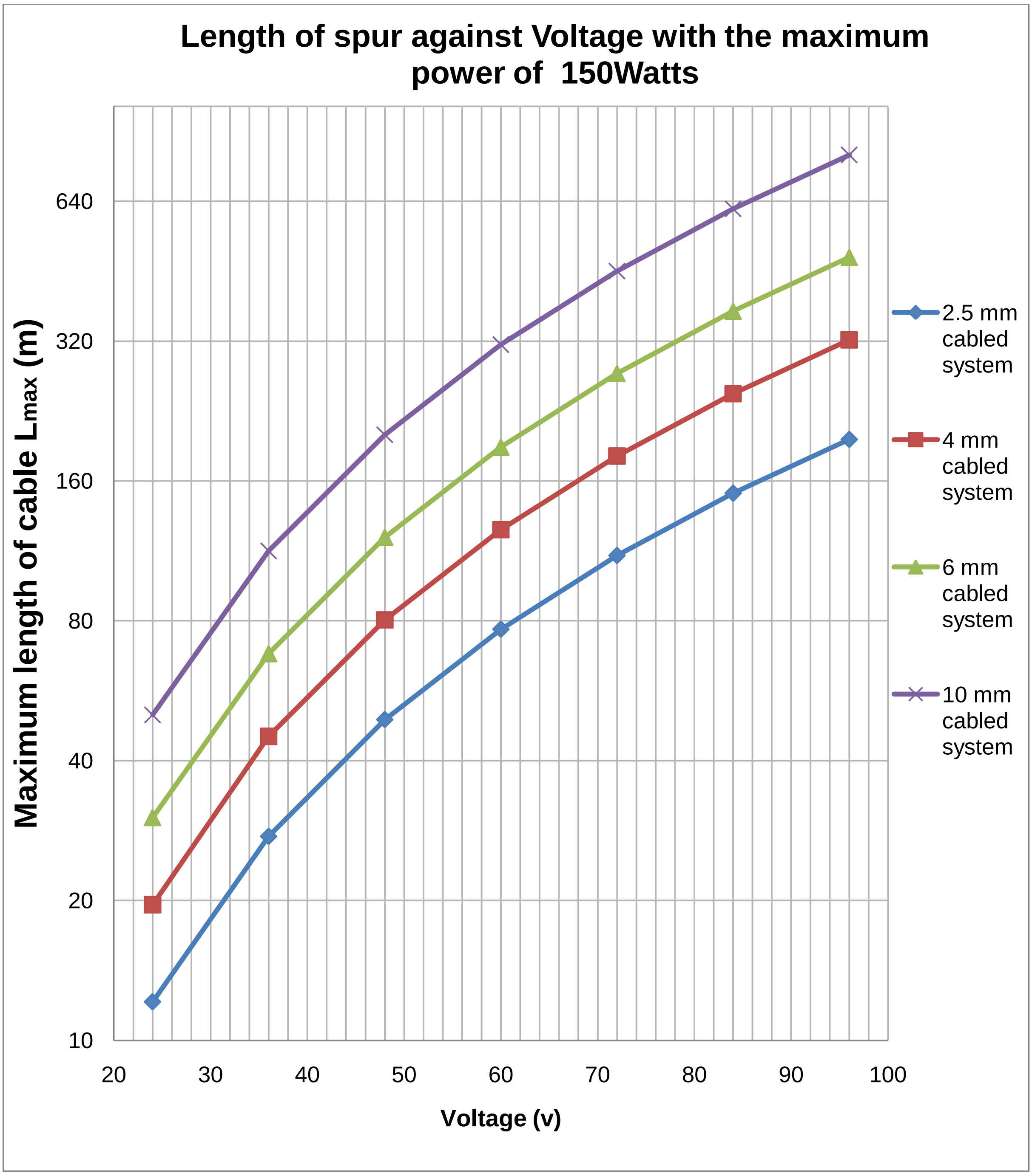
DC current - Ib (A)	tp	230 +tp	Correction factor	Tabulated Voltage drop mV/A/m	Calculated Voltage drop mV/A/m	Maximum length (L) with 24 volt system (m)	Maximum length (L) with 36 volt system (m)	Maximum length (L) with 42 volt system (m)	Maximum length (L) with 48 volt system (m)
5.00	70	300	0.8685	4.4	3.8213	62.81	94.21	109.91	125.61
6.00	70	300	0.8693	4.4	3.8248	52.29	78.44	91.51	104.58
7.00	70	300	0.8702	4.4	3.8289	44.77	67.16	78.35	89.55
8.00	70	300	0.8713	4.4	3.8336	39.13	58.69	68.47	78.25
9.00	70	300	0.8725	4.4	3.8390	34.73	52.10	60.78	69.46
10.00	70	300	0.8739	4.4	3.8451	31.21	46.81	54.62	62.42
11.00	70	300	0.8754	4.4	3.8517	28.32	42.48	49.56	56.65
12.00	70	300	0.8771	4.4	3.8590	25.91	38.87	45.35	51.83
13.00	70	300	0.8789	4.4	3.8670	23.87	35.81	41.77	47.74
14.00	70	300	0.8808	4.4	3.8755	22.12	33.18	38.70	44.23
15.00	70	300	0.8829	4.4	3.8847	20.59	30.89	36.04	41.19
16.00	70	300	0.8851	4.4	3.8946	19.26	28.89	33.70	38.52
17.00	70	300	0.8875	4.4	3.9050	18.08	27.11	31.63	36.15
18.00	70	300	0.8900	4.4	3.9161	17.02	25.54	29.79	34.05
19.00	70	300	0.8927	4.4	3.9279	16.08	24.12	28.14	32.16
20.00	70	300	0.8955	4.4	3.9402	15.23	22.84	26.65	30.45
22.00	70	300	0.9016	4.4	3.9669	13.75	20.63	24.06	27.50
24.00	70	300	0.9082	4.4	3.9961	12.51	18.77	21.90	25.02
26.00	70	300	0.9154	4.4	4.0278	11.46	17.19	20.05	22.92
28.00	70	300	0.9232	4.4	4.0621	10.55	15.83	18.46	21.10
30.00	70	300	0.9316	4.4	4.0989	9.76	14.64	17.08	19.52
32.00	70	300	0.9405	4.4	4.1382	9.06	13.59	15.86	18.12
34.00	70	300	0.9500	4.4	4.1801	8.44	12.66	14.78	16.89
36.00	70	300	0.9601	4.4	4.2245	7.89	11.84	13.81	15.78
38.00	70	300	0.9708	4.4	4.2715	7.39	11.09	12.94	14.79
40.00	70	300	0.9820	4.4	4.3210	6.94	10.41	12.15	13.89
42.00	70	300	0.9939	4.4	4.3730	6.53	9.80	11.43	13.07
43.00	70	300	1.0000	4.4	4.4000	6.34	9.51	11.10	12.68

Table A1-4 Voltage loss and maximum length for **10mm^2** cable operating at different voltage


Graph 4 plot of current against maximum length of 10mm² cable
Maximum length of cable at which a 5% voltage drop occurs (m)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
The rated current for the appliances (amps)
Maximum length (L) with 24 volt system (m)
Maximum length (L) with 36 volt system (m)
Maximum length (L) with 48 volt system (m)
Maximum length (L) with 42 volt system (m)

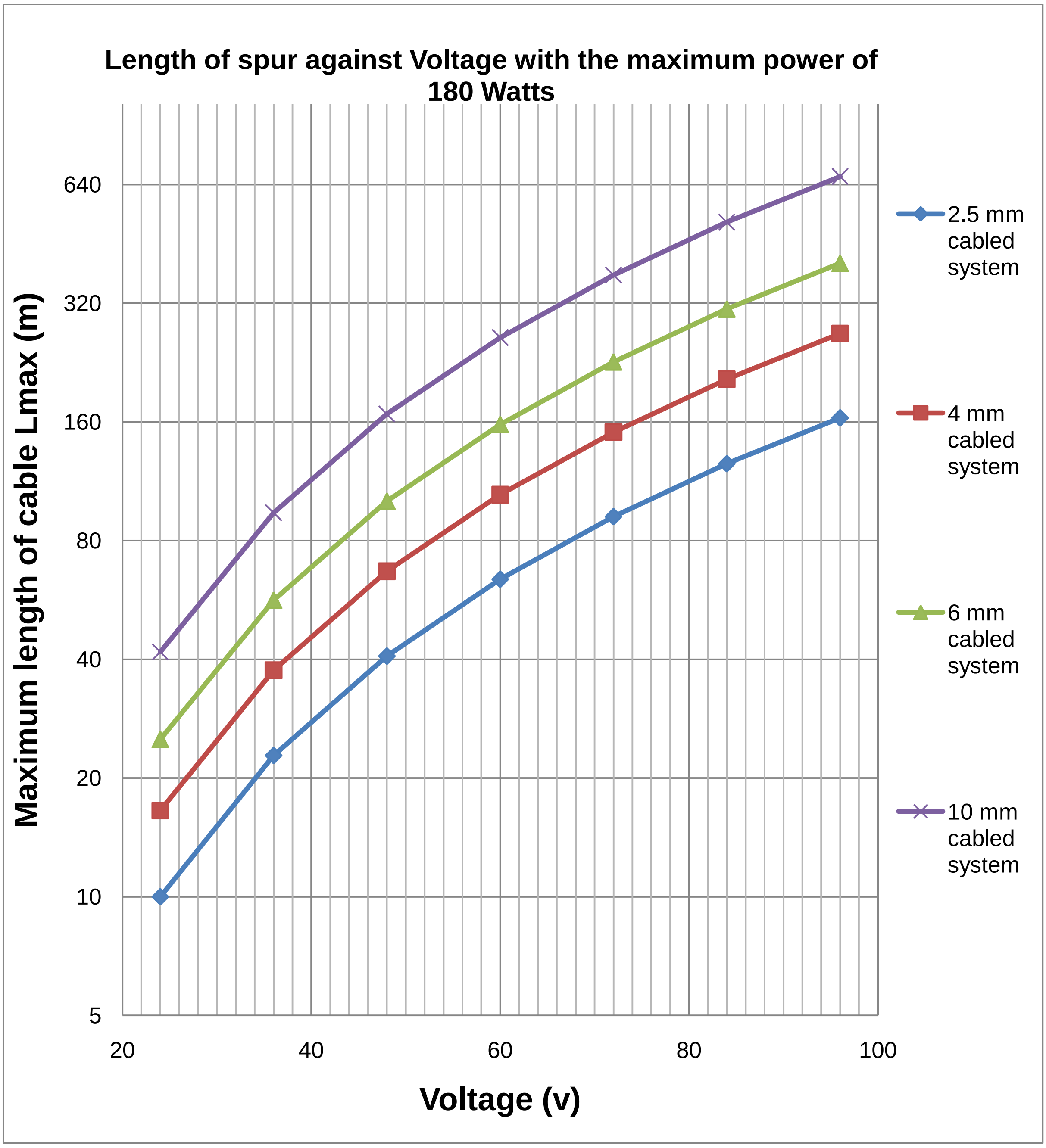
voltage (V)	2.5 mm cabled system	4 mm cabled system	6 mm cabled system	10 mm cabled system
24	12.1	19.59	30.17	50.19
36	27.48	45.12	67.99	113.12
48	49.02	80.37	121.1	201.24
60	76.71	125.68	189.38	314.52
72	110.55	181.07	272.84	452.98
84	150.55	246.52	371.47	616.62
96	196.55	322.04	485.27	805.43

Table A1-5



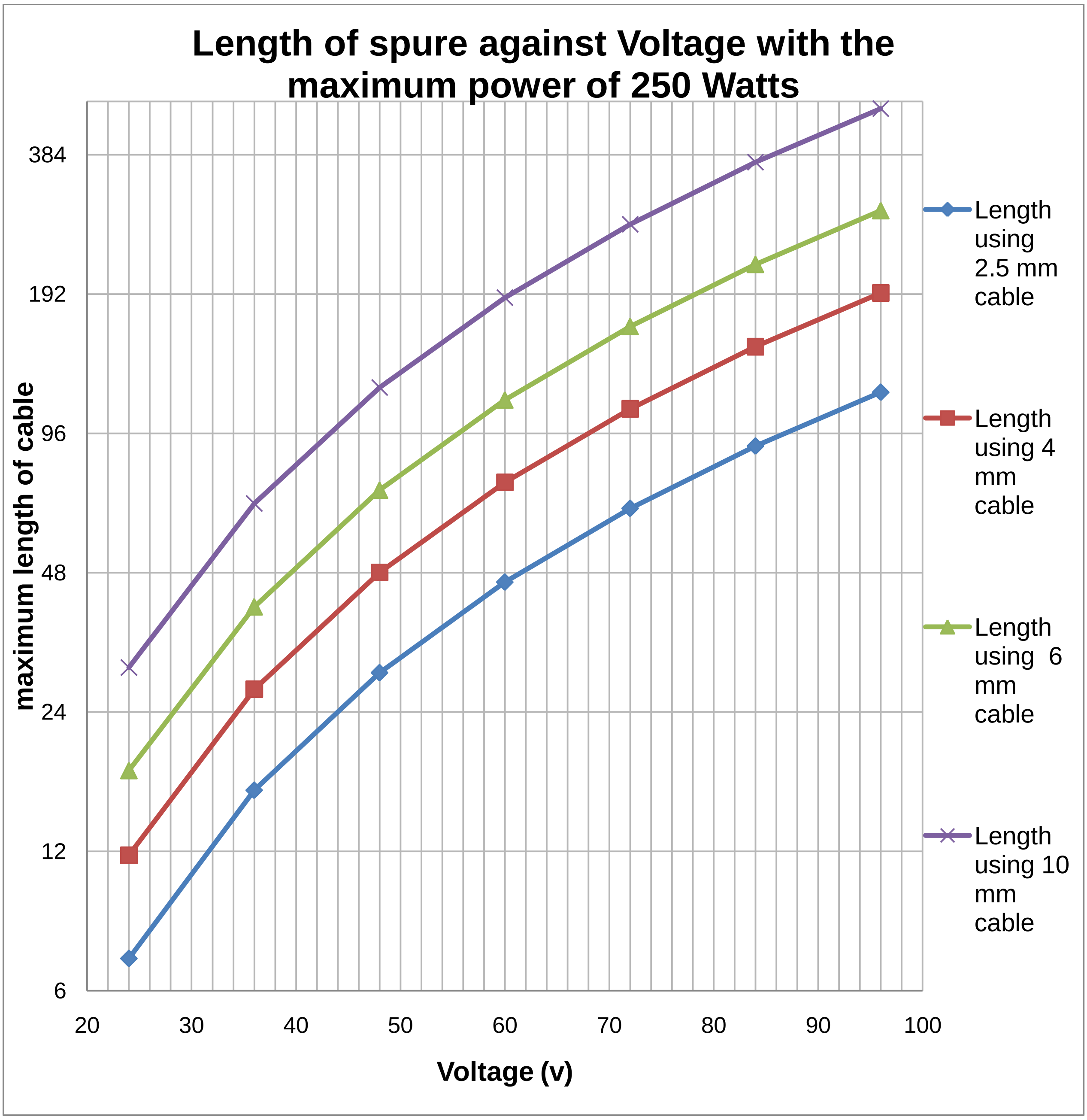
voltage (V)	2.5 mm cabled system	4 mm cabled system	6 mm cabled system	10 mm cabled system
24	10	16.55	25.08	41.76
36	22.82	37.53	56.55	94.21
48	40.77	66.9	100.81	167.64
60	63.84	104.66	157.71	262.04
72	92.05	150.82	227.26	377.43
84	125.38	205.36	309.45	513.79
96	163.84	268.3	404.29	671.13

Table A1-6



voltage (V)	Length using 2.5 mm cable	Length using 4 mm cable	Length using 6 mm cable	Length using 10 mm cable
24	7.04	11.77	17.92	29.94
36	16.26	26.87	40.49	67.7
48	29.18	48.02	72.35	120.57
60	45.8	75.2	113.32	188.54
72	66.1	108.43	163.39	271.62
84	90.1	147.71	222.57	369.8
96	117.79	193.02	290.85	483.08

Table A1-7



Appendix 2: Tables 4D1A, 4D1B, 4D2A & 4D2B from BS 7671:2008

Appendix 3 Data Sheets and Misc

The top picture is the DC mobile phone charger to be used in the car and the bottom picture is the AC one for the home. The AC charger is larger has a transformer and more capacitors that the DC one. The DC one does have a glass fuse. Without further investigations and with only looking at them both in their open state it is postulated that the AC version uses more raw materials to manufacture than the DC version.

Energy Efficiency through better motors

News published: 26 February 2007
Published by: Vent-Axia Marketing

Precise controllability, more reliability and less energy – new energy efficient motors in fans deliver direct benefits to the HEVAC industry. Paul Kilburn, Vent-Axia's Group Sales and Marketing Director explains what this means for ventilation.

The Government, in its national quest to reduce our greenhouse gas emissions, has sharpened its focus on the energy performance of buildings. In the drive for better air quality, greater energy efficiency and the reduction of carbon emissions, the latest editions of Building Regulations Documents F&L are now beginning to take effect.

Building Regulations F & L have signalled a big shift towards energy efficient buildings and have set the standard for the maximum carbon dioxide emissions for whole buildings. This performance-based approach offers designers the flexibility to choose suitable solutions which allow for adequate means of ventilation for people in the building, and which are energy efficient, cost-effective and practical.

However, the revisions to Part L have raised performance standards to a level that has provided a strong incentive to designers to consider low carbon systems, not least the development of the SAP Appendix Q process for ventilation, which affects postively the role of mechanical ventilation with or without heat recovery and with DC motors on Dwelling Emission Rates.

In the context of increasingly demanding environmental legislation and rising awareness of the need to reduce energy consumption, energy efficient motors look set to expand their share of the market for industrial, commercial and residential ventilation.

There are two main types of electric motors: direct current (DC) and alternating current (AC). Compared to AC motors, DC motors are faster, more efficient and offer more accurate speed and position control. Moreover, while AC motors produce an audible 60 Hz "hum," DC motors are much quieter. DC motors are also usually smaller than AC motors, providing manufacturers with the opportunity to design applications that are smaller with different styles and looks.

Generally, DC motors draw less current (about two to four times less) and therefore consume less power compared to an AC motor with equal output power. DC motors also work better for situations where speed needs to be controlled as they have a more stable and continuous current. DC motors are finding their way into new products and applications that previously used AC motors exclusively.

Vent-Axia has been instrumental in using LoWatt DC technology leading, the market for several years. Vent-Axia believes in practical action and has been spearheading the campaign to deliver more affordable long life ventilation. Vent-Axia's residential and commercial product ranges are all available with DC technology, improving performance, reducing running costs, extending fan life whilst ensuring reliability.

However, Vent-Axia is now using a new revolutionary motor, called 'EC' that offer the efficiency and speed control benefits of DC, with built in AC to DC conversion and speed control.

EC motors are a better, more efficient motor at every speed but it doesn't stop there. Utilising EC motors in fan systems offers many benefits; for example, EC fans can use as little as a third of the energy of industry standard AC fans. EC fans offer easy, quiet and efficient speed control and all the electronics are built into the fan making other components more efficient.

The greater reliability and longer life of DC and EC motors has the further advantage of extending the life of insulating materials, lubricants and bearings, thereby cutting the cost and inconvenience of return service visits.

EC fans save energy and increase the longevity of the products, whilst reducing lifetime costs, thereby adding value. They significantly lower noise and generate less heat than conventional AC and DC motors. The EC motor's compact design makes it easy to install in any position, which opens up this motor to a wide range of possible applications.

As technologies become more advanced and cost-effective, we should expect to see more innovative low energy fan systems introduced to the market featuring different designs as well as improved performance. Across Europe, energy efficient fan systems could save almost 200 billion KWh a year of electricity.