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The Future of Electricity in Domestic Buildings – a review

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Glossary

Ampere: Ampere is a unit of electric current equal to the flow of one coulomb per second.

Big Data: Big Data is both a general term for the expected explosion in data as more interactions take place over the Internet and a more specific term in the ICT sector referring to data sets that are too large or too complex to be handled by commonly available software tools.

Central storage: this is electricity storage, typically consisting of batteries, located centrally on the domestic network normally near the Consumer Unit or included with other centrally located equipment or plant, for example a PV inverter.

Centralised inverter: the term centralised inverter refers to a now outdate practice of connecting more than one PV string in parallel to an inverter. Doing this makes it difficult to optimise the performance of each string and for this reason string inverters (one inverter per string) has become common.

Clean AC (colloquialism): clean AC is a term referring to a pure sinusoidal waveform. Many power conversion processes typically rely on rapid switching (Pulse Width Modulation, see later) of the electricity which can produce voltage spikes, harmonics and other irregularities. If these are not adequately catered for in the circuit design or device screening it can interfere with radio and TV transmissions or other equipment.

Closed loop: a closed loop system (simple or complex) is one where the output of a system is sensed and fed back, often as an error signal relative to the input stimuli, to ensure a desired set point (outcome) is achieved.

Consumer Unit: a piece of equipment located where the incoming mains supply is fed to the individual domestic circuits. It typically includes protection and isolation hardware.

Control scenario: a control scenario is a set of rules or instructions that guide the system variables to deliver the required outcomes.

Current density: this is the current density in an electrical conductor measured in A/cm^2.

Current: the flow of electricity through a conductor measured in Amps.

Demand-side: this is a general term referring to everything that consumes electricity. In the context of this report it is related to the 230 V AC mains system in a domestic building from the domestic meter to the point-of-use or in electrical engineering terms point-of-load.

Device: a device in the context of this report refers to an item that consumes electricity which is primarily electronic in nature (mobile phone, computer, TV etc.) as opposed to an electrical appliance (washing machine, fridge etc.). As more traditional appliances become smart and Internet enabled they too will, in terms of their controllability and system performance, become more like modern electronic devices.

Distributed storage: this refers to electrical storage, typically consisting of batteries, distributed throughout the domestic network for example, in laptop computers and mobile phones.

Efficacy: light output measured in lumens per watt (lm/W).

Electro-migration (in integrated circuits): this refers to a phenomenon where the current density in a conductor gets so high that it transports the metal ions along the path of current flow and forms voids at the grain boundaries. When this happens in excess the conductor essentially breaks and the integrated circuit fails. Typically the current density in domestic wiring for example, is several hundred A/cm^2 but for integrated circuits it can be as high as 1,000,000 A/cm^2 for aluminium interconnects or even higher for copper.

I^2R losses: this is the energy lost (dissipated) in a conductor as a result of Joule heating which increases proportionally to the resistance and as the square of the current flowing.

Information and Communications Technology (ICT): is a broader term than IT (Information Technology) and applies to a more integrated network of communication including computers, telecommunications and associated software.

Imaginary impedance: in AC circuits a 'real' resistive component (found in DC and AC systems) has two other impeding mechanisms referred to as reactive or imaginary components. One is related to the changing magnetic field and self-inductance and the other to electrostatic storage and capacitance.

Inductive coupling: inductive coupling is where an alternating electromagnetic field induces a current in an adjacent conductor.

Load: a load is a general term for anything that consumes electricity.

LTE networks – LTE (Long Term Evolution) is a wireless broadband technology designed to support Internet roaming and is often referred to as 4G. It supports browsing, VoIP (Voice over Internet Protocol) and other IP based services.

Machine-to-machine: machine-to-machine refers to communications between machines. As 'things' become smarter and Internet enabled they will communicate with each other without human intervention – it is closely aligned with the Internet-of-Things (IoT).

Network (the domestic network and the local distribution network (DNO managed)): a domestic network refers to the cables, connectors and equipment that connect the electricity supply (the meter) to the end device or appliance (load). More recently the domestic network may also consider conversion processes as many of these are now external to the device itself. The local distribution network is that which is operated by the DNO up to and including the meter.

No-load consumption: this typically refers to the electricity consumed by a power supply or converter when it is not providing any output. Parasitic consumption refers to when a device is on standby mode but is not actually being used, for example a TV. Other examples of hidden energy waste include leaving batteries on charge beyond when they are fully charged.

On-grid: this refers to a domestic dwelling that is connected to the national 230 V AC supply grid supply.

Open loop: an open loop system is one where an input stimuli is given to a system that with good design should achieve a certain set point or output. It does not have any error correcting feedback from output to input compensating for system variations.

Piconet: a Piconet is a very local network between for example, a mobile phone and a computer, usually wireless.

Power Usage Effectiveness (PUE): is a measure of the power used by the computing equipment in a Data Centre compared to the total Data Centre demand. A PUE of 2 means that half of the total power supplied to the Data Centre (including cooling, lighting, fans etc.) is used by the computing equipment; ideally it should be 1.

Pulse Width Modulation (PWM): the simplest way to think of this is the time a switch is on. If a switch is on for a long time current flows for the majority of the time. If it is only on for a very short period then little flows. In the electrical circuits considered in this report the switch is electronic and may operate at about 500 kHz or every several microseconds.

String (PV): a string is where a number of PV panels are connected in series. For a typical domestic installation this is normally in the region of 8 to 16 panels.

Supply-side: this is a general term referring to everything related to the generation, transmission and distribution of electricity up to and including the domestic meter.

System: in the context of this report a system means a number of devices and appliances (loads) connected to an electricity supply (local or national) via a network.

System performance: this refers to how the complete domestic electricity system works in harmony to deliver a final desired outcome and any moment in time.

Three-phase: a three-phase system is where three alternating currents are carried by three separate conductors each of which reach their instantaneous peak 120 degrees apart.

Unit of electricity: electricity consumption is typically measured in kWh or multiples thereof and this is the unit normally used for domestic pricing.

Voltage: an electromotive force or potential difference measured in Volts.

Watt: a Watt is a measure of power and is equivalent to one Joule per Second corresponding to the rate of consumption in a circuit where the potential difference is one Volt and a current of one Ampere flows.

Figures and tables

Acronyms

AC: Alternating Current.
ACS: Average Cold Spell.
ASHRAE: American Society of Heating, Refrigeration and Air-conditioning Engineers.
CCGT: Combined Cycle Gas Turbine.
CFL: Compact Fluorescent Lamp.
CHP: Combined Heat and Power.
CPU: Central Processing Unit.
DC: Direct Current.
DNO: Distribution Network Operator.
DR: Demand-response (ADR, Automatic demand-response).
DSL: Digital Subscriber Line.
EEU: Expected Energy Unserved.
EPS: External Power Supply (typically associated with mobile devices but also used extensively for powering Internet hubs, low voltage desk lighting, desk phones etc.).
FIT: Feed-In-Tariff.
IEA: International Energy Agency
IEEE: Institute of Electrical and Electronics Engineers.
IET: The Institution of Engineering and Technology
kWh: 1000 (10^3) Wh. A measure of energy (power = energy/time).
kWp: this is the peak power of a PV module under standard test conditions.
LAN: Local Area Network.
LED: Light Emitting Diode (organic or in-organic).
LOLE: Loss of Load Expectation.
Mbps: Mega-bits per Second.
MPPT: Maximum Power Point Tracking.
Mtoe: Million Tonnes of oil equivalent.
MWh, GWh, TWh: 10^6, 10^9, 10^{12} Wh.
PAN: Personal Area Network.
PV: Photovoltaics.
RAN: Radio Access Network.
RMS: Root Mean Square is the effective periodic value of an AC current that delivers the same average power to a resistor as that of a similar DC current.
SMPS: Switch Mode Power Supply.
TOUT: Time-Of-Use Tariff.
TSB: Technology Strategy Board, now Innovate UK.
V_{av}: is the average value of a sinusoidal waveform and it is 0.637 times the peak value.
VoIP: Voice over Internet Protocol.
V2G: Vehicle-to-Grid.

WEEE: Waste Electrical and Electronic Equipment.
WiMax: Worldwide Interoperability for Microwave Access.

The Future of Electricity in Domestic Buildings– a review

Key words: domestic electricity; networks and systems; appliances and devices; electricity generation; smart grids; electricity storage; local generation; renewable energy; demand management.

1.0 Introduction

This paper reviews some of the key issues surrounding the supply, distribution and use of electricity in domestic buildings. Its primary aim is to consider the electricity system in a holistic, albeit simple, way and thereby identify some of the inter-relationships and inevitable compromises that inherently arise. By adopting a ‘horizontal’ system wide review the hope is that the paper stimulates an integrated system wide debate surrounding how electricity in domestic buildings will evolve in the future. Only by doing this will electricity generation and consumption be harmonised with national targets and future consumer lifestyle need.

The paper is in response to a number of potentially significant changes in the production and consumption of electricity in domestic buildings, these include:

- Challenging CO_2 reduction targets
- The use of more intermittent renewable and inflexible nuclear generation
- Smart meters and a potentially more dynamic electricity tariff structure
- The growth in local generation through for example, renewable energy installations
- Electric vehicles and heat pumps
- Changing appliance and device electricity demand profiles
- Smart devices (controllable and Internet (IP) addressable)
- Alternative domestic networks
- Conversion efficiencies
- Electricity storage
- Novel control scenarios.

The paper focuses on on-grid domestic buildings only and considerers how the changing supply environment driven by the need to reduce carbon emissions and ensure security of supply will impact the domestic electricity installation and the consumer in the future. The paper questions whether there are alternatives to the existing 230 V AC domestic electricity system and if so how they compare today and how they might evolve to meet the future of electricity.

The paper breaks the electricity system down in to its component parts and by doing so attempts to disaggregate the functional performance of each part and identify its potential strength and weakness. Each component or building block can then be considered in the context of the existing 230 V AC electricity system or how it might work with any new solution or technology that may come along in the future. Also, by taking this approach new ideas or solutions that may have several distinct strands of technological or market benefit can be deconstructed to identify the parts that are backwards compatible with the existing 230 V electricity supply.

By taking a relatively holistic view the paper also brings in to sharp focus the compromises that, like in any system, need to be made both in terms of technical performance, practical delivery and financial constraints. There are many apparently very justifiable reasons to optimise the domestic electricity system in the future not least because of micro-generation, the proliferation of low power low voltage DC devices, high power heat pumps and electric vehicles. While each sub-system might bring advantages it is a truism that, in general, as a system becomes more bespoke it often becomes less flexible. While inevitably new electricity sub-systems will arise in the future based on a case-by-case basis, when taking an overarching view of electricity in domestic buildings, an equally valid question is how can the existing 230 V AC system be made more efficient and flexible in the future? Can it be made more agile and adaptable to a wide range of loads with the help of new hardware, the smart agenda, system integration and intelligence? If it can then the smart agenda may be able to configure what we have today to maintain its flexibility in terms of the loads it can supply while becoming more bespoke in terms of how and when, and against what outcome, this happens - essentially providing the best of both worlds.

The paper considers the fundamental differences between AC and DC and how these impact practical electricity systems. While AC has dominated electricity supply and demand for many years there are still many situations where DC is used and this is likely to increase with the growth in electronic devices, renewable energy and electricity storage. As to whether DC on its own has any real advantages in like-for-like situations over AC is highly dependent on the particular circumstances. As a result it brings in to question whether there is one size that fits all and if not whether the technical or commercial reasons are strong enough for more than one electricity system to be introduced in to housing up and down the country.

The paper considers the life cycles associated with different components within the electricity system. This is particularly important as they vary widely. The buildings themselves and the existing electricity system can be classed as very slow changing whereas many of the electronic devices that now consume electricity no longer resemble those of ten years ago let alone when the National Grid was established back in 1933. This raises a debate as to whether there is a better way to supply these new relatively fast changing devices or whether the fact they are fast changing could provide the opportunity for improving the way they perform in relation to the existing 230 V system in the future.

2.0 Electricity supply

Although this paper is primarily focused on the demand-side use of electricity, most buildings [1] in the UK are connected to a world class, albeit ageing, electricity generation and supply network that has benefitted from immense investment over the years. As a result it is important to first review how the supply-side is changing and what impact that will have on the demand-side, the domestic consumer.

In 1925 Lord Weir was asked by the UK Government to solve the issue of a fragmented electricity grid that up until then consisted of a myriad of independent producers all with local networks using different voltages and frequencies. In 1926 the Electricity Supply Act [2] created the Central Electricity Board that oversaw the development of the UK's first nationwide AC grid in 1933. Since its introduction the grid has been founded on large scale centralised AC generation primarily based on fossil fuels with the introduction of nuclear electricity in the last sixty years.

Power stations are normally located away from centres of population where fossil fuels are abundant or good transport links exist. Many of these locations are well away from the towns and cities where the electricity is used and hence there is a need for electricity transmission and distribution. To do this efficiently the voltage at which electricity is generated is stepped up for efficient transmission and distribution and then stepped back down for safe usage. At the time of the grid being established this could only be achieved by the use of linear transformers and these only work on AC [3]. As a result AC grids now dominate throughout the world [4].

2.1 The electricity supply network

The UK's electricity transmission network is based on a 400 kV AC super grid and a 275 kV transmission network. The local distribution network steps this down through a number of stages from 132 kV to 11 kV although some big industrial users will be supplied with 33 kV or higher. The voltage is then reduced further to 415 V three-phase for small/medium sized commercial and industrial users and finally it is supplied to domestic dwellings at 230 V single-phase (the voltage between one of the three-phases and neutral). As already mentioned conversion is by way of linear transformers but unlike some of their smaller counterparts the ones used in the supply of electricity can be extremely efficient, in the region of 99.8 per cent [5], however reactive loads and their non-zero imaginary impedance can reduce this figure under normal operating conditions.

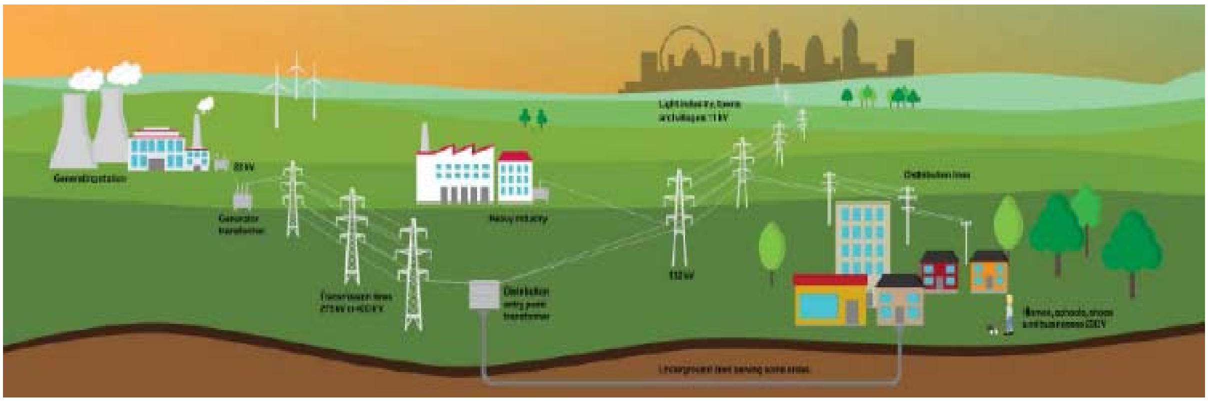

Figure 1. How electricity is made and transmitted (reproduced with kind permission from National Grid).

Since de-regulation of the electricity sector the supply network, from generation through to the consumer, is managed by four separate organisations that fulfil very different functions [6]:

- Generators - responsible for producing the electricity
- Suppliers - responsible for supply and selling electricity to consumers
- Transmission network - responsible for the transmission of electricity across the country
- Distributors - those who own and operate the local distribution network from the national transmission network to homes and businesses.

The national grid transmission network is on average 93 per cent efficient and is one of the most reliable in the world with an operational reliability of 99.99998 per cent [7] although these figures only apply to the main transmission network. Reliability and efficiency figures for the local distribution networks are more difficult to come by due to individual network characteristics and estimated billing. However, with the introduction of smart meters (see later) electricity consumption and availability will become a lot clearer allowing local distribution network performance to be better characterised. Overall the conversion of energy from primary fuel at the power station to usable electricity in the home is only in the region of 35 per cent for coal fired power stations and 45 per cent for the most modern Combined Cycle Gas Turbine (CCGT) power stations [8].

2.2 Decarbonising the grid

Peak demand for electricity across all sectors on an Average Cold Spell (ACS) in Great Britain is approximately 60 GW (2013/14). In 2013/14 approximately 350 TWh of electricity was generated and consumed the majority of which was produced by burning coal and gas, and by nuclear power stations. In 2035/36 total electricity generation is expected to be over 365 TWh with a peak demand of 68 GW (National Grid, Gone Green scenario). This will rise still further to approximately 600 TWh/yr by 2050 primarily driven by increased electricity exports and the electrification of transport and domestic heating using heat pumps [9].

Domestic electricity consumption has increased by approximately 40 per cent since 1970 although it peaked in 2005/6 and has fallen slightly to 118 TWh in 2013/14. Under the National Grid Gone Green scenario this is expected to fall further to just over 100 TWh by 2025/26 and then rise to over 125 TWh by 2035/36 [9] (*note; see reference [9] for other 'less green' scenarios*). To achieve these modest growth figures requires the domestic sector to meet challenging energy efficiency targets over the next 20 years.

The UK Government has set challenging targets for carbon dioxide reduction and together with the EU's Large Combustion Plant Directive [10] and the Industrial Emissions Directive it is having a big impact on the UK's electricity generation capacity. The UK has committed to a 34 per cent reduction in carbon dioxide emissions by 2020 (over 1990 levels) and an 80 per cent reduction by 2050 and to help meet these targets the national electricity supply will need to be more-or-less decarbonised.

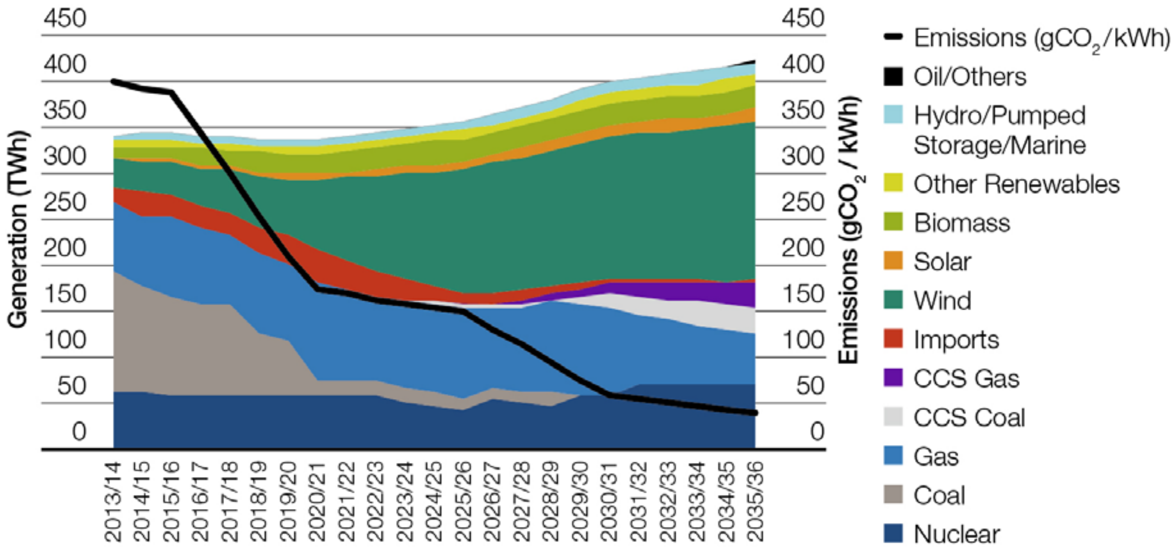

Figure 2. Generation output to 2035 (reproduced with kind permission from National Grid; Gone Green scenario [9]).

In the short term approximately 20 per cent of the existing power plants (coal and nuclear) are due to close in the next five years. This shortfall calls for over £110 bn of new investment in the next decade [11], [12]. To meet carbon dioxide targets the new capacity will be more intermittent and inflexible as a result of renewable generation (primarily wind) and less flexible as a result of nuclear generation. Due to the intermittency of renewable electricity generation it has a load factor, the estimated contribution as opposed to the maximum potential, of between 30 and 40 per cent for wind, onshore and offshore respectively, and just over 10 per cent for PV. As a result, renewable generation is driving the need for a near doubling of installed capacity over that of today from 91 GW to over 163 GW in 2035 despite only a slight increase in peak demand assuming energy efficiency targets are met [9].

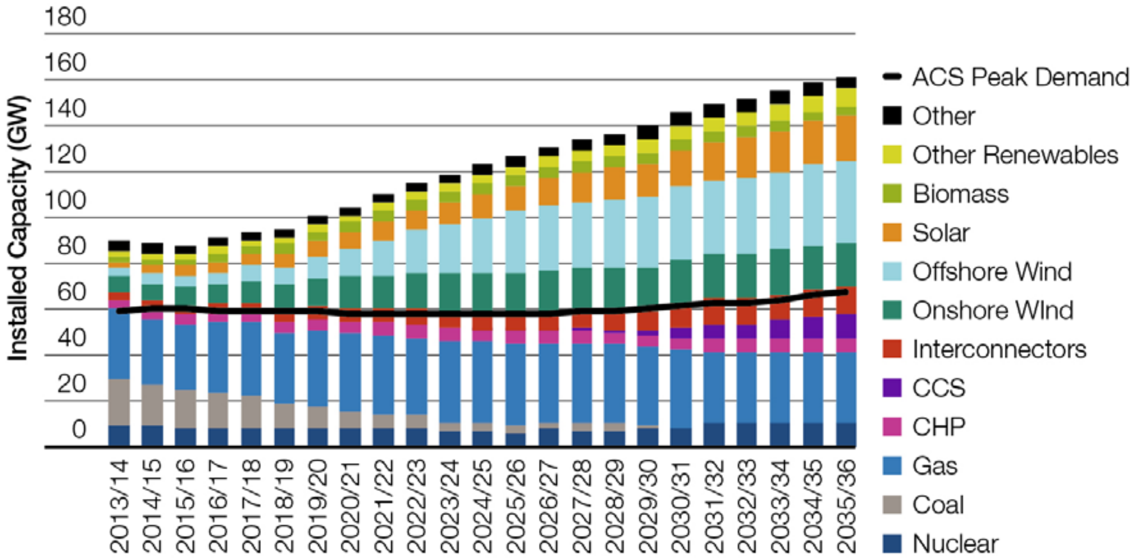

Figure 3. Installed capacity to 2035 (reproduced with kind permission from National Grid; Gone Green scenario [9]).

In the shorter term however, at periods of peak demand the loss of generation capacity will have an impact on the headroom available between supply and demand. The prediction is that in high demand periods supply may only just exceed demand by a few per cent, probably around 4 per cent or less. In the past this has typically been held between 10 and 20 per cent so it represents a significant drop in headroom. As a result, the probability of a large shortfall in electricity requiring the controlled disconnection of consumers increases from around 1 in 47 years in the winter of 2013/14 to 1 in 12 years in 2015/16 or lower if energy efficiency measures don't materialise.

In terms of security of supply two probabilistic measures are used, Loss of Load Expectation (LOLE) and Expected Energy Unserved (EEU). LOLE estimates for the next few years show that demand may exceed supply for more than the target of 3 hours and that this shortfall may be made up of a number of relatively frequent small events or infrequent larger events.

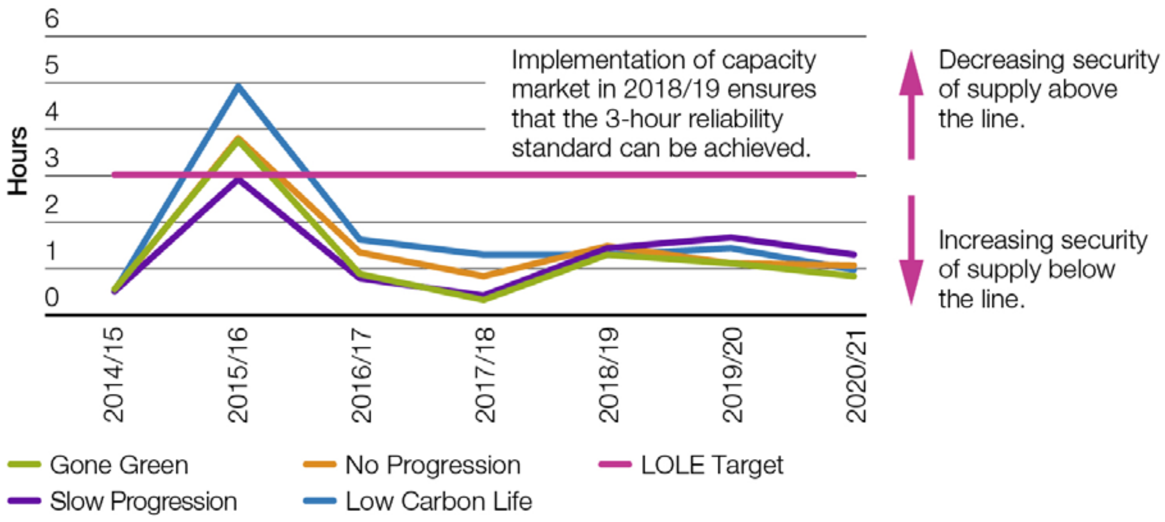

Figure 4. Security of supply for the four National Grid scenarios (reproduced with kind permission from National Grid [9]).

However, the National Grid power supply background has been developed so as not to exceed the 3 hour LOLE threshold from 2018/19 onwards. Before then, while the shortfall is of concern, system operators have some control over the network by for example, reducing electricity exports or selectively disconnecting industrial users, so there may be little or no significant impact on domestic consumers [13].

In general terms the total energy consumption in the domestic sector has seen a change in makeup over the past 40 years with an increasing use of electricity which is likely to continue in the future. Coal has been substituted by natural gas and as the grid becomes decarbonised natural gas will be slowly displaced by electricity.

2.3 The use of AC and DC in the supply network

While the existing electricity supply network is AC there are specific situations where DC transmission has an advantage [14]. In applications where high power needs to be transmitted efficiently over long distances, for example between countries, the sinusoidal nature of AC gives rise to certain problems. Where these situations arise DC interconnects are preferred typically using coaxial cables buried underground or submersed at the bottom of the sea. The advantages of DC over AC for long distance transmission include:

- Cable size and rating
- Dielectric losses
- Skin effect (and broader magnetic interference)
- Harmonics
- Synchronising grids

Each of these will now be considered in very simple terms.

Cable size and rating

Unlike AC the peak and average levels of DC are the same. This means that by using DC the maximum amount of power can be transmitted along a cable thereby making DC more cost effective in terms of cable cost.

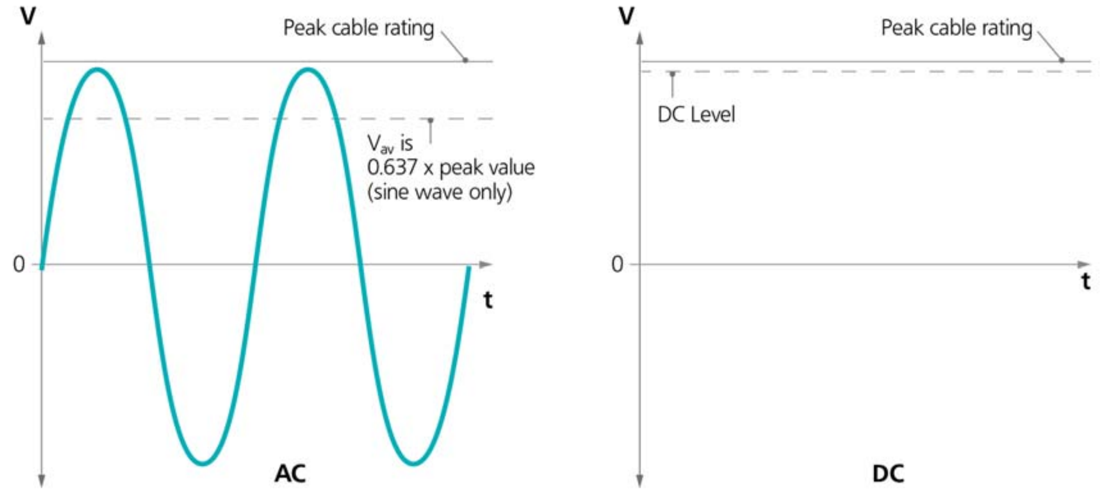

Figure 5. Average for AC and DC and its impact on cable rating.

Inductive and capacitive (dielectric) losses

The alternating nature of AC can produce significant inductive (self-induction) and capacitive (dielectric) losses as cable distances increase. Losses also occur depending upon the voltage and current. Voltage-dependent losses include polarisation effects within the main insulation and current-dependent effects include resistance losses of the conductor, skin effect, sheathing losses and other losses associated with proximity.

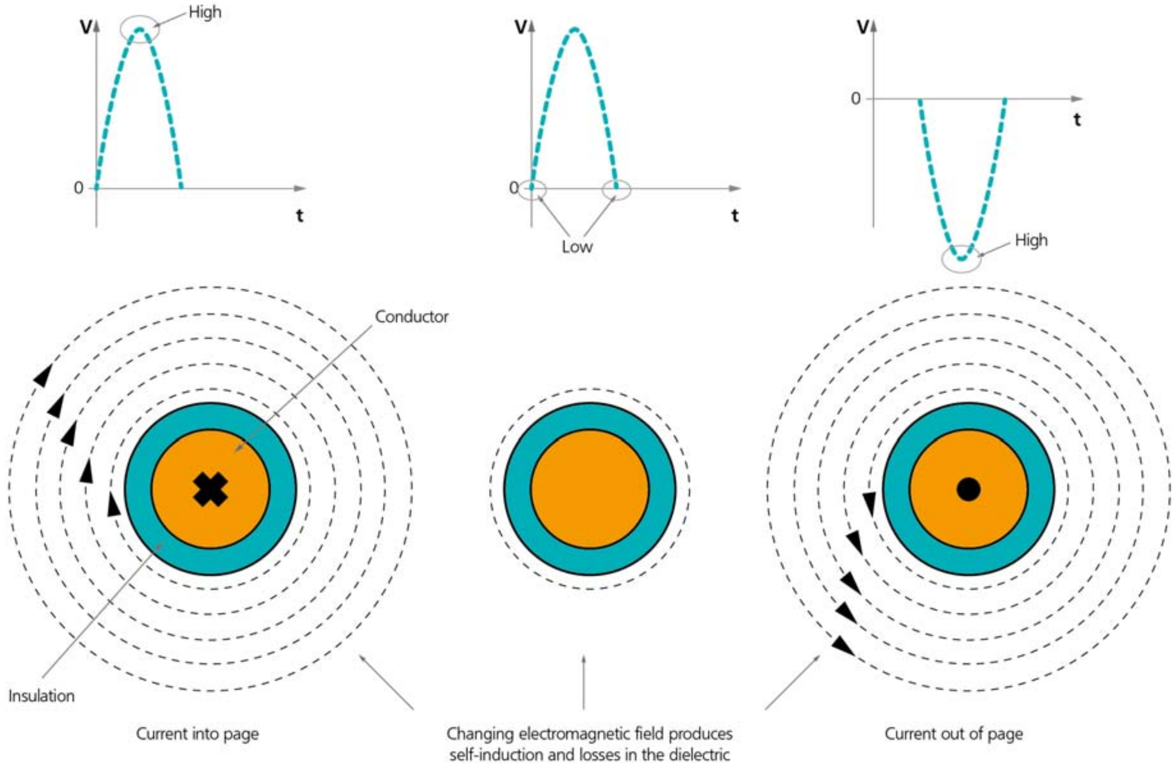

Figure 6. Self-inductive and dielectric losses resulting from an AC waveform.

Skin effect

As current passes through a conductor it produces a magnetic field. The very interaction of this field with the current that caused it forces the current to flow in the perimeter of the conductor. At AC supply frequencies (50 Hz) the skin depth is approximately 8 mm and where very large conductors are used it is possible that the central part may not be carrying any appreciable current. This means that losses increase as a result of the effective loss in conductor cross-sectional area and material, usually copper or aluminium, is wasted. Where this is the case a number of smaller conductors can be used in parallel or the conductor can be hollow in the centre like a pipe.

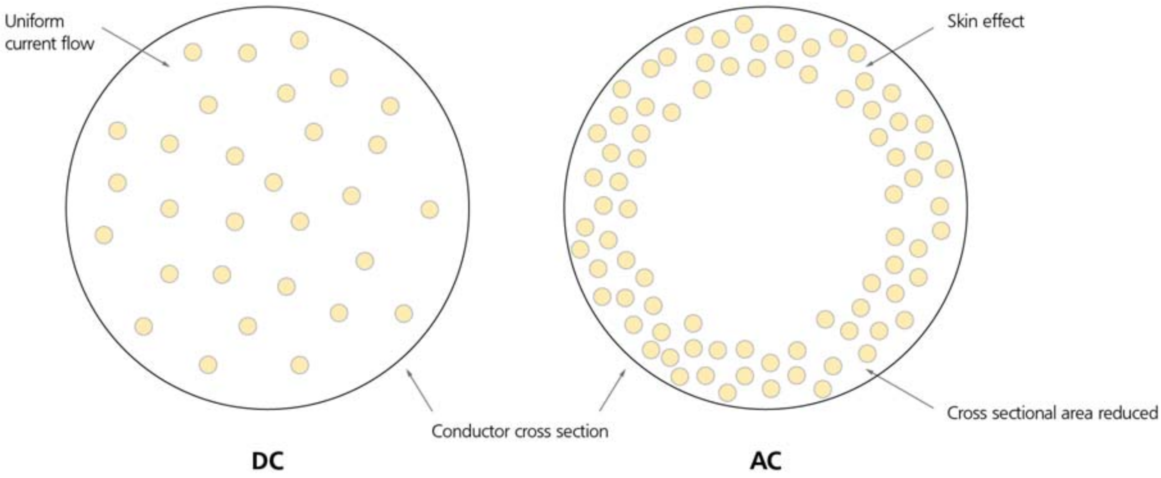

Figure 7. An indication of how skin effect reduces the effective cross-sectional area of a conductor.

Harmonics

Where any non-linearity in I/V (current/voltage) characteristics arise in a component or system there is the potential to produce harmonics or intermodulation products if more than one AC waveform exists. Non-linearity in an electricity network is typically caused by the use of dissimilar metals, connectors or less than perfect dielectrics. The resulting frequencies can, if the distances are appropriate, interact with the original waveform either reinforcing or reducing it in what is called constructive or destructive interference. If this happens it can produce areas along the cable where the peak voltage is significantly higher than that originally transmitted thereby destroying the cable if not accounted for.

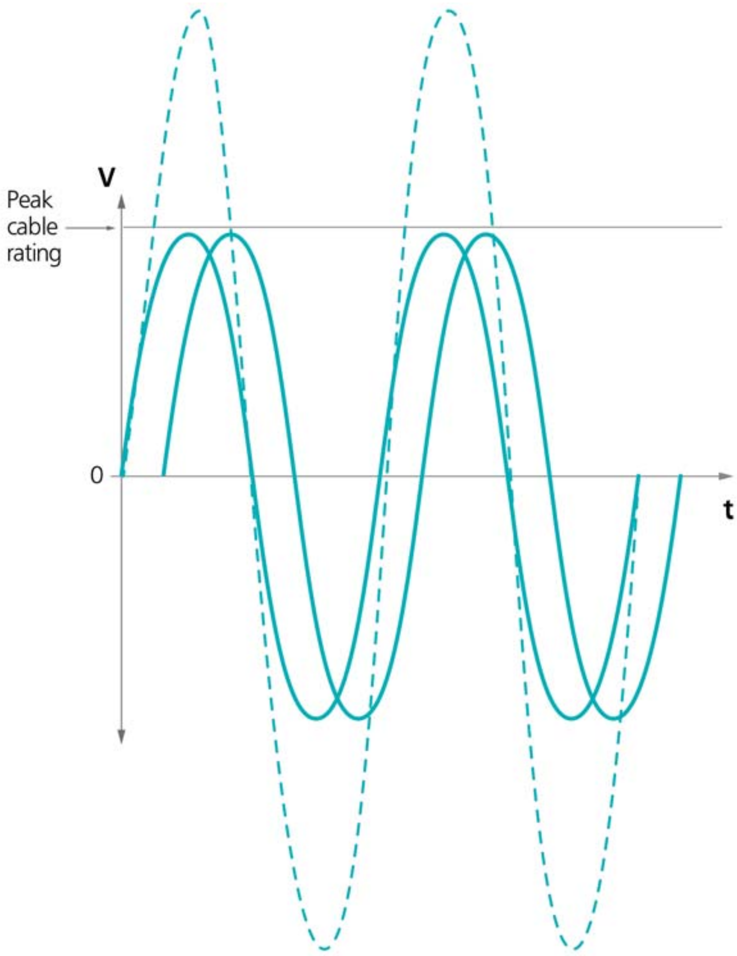

Figure 8. An indication of how peak cable rating might be exceeded.

Synchronisation

Where electricity is fed between two separate AC grids, for example between countries, there is a need to synchronise the waveform before they can be connected. This can sometimes be very difficult and the use of DC transmission, with conversion stages at each end, allows each end to synchronise with its connecting grid irrespective of what the other end of the interconnect is doing.

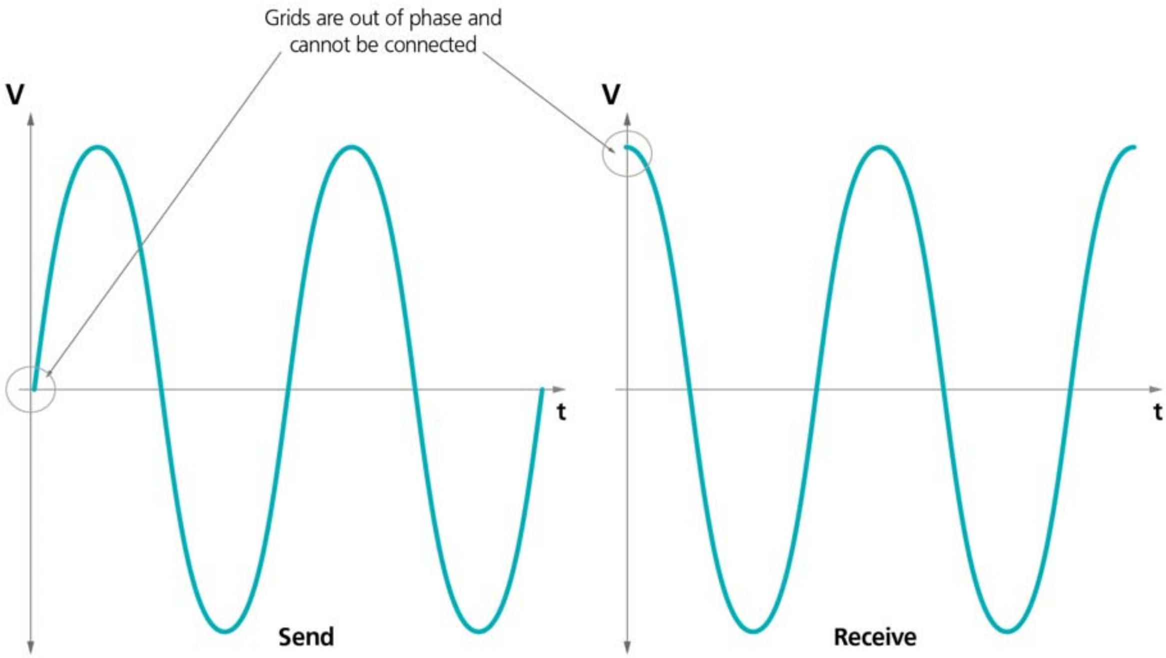

Figure 9. Synchronising Sending and Receiving Grids.

Where there is a need for high power transmission over long distances or between countries DC has some distinct advantages in terms of transmission efficiency. As a result the cost savings in transmission justify the investment in conversion equipment necessary to convert from AC to DC prior to transmission and then from DC to AC before connecting to the receiving grid. Often the converters are design to work in either direction depending on whether electricity is being imported or exported. Examples of interconnects include those between mainland UK and France and between UK and Ireland.

2.4 Smart Grids, why are they required?

To help meet carbon reduction targets in a more dynamic supply environment the entire grid from generation to the domestic meter and beyond will need to get smarter. The term smart grid refers to the application of ICT to the electricity grid and by using real time data the grid will be able to be very much more dynamic and efficient both in terms of how it functions within itself and how it interacts with the demand – the consumer. By doing so it will be very much better positioned to manage the delivery of electricity in a low carbon future both in terms of efficiency, reliability and security [15], [16], [17]. In terms of generation and transmission a smart grid will help manage a number of inter-related and often conflicting issues which will now be considered in simple terms.

Generation

Primary fuels (gas and coal) currently account for the majority of generation and are traded on international markets often months or even years ahead with their costs governed by fluctuations in production and world demand [18], [19]. As electricity becomes increasingly decarbonise relatively flexible centralised fossil fuel generation plant will be replaced by intermittent renewable and less flexible nuclear generation. In addition, many other types of generation sources will come on stream that will be geographically dispersed across the grid right down to local community or building micro-generation. To maximise the contribution of these new and distributed generation sources a smart grid will be required to harmonise each of their unique characteristics within the overall supply and demand mix.

Generation efficiency

The efficiency with which generating plant converts primary fuel to electricity varies depending upon the load. In general terms it becomes higher as the plant approaches full capacity and a Combined Cycle Gas Turbine plant may have an efficiency of 45 per cent at 60 per cent load but this could rise to nearly 55 per cent as it approaches full load [20]. To help optimise the generation of electricity, either for minimum cost or carbon emissions, a smart grid will need to ensure that the right number of generation plant are kept running at the right conditions across the entire grid to meet demand.

Availability

In the UK consumers take it for granted that electricity is always available and almost always this is true despite electricity consumption varying widely throughout the day and year. In terms of domestic use the total demand represents approximately one third of the electricity consumed in the UK but two thirds of the volatility [21], [22]. To manage these peaks and troughs in demand using existing relatively flexible generation is difficult enough but becomes even more critical if the low carbon benefits of intermittent renewables and inflexible nuclear are to be maximised.

Managing the peaks and troughs of supply as a result of demand variations can also have an impact on the carbon performance of renewable technologies. If the intermittency of renewables cannot be adequately planed for, and availability is to be guaranteed, then additional conventional spinning reserve must be held in standby to meet the need when the wind drops or the sun goes in. Conventional spinning reserve held in standby and by necessity running at part load will be less efficient and likely to produce more carbon emissions per unit of electricity.

Typically the amount of spinning reserve is sized to replace the loss in generation should a power station fail but in the future it will also need to cope with the variability of renewable generation sources. An alternative solution is to use demand management techniques to reduce peak demand generally and/or reduce demand when renewable generation is low. Demand-side-management or demand-response is a powerful tool for harmonising supply and demand but to do this effectively, and automatically, in the domestic sector requires comprehensive communication and control platforms. Without such integrated solutions some of the low carbon benefits of renewable technologies could be undermined.

Smart grids and demand-response will not only be able to improve the management of the grid itself but it will also turn historically passive domestic consumers to active participants both in terms of when and how much electricity they use and what they generate locally. Demand management is not a new concept and it has been used in the industrial and commercial sectors for many years. In practice it can be accomplished either actively or passively. In the case of industrial users a contractual arrangement is put in place where the user reduces demand, usually through on-site automatic switches, when required to do so by the electricity supplier. An alternative approach that has been used for domestic consumers in the past is for the electricity supplier to distribute, often for free or at a reduced price, low energy light bulbs.

In the future electricity consuming appliances and devices are likely to be controlled automatically with the consumer making choices as to what can be turned off and for how long. For this to become a reality a standardised open information exchange model capable of working across any IP addressable platform will be required. Two such standard protocols are emerging, EEBus and openADR (see later).

The transmission grid

As the grid becomes decarbonised more electricity will be consumed for transport (plug-in vehicles) and domestic heating (via heat pumps) placing an increasing demand on the electricity infrastructure. The general flow of electricity is from North to South and this is likely to become more-so in the future as wind energy, positioned in favourable locations in the North, increases. This will place new demands on the North/South interconnect and a smart grid will allow the existing transmission and distribution system to be much more dynamic in how it routes and re-routes electricity around the UK in response to changing national and local demands [23]. The adoption of a smart grid will mean more can be done with the existing supply network thereby reducing the need for large, costly and disruptive infrastructure projects.

The cost of electricity

Readily available and affordable energy underpins most economies in the world whether it is used to drive industry and commerce or to power homes. The cost of energy for the domestic consumer has a significant social dimension and in 2011, 4.5 m households were fuel poor in England (4.5 m relates to the 10 per cent measure, this figure is 2.6 m for the LIHC measure) [24]. The average domestic electricity bill in 2012 was approximately £550 which is nearly 40 per cent higher than in 2003 and this is partly due to the increased price of gas used to generate the electricity. As part of a package of measures the introduction of domestic smart meters could help reduce domestic consumption by 5% but their impact will be initially limited due to the installation programme and the adoption of Time-of-Use Tariffs (TOUTs) [9].

2.5 The local distribution network

In terms of supplying utilities to any building whether it is electricity, gas, water or telecommunications there is a saying that ‘the last 100 metres is the most difficult’. This is not to say that high voltage grid infrastructure projects are easy or cheap to install and maintain but that the legacy issues associated with the local distribution network and the cost and disruption of any upgrade at a national level is very significant.

Electricity consumption over the last 40 years has increased considerably however to provide sufficient headroom at both a national and local level to decarbonise domestic heating and transport through the use of electricity challenging energy efficiency targets must be met. Even if the targets are met the introduction of new transport and heating loads, which will be high power and intermittent in nature, combined with local generation, is likely to exacerbate the already ‘peaky’ domestic electricity profile. This will place a whole new control dynamic on the local distribution network and the impacts on capacity, availability, power quality and many other issues is not yet fully understood. However, with the adoption of smart meters, smart grids and demand response the hope is that the tools will be in place to manage these issues should they arise.

2.6 Smart meters

The Government’s vision is that every home and small business in the UK will have a smart meter by 2020 [25]. This will require the replacement of over 53 m gas and electricity meters requiring 30 m visits to homes and small business.

Consumers will be offered an In-Home Display (IHD) and this will provide real time information on their energy use both in terms of consumption and cost as well as other useful information. This will allow the consumer to manage their energy, save money and reduce carbon emissions. Smart meters will also allow for easier switching between suppliers, end estimated billing and eliminate the need for meter readers to visit premises. To protect consumers the Government has put safeguards in place to ensure that consumers are not subject to any sales pressure during meter installation and that consumers' privacy is protected by providing them with control over their smart meter data.

By providing consumers with near real-time (potentially 30 minute settlement) data that reflects the true cost of supplying electricity a whole new supply and demand relationship will be established. Smart meters will facilitate a more reactive, price driven, demand-response from the consumer. Time-of-Use Tariffs (TOUTs), enabled by smart meters, will mean that energy consumers will in the future need to be much more aware of what they are using and when they are using it:

> "Domestic users, who represent one third of the total demand for electricity but two thirds of the volatility will progress from passive bill payers to highly informed energy consumers and producers" [21].

As the deployment of smart metering proceeds an increasing range of market-led devices will become available to help consumers manage their energy use including enhanced energy displays, smart appliances and home automation tools. These will be able to securely connect to the smart meter receiving and reacting to gas and electricity consumption and pricing data.

The introduction of a smart grid and smart meters are important elements in decarbonising electricity in the UK. As this happens the relationship between the supply and demand of electricity will become very much more dynamic and interactive. The price of electricity will move away from a relatively fixed tariff to one where it may change every half-an-hour as it does already for many non-domestic consumers [26]. While the changes will inevitably bring some problems and issues the prediction is that the average household bill will be reduced by between 5 per cent and 9 per cent between 2016 and 2030 compared to existing policies [12].

3.0 Demand-side use of electricity

Ever since Rachel Carson wrote Silent Spring in 1962 the environment has grown to become a household word [27]. While Silent Spring was primarily concerned with chemical pollution of the biosphere ten years later energy came on to the agenda with the first oil crisis in 1973. This was initially based on security of supply but during the 1980's energy consumption and its association with carbon dioxide and global warming rose to the fore.

In late 1970 an overtime ban by electricity supply workers bought serious disruptions to supply in a matter of hours and not weeks as predicted. Since then electricity has become absolutely fundamental to our way of life and the demand has grown. Like the supply-side, domestic consumption, the demand-side, is also about to experience some significant changes including:

- A reduction in energy consumption of traditional appliances for example, fridges
- An increase in the quantity and time-of-use of appliances and electronic devices (such as ICT and those used for entertainment)
- An increasing amount of local (often renewable) energy generation primarily driven by Government financial incentives
- Growth in new technologies to generate electricity and/or heat domestic buildings (micro-CHP, fuel cells, heat pumps etc.)
- Plug-in electric vehicles
- New control devices and platforms supplied by utilities and product manufacturers
- Increasing availability of medium cost electricity storage.

Given the magnitude of these changes and those already discussed in the supply-side it is interesting to review what implications all these changes might have on electricity consumption and the existing domestic electricity installations up and down the country.

Before proceeding it is important to consider the context in which the review is undertaken. Unlike many countries in the world consumers in the UK benefit from a good, albeit aging, electricity system that within any realistic assessment ensures that when electricity is needed it is there to be used. The expectation is that this will still be the case in the future although to achieve it will require a complete change in the way electricity is viewed by the domestic consumer. This will range from something as simple as switching a light off when not needed to which domestic appliance to purchase, when to charge the plug-in electric vehicle or what energy management option to use when controlling the dwelling. As a result, the context of this review is perhaps more influenced by how the consumer and the existing domestic electricity installation deals with these changes rather than whether the grid is going to become so unreliable that wholesale alternative strategies, such as island off-grid operation, need to be considered. However, while off-grid scenarios are not considered the review does consider how local storage, either centrally configured or within domestic appliances and devices, might support electricity management strategies to reduce volatility, manage cost or reduce carbon emissions.

3.1 How electricity demand is changing

Before a domestic electricity system can be considered in detail is interesting to review how the loads might change and what implication this might have on the component parts and the system performance as a whole. Despite the inevitable uncertainties of looking to the future it is already apparent that appliances and devices of the future will be a lot more efficient and smarter in their own right. They will also be a lot more 'connected' opening up the possibility for local and/or national electricity strategies to be played out. As a result, before any review of what a future electricity system might look like a fundamental question needs answering, what loads need supplying?

Appliances*

Historically electricity would have been consumed by crude incandescent filament lighting, induction motors and resistive heating applications either stand alone or as part of various domestic appliances. These still exist today but the majority of newer appliances such as fridges and freezers are thermally and electrically much more efficient than even 10 years ago. However, at the same time their numbers and use has grown significantly and as a result appliance electricity consumption now accounts for approximately 14 per cent (approximately 62 TWh per annum nationally) of the overall domestic energy consumption from just over 4 per cent in 1970 [22].

*Note: for many domestic energy models and assessments (Cambridge Housing Model for example) an appliance is everything that consumes electricity except that used for space and water heating, lighting and the main cooker.

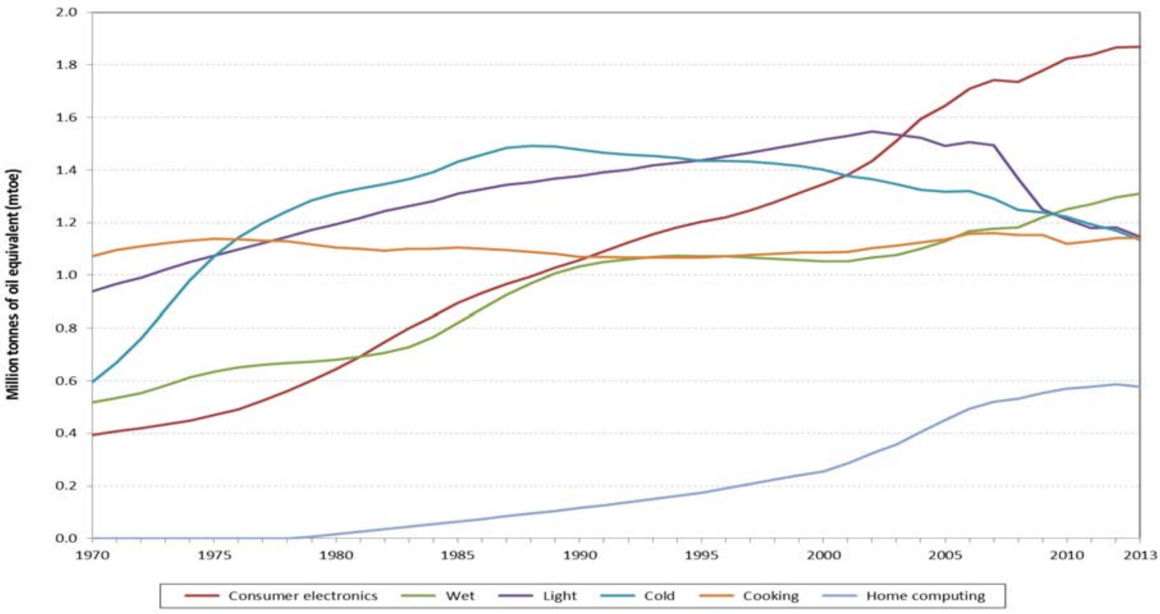

Figure 10. Electricity consumption by household domestic appliance, by broad type, UK (1970 to 2013). Source, DECC ECUK [28].

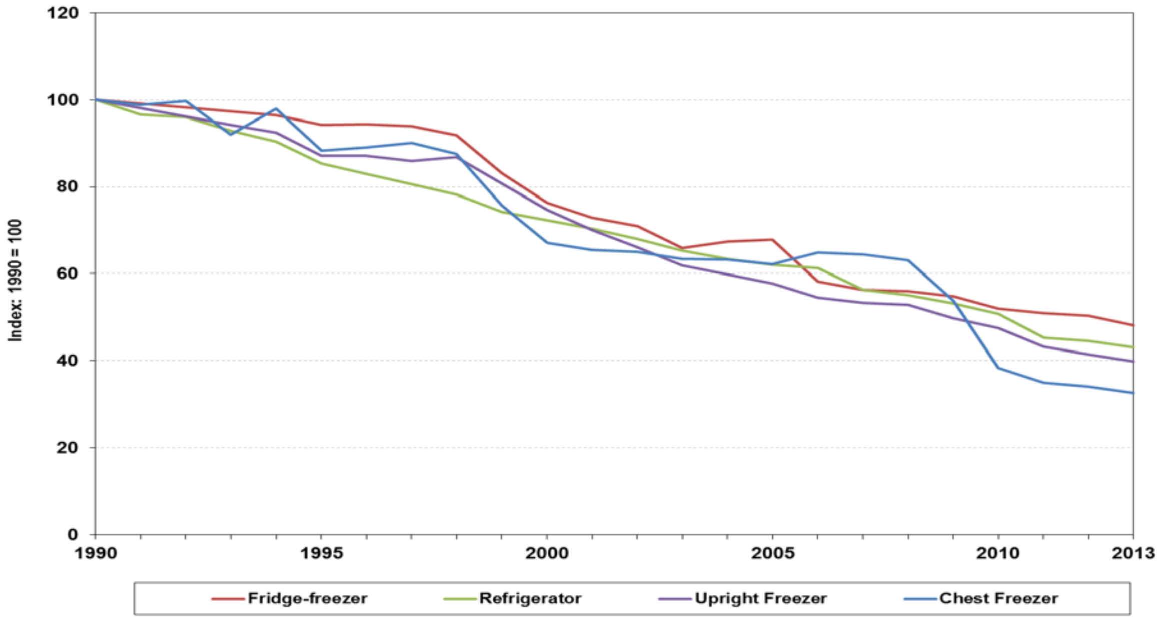

Figure 11: Average energy consumption of new cold appliances, UK (1990 to 2013). Source, DECC ECUK [28].

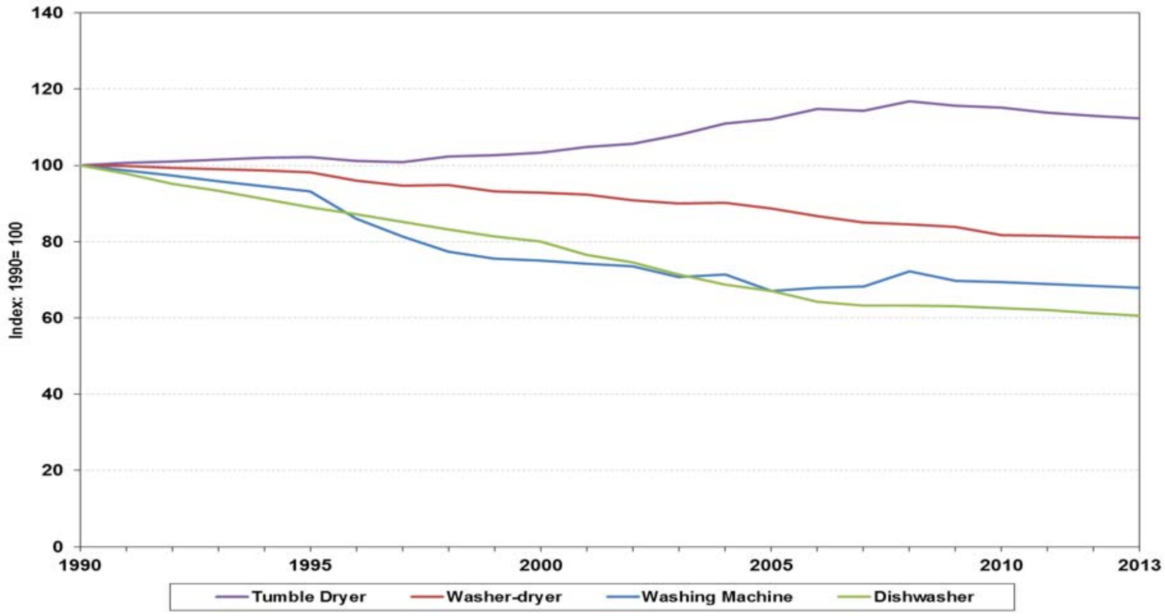

Figure 12: Average energy consumption of new wet appliances, UK (1990 to 2013). Source, DECC ECUK [28].

The semi-conductor (micro-chip) revolution and big data

It is beyond the scope of this document to undertake a full review of every electrical and electronic device but there is one key theme that, to a greater of lesser extent, appears to be common and that is convergence. Convergence is happening both in terms of increased device functionality encroaching on other product segments as well as bundling products and services to reposition commercial offerings away from commodity markets.

When Shockley, Bardeen and Brattain invented the first transistor back in 1947 [29] they launched a technological revolution and more transistors are now made every year than farmers produce grains of wheat and rice. By 2015 there are expected to be 1,200 quintillion (10^{18}) transistors [30] in the world and the cost of computing has plummeted unlike any other technology before or since [31].

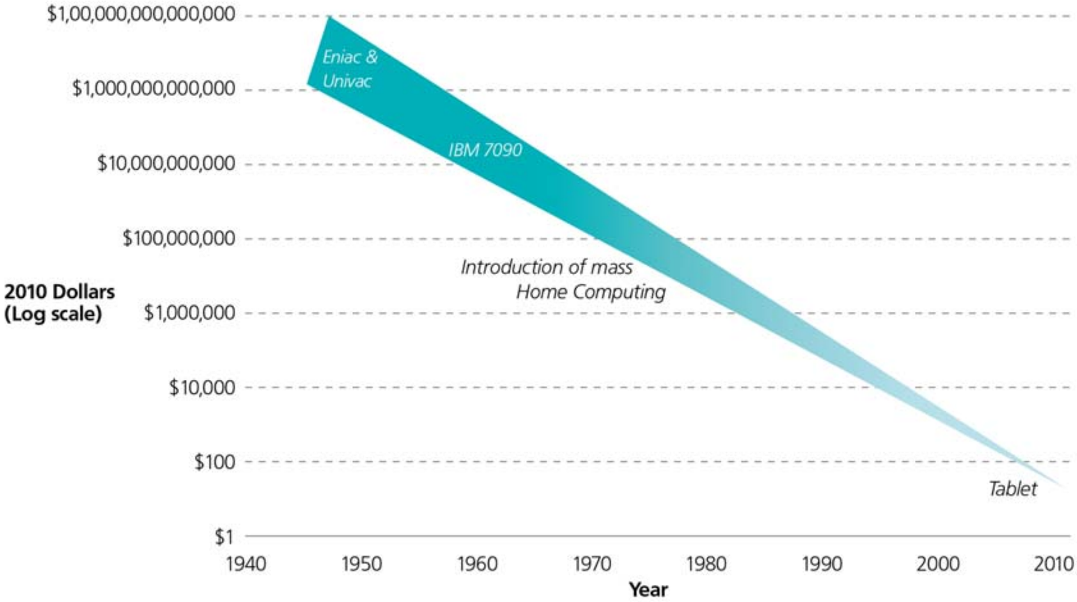

Figure 13. Cost of computing power equal to a tablet.

Despite each semi-conductor and the devices using them becoming more efficient the number of electronic devices has increased so rapidly that their overall energy consumption continues to rise. Many of today's devices and increasingly so in the future, not only consume electricity themselves but function in a connected environment via the Internet and increasingly cloud operations. This characteristic makes them unlike any other sector where simple user operations for example, web searching and video streaming, trigger responses and hence energy consumption around the world [32], [33].

The production and use of data is set to expand rapidly in the next ten to twenty years as e-commerce gives way to 'service provision' and then 'sensations' [34]. In the future users will essentially change the state of their world in accordance with their personal needs, style, values and culture [35].

Despite the Power Usage Effectiveness of Data Centres and telecommunication networks being improved as each new generation of hardware is released the expected explosion in data will mean that a meaningful part of an individual's electricity consumption in the future will no longer be confined to their own home or office.

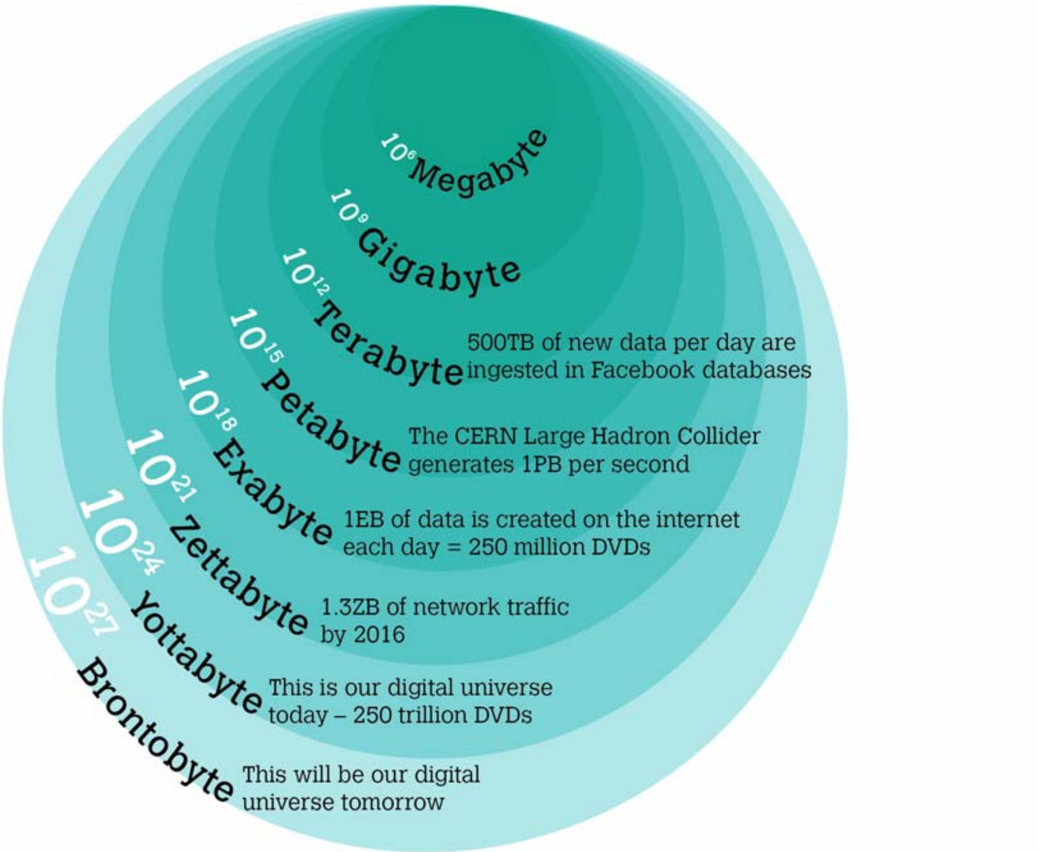

Figure 14. Big data and the Internet-of-Things.

Machine-to-machine communications and the Internet-of-Things, while initially representing a small level of traffic estimated to be 0.5 kB per second as compared to the estimated 100 GB of data traffic per person in 2020 [33], will further increase data growth as smart cities become a reality. Despite the growth in M2M communication the estimated four-to-one ratio of human subscribers to M2M communication associated with the 7 bn devices in 2020 is expected to be well within the capacity of the deployed networks.

Smart TV

There are approximately 25 m TV licenses in force in the UK and it is estimated that there will be over 70 m TV's by 2020, more than people to watch them. People are watching more TV than ever but as broadband speeds and penetration around the world increases it is reshaping how video content is viewed. In Europe the top five connected countries have 50 per cent Internet penetration and 80 per cent of those are capable of supporting TV. The historic model of over the air and cable vertical content providers is being supplemented by an anytime, anywhere online distribution model termed Over-The-Top (OTT) television. Internet TV (OTT), as opposed to IP TV which delivers high quality content to captive audiences, allows content to be delivered to any un-managed IP addressable device whether it is a TV, PC, laptop or tablet.

As the market expands new organisations are entering the television market from sectors as diverse as software suppliers, chip manufacturers, product manufacturers and many others. Many of these are also focusing on original content generation one of which for example, is Sony which is one of the largest content producers and distributers in the world.

In the UK 7 per cent of dwellings have a smart TV with an integrated Internet connection. While the average time spent watching TV is increasing over 50 per cent of people are media meshing, doing something related to what they are watching on TV, or media stacking, doing something completely unrelated to what they are watching [36].

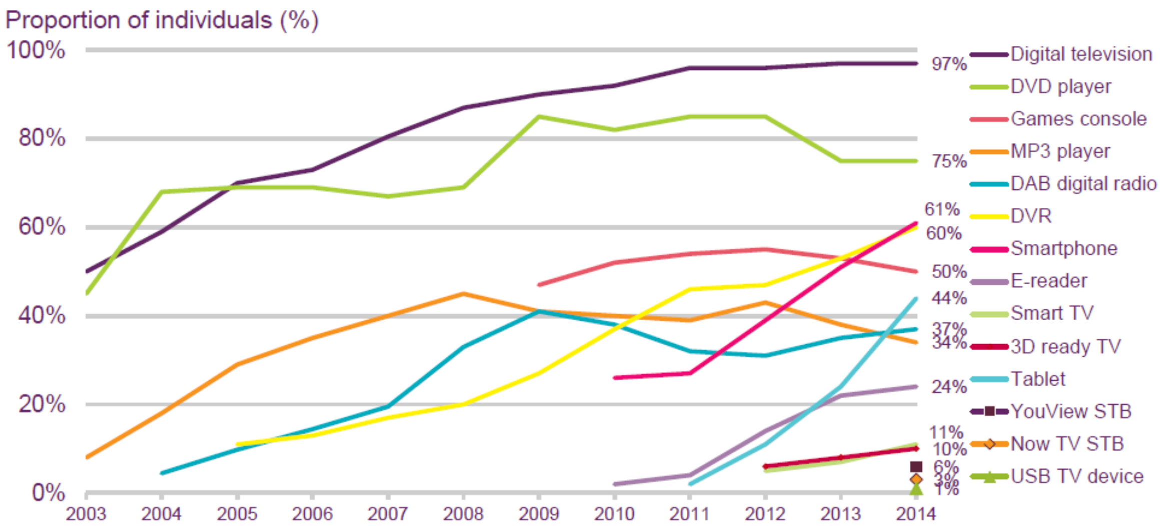

Figure 15: Household take-up of digital communication/AV devices 2003 to 2014 (reproduced with kind permission from Ofcom).

The energy consumed by TV's in the UK is estimated to be over 25 TWh by 2020 and energy consumed in standby for all electrical equipment is currently estimated to consume approximately 7 TWh or equivalent to approximately two power stations worth of electricity.

In terms of the TV's themselves, new technologies are generally reducing consumption but the size of TV's is gradually increasing offsetting some of the gains. A 40 inch TV of several years ago may have consumed around 300 W but this can be as little as 70 W or less today. New technologies such as OLED's (Organic Light Emitting Diodes) will drive down electricity consumption still further although 4K and 8K TV's, the horizontal resolution in pixels, and curved screens up to 105 inch are likely to push the energy consumption of TV's back up again [36].

Computers

The dominance of the PC is being challenged by mobile phones, tablets and for some functions the smart TV. While each of these has very different core capabilities it is now possible to fulfil many of the everyday operations on any platform. As cloud capabilities are enhanced even the more complicated operations once reserved for a PC will be able to be supported on devices that were confined to just web browsing in the past.

The total unit shipments of smart phones outstripped PC's in 2010 and sales are forecast to be over 1700 m units in 2017; laptops and desktops are forecast to be approximately 200 m and 125 m respectively. The forecast is that in just seven years from its introduction the total unit shipment of tablets by 2017 will grow to over 400 m units exceeding that of PC's [37].

A laptop computer typically consumes around 80 per cent less electricity then a desktop PC [38]. While there is no technical barrier to desktop PC's being as energy efficient as laptops they are not constrained by the need to be mobile and hence the design generally focuses on computing performance and cost rather than battery life. In terms of the mobile revolution the development of power management techniques is clearly indicated by how mobile phones have progressed in just the last ten years.

Mobile phones (and other mobile devices)

There are now approximately 7 bn mobile phones in the world and approximately 5 bn mobile subscribers. In Western Europe mobile phone penetration has reached 130 per cent and in the UK 30 m phones are sold every year. In terms of the global metrics for mobile communications it is estimated that by 2020 approximately 1.7 bn will be sold annually.

With the growth of mobile communications many devices today are equipped with battery storage allowing them to function on-the-move. Mobile devices not only consume electricity in themselves but they also consume electricity in communicating with the remote network hub and then across the telephony/web network. The performance of these aspects has received considerable attention over the past ten to fifteen years to minimise electricity consumption and improve data security.

The Nokia 3310 was one of the most successful models of pre-smart mobile technology, first announce in 2000. By today's standards it is extremely limited in functionality and it had a very small monochrome LCD screen and a 1000 mAh battery. The first smart phone was released in 2007 and since then there has been an unprecedented growth in network traffic mainly relating to downloading data rather than voice communications. In terms of global carbon emissions it is estimated that by 2020 mobile communications will result in more than 235 million tons (Mton CO_2e) which is approximately one-third of present UK emissions. Of the 235 million tons approximately 30 per cent is produced as a result of device manufacturing, 30 per cent from the radio access network infrastructure, 20 per cent from Data Centres, 10 per cent from user device operation and 10 per cent network operator activities [33].

As the mobile revolution continues and a balance is struck between device power consumption, speed/capability and battery life all subsystems in the chain are becoming increasingly self-configurable and adaptable to a particular mode of use or network requirement thereby driving down their electricity consumption. For example, the latest Bluetooth technology is Bluetooth Low Energy (BLE) or Bluetooth 4.0. The iPhone 4S released in 2011 was the first BLE device and the BLE modules are claimed to use between 1 and 50 per cent of the power used by previous 'classic' Bluetooth modules. In 2005 the IEEE introduced a standard for WiFi protocol that utilised a sleep mode called WMM-Power Save where the WiFi enters a sleep mode while waiting for packets of data. Even the radio frequency power amplifier of a GSM mobile phone intelligently reduces its power output to the minimum required to maintain good communications.

The mobile revolution is also changing the energy consumption of the network. LTE (Long-Term Evolution, known as 4G) networks provide accelerated mobile Internet performance but need several times more data per task than 3G networks with an associated increase in electricity consumption.

Further information on Communication Protocols is provided in Section 7.

The proliferation of ICT electronic devices many of which are equipped with storage, have sophisticated power management techniques and are Internet enabled raises a number of interesting questions:

- Will the advanced power management strategies driven by the need to extend battery life in mobile devices extend beyond the device and interact with the broader electricity supply itself?
- In-use device power consumption may be reducing relative to speed and capability but device batteries are increasing in size often requiring higher power chargers to charge them in shorter times.
- Given the growth in mobile devices, can the embedded storage play a part in a demand management strategy?

Power management has come a long way in just 10 years driven by the need to increase performance and extend battery life. It is interesting to consider how the lessons learnt from the mobile revolution can be applied more broadly within the domestic electricity environment and how devices or sub-systems will interact with each other in the future to drive down electricity consumption and hence carbon emissions.

Lighting

Global energy consumption for domestic lighting is estimated to be almost 1000 TWh in 2012 of which over 70 per cent is used by incandescent bulbs. In the UK the electricity used for lighting is decreasing in domestic dwellings and stood at approximately 14 TWh in 2014 or approximately 12 per cent of domestic electricity demand or 3 per cent of overall energy demand. It is however increasing in the services sector and in total the overall UK energy consumption for lighting has stayed stable; consuming 4.82 mtoe in 2000 and 4.83 mtoe in 2012.

Over the past 5 years tungsten lamps have been phased out and some of the less efficient tungsten halogen and fluorescent lamps are in the process of being removed from the market. Incandescent bulbs have an efficacy of approximately 10 lm/W and transform only about 10 per cent of electrical energy to useful light. In comparison efficacies for LED packages, the semiconductor device itself, are set to achieve 250 lm/W and for luminaires of over 200 lm/W [39], [40].

In the UK LEDs are expected to increase their revenue share from 13 per cent in 2011 to 35 per cent in 2018 despite a rapid fall in prices. The prediction is that by 2030 all of the 1000 m light bulbs in the UK will be LED (Gone Green scenario; CFL's and halogen lamps may also be present depending on the scenario [9]).

The LED's themselves are also getting more powerful and efficient and continue to benefit from considerable research funding. Experiments at the Massachusetts Institute of Technology have even tested an LED which gives out more energy in light than it consumes in electricity [41]. While the LED is ultra-low power and only produces 69 picowatts of light it achieves this on only 30 picowatts of electricity. The apparent efficiency of over 230 per cent does not break the laws of thermodynamics as the additional energy is drawn from lattice vibrations making the LED cool down.

As with most semiconductor devices individual LEDs run on a low voltage typically in the region of one or two Volts however, many different configurations exist and some contain internal circuitry which allows them to work directly from a 12 V DC supply or even directly from a 230 V AC supply.

Plug-in vehicles (plug-in-hybrids, pure-electric, range extended)

The Government has ambitious plans for the introduction of Ultra Low Emission Vehicles (ULEVs) and its vision is that by 2050 almost every car and light van in the UK will be an ULEV [42]. In terms of plug-in vehicles, just one of the potential ULEV options, they will primarily be recharged at home or at the workplace with some provision for public recharging either via charging stations or in-road inductive coupling. As the number of plug-in vehicles increases so will the demand for electricity. By 2030 there is expected to be in the region of 3 m vehicles consuming 8 TWh annually depending on market uptake [9]. At a national level it is anticipated that this is unlikely to be entirely an additional load on existing peak generating capacity. Research has shown that the majority of vehicle owners will charge their vehicles at home, at night time, during the off-peak period. This is not only most convenient for owners but also maximises the environmental and economic benefits by using cheaper, lower carbon, gas, nuclear and when available renewable electricity. By doing so plug-in vehicles will help to balance the demand for electricity consumption and smart meters will act as a platform to control plug-in vehicle recharging. Cars (for example the Cadillac ELR) are already being sold as 'smart grid ready' [43].

The charge management of plug-in vehicles can go further than just using night time off-peak electricity. Smart charging will also allow the utility, or an intermediate aggregator, to decide when and how fast to recharge the vehicle within limits set by the owner. Future business models may allow intermediaries or aggregators, possibly a service offered by the vehicle manufacturer themselves, to negotiate with utilities on behalf of a collective group of owners, perhaps in a street or neighbourhood. Home Area Networks will interface with Auxiliary Load Control Switches (ALCS) to control scheduled charging of plug-in vehicles as well as many other loads throughout the home. Intelligent power networks will work seamlessly to harmonise electricity with lifestyle and at all times balancing consumption with cost, carbon emissions and availability of electricity.

Vehicles can also export electrical energy stored in their batteries back to the grid at times of peak demand either at home or at work. Several car manufacturers have developed Vehicle to Grid (V2G) capabilities where a bi-directional on board charger allows the vehicle battery to be charged from the grid and discharged to the grid [44], [45]. Nissan have used V2G in the work place by importing and exporting electricity from employee plug-in vehicles throughout the day to minimise their energy bills while leaving employee cars fully charged ready for the journey home. Whether there is a need to export energy from the vehicle depends on whether sufficient flexibility can be gained by just smart charging, i.e. not charging at times of peak demand. If this isn't the case then exporting may become necessary to manage the peak demand but this will have an impact on battery lifetime and vehicle warrantee.

In terms of plug-in vehicles and the domestic electricity installation, the installation of most domestic charging outlets does not require a new connection to the grid. Currently most vehicles can be charged from either a 13 A or 32 A circuit with charging times typically in the region of 8 hours to 2 to 3 hours (80 per cent charge) respectively. Where satisfactory charging can be delivered by the existing domestic installation the DNO does not need to be notified although the IET Code of Practice for installers does stipulate that the installer should inform the relevant DNO of the installation within one month.

The main issue with charging plug-in vehicles in the home surrounds the capabilities of the low voltage local distribution network to meet the power requirements. When sizing any electricity network whether it is the 230 V ring main in a home or a number of homes being fed by a local distribution transformer, a diversity factor is introduced. Diversity in an electricity system relates to the fact that not all of the appliances or devices in a home will be on together or, in terms of a housing estate, not all houses will be consuming their maximum. Often when considering diversity the assumed consumption can appear quite low and in the case of domestic dwellings this can be as low as a couple of kW per house. This is not to say that this is the limit but that diversity across a number of houses means it is sensible way to size the electricity infrastructure. While this has worked well in the past as the installation of charging points increase in a local area there may be a cumulative effect known as ‘clustering’ which could require the local distribution network to be strengthened. To help overcome this tariff structures encouraging off-peak charging will have an impact but they are unlikely to solve the problem altogether. As plug-in vehicles become common place smart chargers will be required. These will interface with other smart chargers, the local distribution network and even the grid to ensure the vehicle is ready at the right time while working within the capabilities of the local and national supply network.

Heat pumps

Air conditioning in growing rapidly in the US, China and India where the growth in renewable energy generation is more or less offset by the growth in consumption of electricity by air conditioning systems. Similarly there is also a move towards more domestic air conditioning in the UK ranging from packet systems to portable units providing cooling, dehumidifying and fan options. Often portable systems are a distressed purchased during a heat wave but thereafter are used every time the temperature rises above ‘normal’.

Heat pumps, as opposed to air conditioning (cooling), are an important part of the effort to meet the UK’s carbon reduction target. Like air conditioning and domestic fridges they use the compression-vapour cycle to essentially ‘pump’ heat from one location to another. They typically extract heat energy from sources outside the building for example, the air, the ground or a water course and then supply it, often via air or wet under floor heating systems, to the dwelling. In practice the commonalities between heating and cooling systems are such that where air is used they can work in reverse to cool the dwelling if required.

Heat pumps use electricity to power the process but they supply more heat output than they consumed in electricity. This gives rise to a factor for heat pumps call the Coefficient-of-Performance (COP) which is a ratio of the thermal heat output to electricity required to drive the process. The theoretical performance for heat pumps can be in the region of 4:1 but in practice it is often closer to 3:1 or even 2:1 in cold weather. In January 2013 EU legislation came in to force for air-to-air heat pumps that included both energy efficiency requirements and energy labelling for both heating and cooling systems less than 12 kW (approximately the size needed for a domestic dwelling). The energy labelling is based on the Seasonal Coefficient of Performance (SCOP) and the Seasonal Energy Efficiency [46].

Initially heat pumps will be more applicable to heating domestic buildings that are not on the gas grid but in the much longer term, 2030 and beyond, they are expected to play a significant role in all residential heating and hot water [47]. Currently 2.3 million homes in Britain are heated by electricity and it is estimated that by 2030 there will be between 4 and 7 million heat pumps in residential buildings depending upon market uptake [9]. Many of these are likely to be air to water systems as despite their lower performance than ground sourced heat pumps they are relatively easy to install in existing buildings as they don’t need large and disruptive earthworks normally associated with ground sourced heat pumps.

As with many high power applications associated with heating purposes heat pumps can consume a large amount of electricity. This can become a particular concern during switch-on and switch-off when voltage fluctuations must say within recognise limits as specified by the Electricity Supply Act 1988. This depends on the domestic network impedance at the point of supply to the heat pump and it is advised that the DNO is contacted to determine the maximum load that can be connected at the chosen location on the network. Heat pumps with a heating output greater than approximately 12 kW are unlikely to be suitable for use with a single phase electricity supply as, depending on the COP, the power taken from the domestic electricity network might exceed local supply capabilities [48].

3.2 Local supply and connection

Micro-grids

Micro-grids are small scale versions of the traditional grid that allow specific local goals to be met. They can be connected to the macro-grid or function independently and typically mange real-time demand, supply and storage of electricity often in a large campus such as a University. A micro-grid can be a well-defined network of physical hardware, generation sources and storage or it can be considered as a local electricity management strategy using existing infrastructure but optimising it to achieve the best local outcome.

Where local generation is available, micro-grids have the potential to improve efficiency by connecting local consumers to decentralised electricity generation (PV or other micro-generation technology) and thereby reduce transmission and distribution losses associated with the grid supply. This is particularly applicable where new housing developments are constructed and the appropriate hardware and infrastructure can be installed from new. In the future new business models may arise surrounding micro-grids where commercial organisations act as intermediaries and install the necessary hardware to allow a local electricity management strategy to be played out and at the same time negotiate with the electricity supplier on behalf of their consumers.

Local generation of electricity – micro-generation

At a domestic scale there are a number of technologies that can be used to generate electricity including solar PV, wind generators, micro-CHP, fuel cells etc. These fall in to two broad categories. The first uses fossil fuels to produce electricity often at a building or community scale thereby eliminating transmission and distribution losses associated with the National Grid and the second uses renewable sources such as the wind and sun.

Since the introduction of the Governments Feed-in Tariffs (FIT’s) in 2010 there has been a significant increase in micro-generation and this is expected to continue in the future.

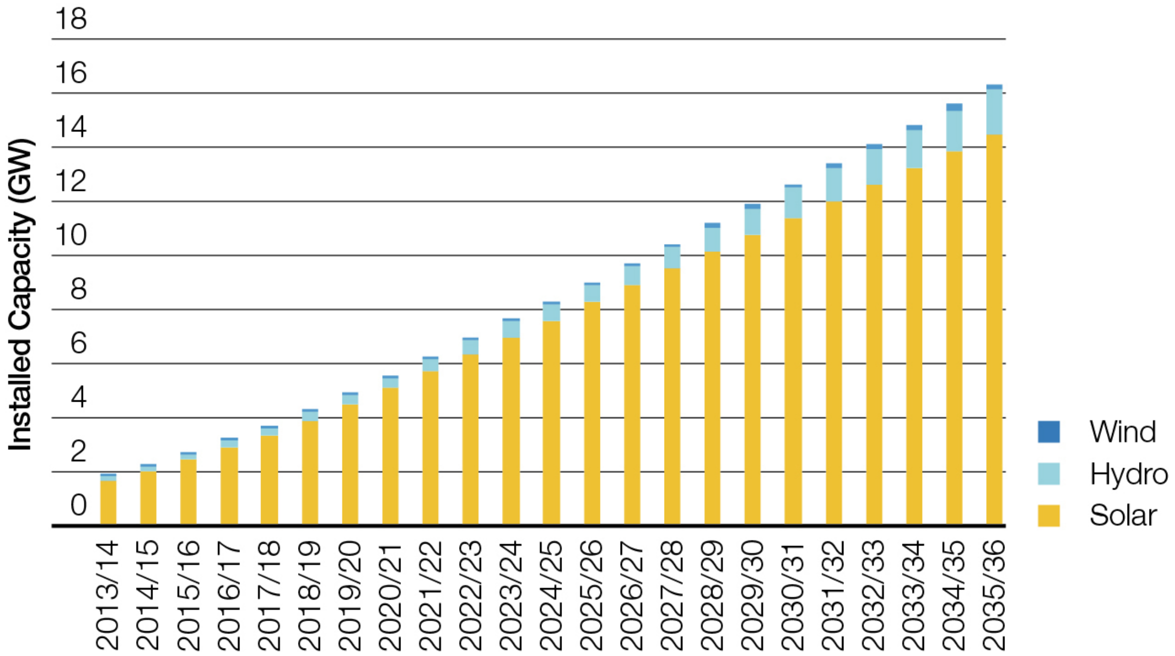

Figure 16. Micro generation (<1 MW) installed capacity (reproduced with kind permission from National Grid; Gone Green scenario).

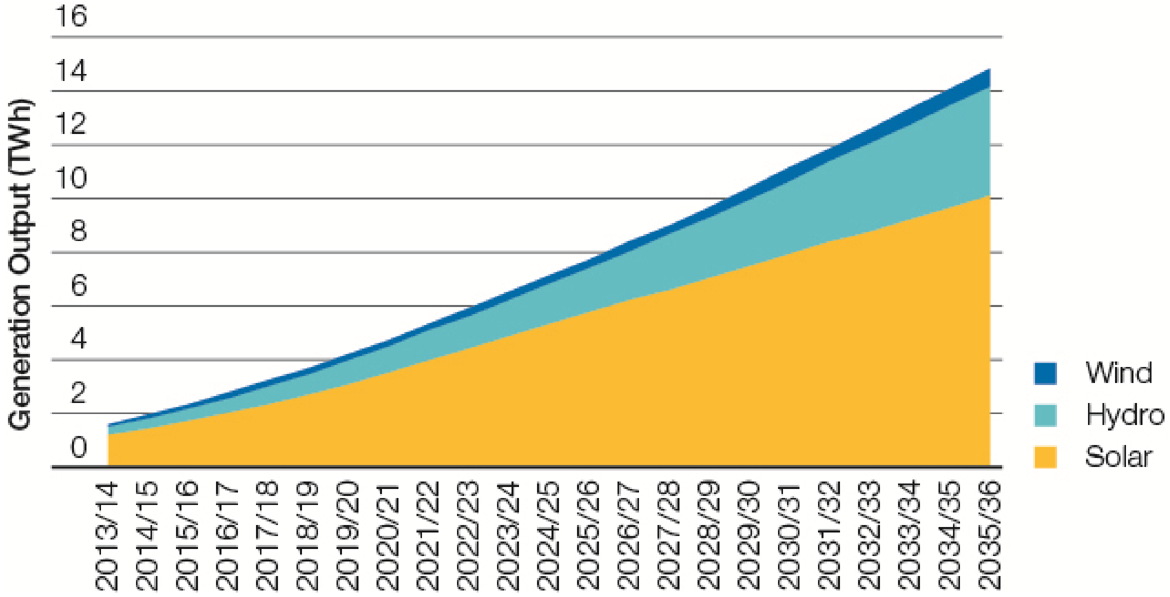

Figure 17. Micro generation (<1 MW) generation output (reproduced with kind permission from National Grid; Gone Green scenario).

In terms of the domestic sector by far the most installations registered under the Government's FIT scheme are solar PV and this will now be considered as an example.

Solar PV has grown rapidly across the world to a total capacity of over 70 GW and a total output of approximately 80 TWh per annum. In terms of global installed capacity, solar PV is now third behind hydro and wind generation.

The UK solar market is ranked 8th in the world [49] and currently PV is viewed by the Government as having the potential to make a significant contribution to low carbon electricity of the future. Installed costs of PV have dropped by approximately 50 per cent between Summer 2011 and March 2012 [50] resulting in 1.4 GW of installed capacity in 2012 growing to 2.4 GW by the end of June 2013. Of this approximately 1.7 GW [51] was small scale, below 50 kW installations.

A typical domestic installation is between 1.5 and 4 kWp and each kWp will produce approximately 800 kWh over an average year depending on the particular situation. This is a meaningful figure compared to the average household consumption which is approximately 4000 kWh a year.

Micro-generation is a key part of the future electricity strategy but as it grows it raises a number of questions relating to the local distribution network supplying dwellings. For example, if the PV installations fitted to houses on the sunny side of a road are exporting much of their electricity does this have any detrimental impact on the local distribution network or the sub-station transformer as a result of potentially unbalanced loads? Also, how might local micro-generation interact with new heating and transport demands and will hot spots or other strange effects occur? At a national level there are also discussions surrounding the stability of the grid as renewable energy approaches 20 per cent of the total supply and solutions to this may call for the installation of huge grid storage ‘batteries’ to restore balance to the system.

Whether at a national or local level there are clearly significant challenges to decarbonising the grid. If it can be achieved however, it potentially decarbonises much of domestic heating and transport and as a result reflects the key role electricity will take in a low carbon future.

4.0 Connecting the supply to the load – a review of potential approaches

Any domestic electricity network must be able to distribute electricity to the end appliance or device safely, efficiently and cost effectively. In the past most domestic loads would be supplied with 230 V AC and it would be utilised directly to supply electric motors or resistive heating with only rudimentary switching between the wall outlet and the point-of-load. However, in very general terms electricity is now converted, controlled and managed much more than in the past driven by the need for tighter voltage tolerances and improved power quality associated with increasingly more electronic devices.

Also, in very general terms, consumption in the future may become more polarised with the proliferation of low power electronic devices at the low end and a whole new category of high power applications in the shape of electric heating and transport at the high end. If this hypothesis is correct and the current 230 V AC system is classed as a high power network then it raises the question as to how well it is suited to low power domestic needs in the future.

Meeting these diverse needs is likely to call for compromises in network design although there is one part of the domestic electricity load that appears to be open to being considered as a separate sub-system; that of lighting. In theory at least domestic lighting with the use of LED's for example, is relatively well defined both in terms of its end use, electricity demand, potential supply voltage and the existence of dedicated lighting circuits installed in nearly all dwellings up and down the country. However, installing a new low voltage network or converting the existing lighting circuit to anything other than 230 V with point-of-load conversion to power the LED luminaires raises a number of issues ranging from retrofit costs to electrical safety.

If for the moment a hypothetical review is undertaken of a domestic network then a series of questions arise that start to structure a review process. Clearly there are many inter-related issues in the following chart but some of the major components will now be considered.

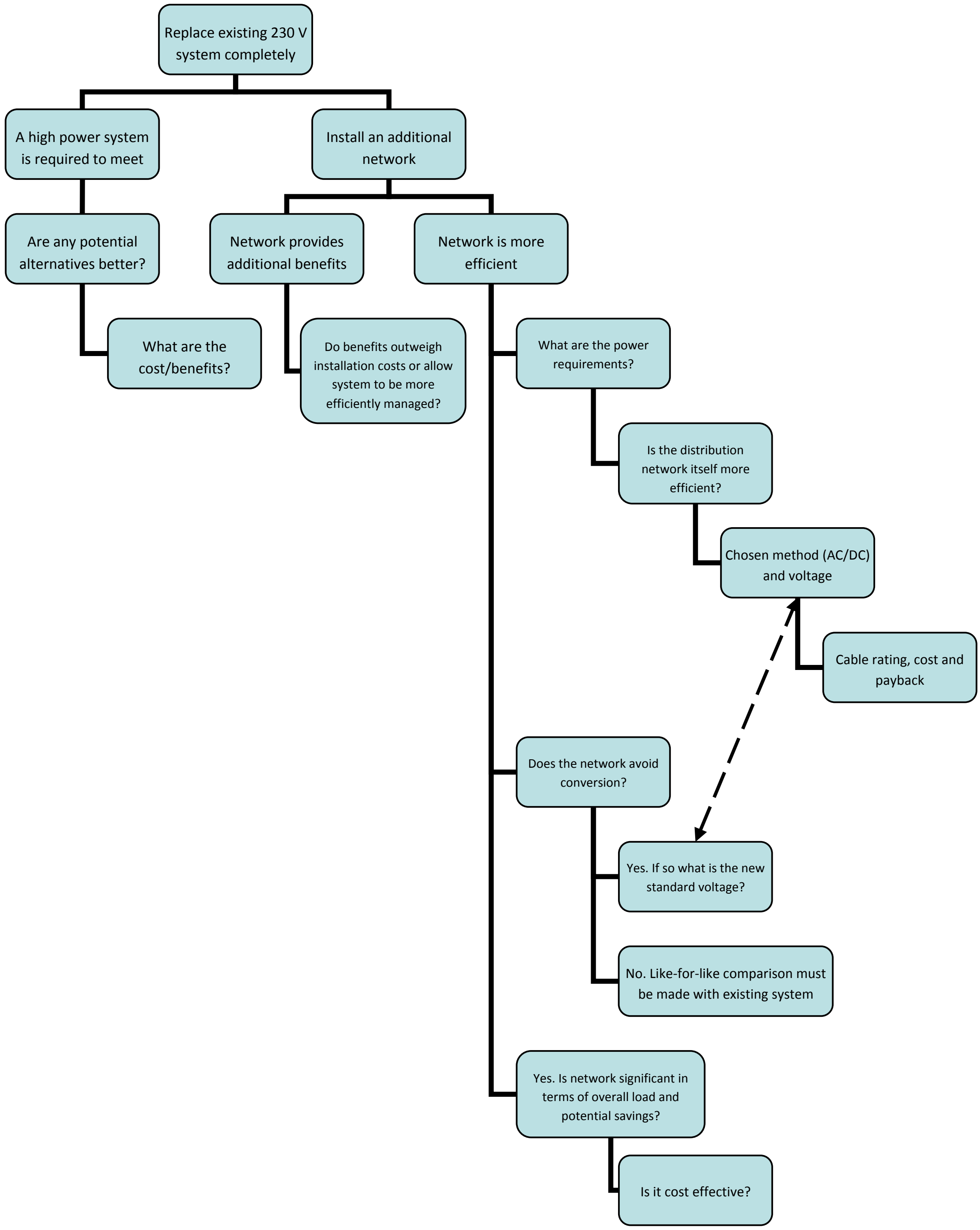

Figure 18. A simple review process for a domestic electricity installation.

4.1 Alternative networks

There are two well established networks that combine both power and data capabilities thereby bringing significant additional benefits to just supplying electricity alone – both of these provide DC to power electronic devices. The advantage of these two systems is that they are both end-to-end solutions that can be bought off-the-shelf:

- Power over Ethernet (PoE) is currently primarily a commercial system where structured network cabling is also used to supply electricity to end devices.
- USB (Universal Serial Bus) is a ubiquitous ICT orientated protocol that was originally used to charge phones and run low power peripherals from for example, a laptop, but is now capable of supplying more power hungry devices further afield.

Power over Ethernet

PoE is a technology for hard wired Ethernet LAN's (Local Area Networks) and it simply allows power to flow along the CAT5e cable (the minimum cable type) that would normally be reserved for data signals only. A standard (802.3af) was established by the IEEE in 2003 that specified a 15.4 W maximum power delivery (12.95 W at the end device) using two pairs of wires in the CAT5e cable. This was then uprated to 30 W (802.3at) later but there are propriety offerings that boast 60 W by using all 4 pairs of wires in the Ethernet cable.

The system works by injecting approximately 50 V DC on to the Ethernet cable from a central point which can be a suitable existing network switch or an additional injector. If the end device does not have the inbuilt capability a splitter is used near the point-of-load to split the power from the data and convert the 50 V to what's required by the end device. Where a fully configured network is not used a single channel injector can be used to power just one end device using a single Ethernet cable. As with normal Ethernet networks the maximum cable length between injector and end device, which is defined by the data component, is 100 m however this can be extended by various means.

The combination of data and power capability over one cable makes product installation easier and potentially safer through avoiding the need for 230 V at the end device. Energy efficiency may also be improved by removing local power adapters but this depends on the relative efficiencies of these compared to the power supply in the injector. By interrogating the injector via the network it is also possible to read the current supplied by each injector port and to switch the port on and off thereby saving energy. PoE can be used to power almost any device that falls within the power limits whether it has the inbuilt capability or via a suitable external splitter. This includes things such as VoIP phones, access cameras, terminals, VDU's, thin clients (computers) and much more. Recently with the growing popularity of low power LED lighting PoE has been used to power luminaires where its data capabilities also allows additional functionality such as occupancy and lighting level sensors to be included.

USB

Similar to PoE the Universal Serial Bus (USB) is designed to provide power as well as data communications. It can support 127 devices and has developed over the years from 1.5 Mb/s to 480 Mb/s. Currently a normal USB 2.0 has a low current limit of 100 mA and a high current limit of 500 mA at 5 V although a Thunderbolt connector is able to deliver 2 A at 5 V. Several years ago USB 3.0 was introduced which increased the theoretical bit rate by 10x's to 5 Gb/s and raised the low current limit to 150 mA and the high current limit to 900 mA. More recently the USB 3.0 Promoter Group has announced a new specification which will allow USB 3.0 compatible sockets and cables to deliver up to 100 W by changing the voltage from 5 V to 20 V and increasing the current to 5 A.

USB also has limitations on the maximum cable length and in most cases this is restricted to 3m. With special cables this can be increased to over 6 m and with a USB bridge this can be extended to over 30 m. With such a large increase in power a single USB 3 SuperSpeed hub could be charging a laptop, powering an external hard drive as well as a second monitor. In future, TV manufacturers could include high-powered USB hubs to power nearby AV and communication equipment thereby reducing the need for multiple wall outlets.

Both USB and PoE bring power and communication functions together by using the data exchange capabilities to negotiate power need with the device in a number of incremental stages. This level of power control allows a common supply to deliver a range of different power profiles best suited to whichever device is connected to that particular port. For example, in the future a USB 3 might provide 60 W (20 V at 3 A) for a laptop or 5 to 10 W (5 V at 1 or 2 A) for an average smart phone.

The benefit of both of these systems is that they are well developed solutions that are supported by appropriate standards, research and testing. Components are readily available and system design expertise is relatively common.

In terms of network distribution efficiency both PoE and USB are still subject to conversion and distribution losses as any other network. Whilst a modern PoE injector may have a very efficient power supply (see later), power is still converted from 230 V AC to approximately 50 V DC, distributed to the point-of-load and then converted again to what's required by the end device. In the case of PoE the voltage is higher than USB potentially reducing its distribution losses although conductor sizes are relatively small.

In the domestic environment USB ports are much more common and could in the future be used not just for connecting between devices, for example a laptop and a peripheral, but also as an additional low voltage power outlet complimenting the existing 230 V wall outlet. This may reduce the need for individual power adapters and bulky 230 V plugs and sockets although where this is the case, USB sockets are still likely to be associated with a central device such as a TV or computer.

Beyond these two propriety systems there are a number of alternatives that focus on specific aspects of an electricity system such as the use of DC or high frequency AC. In terms of DC there is a tantalising thought that low voltage DC generation sources, for example PV, can be used to directly supply low voltage DC lighting and other devices without the need for any conversion stages and their inherent losses. This is especially considered an issue where low voltage PV is available which is then inverted to 230 V AC, fed in to the domestic network only to be converted back down to a low voltage to power an electronic device. In practice however, this rarely happens as while PV panels are readily available for most common low voltages such as 5, 6, 12, 24 V most domestic installations use panels with an output voltage typically in the range of 25 to 35 Volts. To help reduce cable losses (conductors are normally sized for only a 1 per cent [52] voltage drop in PV installations) these are then placed in series to produce a string voltage of approximately 200 to 300 V DC before being fed to the inverter. The assertion that PV is low voltage and that it can be used directly to supply devices is called in to question by the need to reduce distribution losses which can quickly rise unless the system is very low power or supply and demand are in close proximity (see later).

Typically any potential alternatives to the existing AC system are more suited to low (or very low) power applications generally as a result of the voltages used. As a result they may or may not provide advantages (see later) but where they do it is only for part of the domestic load and is often only in very specific circumstances.

Having briefly considered alternative systems to the existing 230 V AC system the characteristic of a domestic electricity network will be examined in more detail. This can be broken down in to two parts:

- Energy conversion losses (External Power Supplies (EPS's), DC to DC converters, etc.)
- Network parameters (power, voltage, cable losses, fault protection etc.).

4.2 Conversion

The first thing to note about electricity conversion is that it takes place throughout the whole generation, supply and demand network. Even within the appliance or electronic device itself it is likely to be further converted from the nominal nameplate voltage to voltages as low as 1 or 2 V typically used to power CPU and memory chips respectively. Good practice in energy conversion usually dictates that it is done locally to the point-of-load to minimise distribution losses and voltage fluctuations.

While losses are very important in any system voltage fluctuations can also have a large impact on product performance and lifetimes. For example a computer or an electronic device with a microprocessor (CPU) requiring 1 V its supply voltage must be held within -/+5 per cent or approximately 10 mV. At the upper limit there is an increased risk of electro-migration that can lead to early chip failure and at the lower limit switching speed and performance is impaired.

For many microprocessor based devices there are usually three or four stages of conversion each fulfilling its own particular function and each with its own efficiency. While the diagram below shows point-of-load conversion for the CPU and memory there are often many other voltages required and 4 or 5 is not uncommon, each with its own dedicated conversion stage.

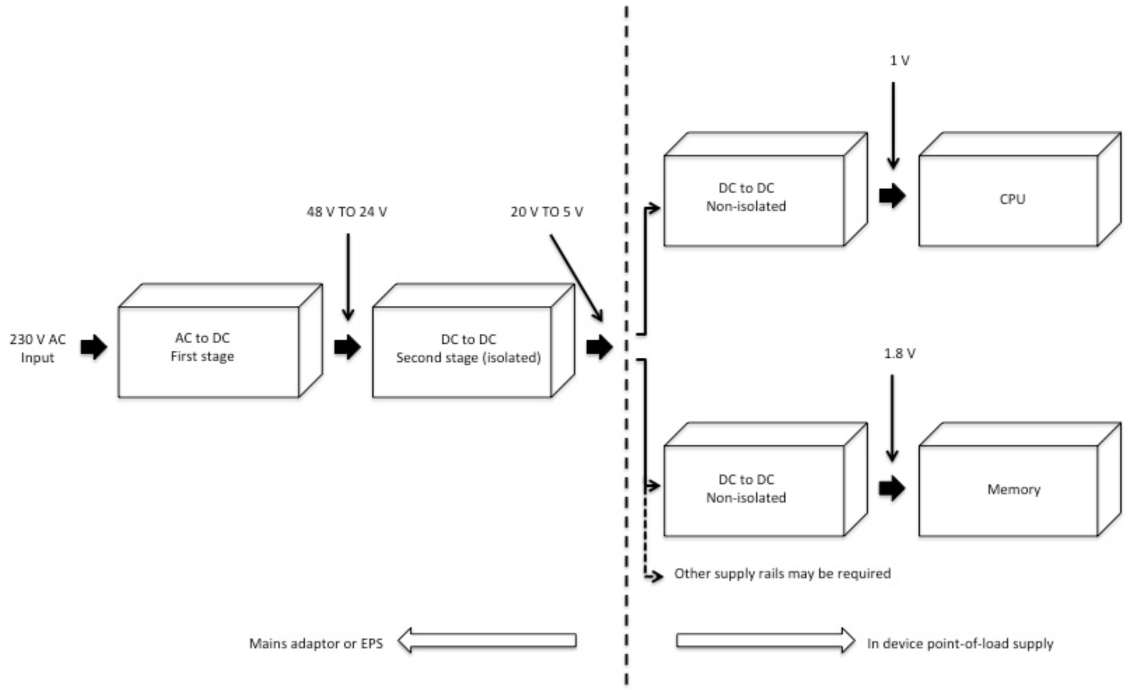

Figure 19. A typical conversion process for a microprocessor (electronic) based device.

AC power supplies

Historically a power supply would utilise a low frequency (50 Hz) transformer with a 230 V primary and a secondary at the appropriate voltage. The secondary output voltage from the transformer would be rectified, smoothed and then regulated depending on the needs of the final device. This is usually referred to as a linear power supply however with modern day electronics and circuit design the need for these bulky and expensive transformers is no longer required.

In general terms a modern power supply, while being fed with 230 V AC from a wall outlet, will immediately convert it to DC. The DC is then switched electronically at a high frequency, for example around 500 kHz, before it is fed in to a small transformer the output of which is converted back to DC to power the device. This is what is referred to as a Switch Mode Power

Supply (SMPS). In some supplies this process is undertaken more than once to achieve the necessary conversion. Not only is the conversion process more efficient for a SMPS but unlike linear supplies where the output is often regulated by ‘dumping’ unwanted power as heat, the SMPS regulates its output by controlling the input power by way of Pulse Width Modulation thereby improving overall efficiency still further.

Power supplies do more than just convert the voltage:

- Voltage stabilisation: many devices need a relatively constant voltage to work correctly and one function of the power supply is to reduce the voltage fluctuations at the point-of-load due to varying supply voltages, varying voltage drop along the distribution cable (s), changing cumulative load etc. In the case of many laptops the DC supply must be within -/+ 5 per cent or -/+ 1 volt for a 19 V supply. Without voltage stabilisation near the point-of-load it is difficult to guaranteed performance or warranty the device.

- Power management: in many cases the power supply manages the delivery of power to the load it supplies. For example, a laptop computer typically uses a Lithium-ion battery that to maintain its capacity and life requires precise control of the charging regime which typically includes parameters such as current State-Of-Charge (SOC), charging current/voltage and time [53]. Each type of battery has its own specific charge and discharge profile and the power supply design needs to be customised to that battery characteristic. Some manufacturers even go to the extent of using a different plug and socket or a digital ‘key’ to ensure laptop and power supply are matched.

- Harmonics/transient suppression: power supplies also provide isolation between the supply and the device to stop interference from the supply effecting the device and from the device feeding back to the supply and interfering with other devices.

- Fault protection/isolation: in the event of device failure the power supply will often limit the consequences for both the device, the power supply itself and the domestic network to limit the risks associated with the possibility of fire. Typically this might include over voltage/current protection.

- Power factor compensation/correction (AC supplies only): with any AC system there is often two components related to consumption one is known as true or real power and the other is known as reactive or imaginary power. Reactive power is unwanted so power factor correction is used to essentially reduce the reactive component to zero, or near zero, thereby improving power usage and efficiency.

- Isolation: isolation is required for safety reasons when high voltage AC or DC inputs are converted to low voltage outputs. It ensures adequate protection is designed in to the power supply to reduce the risk of high voltages appearing on the low voltage ‘safe’ side.

Efficiency and the External Power Supply (EPS)

As the number of mobile and low voltage devices has grown so has the number of external power supplies. By externalising the power supply both weight and space are saved for mobile applications and device design can be simplified and made independent of different voltages used in different regions around the world. It also means unfortunately, that the power supply can be left connected to the wall outlet and continue to consume electricity irrespective of when and where the device itself is being used.

As with nearly all devices the final design is a compromise between performance and price and in the past some low cost external power supplies have only been in the region of 70 per cent efficient with a power factor as low as 0.6 [54], [55]. A good quality SMPS however can achieve efficiencies of over 90 per cent across the majority of its load profile with a power factor of over 0.9 [56]. New electronic design principles such as synchronous rectification, resonant inductor-inductor-capacitor conversion and boundary conduction interleaving can raise efficiencies even further to low 90's per cent if required [57].

On the 1 January 2014 a new European Directive [58] was introduced setting performance standards for a range of external power supplies. For example, for power supplies between 50 W and 250 W (AC to DC or AC to AC) with a single output voltage of 6 V and above the no-load consumption must be 0.25 W or less (falling to 0.15 W in 2016) and its efficiency must be 89 per cent or higher. In terms of external power supplies energy savings resulting from these standards are expected to grow annually and reach 1.04 TWh in 2020.

Where appliances or devices have internal power supplies the EU has also introduced eco-design legislation which calls for efficiency improvements for many electrical products ranging from food preparation equipment to imaging equipment [59].

DC to DC converters

A DC to DC converter is also an electronic device and it too uses high frequency switching to achieve efficiency and compactness. There are many circuit designs for isolating and non-isolating converters including Buck, Boost, Buck/Boost, Cuk, Charge-Pump, Flyback and all of these use a small inductor or transformer similar to their AC counterparts except for Charge-Pump converters that use capacitors to store energy as an electric charge.

While some of the circuitry may appear similar between an AC to DC power supply and a DC to DC converter the AC power supply needs power factor correction by nature of its reactive input impedance and also galvanic* isolation. Both of these introduce inefficiencies making the DC to DC converter more efficient. The combination of these two factors and the use of additional techniques such as synchronous rectification using FET's rather than conventional or Schottky diodes means a DC to DC converter can achieve efficiencies of just over 95 per cent.

Note* galvanic isolation is required whether the supply is AC to DC or DC to DC if the input voltage is over approximately 100 V and the ratio of the input voltage to output voltage is greater than 4:1. For example, a 230 V AC power supply providing 12 V DC it is 20:1.

PV inverters (DC to AC)

A PV inverter is an electronic device that converts the DC supplied by the PV panels to AC which is then normally fed to the 230 V mains supply. PV inverters are usually configured as a string inverter where all the PV panels are connected in series or they can be much smaller, a micro-inverter, and assigned to each individual PV panel. PV inverters generally consist of three distinct stages. Firstly the variable DC output from the PV is fed to a DC to DC converter the output of which is then converted to 230 V AC by a DC to AC converter using high frequency Pulse Width Modulation. The performance of the whole inverter is managed by a real-time micro-controller that by executing a number of control scenarios fulfils all the power management and communication functions required, including:

- Continuously varying the input impedance of the DC to DC converter to ensure that the point of maximum power is maintained irrespective of PV operating conditions for example, panel temperature and shading. This function is call MPPT (Maximum Power Point Tracking)
- Ensuring that the AC output connected to the grid is synchronised and at the appropriate voltage and frequency to enable power to be exported from the inverter to the domestic network or, if not required locally, exported to the grid
- Managing battery storage if fitted
- System configuration and communications.

Both string inverters and micro-inverters have their own pros and cons:

- A single larger inverter can be more cost effective than many smaller units
- If a micro-inverter fails the output from just one panel is lost having little impact on the overall output
- Micro-inverters are typically mounted on the back of each PV panel often in a harsh and difficult location to access thereby making replacement difficult should they fail
- If one panel in a string becomes shaded it reduces the output of the whole string whereas with micro-inverters just the output from that one panel is reduced.

A typical domestic string inverter will have a rating of approximately 1.5 to 4 kWp and a maximum DC input voltage of 500 V or above allowing for a number of panels, typically around 30 V, to be connected in series. By comparison micro-inverters, being dedicated to one panel, have a rating of typically around 250 W and a maximum DC input voltage of approximately 45 V. The output of each micro-inverter is typically 230 V AC which is connected to the domestic network via an interface box. Currently inverters can have an efficiency of well over 90 per cent at 20 per cent of rated output rising to over 95 per cent at 40 per cent output and above (European Weighted Efficiency [60]).

4.3 Conversion losses – indicative AC and DC systems

As already mentioned in terms of delivering a practical low voltage electricity system it is often a compromised between conversion losses and distribution losses. If the voltage is set higher the distribution losses are lower but there is likely to be a need to use point-of-load conversion stages. If the voltage is set lower then conversion stages might be eliminated but distribution losses will be increased. To shed some light on how this very simple issue has an impact on like-for-like systems the following graph has been constructed.

The figure below shows conversion losses against power supply efficiency for a 230 V AC system and a low voltage DC system with ten circuits each feeding ten loads. The AC system requires conversion for all ten circuits whereas the DC system has five 'ideal' circuits with no point-of-load conversion and five that require a conversion process due to incompatible voltage requirements or excessive voltage fluctuations. Clearly this simple calculation does not take in to account possible improvements in efficiency as power supplies increase in size, part load efficiencies and many other issues. It does show however, that for an indicative system meaningful savings can be made by adopting a low voltage DC system that eliminates, or at least reduces, a number of conversion processes.

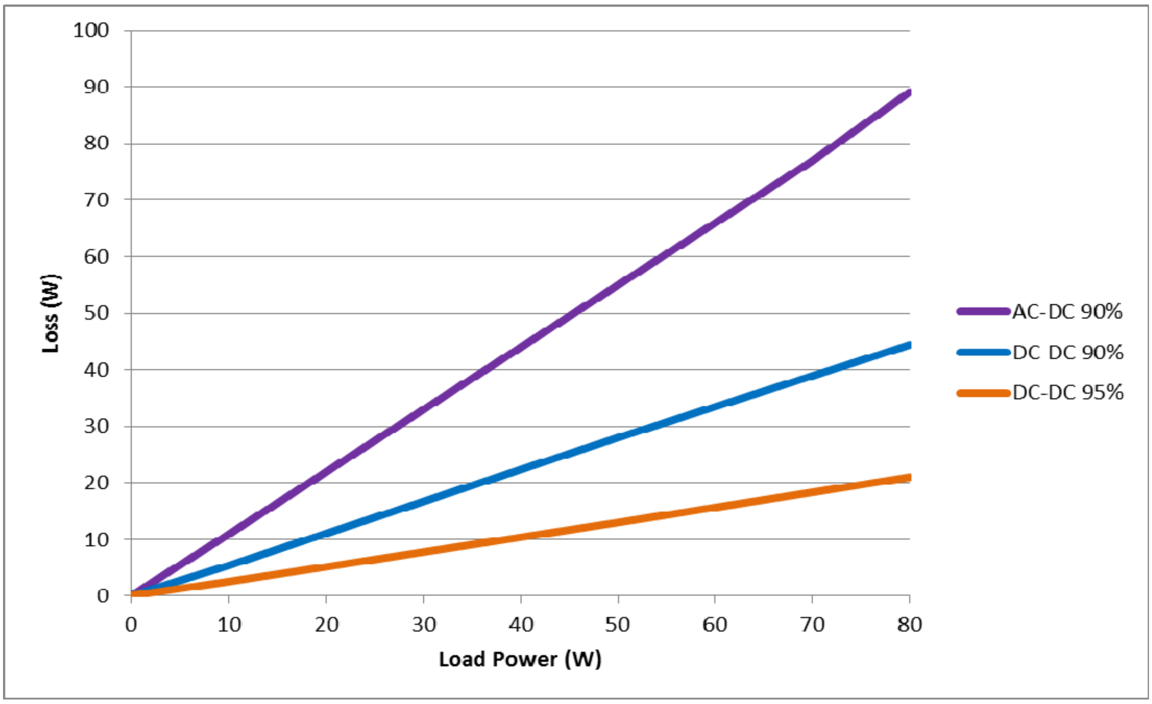

Figure 20. Total conversion losses for a 10 circuit network using AC to DC power supplies and a practical DC system.

Note: AC system

AC to DC conversion, for example 230 V to 19 V DC.

Conversion for all ten circuits.

Efficiency of conversion process 90 per cent (the approximate minimum required by the EU Directive as of 1st January 2014)

Conversion efficiency constant for all load conditions

Note: Practical DC system.

5 ideal circuits (no conversion) and 5 with DC to DC conversion

Efficiency of 90 and 95 per cent for DC to DC converters (Note: DC to DC converters are exempt from the EU Directive)

Conversion efficiency constant for all load conditions

In terms of alternative electricity systems anything short of eliminating power conversion stages altogether raises issues surrounding true like-for-like comparisons with the existing AC system. While alternative approaches will inevitably arise for specific situations the debate often gravitates to cost effectiveness and market forces especially as reductions in conversion losses associated with low voltage systems can quickly be offset by distribution losses, see later.

4.4 A review of network parameters

Having considered the supply (national and local), the nature of the demand and the conversion process it is now time to consider the electricity network that connects them all together. Central to the debate in any network design is what is required by the load. This then dictates the voltage and network characteristics to deliver that efficiently, safely, practically and cost effectively. In any practical design scenario it is prudent to review what voltages are in common use so as to build on existing knowledge, standards and components.

Network voltage

There are a number of existing voltages that might be adopted as a standard voltage for any new network but, with the exception of USB and PoE, very few have end-to-end standards or system components that are appropriate to the built environment; this is not to say that automotive, communication and rail sector standards might not be applicable.

	Main uses	Pros	Cons
5 V (DC)	One of the primary voltages used for computers and local connection between peripherals	Standard already exists for USB providing power as well as communications.	Primarily for desktop distribution only but likely to expand to local (room) use. Currently relatively low power but increasing.
12 V (DC)	Automotive	Many system components and end devices already exist	Possible use at domestic scale but losses and voltage drop may be a problem for moderate cable runs.
16 – 20 V (DC)	Laptop	Capable of delivering higher power than 12 V	Currently no standard voltage adopted.
24 V (DC)	Automotive/commercial	Many system components and end devices already exist.	Losses becoming more acceptable for practical systems.
48 V (DC)	Telecoms (likely to become more common	Higher voltage makes distribution	Commercial devices available but few

	in control circuits in electric vehicles)	house wide more sensible	apply to the domestic environment.
48 V PoE (DC)	Commercial IT Networks	Range of PoE devices is increasing as device power drops and power capability of PoE increases. End-to-end solutions available. Data and power on one cable.	Currently limited to ICT network devices but this will change in the future.
110, 230, 415 V (AC)	Domestic and light/medium commercial	Low distribution losses. Worldwide system standards and components.	Needs conversion for electronic devices and safety issues increase with voltage (note SELV).
50 – 600 V (DC)	Various industry standards. Common voltages may arise in the future as a result of vehicle batteries and possible integration with the built environment.	Good power distribution efficiencies	Switching, conversion and safety issues increase as voltage increases (note SELV).

Figure 21. A review of voltages in common use.

Note: Separated Extra-Low Voltage (SELV) and Protected Extra-Low Voltage (PELV); a category of shock protection limited to a voltage not exceeding 50 V AC or 120 V ripple free DC (see later).

Whilst considering the network voltage it is also necessary to consider the permissible voltage drop across the network conductors and the voltage tolerance of the load. This is the amount by which the voltage can fluctuate and still maintain device performance. As already mentioned for a microprocessor in an electronic device such as for example, a laptop, this is often -/+5 per cent.

In terms of the existing AC supply European harmonisation has set the nominal voltage at 230 V across Europe but in the UK the actual average voltage has not changed and still remains 242 V. The tolerances prior to 2003 were -6/+10 per cent (216 V to 253 V) and in 2003 this was supposed to change to -/+10 per cent (207 V to 253 V) but this has yet to happen. At the wall outlet this can drop by a further 3 per cent as a result of losses in the domestic network.

Voltage fluctuations do not represent a major problem if conversion takes place near the point-of-load as the power supply is able to stabilise any fluctuations. However, in the case of a switch mode supply if the input voltage drops too low it will draw more current to meet the output requirements and as a result may possibly overheat or its life might be shortened.

Voltage tolerances can also have an impact where battery storage is used (see later). For example, in a system where lead acid batteries are used their nominal voltage is 12.6 V but this can vary from between 10.8 V to over 14 V depending on whether the battery is flat or being charged. This is a variation of between -/+ 12 to 14 per cent before any distribution losses are taken into account. If this voltage tolerance is too large for the load without the use of point-of-load conversion and voltage stabilisation then it might be considered that an alternative is to tighten the acceptable voltage tolerance by only using part of the batteries overall capacity and hence voltage variation. For a given power requirement this will require a greater installed battery capacity which will lead to higher costs. Battery life is also driven indirectly by voltage tolerances as excessively charging or discharging batteries often reduces their life considerably particularly in the case of lead acid batteries.

In terms of the conductors used in the network voltage tolerances also have an impact. If conversion and stabilisation stages are to be avoided and the voltage drop across the network is designed to be low to meet point-of-load voltage tolerances then unless the power requirement is very low, cables and connectors can become physically large and costly. If the point-of-load voltage is allowed to vary as a result of voltage drop in the network cables then while cable costs might be reduced many electronic devices will need a stabilisation stage either externally or internally to function properly – again reducing overall efficiency (see later).

Network sizing and losses

As already discussed the existing 230 V AC electricity network may be considered as a high power network relative to the burgeoning number of lower power ICT and electronic devices. Some of these may consume one or two hundred watts, for example a large TV, while others may be much lower power, or where they are mobile, dominated by battery charging times and not their actual consumption per se.

Having already established the losses arising from conversion for an AC to DC system and a practical low voltage DC system it is now time to put them in to context with network distribution (conductor) losses. This will provide a balanced view of the opposing strategies of using high voltage distribution with point-of-load conversion or low voltage distribution with no (practically no) conversion stages.

Conductor losses – the basics

In terms of electricity distribution the choice of what voltage to use is usually a compromise between the power required, safety, cost and practicalities of the installation. If for a given power requirement the voltage is increased (assuming constant conductor losses) by say a factor of ten then the current flowing in the conductor decreases by a factor of 10 and the power lost in distribution reduces by 100.

$P = I^2 / R$

I = current in Amps

R = resistance in Ohms

P = power in Watts

In terms of a practical system even if the conductor cross sectional area is now reduced (to reduce costs) by 10 to once again bring it back in line with the original conductor current density, the power loss is still reduced by ten from that of the starting point. The only alternative to raising the voltage, whilst maintaining the power required, is to reduce the losses in the conductor by using thicker conductors and this has cost implications.

The existing domestic 230 V AC supply typically uses a ring configuration with 2.5 mm^2 (cross-section area) copper wire for the power circuit (s) and 1.5mm for the lighting circuit (s). Other distribution configurations include radial, star and tree but these do not generally apply to domestic situations.

Normally wire sizes in a domestic building are sized for a maximum of a 3 per cent voltage drop. This figure has been arrived at as a compromise between:

- Losses in the cable conductors
- Over-heating (cable rating is dependent on its ability to dissipate any heat generated for example in open air, in conduit, plastered-in etc.)
- Voltage fluctuations at the wall outlet under varying load conditions
- Cost of the cable

To investigate the impact of network conductor losses the indicative 10 circuit system will now be considered as before. As already identified the reduction in conversion losses by using a practical low voltage DC system over an AC to DC system is, for a 20 W load for example, 17 W (losses are 5.3 W for the low voltage DC example with 95 per cent efficient conversion; 22 W for the AC to DC example with 90 per cent efficient conversion). If the conductor losses are now considered using the 20 W load example as before and a system voltage of 5 V is chosen, the saving of approximately 17 W by reducing conversion processes is far exceeded by conductor losses. If 12 V is chosen as a system voltage then conductor losses are one third of the savings from reducing conversion losses.(2.5 mm^2 conductor). If the load is now increased to say 50 W then the reduction in losses from conversion is approximately 42 W but the conductor losses for 12 V are broadly comparable at 38.5 W. This is, of course, reflecting the fact that losses increase by the square of the current flowing.

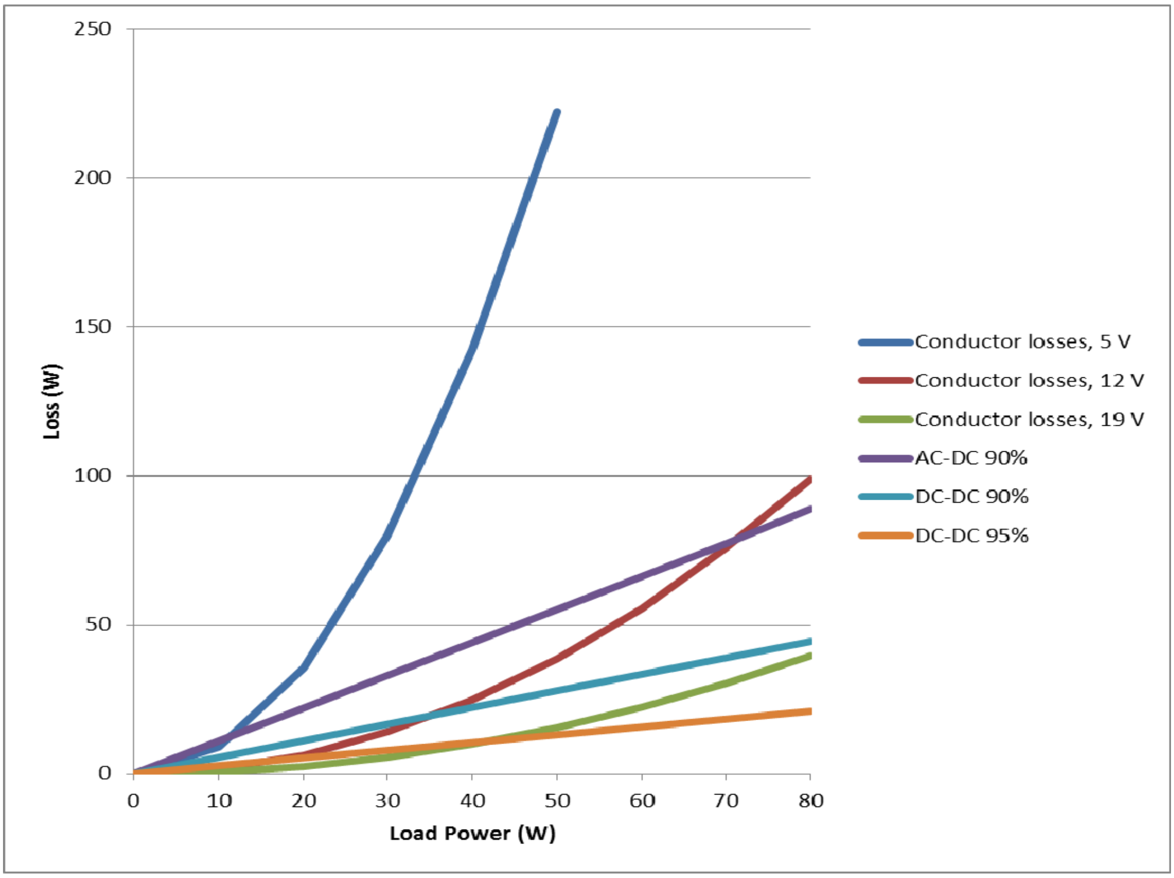

Figure 22. Comparison between reductions in conversion losses and increased conductor losses for an indicative electricity system.

Note:

1. 10 circuit distribution network.
2. Conversion losses using AC to DC (90 per cent) for all 10 circuits. Conversion losses DC to DC (90 per cent & 95 per cent) for 5 circuits without conversion and 5 with conversion (required due to excessive voltage drop/fluctuations or the load needing a different voltage from that supplied).
3. Conductor losses calculated using individual cables for each circuit (10 off). 15 m between supply and load (30 m conductor length). Conductor resistance (copper) 2.5 mm^2 = 7.41 mOhms/mtr (20^{0}C).
4. The most common device voltages are 5, 12, 19 [54].

Once again these calculations are only indicative but they highlight the compromises that exist in the design of an electricity network. The key to which is the most efficient is highly dependent on the power demand of the end device. If this is very low and the cable runs are short then avoiding point-of-load conversion can make the overall network more efficient. If a very low voltage is used, the cable length increases or the power demand starts to rise then a low voltage system (DC or AC) offers few practical benefits especially considering the costs of installation.

Clearly it is possible to increase the conductor size but over engineering electricity networks in buildings presents many problems not least additional cost. Installation costs would be less in new build and may be reduced in retrofit situations if cables are surface mounted but this is unsightly and unlikely to be unacceptable to most home owners. Given the cost to completely rewire (although any alternative system is likely to be a part system) an average 2 bed terrace house is £2500, 3 bed semi £3200 and 4 bed detached £4000 [61] (note, IET discussion forums suggest a lower figure) then in energy savings terms alone it is just not economic.

Alternative DC solutions can have significant advantages for industrial and commercial installations but they are often optimised to fulfil just one purpose for example, large machine applications or server farms. In domestic buildings alternative approaches (AC, DC, low voltage, high frequency) can have some useful benefits for part load applications, for example lighting, but these are often just as valuable for their additional benefits such as storage and/or smart controls as they are for potential improvements in energy efficiency per se. The only questions then remaining is what proportion of the total demand can any alternative network supply, what impact does it have on the overall efficiency of the domestic system as a whole and is it cost effective to implement.

So far in the report a relatively simple approach has been taken in terms of electricity and its basic components that has not for example, considered how conversion efficiencies might change with the size of the power supply. Typically efficiencies improve slightly as the power supply gets bigger opening up the potential to improve the overall performance of a system by using one larger central power supply to supply a DC network rather than a number of small ones located at the point-of-load. While this might be the case, if the system is configured using a low voltage to power devices directly the conductor losses in the network are still likely to be relatively significant and the cost of installation would be high in terms of electricity savings achieved. If a high voltage DC is used then down conversion with its associated losses would still be required.

Note: the significant advantages offered by DC in high power and long distance transmission are insignificant or not appropriate in the domestic environment.

4.5 DC network design issues

Moving beyond just network losses the design of a practical DC system also varies significantly from that of its AC counterpart. Much of the difference arises from the fact that DC, unlike AC, does not have zero volt crossing as the sinusoidal waveform passes from positive to negative and vice versa.

Protection against overcurrent

Any electrical network must be protected against overcurrent when a fault occurs primarily to reduce the risk of fire. This includes short circuits, overloads, earth faults (if the network is earthed) and rail-to-rail faults. Where a low current short circuit exist the difference between minimum and maximum fault current clearing times can be excessive making selective protection of low voltage networks particularly difficult.

Switching

Arc and arc-flash are a problem when switching DC and it is much more difficult to break high voltage DC than AC. A switch or relay may have a rating of 10 A at 240 V to 380 V AC but this will typically be de-rated to 10 A at 30 V for DC applications.

Residual current protection

Residual current protection devices for DC systems are not commonly available and where this is needed it is likely to be best accomplished by electronic means rather than electro-mechanical hardware.

Electro-corrosion

DC is uni-directional and as a result is much more prone to electro-corrosion at terminations and joints that if not accounted for can lead to premature failure.

Plugs and wall outlets

There are many plugs and sockets used in the rail, automotive, marine and leisure industry that are designed to be used with DC although many will require modification to work in the built environment sector.

Protection against direct contact

The provision of barriers, enclosures and insulation is the normal method adopted to prevent personal contact with live parts. This will be different for an AC system than a DC system. SELV (Separated Extra-Low Voltage) [62] describes systems of voltages less than 50 V AC and less than 120 V ripple free DC and includes specific issue surrounding separation of the supply source. If the network is to be connected to the 230 V AC supply, perhaps to charge batteries for storage, high standards relate to mains isolation to avoid the risk of high voltages being present on a low voltage network. There are also other issues relating to protection against indirect contact, exposed conductors, earthing and equipotential bonding.

The IET is currently preparing a *Code of Practice for Low and Extra Low Voltage Direct Current Power Distribution in Buildings* which is due for publication in 2015 [62].

As mentioned at the start of this document this is only a very superficial review of electricity in buildings and it has not considered in any detail part load efficiencies, alternative wiring configurations, connector/switching contact resistance and life times, fault detection and isolation, power quality or a myriad of other electrical engineering issues related to the practical delivery of an end-to-end solution. In terms of losses and basic electrical engineering principles however the physics stands true; distribute electricity at as higher voltage as possible and convert it as efficiently as possible as near to the point-of-load as possible – this message has not changed since the National Grid was established back in 1933.

5.0 Balancing supply with demand, peak shaving and energy management

Moving beyond the basic electricity system to its control and management there are three primary issues associated with electricity as far as the consumer is concerned:

- is it available when I want it
- is there enough to do what I want
- how much does it cost.

Perhaps in the fullness of time a fourth will be added:

- how much carbon emission are resulting from my electricity consumption?

In terms of the domestic consumer the supply and demand of electricity essentially operates in an open loop system with no active demand-side management. The demand-side, the consumer, uses electricity as and when they need it and the supply-side meets the demand as cost effectively as it can in relation to national standards, primary fuel costs and the economic and social value of electricity.

While the domestic consumer might know little of the efforts made to balance supply with demand this is not the case for the supply-side. All AC grids are required to maintain a certain frequency and the statutory limit in the UK is set at 49.5 to 50.5 Hz but operationally the limit is set at 49.8 to 50.2 Hz. Electricity generation is based on rotating machines and as electricity demand increases the mechanical load on the generator increases and it spins slower resulting in a drop in frequency. By maintaining the frequency the supply is kept in balance with the demand.

National Grid has two options to maintain the frequency and it is obligated to ensure that sufficient generation and/or demand reduction is held in automatic readiness to manage all creditable frequency change contingencies. Matching supply with demand is fundamental and solutions predicated on increased supply and/or reduced demand are equally valid. There are three response levels [63].

Mandatory Frequency Response (MFR)

All generators are required to have the capability to provide MFR. MFR is an automatic change in active power output in response to a frequency change. There are three response services:

- Primary Response, provision of additional active power (or demand reduction) within 10 seconds after an event that can be sustained for 20 seconds

- Secondary Response, provision of additional active power (or decrease in active power demand) within 30 seconds after an event that can be sustained for 30 minutes

- High Frequency Response, the reduction in active power within 10 seconds after an event and can be sustained indefinitely.

Frequency Control by Demand Management (FCDM)

FCDM is where consumers are prepared for their demand, or part of their demand, to be interrupted for up to 30 minutes where statistically this is likely to happen between approximately 10 and 30 times per annum. FCDM uses an onsite relay to interrupt the demand as the frequency drops below a set point.

Firm Frequency Response (FFR)

FFR is a service procured by National Grid from both generators and consumers and it deals with the same incidents as MFR. FFR provides a mechanism for service providers to reduce demand or increase generation when instructed by National Grid. The service can either be dynamic where energy changes are in line with system frequency or static where energy change occurs at a pre-set frequency and remains at a set level [64].

5.1 Demand management (demand-response) and peak shaving

Over the past 20 years there has been an increase in consumption but just as importantly the profile has changed and the variation between minimum to maximum has increased to approximately 20 GW or 30 per cent of the peak demand in a 24h period. As already mentioned this is not ideal as generation capacity and transmission systems must be sized to cope with the peaks but for much of the time they are underutilised.

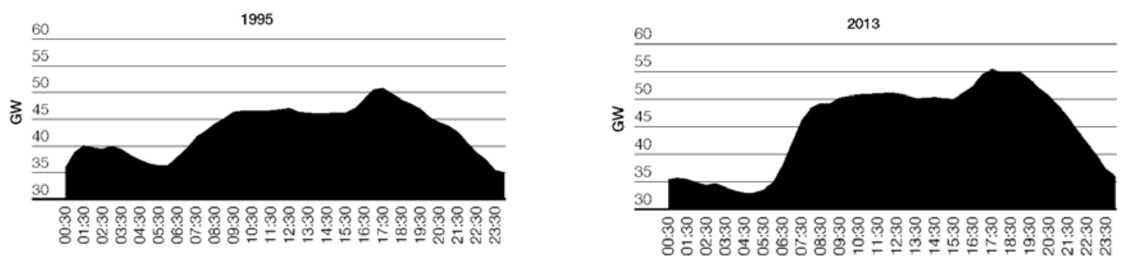

Figure 23. Changes in peak demand profiles for 1995 and 2013 (reproduced with kind permission from National Grid [9]).

The picture is similar when considering the consumption of an individual domestic dwelling over a 24h period. As a result domestic consumption in the future not only needs to be reduced but it also needs to be made smoother throughout the day.

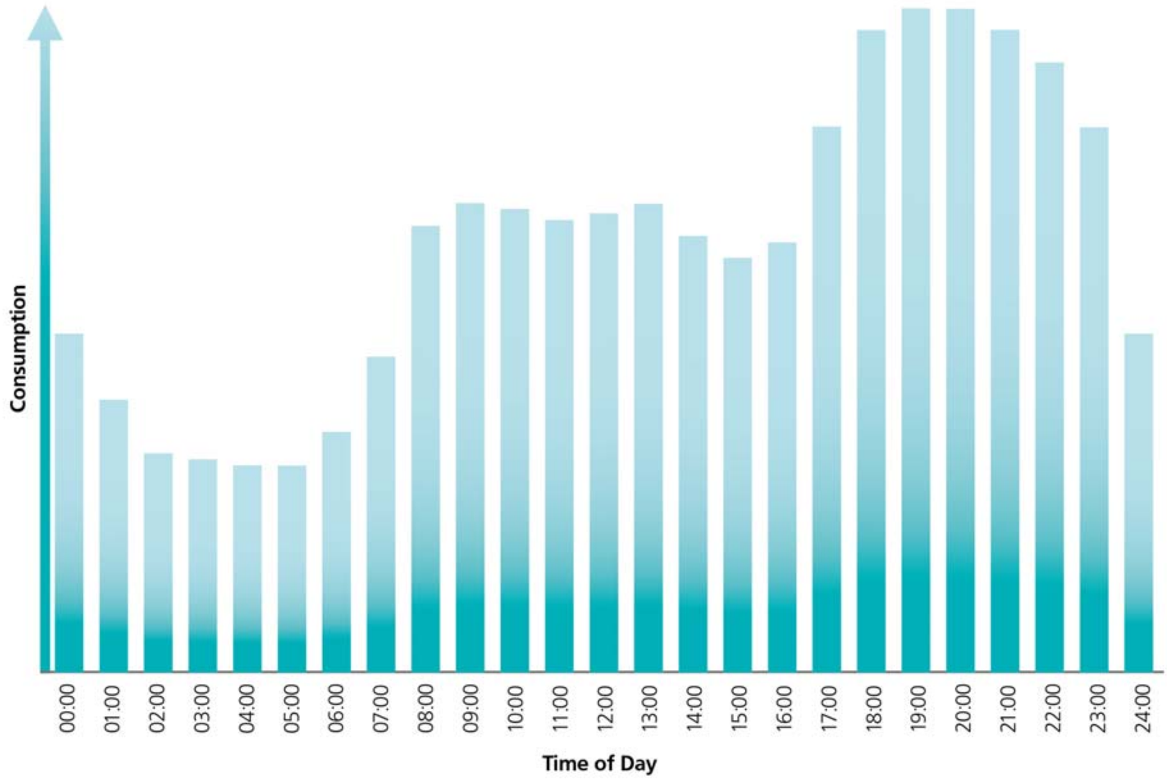

Figure 24. An indicative daily electricity consumption profile.

There are three primary ways to influence consumption throughout the day, they are:

- Change consumption patterns through user awareness campaigns and Time-Of-Use Tariffs
- Undertake automatic demand-response/management
- Introduce storage on to the domestic and/or local distribution network.

Good housekeeping

Energy efficiency is in fact very simple:

> "use as little as you can, and only when needed".

The first part of this statement is satisfied by efficient appliances, devices and homes and the second part is satisfied by something as simple as a switch and human intervention. Good housekeeping and behavioural change, whether altruistically, morally or ecologically based has many advantages. They are simple and fast to implement, they are highly cost effective and they provide immediate cost savings to the consumer. The mantra of good housekeeping and behavioural change has been around for 40 years but it will receive a further boost with the additional transparency surrounding price, consumption and time-of-day provided by smart meters.

Demand management (demand-response)

Smart meters and varying tariffs will inevitably bring about behavioural change but it will be interesting to see if automatic demand management/response incentives are offered to domestic consumers similar to those currently in the industrial sector. The incentive could be associated with a reduction in demand at peak times and may include actions such as delaying the switch-on of a fridge for a few minutes or not charging a laptop battery when it has sufficient capacity to meet short-term needs. Minor changes in the consumption of each dwelling will make a huge impact nationally across the 26m homes in the UK. If done correctly the changes will have little or no impact on consumer's way of life but could change the whole dynamic of electricity supply and domestic demand in the future. The technology to do this, either by local frequency sensing or remote Internet control, is available today but consumers need to change their views to accept these new scenarios.

5.2 Electricity (energy) management

There are two relatively distinct stages in managing electricity; the first is to be able to monitor the consumption and report the findings and the second is to use the data to actively manage consumption.

Electricity monitoring and reporting

Energy monitoring and reporting is an essential first step in gaining control over consumption as it raises consumer awareness of the units consumed, cost and possibly other parameters. With the increasing importance of electricity and the introduction of smart meters electricity monitoring and reporting systems (the in-home-display connected to the smart meter) will become widely available. At the same time the increasing functionality of smart phones and domestic heating systems and appliances will allow greater manual control via remote connection. These offerings are already available for the domestic sector in the form of smart phone applications or more specific services from mainstream energy companies.

Electricity management

Electricity management implies that not only is consumption monitored and reported but that the system undertakes some degree of self-management to meet a pre-defined outcome. In the future domestic consumers will need to be much more aware of their energy consumption but they are unlikely to have the time or interested to become experts given all the other pressures on their time. For this reason successful energy management control strategies must evolve to a position where they not only deal effectively with the technical and commercial issues associated with electricity and system optimisation but they also have user friendly interfaces that embrace different consumer lifestyle choices. As more and more electrical devices become Internet enabled out-of-the-box there will be a burgeoning of propriety and open sourced energy management systems that contain both hardware and the accompanying cloud based interactions to manage electricity in a connected world. As convergence take place hardware and consumer services will be bundled together and consumer purchasing decisions will be strongly influenced by trusted commercial brands in the energy, retail, consumer electronic or ICT/Internet sector.

Energy is often seen as a commodity and consumer decisions are primarily based on unit price. At what point price or carbon emissions start to make an impact depends on many economic and social factors and the implications of the risk and benefit to the consumer of taking, or not taking, the appropriate actions. The key to success is not a technical one but one of winning the hearts and minds of the consumer.

Energy management and the cloud

Historically energy management has been seen primarily in the context of one building or one site. Already in the commercial sector cloud based energy management systems are allowing those with significant property portfolios to collect, analyse and control energy across all their sites with all the interactions happening via the cloud [65]. Cloud based operations open up the opportunity for many bits of fragmented and disparate data, from different sites, buildings, devices, databases, equipment and sensors to be bought together. In the domestic sector while each building is different, shared data and cloud operations could provide new insights as to how buildings perform and how physically and managerially they could be improved. Cloud based operations will also ensure scalability and cost effectiveness by providing significant computing power and data storage that is well beyond the average domestic consumer.

Service aggregation

In the future smart homes will use various communication technologies to enable convergence between smart homes, building services, appliances, devices, sensors and smart meters. They will use a home hub to enable various control systems and aggregated data from servers distributed across various sites, including the cloud, to predict and intelligently manage and interact with the building and occupant lifestyle. One such demonstration project, SASH (Service Aggregation for Smart Homes), was funded by the TSB [66].

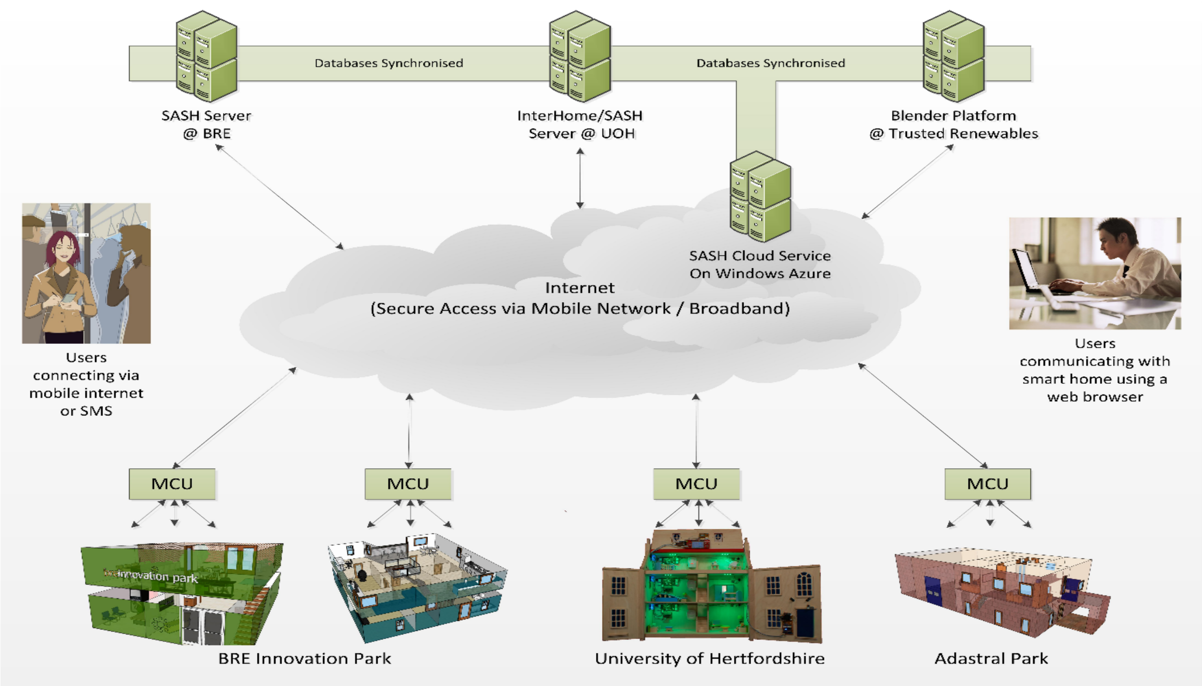

Figure 25. Service Aggregation for Smart Homes (SASH).

6.0 Local storage

Having considered the building blocks of a demand-side electricity system it is interesting to explore how it responds to changes in electricity supply whether from grid or local micro-generation sources and the role storage might play in future systems.

If electricity supply in the future is founded on electricity ‘always being available at a price’ and not the more draconian, ‘only when it is available’, then the adoption of local storage as far as the consumer is concerned is governed by a relatively simple financial assessment. This is based on consumption (quantity and timing), relative price throughout the day (including local generation sources) and cost and capacity of storage.

The smart agenda will allow automatic or remote control however, if for example clean clothes are needed even if the washing machine is used in the middle of the night or at times of high renewable generation, then electricity has to be used. If local storage is available it decouples electricity use from supply and offers a choice of not only when to use the washing machine but also when to take electricity, and at what cost, from the national or local supply.

Applying storage to the demand-side system provides much greater flexibility and allows the system to:

- Maintain continuity of supply for short periods should the grid supply fail (essentially an uninterruptable power supply)
- Decouple the consumption of electricity from the supply of electricity to support peak shaving or other control scenarios
- Maximise the use of local renewable generation.

While having storage brings a whole new dynamic to an electrical system it does also have some drawbacks in terms of complexity, cost, maintenance and physical location - especially in domestic dwellings. The key question to the widespread adoption of domestic storage is whether or not behavioural change and the smart control of appliances and devices provides sufficient system flexibility to deal with supply and demand changes. If not then storage may be required.

Continuity of supply

As already mentioned supply may only just exceed demand by a few per cent during Average Cold Spells in the next few winters. While this may not lead to any significant disruption to domestic consumers if local storage were available it may be able to fill the gap. In terms of cost and complexity it is very difficult however to argue that such a system would be worth it for what might be short-term power outages. This is especially when as the decade nears its end the power supply background prepared by National Grid shows that the 3 hour limit will be met.

Maximising the use of renewables and peak shaving

Even without storage as devices and appliances become smarter and more controllable there is an opportunity to use them during the day when for example, renewable energy from PV might be available. By turning a washing machine on during the day it not only uses locally produced electricity when it's available but it doesn't consume it in the evening at times of peak demand, a double benefit [67].

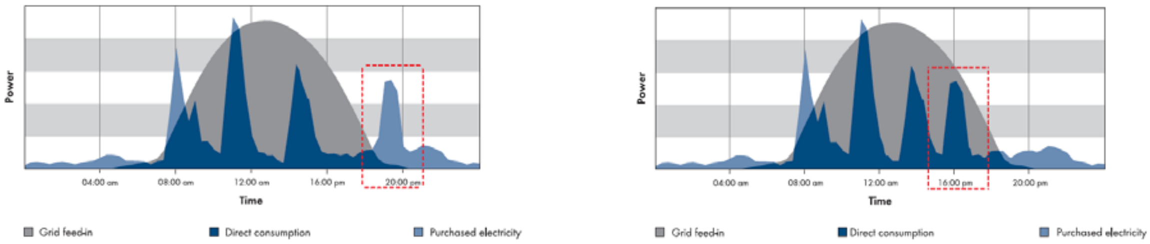

Figure 26. Using behavioural change or automatic control to move demand to when local generation is available (reproduced with kind permission from SMA).

Storing day-time electricity and using it in the evening also means that electricity is not exported at a low rate per unit during the day only to be bought back from the grid several hours later at approximately three times the price. The export tariff, not to be confused with the Generation Tariff, for a typical domestic FiT compatible installation is 4.77 p/kWh whereas the average cost for domestic electricity is in the region of 15 p/kWh depending on the quantity consumed and tariff structure etc. [68]. It is possible that in the future local storage could be funded by such a price difference (a notional price today of for example, 10 p/kWh) and this could benefit the consumer and the local network operator in terms of daily load management and infrastructure costs. If electricity price increase generally and/or it increases significantly at peak times then the case for storage will improve especially if battery technology improves and costs come down.

If automatic control of appliances and devices is available and the domestic network is also equipped with storage then there are many options open to optimise electricity in line with lifestyle need and local and national electricity drivers. This can go one stage further if the control scenarios embrace/engage with the distributed storage held within mobile devices. The growth in mobile devices and gadgets, while being part of the problem in terms of increased consumption, could also be part of the solution especially as many of these devices have advanced communication capabilities and increasingly accessible externalised power management capabilities [67].

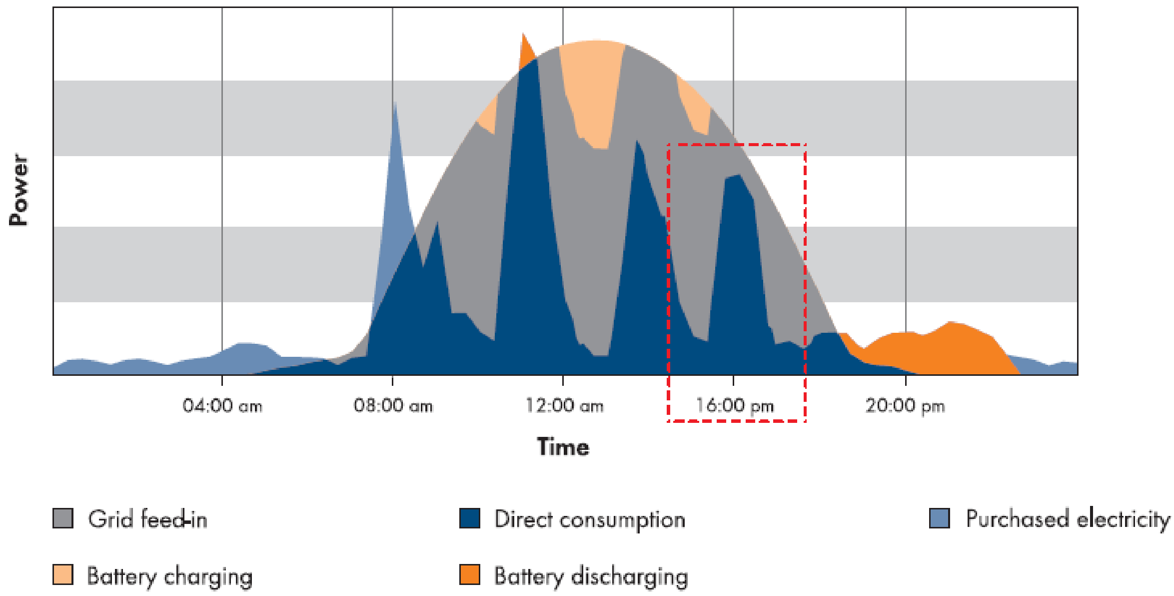

Figure 27. The potential impact of automatic control and storage on an indicative electricity profile (reproduced with kind permission from SMA).

6.1 Storage Technologies

There are many ways that electrical energy can be stored ranging from conventional lead acid batteries and more advanced batteries through to compressed air, flywheels, super capacitors and it can even be transformed to heat or gas [69]. Each technology has its particular characteristics making it better suited to some applications than others. In the future energy storage is likely to become increasingly important whether to supply a low power electronic device on a desk or a megawatt installation to stabilise the grid.

Batteries, an example of electrochemical storage, can be divided in to three main areas, conventional, advanced and flow batteries. A typical example of a conventional battery is a Lead-acid (Pb-acid) or Nickel-Metal-Hydride (NiMH) battery and that of an advanced battery is Lithium-ion (Li-ion). Flow batteries are interesting as the chemical storage is external to the battery. The power capability is set by the size of the battery whereas the energy available is governed by the amount of external (to the battery) stored reactant; the anolyte and the catholyte [70]. This means that by decoupling energy and power the distance a vehicle can go for example, is effectively governed by the amount of reactant that can be stored. ‘Charging’ is not like normal batteries as it’s just a matter of replenishing the reactant which can be a process that is potentially as simple and quick as refuelling a conventional car.

Already there are more battery powered mobile smart phones, tablets and laptops than there are humans without counting all the other battery (primary or secondary cells) powered devices. Over 15 bn batteries are sold worldwide and the average UK household uses over 20 batteries a year. However, it is interesting to note that while battery capacities are generally getting bigger they are not keeping pace with the progress of electronic hardware. Since the introduction of Li-ion batteries back in 1991 micro-processor transistor count has increased over one thousand fold whereas the energy density of Li-ion cells, now the pouch cell, has only increased by a factor of three.

In terms of electricity storage in a domestic system where the battery is static the upfront costs, round-trip efficiency and life-time (years and cycles) will be the most important criteria. There are many factors that impact the round-trip efficiency of batteries ranging from the efficiency of the charger (typically 80 per cent to 90 per cent) to the performance of the battery itself at the State-of-Charge (SOC) when charging commences. As an example, the charge efficiency for a Lead-acid battery may range from 80 per cent to 90 per cent from zero to 80 per cent SOC but falls to only 50 per cent to 60 per cent at 80 per cent SOC and over.

Local domestic storage can either be centrally configured possibly using a vehicle battery or a stand-alone installation or it distributed throughout the system for example, in a laptop. In the future it will be interesting to see how the power management strategies of electronic devices evolve from just managing the state-of-charge of their own internal battery to consider how this is done in relation to the broader supply status. As greater power intelligence gets applied to devices, the nature of their use, their power management capabilities and the power supply environment, mobile devices could play their part in an intelligent demand-response strategy.

Whether or not plug-in vehicles are commonly called on to export electricity back to the grid (Vehicle-to-Grid) depends on warrantees and many other factors but if this becomes the case network storage (domestic or local) will be enhanced by a very powerful transport agenda. Unlike storage associated with plug-in vehicles, stand-alone batteries perform no other function so as a result the technical challenges are more easily understood and accounted for. The commercial viability of such installations is mainly connected with the relative cost of electricity throughout the day and issues of security of supply and don't benefit from piggybacking on the transport agenda.

One suggestion is that partially spent electric vehicle batteries are given a second life in a static application. This is seen by some as a way of improving the useful life of vehicle batteries and hence their environmental credentials. If for the moment the detailed electrical, physical, commercial and safety issues surrounding high capacity vehicle batteries are ignored, if the average 20 kWh vehicle battery has degraded by 30 per cent it still has significant storage capacity in relation to the daily use of electricity in an average domestic dwelling. In fact if some of the larger electricity loads are moved away from peak times, for example 6 pm to 8 pm, then very significant control options open up in relation to optimising electricity with only a relatively small amount of storage, possibly less than 5 kWh.

Having physically large and often chemically dangerous and relatively complex high capacity DC storage is not ideal when trying to design a simple and cost effective electricity system. Whether storage is required very much depends on how consumers respond to electricity supply changes and other market drivers. If behavioural changes and automation allow the domestic profile to be sufficiently smoothed and integrated with the supply environment then they may not be necessary. If this does not bring sufficient control options or consumers are unwilling to change how and when they use electricity then local storage may be the only option. The key questions surrounding storage is do the benefit outweigh the drawbacks, what impact does storage have on overall efficiency and how will the cost come down in the future?

7.0 Communication and protocols

Increasingly devices and appliances are equipped with various communication protocols and these enable them to communicate inside the building and beyond thereby potentially supporting a future smart electricity strategy. For existing buildings it is generally more difficult to install hard wired communication networks (such as Ethernet) but they have the advantage of being more resilient in terms of radio frequency interference and the impact of building structure on communication paths. Wireless systems are easier to install in existing buildings and the ability of them to function in a mesh configuration helps them seek the best path between units to ensure consistent connection. The exception to both of these is power line communication that uses the existing 230 V AC domestic power network to convey data. While this appears at first sight to be a simple solution by using unshielded 230 V power cables it too can suffer from interference and the digitally transmitted signal can interfere with other local devices or radio reception.

Moving beyond these basic characteristics there are currently many commercial standards and systems that, subject to local conditions, provide effective communication in buildings. Some of these will now be considered.

BACnet

The BACnet protocol was developed by ASHRAE and it is an open standard allowing building owners and managers to choose BACnet compliant products and equipment from various suppliers. BACnet uses object modelling and defines a number of services (I-Have, Who-Has etc.) that can be used to interact with 54 object types across the whole range of building services including HVAC, access, security and life safety systems.

DALI (Digital Addressable Lighting Interface)

Lighting control systems typically use analogue (0-10 V) or digital protocols. The DALI protocol is an open standard bi-directional digital system that allows communication between ballasts, dimmers, switches, controllers, sensors and other system components. It uses a pair of wires that typically run alongside the existing lighting power cable or it can be part of a multi-core cable. DALI has good immunity to interference and can be configured in a number of topologies to directly address 63 devices or more via a DALI gateway.

DMX (Digital Multiplex Data Transmission Standard for Dimmers and Controllers)

DMX protocols were initially designed to control lighting and stage equipment in the entertainment industry where high channel capacity and high speeds are essential. It is gaining popularity in architectural lighting such as building exteriors and even some high-end residential projects. The system uses a uni-directional protocol and a central controller that can communicate over a twisted pair of wires with 512 devices configured in a daisy chain.

KNX

KNX is a standardised communications protocol for intelligent buildings that allows it to communicate with a wide range of building equipment including lighting, heating and ventilation systems, audio and video communication and much more. The KNX protocol is supported by many manufacturers and device compatibility is independently verified. The controller can be a small embedded microcontroller or a full network PC and over 50,000 nodes can be addressed typically via a twisted pair although power line, radio, infrared and Ethernet can be used.

LonWorks

The LonWorks protocol is an open standard that can be used to control building plant and commercial and municipal infrastructure and it is supported by many large players in the building automation industry. It is a peer-to-peer network that allows data to be exchanged between devices and not just through a master device. It can also operate over any media type including twisted pair, free topology twisted pair, radio, power line and coaxial cable.

X10

X10 is an example of a control protocol used in mains signalling for home automation. It uses the domestic power network for signalling and control data and provides a means of communicating between mains appliances and lighting. Embedded in the X10 signal is a house code and a unit code both of which can have a value of between one and sixteen or these can be combined in some situations to give control over 256 devices.

Z-Wave

Z-Wave is a suite of wireless communication protocols designed for automation and control specifically for remote control of devices in residential and light commercial environments. It is ideal for home-area-networks and uses small data packets and relatively low data rates compared to other systems making it ideal for simple control functions for domestic appliances etc. Z-Wave is a far simpler protocol than ZigBee making development faster and simpler although there are many existing profiles for ZigBee that can reduce its development time. Z-

Wave can support up to 232 nodes and operates at around the 900 MHz band well away from the more popular 2.4 GHz band used by WiFi, Bluetooth and ZigBee units. This means that its range is generally better, typically 30 m depending on the environment, and there is less competition for communication frequencies.

ZigBee (IEEE 802.15.4)

ZigBee is a suite of high level communication protocols using small, low-power digital radio signals to allow any enabled device to communicate wirelessly. Depending on the manufacturer, ZigBee nodes communicate at relatively low-power which limits their range to approximately 10 m to 30 m indoors but several hundred metres outdoors depending on line-of-sight and environmental conditions.

ZigBee devices can be programmed to operate in three different modes; coordinator, router and end device. This enables ZigBee devices to form a complex network of mesh and routing nodes similar to how the Internet operates. ZigBee devices are equipped with radio transceivers through which they discover each other and then a master unit applies an appropriate addressing scheme. This allows ZigBee networks to daisy chain devices through mesh network routing (Multi-Hop Ad Hoc Network) [71], [72] and hence span larger distances than a single module's radio range.

ZigBee is designed to offer low power consumption, low cost (device, installation and maintenance), a high density of nodes per network, simple protocol and global implementation. It can go from sleep to active mode very quickly which means that average power consumption can be very low and battery life is normally over 2 years.

As a way to help reduce the cost even further the devices come in two types; Full Function Device (FFD) and Reduced Function Device (RFD). The limitation of the RFD is that it can only connect to an FFD and therefore is only suitable for star topologies. FFD's can be both coordinators and network coordinators (peer-to-peer intermediates and central network master controllers) making them suitable for any topologies [73].

ZigBee is a more complicated protocol than Z-Wave but it can come with different profiles that pre-configure the device for specific applications such as smart energy, healthcare, building automation etc. ZigBee is currently being implemented in the rollout of smart meters across the UK.

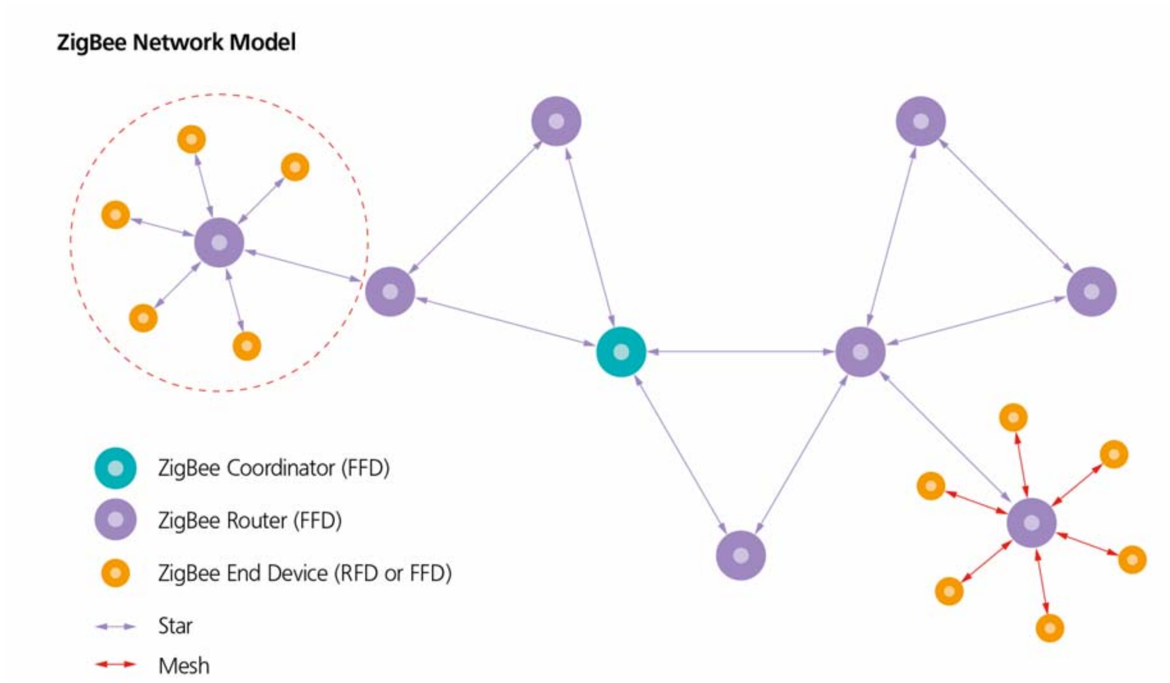

Figure 28. ZigBee topologies.

Bluetooth

Bluetooth (IEEE 802.15.1) is the most predominant of communication systems in portable devices. It is typically used for Personal-Area-Networks (PAN) or Piconets and communicates using FH-CDMA (Frequency Hopping Code Division Multiple Access) an ad-hoc paradigm also sometimes referred to as FHSS (Frequency Hopping Spread Spectrum) [74], [75], [76].

Bluetooth uses one of the ISM (Industrial, Scientific and Medical – ISM category) radio bands (2400-2483.5 MHz) specified by the International Telecommunication Union's Radio communication sector (ITU-R). These bands are dedicated for use by one of the three ISM categories and are not subject to licensing [75].

Within this frequency band, the devices use 79 different 1 MHz channels in their hopping sequence which is pseudo-randomly generated. Each hop from channel to channel occurs 1,600 times per second for voice and data transmission and 3,200 times per second for page and enquiry scanning [77]. To avoid collisions or cross channel interception the streams are coded (Code Division Multiple Access – CDMA) from each other so if two different communications are occupying the same frequency the transmissions are ignored if they do not suit the pre-agreed code for the appropriate data stream [74], [75], [78].

The latest in Bluetooth technology is version 4.0 or Low Energy Bluetooth. It was first deployed in the Apple iPhone 4S which was released late in 2011. Low Energy Bluetooth uses between 1 and 50 per cent of the power of classic Bluetooth devices allowing the communications platform to run for months or possibly years on small button batteries even with a range of 50 m which is 5 times that of classic Bluetooth class 2 radios [79]. Although Bluetooth is capable of transmission via its own protocols since the development and release of Bluetooth 3.0 High Speed in 2009 greater speed is achieved by using a hybrid system using both Bluetooth and WiFi.

WiFi

Wireless Fidelity technology (IEEE802.11) can be broadly categorised to IEEE802.11 a/b/g/n/ac. Each is an improvement in transmission speed and/or signal range from the previous, although these days only ‘G’ and ‘N’ are used. The standard G versions of networking devices have an optimal transmission speed of 54 Mbps with an indoor range of approximately 40 m whereas the N versions have a theoretical maximum speed of 300 Mbps (practical of approximately 150 Mbps and above) with an indoor range in the region of 70 m. In addition to this N variations offer the choice of two frequency ranges; 2.4 GHz or 5 GHz. The higher frequency has no impact on the range but offers a potentially less polluted frequency to help reduce crosstalk noise.

Both the G and the N devices utilise the same channel capabilities but these vary regionally. In Europe (including UK) a channel system of 1-13 is used whereas in the US the system uses 1-11. Both use the same frequency ranges resulting in an approximate frequency void of 16.5 MHz at the end of the 2.4 GHz range. Japan utilise a different system still, expanding the 2.4 GHz range beyond the acceptable ISM guidelines by 10.5 MHz to allow for an additional 14th channel with 11 MHz of non-interference from other channels (see Figure n below) [80], [81], [82].

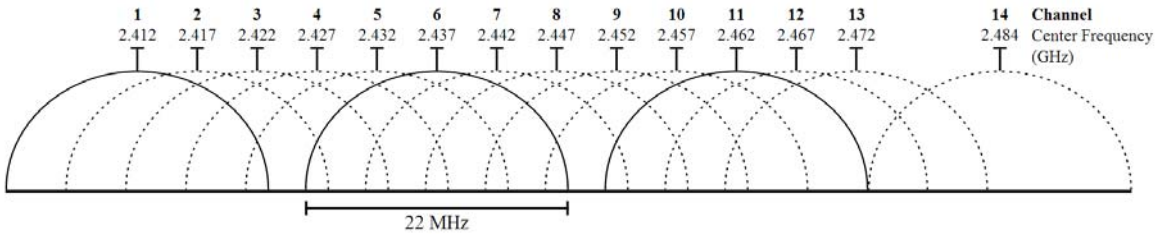

Figure 29. 22MHz channel allocations for WiFi 2.4GHz frequencies, with curvatures implying affinities for intra-channel frequency selection.

Figure 35 above shows the affinities for the frequency selection within each 22 MHz channel and the overlap between channel frequencies. The same would be seen for 40 MHz channels with the obvious exception that there would be twice the amount of overlap between channels, leaving fewer isolated channels. The solid lines in Figure 35 show the 3 channels in the US 11 channel system that do not encroach on each other's range at all. Each WiFi access point will secure its own channel and use that channel for all communications. Multiple channels will not be utilised by one access point other than during overlap.

WiFi communication protocols are Internet Protocol (IP) based where the destination address is in packet headers allowing large amounts of data to be transmitted through a network of nodes at high speed. This means that on any WiFi network a central control node (network coordinator) will allocate all IP's in the network on discovery allowing for any packets to be addressed and routed to a connected device [82].

Ethernet and Power over Ethernet (PoE)

Ethernet (IEEE 802.3) is the most widely installed Local Area Network system and has been around since the 1980's. In terms of adoption for commercial ICT devices it is more-or-less ubiquitous and as a result many of the system components are commoditised and within reach of the domestic user. Originally it was capable of carrying data at 10 Mbps (10 Base-T) but Fast Ethernet extends the maximum data rate to 100 Mbps (100 Base-T) and Giga-bit Ethernet increases this even further to 1000 Mbps. Ethernet started by using a single coaxial cable but this had the problem that failure of the cable or one connection meant failure of the whole loop. It also meant that every device received all data and if two devices transferred data at the same time a conflict would arise and it would need to be resent. Today installations typically use a dedicated cable although wireless and fibre optic Ethernet connections can be used. Each cable consists of 4 twisted pairs, one which is used for transmit and the other for receive – the other two pairs are spare. The point-to-point connections are typically limited to 100 m between device and network switch depending on the required speed and cables used (there are several types of Ethernet cable) although this can be increased by using additional range extending hardware.

PoE (IEEE802.3at – 2009) is an internationally recognised networking standard that has evolved from IEEE802.3af – 2003 and it introduces a new method of connecting devices that supplies low voltage DC power as well as data between Ethernet-enabled devices such as IP telephones, IP cameras etc. The standard is an extension to the IEEE 802.3 standard which means that the current suite of devices is compatible. Its key advantage is that depending on the power required an increasing number of low power devices can be enabled by using just one cable thereby simplifying use and reducing the number of wall outlets and power adaptors.

WiMax

WiMax [83] is a wireless communication platform that uses a microwave link to provide Internet access across a wide area, possibly as big as 3,000 square miles. It uses a microwave base station with a range of about 50 km and it is capable of providing 70 Mbps and higher connectivity using licensed and un-licensed frequency bands of 2 – 11 GHz and 10 – 66 GHz.

In many ways it can be considered as a large area WiFi reducing the need to move from hot spot to hot spot when trying to use a laptop on the move. For mobile applications it competes with LTE (4G) which is more-or-less a plug-and-play extension of the existing 3G system in the UK meaning operators have increased speeds without the need to install a completely new platform. For fixed connectivity the wide area coverage of WiMax has proven to be effective for establishing connectivity in disaster zones and it has become more popular in emerging markets where established cable connections are not available.

7.1 Interfacing smart grids, appliances, devices and the consumer

Many of the systems above can provide effective communications between appliances, devices and other equipment and therefore offer the opportunity for electricity to be managed. However, to do this efficiently and effectively across the whole electricity grid from generation to consumption requires a specific set of interfacing, control and reporting functions. Two industry standards are emerging one originating from Europe and other from North America.

EEBus

EEBus is middleware that provides a universal translator between existing field bus systems. This allows it to act as an interface between a whole range of different products from different manufacturers targeted at smart grids, smart devices and consumers. It is a modular system that allows for applications to be extended to areas of for example, health and transport (e-mobility). Its overall aim is 'an increase in energy efficiency, comfort and security for the good of consumers, society, the environment and economy' [84].

openADR

As already mentioned demand response will be a powerful tool in balancing supply and demand and ideally with automatic demand-response (ADR) much of this could happen in the background without any noticeable impact on the consumer. OpenADR is an open and standardised language that uses any IP–based communication network to communicate between electricity producers, network operators, aggregators and consumer equipment and devices [85].

8.0 Innovation, timing and the building stock

Looking beyond the electricity hardware associated with a domestic system one key part of any system review is the life expectancy of each component and particularly how they change relative to each other. In terms of the buildings themselves a leading theorists of change rate in buildings, Frank Duffy [86], states that:

"our basic argument is that there isn't such a thing as a building". "A building properly conceived is several layers of longevity of built components. "The unit of analysis for us isn't the building, it's the use of the building through time".

Duffy breaks the building down in to 'four S's'; shell, services, scenery, set. Later Brand [87] expanded these to site (geographical setting), structure (foundation and load bearing elements), skin (exterior surfaces), services (the working 'guts' of the building), space plan (interior layout, walls), stuff (desks, chairs, lamps). Each of the S's change at a different rate with the site and structure possibly lasting between 60 to 300 years to 'stuff' changing almost daily.

In terms of the UK building stock timescales are also measured in many decades or even centuries. Over 80 per cent of the approximately 26 m existing domestic buildings and 70 per cent of the nearly 2 m non-domestic properties will still be in existence in 2050 making the retrofit and management of existing stock essential if carbon targets are to be met [88].

Figure 30. Age profile for domestic building stock. Source, Energy efficiency in new and existing buildings, comparative costs and CO_2 savings.

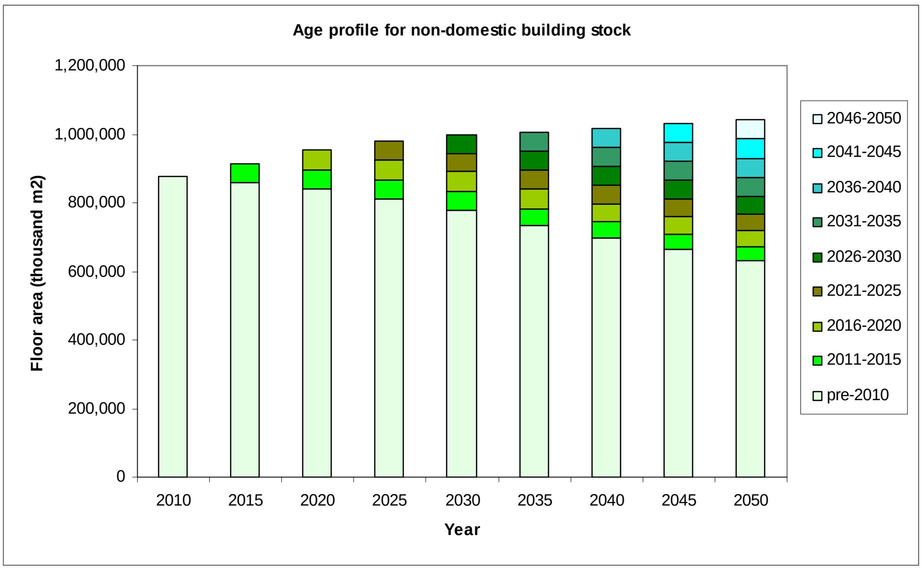

Figure 31. Age profile for non-domestic building stock. Source, Energy efficiency in new and existing buildings, comparative costs and CO_2 savings.

When considering the electricity system as a whole, from generation through distribution and ending at the wall outlet, the shortest lifespan of any component is probably that of the domestic wiring and its associated components which is measured in two or three decades. Many other components including generation, transmission and distribution have a longer lifecycle and the investment, both legacy and proposed in the future, are immense.

In terms of the system performance the rate of change is important. Potentially changing a long lifespan component to overcome a perceived problem in relation to a short lifespan component is foolhardy. Product evolution and economies of scale are likely to make the short lifetime devices evolve to suit the longer-term environment. While it's impossible to predict the future it seems likely that:

- The largest challenge, and potential benefit, is making existing domestic electricity installations more efficient and adaptable – having every domestic dwelling improve by 10 per cent is much more valuable nationally than having a few improve by 90 per cent

- There is a need for a high power domestic network to charge plug-in vehicles and supply an increasing amount of domestic heating using heat pumps as the grid becomes decarbonised

- Any current perceived mismatch between the proliferation of low voltage, low power DC devices and the existing 230 V AC system are often driven by short-term cost issues

- The smart agenda will provide much better control of appliances and devices and hence their electricity performance
- The mobile agenda will increase and as a result so will the potential to control distributed storage in relation to electricity availability and device use.
- Low power mobile DC devices may not actually be low power as battery charging will dominate as battery capacities increase and the market calls for shorter charge times
- Local and relatively high power local generation will become more common place requiring an efficient domestic electricity distribution network.

A smarter demand approach will allow the existing AC system to perform in ways that enhance its strengths and mitigate its weaknesses either at a system level, a component level or in terms of market adoption. Much of the technology for this new control regime is available now and as smart meters are introduced in the next 5 years many more smart appliances and home automation tools will appear on the market. With this enhanced controllability comes the potential to adopt a holistic system based approach to domestic electricity demand not constrained by simple supply and demand mechanisms. Future systems will be adaptable and agile changing their objectives at any moment in time in relation to electricity sources, product requirements and the lifestyle of the consumer. When such a scenario exists it will truly provide a proportionate demand-side response to what will happen in the supply-side over the next ten to twenty years.

The next paper will explore some of the hardware configurations, control scenarios and user interfaces that might be used to make the existing AC system more dynamic or even near instantaneous in relation to how it responds to the national and local electricity environment.

Driver	Low voltage DC system	High voltage 230 V AC system
Network to supply the proliferation of DC devices	Ideally an excellent fit but difficult to eliminate all conversion processes in practice New standard voltage required New system standards need to be adopted Low (very low) power only	Need conversion for every load (even those traditional appliances using AC electric motors are likely to use new motor types and advanced digital controllers in the future) Existing standards exist Suitable for low and high power applications (assuming conversion efficiencies/cost are acceptable) Very low distribution losses

	Relatively high distribution losses Only applies to part of domestic system (need more than one system) Potential benefits may be undermined by the smart agenda May have other advantages such as power quality	Applies to whole system Potential weaknesses may be mitigated by the smart agenda Economy of scale keeps cost low
Network to supply 230 V AC products	Unlikely to invert from a low voltage DC system to supply high voltage (higher power) AC products	Current 230 V system ideally placed
Local generation	PV strings often not low voltage to reduce distribution losses	Some micro-generation technology can directly generate electricity at 230 V AC
Grid Connection	FiT generation tariff applicable but will require conversion (up) to export	FiT generation and export applicable
Storage (central) (a relatively small amount of storage could provide a whole new system dynamic)	Unlikely to be very low voltage (< 20/24 V) given power requirements (if <<24 V only small parts of the total system will be supplied) Conversion will be required in most situations	Compatible with automotive, stand-alone and PV associated central storage Systems currently available Conversion will be required
Storage (distributed) (also review 'proliferation of devices' above)	Many low voltage DC devices are equipped with storage which will potentially help with system dynamics Any low voltage system must be powerful enough to charge	Conversion required EPS's now have standards setting minimum conversion efficiencies and no-load consumption (smart agenda could also provide better control to help reduce losses further)

	as well as run the device Inherent device power management typically very advanced	
Smart agenda	Compatible Technically feasible but end-to-end solutions are currently niche Where niches have grown the control scenarios are well developed	Compatible New smart appliances available now (socket adaptors to convert existing appliances are now available) Control scenarios for electricity (smart homes) available now from utilities and product manufacturers

Figure 32. Summary of some key issues.

9.0 Summary

Electricity supply is undergoing a revolution as it responds to the need to decarbonise the grid and deliver sufficient low carbon electricity to power homes and transport of the future. The introduction of smart meters in the domestic sector, while actually not that smart, will introduce a Time-Of-Use Tariff that will encourage consumers to think completely differently about how much and when they use electricity. The ramifications of simply being able to associate electricity consumption with time of use and cost will generate a financial lever the implications of which will pervade many domestic decisions related to electricity use, product purchase and behaviour.

The existing 230 V system is well suited to the future of electricity whether through design or Darwinian processes. Any current perceived weakness is generally a result of cost reduction and market forces rather than any fundamental technical difficulties. Questions as to whether there are alternatives to the existing 230 V AC system are often overshadowed by legacy issues, the future smart agenda and cost in all but specific situations. Where opportunities do exist they are often for specific parts of the overall load and often small parts in terms of total demand. Many of the advantages of such systems can be replicated on the existing 230 V AC system although at a national level it will take time.

As the cost of electricity (and energy more generally) becomes more variable throughout the day reflecting its true financial, social and environmental impact at any moment in time whole new electricity management strategies will open up. Demand-side electricity will become increasingly polarised between a myriad of low power DC devices and high power applications such as heating (via heat pumps) and plug-in vehicles. Local storage will become more popular particularly where local generation is available and where available it will provide a whole new range of options for managing local consumption and optimising self-consumption of local micro-generation. The individual components to deliver this technology are available today and leading manufacturers are just launching integrated solutions complete with control scenarios and user friendly consumer interfaces. Storage does however bring increased cost and complexity and it will be interesting to see how batteries develop and their costs come down.

Plug-in vehicles will make use of night time electricity and they may even be called on to export electricity to help domestic consumers and/or their places of work manage their daily demand. The increasingly dynamic nature of electricity control, local generation and possibly storage will present a whole new set of issues for the local distribution network to cope with which may be exacerbated towards the ‘end of the line’. However, increased functionality will mean that devices and appliances will move away from just demanding electricity to requesting and even negotiating with their neighbouring devices and/or the supply - nationally or locally. Automatic demand-response (demand management), already in the commercial and industrial sectors, will become more common place in the domestic sector as appliances and devices come Internet enabled out-of-the-box and consumers are rewarded for their willingness to allow parts of their electricity demand to be managed accordingly.

As the functionality of domestic appliances and devices improve system integrators, energy companies and others will launch new packaged deals. These are likely to embrace hardware, building communications, control/management regimes and possibly consortium electricity (energy) purchasing deals. Consumers will have options as to whose system to buy and what control philosophy to adopt as they harmonise day-to-day lifestyle with energy costs.

The smart agenda will pervade every part of the domestic environment as convergence brings together not only ICT, TV and communications but also electricity (and energy in general) and lifestyle. Appliance and device lifecycles and commercial pressures will mean that initially the smart agenda will be delivered through add-on black boxes and intermediate equipment but as smart becomes embedded from new, and matures, costs will come down. Interoperability will become increasingly important not just in term of how one appliance or device talks to another but more importantly how they all come together to optimise electricity in line with lifestyle need. Data security and ownership will become important as machine-to-machine and cloud communications contribute to an explosion in data – big data.

The relationship between electricity consumption, building/community performance and consumer behaviour will become closer coupled and future success will be strongly linked to a 'horizontal' system level approach. Without providing integrated consumer orientated solutions not only will ideas not work technically but they will alienate the consumer. If this happens it will delay the progress of electricity development by 15 years. The failure of a WiFI connection resulting from aluminium backed thermal insulation is annoying when streaming audio between rooms but it is much more serious if the heating doesn't work or the plug-in vehicle is not charged. While consumers in the future must manage their electricity consumption those that sell electricity products must equally understand that electricity is just one of the many issues dealt with by consumers on a daily basis – it is important but it must be kept in context.

Looking to the future and the longevity of an electricity system it probably mirrors that of buildings themselves. In the case of buildings, those that survive, often for hundreds of years, are the ones that are resilient, flexible and provide adaptable and usable human scale spaces. Similarly, an electricity system of the future must be flexible, adaptable and agile in the way it responds to electricity generation, distribution and use. Now is the time to think about future electricity systems and the old adage when designing buildings of "all the really important mistakes are made on the first day" must not be allowed to happen to electricity. Ideally taking a system based approach and 'tunnelling' [89] to a new way of thinking about electricity, and energy more generally, will ensure that it is available and environmentally benign in the future.

Looking to the future, where the primary fuel sources used for electricity generation change both in their type and geographical origins together with the introduction of renewable and distributed generation, electricity could be seen to be standing at a watershed. Whether the planned changes for electricity enable it to be more-or-less decarbonised and whether running the network at full capacity 24/7 delivers enough energy to significantly reduce the need to consume fossil fuels in domestic dwellings and transport remains to be seen. For this to even be a possibility challenging energy efficiency targets must be met. The upside of meeting the challenges is a much more efficient and energy secure future that has social, financial and environmental benefits for the individual consumer, the nation and the world.

For many consumers some of the issues outlined in this paper may seem a long way off. Technically the challenges are significant but the real challenge is for domestic consumers up and down the country to view electricity in a whole new light. This reflects electricity, or perhaps more-so consumer demand, both technically, environmentally and socially in transition. Discussions surrounding the need to decarbonise the grid and hence reduce emissions associated with domestic buildings and transport are similar to all discussions surrounding resource security, efficiency and environmental performance. In the end the debate just comes down to the chosen time horizon; 25 years, 50 years, 100 years or 500 years [90]? Even the shortest of these requires immediate action if electricity is to play its part in a low carbon, energy secure future.

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