The Schumacher Institute

On our systems

Introduction

This is a wide ranging study conducted by Luke Hatton in early 2018 for the Schumacher Institute. It covers the interactions of technology, energy, logistics, communications, and waste disposal all of which are characteristics of the open systems in which human life flourishes.

Technology

From reading the Nature of Technology [1], I discovered that technology is a multipurpose word, being used to define several concepts, similar in nature but also subtly different. There is technology in the singular sense – a harnessing of specific natural phenomena in order to fulfil a human need or purpose. This embodies a sequence of operations (software) and the physical equipment to realise these operations (hardware). In the plural sense, it refers to a 'domain' of related singular techs which build around certain phenomena and components – centring on a central concept/principle. Examples of this are electronics, which builds around the central phenomena that is the flow of electrons as current. Technology in the general sense refers to the whole collection of plural and singular technologies in society and builds up and develops as new technologies are introduced.

In order to understand how new technologies are formed, we must first understand some of the characteristics of a technology. We have seen the main principle already – that technologies are at their essence some phenomena captured, and as a result provide a functionality. We can say that they are executable – they fulfil a purpose, the generic task that they carry out, and they do this through a reliance on an effect or phenomenon of nature which can be exploited (i.e. captured and put to use).

Another definition (related to the plural technology definition) is that of an assemblage of practices and components – a system. We have seen already that technology can be split up into software and hardware in order to provide the functionality. Upon examining any technology further, we can see that it is recursive – that one technology consists of component building blocks which are themselves technologies, and these consist of sub-components which are also technologies. The 'depth' of this recursiveness can be measured and is one of the things we refer to as

[1] (Arthur, 2009)

'technological growth' – an increase in the capacity (depth and recursiveness) of new technologies. Thus, technologies continue to grow in complexity.

Now that we understand the two main characteristics of technology – its recursive nature and the executability of technology – we can then understand how technology grows and 'evolves'. Technology can be regarded as autopoietic (self-creating), in that it forms out of itself. Early technologies form as primitive technologies (i.e. a few steps away from nature – for example using rocks as tools) are used as components. Thus, new technologies then become possible components for the construction of new technologies - the source of change is the combination of previous technologies. However, this doesn't account for the initial technologies, nor the influx of new domains of technologies – and the explanation of this is the harnessing of previously unharnessed natural phenomena's through radical technologies and innovation, and the normalisation of these technologies into accepted technologies. Thus, technology grows through a cycle of combinatorial evolution, where current technologies are combined to form future technologies, with a constant input of radical techs, formed by the harnessing of new phenomena from the environment. This perhaps accounts for the exponential growth of technology, as this is in essence a positive feedback system.

The Economic System

In this mindset, we can see that the economy is itself, in essence, a technology. It is a clever system used for the reallocation of goods/services, and the meeting of human needs, held together through components such as money, the social contract, the legal system, governance and regulation – it shows recursiveness and functionality. The key idea in economics is that of the means of production – land, labour and capital – however without technology none of these means of production could be put to production, and through being put to use they become part of and a technology in themselves. Technology is in itself a means of putting to work the factors of production in order to provide for human needs and requirements.

Thus, as the economy is just a technology made up of all the total technologies which exist (i.e. technology in the general sense) any sort of technological change will result in economic change, whether in structure or in size. We see this as economic growth. Schumpeter proposes that the economy experiences 'waves of creative destruction' due to technological change[2], as the subsequent impacts and ways the technology changes the economy are realised, however, while this is a good explanation, there is more to it than that. The economy constantly experiences these waves of creative

[2] (Schumpeter, 1942)

destruction – we refer to the large, noticeable waves as 'revolutions' – and as such the economy is in a constant state of flux, changing and absorbing new technologies, and subsequently becoming a more efficient technology.

Looking back over history, the large scale 'waves of creative destruction' are noticeable. The first such wave was seen 10,000 years ago, in the Agrarian Revolution, where human activity transitioned from foraging based to farming based. This was made possible by the domestication of both plants and animals, increasing food production and allowing for larger human settlements.

The next such wave occurred from 1760-1840, with the advent of the steam engine and railroads, which is known as the first Industrial Revolution. This resulted in a transition from muscle-based production to mechanical production, beginning with mechanisation of the textile industry and the creation of cotton mills[3]. The second Industrial Revolution occurred at the turn of the century, and with the development of electricity and expansion of heavy industries such as steel, combined with the creation of the moving assembly line and specialisation (introduced by Henry Ford) resulted in the age of mass production.

The third industrial revolution began in the 1960s, and is normally referred to as the computer or digital revolution as the new technologies discovered, such as the integrated circuit, semiconductors, mainframe computing, and the internet.[4] The revolutions resulted in falling marginal costs of production, due to the increasing introduction of fixed capital, economies of scale, and specialisation in provision of products and services, transitioning the economy – of countries which have gone through these revolutions at least – towards a post-industrial society, and into the age of mass consumption[5].

Modern literature is split between whether we are the eve of a new fourth industrial revolution – facilitated by further physical, biological and digital discoveries or innovations[6] - or whether the third industrial revolution is still ongoing[7], but regardless, we are soon going to experience a paradigm shift (a change in technological systems that has a major influence on the behaviour of the entire economy[8]) in the way our society functions and operates, due to the exponential changes and advances in technology we are set to experience.

[3] (Economist, 2012)
[4] (Schwab, 2016)
[5] (Rostow, 1960)
[6] (Schwab, 2016)
[7] (Rifkin, 2014)
[8] (Perez, 2009)

One noticeable characteristic of these large-scale waves is that they are not sparked by a distinct, singular technology – they are often influenced by a domain of similar technologies, which can interact to form more complex technologies, through combinatorial evolution

In this report I am going to take a systematic view of the built infrastructure in order to understand exactly how the next 'waves of creative destruction' may alter the way our infrastructure systems function.

Theories behind innovation

Technology grows through combinatorial evolution, drawing from current technologies and so called 'radical' technologies (new forms of harnessing natural phenomena's), to form the future technologies which are then absorbed into the economy, creating waves of creative destruction, as Schumpeter refers to them as. However, this does not account for the reason behind the creation of new technologies – it only explains the mechanism by which new technologies are formed. The main driver of innovation – the exploration and creation of new technologies through this mechanism of combinatorial evolution – is that of the need for the technologies functionality by society. For example, without a need to produce, on a larger scale than just gathering, crops for human consumption, the Agrarian Revolution wouldn't have taken place. Equally, for functionalities that are already provided for by a technology or technologies, there is often a need for a more efficient or 'larger' functionality Efficiency is defined as the state of achieving maximum productivity with minimum wasted effort or expense[9] - i.e. maximum output with minimum input. Sticking with the need for crops for human consumption – there already exists an agricultural system that provides crops for our society – however there is a need for a more efficient or larger scale agricultural system, facilitated by new technologies, due to increasing consumption in society. Overall, as technology (in the general sense) is concerned with providing for human needs and requirements, there is a constant drive for higher efficiency of technological systems, due to increasing needs of society through mechanisms such as economic growth, rising wealth and population growth.

Technological development and growth thus are linked intrinsically to economic growth, and thereby to the social-economic structure and demographics of the population. New technologies cause economic growth, as the creative waves of destruction are absorbed by the economy and result in a more efficient system, but economic growth drives innovation into new technologies by providing the conditions necessary for further development of technology through combinatorial

[9] (Oxford University Press, 2018)

evolution – thus technological/economic growth form a positive feedback system by positively influencing each other, which perhaps explains why technology is characterised by exponential growth.

Technological innovation through combinatorial evolution is dependent on the education levels of the population, the size of industries utilising and exploring new technologies and the investment into research and development. Economic growth leads to an increase in the quality of life of the population, resulting in improved access to education, healthcare, sanitation, and employment opportunities. It also results in an increased tax base for the government, which can be invested into further education and research institutions – i.e. universities, or military projects. For example, the Internet started out as a military tool, developed by DARPA and thereby funded by the US Government.

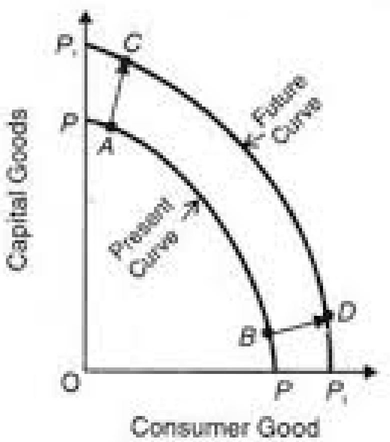
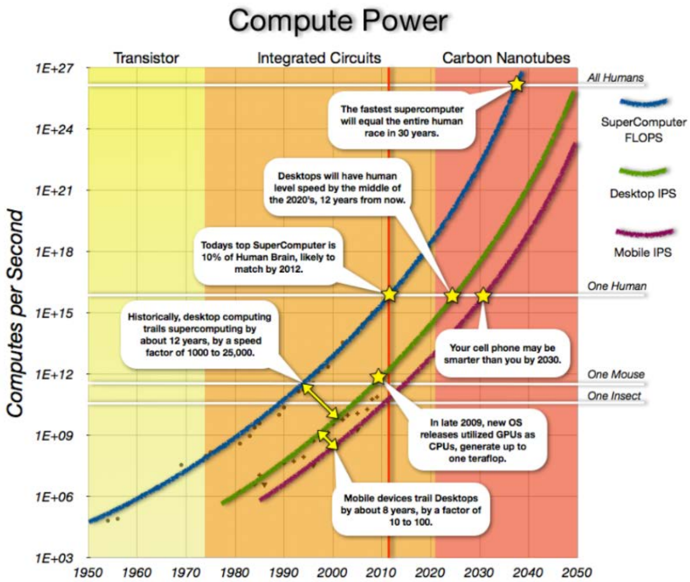


Fig. 5.12

A useful tool in economics is the production possibility frontier diagram, which illustrates the trade-off of production between two sets of goods. This could be in micro-economics – e.g. a firm deciding the production levels of two types of goods – or in macroeconomics, where, as shown on the right, we can see the trade-off between consumer and capital goods. What technology does is increases the productivity of the workforce (and thereby the economy as a whole) which leads to an expansion of the PPF curve outwards – i.e. economic growth. It expands the economies potential, due to technology being improved in order to meet society's needs and thereby the measure of the potential of the economy increases as it can more efficiently meet our needs (for the same input), and thus facilitates future innovation into technology, continuing the positive feedback cycle – leading to exponential growth in technology.

Exponential nature of technological growth

As we can see, due to the mechanism of technological growth (combining current technologies as well as the introduction of radical technologies to form new technologies), as well as the positive feedback system of economic/technological growth, it is not a surprise that technology experiences exponential growth. However, this is often difficult to observe.



1 Ray Kurzweil, The Singularity is Near

The difficulty here is because while life is experienced at a linear pace – i.e. steady – technology and in particular technological growth, innovation and change occurs at an exponential pace [10] – i.e. the rate is accelerating. It is hard to imagine exponential growth when we are so used to linear growth and as a result, it is hard to picture a time when technology was so less developed, or a time when technology will be so over developed. It contributes to our natural tendency to assume or take for granted the technologies which are such a large part of our life now.

This is further compounded still as, when looking at an exponential curve at a zoomed in perspective, it appears to be linear (this forms the principle of calculus). The same can be said for technological growth and innovation – it is only when looking towards the future or looking back that we can see the exponential nature of technology[11]. Moore's Law, based off an observation made by Intel's co-founder Gordon Moore in 1965, is perhaps the most well-known example of the exponential nature of technology. It states that the number of transistors per square inch on a circuit chip will double every 18 months – i.e. exponential growth. This illustrates one of the three ways to measure technology trends – size of the technology, the other two being cost (either financial or energy consumption) and capabilities (generally computing speed)[12]. Overall, Moore's Law has been reflected in industry, over the past couple of decades, and is only now beginning to slow down – this is due to the material constraints meaning that it is incredibly difficult to add more transistors onto a circuit

[10] (Thinking Exponentially, 2013)
[11] (Kurzweil, Law of Accelerating Returns, 2001)
[12] (Thinking Exponentially, 2013)

chip – however computing power will still continue to growth, as other technologies develop which provide the same functionality, just faster – quantum computing perhaps, or harnessing of the structure of nature's most powerful computer, the human brain. Exponential growth will still potentially continue, due to the inclusion of new technologies, and this makes it difficult to analyse what future technologies will be capable of, and thereby makes it difficult to examine how they made change the systems which we rely on in our everyday life – such as those comprising the built infrastructure.

Infrastructure

Infrastructure comprises the facilities, systems, sites and networks that are necessary for the functioning of a country and the delivery of essential services. These services fall within the sectors of energy, water, communications, transport, finance, government, health, food and emergency services.[13] This can be split into the hard infrastructure – the physical networks necessary for the functioning of a modern industrial nation– and soft infrastructure – the institutions required to maintain the economic, health, cultural and social standards of a country. However, although this report is restricting the perspective to technology's impacts on the built environment, it is important to maintain a systems mindset – the physical networks and assets are not just independent, they function with the soft institutions and infrastructure in order to provide the essential services a modern industrial nation requires. Thus, it is important not only to think about the impacts and changes to the physical networks technology will have, but also the change in the way soft infrastructure is set to function and operate, as this will have a subsequent impact on the requirements of the soft infrastructure on the physical networks and vice versa.

Infrastructure facilitates long term economic growth by improving productivity – similarly to how technology results in an expansion of the potential of the economy. Thereby expansion of infrastructure represents sustainable long-term growth, expanding the potential of the economy to produce. This can be seen as the other side of how technology facilitates growth – expansion of productivity in the production process, but also through the facilitation of infrastructure systems, their increased complexity and sophistication.

The built (hard) infrastructure can be split up into multiple sectors[14], although the boundaries are often blurred, these being: a communications medium, an energy source and distribution network, a logistics medium, and a waste

[13] (CPNI, 2017)
[14] (Rifkin, 2014)

management/recycling system. All these sectors work together as one system to provide the physical networks required for an industrial nation to function and are all inter-connected. All of the sectors require energy, as all systems do, while equally, all of the sectors require co-ordination and management which is facilitated by the communications medium. In the same way, in order for the system to be maintained, a logistics medium is required for the upkeep and maintenance of these sectors. And equally, all of these systems are not circular systems – they create waste, and as a result, the waste disposal system is needed, either to improve the sustainability of the other systems, or to deal with the waste by-products of these systems.

Energy – the extraction of energy resources, and the generation/distribution of secondary energy resources such as electricity. This system is quite complex as all stages and processes within the system require energy in themselves to function.

Communications – this system is focused on the connectivity between operators and 'nodes' in the system – the nodes can be machinery, people, organizations or locations – in order to transmit data and information.

Logistics – flow based – this system focuses on the need to move products and materials between different points, due to the spatial differences in supply and consumption of goods and services.

Waste Disposal – cycle based, this sector is often overlooked, but is also in some ways the most important, as resources are finite and limited, and our processes are often non-circular – we create waste products through almost every process in our economy.

And in the same way, these sectors are also dependent on the soft infrastructure, technology and human capital/labour that is required for their operation. As a result, an understanding of how technological change will impact each of the sectors is important, in order to maintain a resilient network and to ensure that the essential services are provided by the system.

Growth

There are two distinct ways in which infrastructure systems develop as new technologies/systems develop:

- **Upgrading of the existing system –** an example of this is the development of the mobile phone network, moving to a new generation approximately every decade[15] (we are currently on 4G). This is made possible through building on top of the

[15] (IEEE)

existing obsolete generation of network infrastructure and upgrading it. However, this can be a slow and costly process, especially in the case of networks which lack resilience (e.g. the logistics network), and so an attempt to upgrade would disrupt the existing systems functionality and running.

- **Facilitating new systems which operate independent of the old –** an example of this is the introduction of mobile phones as a method of communication. Although these have resulted in a sharp decrease in the use of landlines – the previous 'obsolete' technology – they operate off of different system architecture and as a result, while they are in some ways in different conflict as they provide a similar functionality, one has not completely replaced the other as they are two distinct systems. This is a less complex, costly and time-consuming process as it does not cause major disruption to the existing system, and is often more appropriate and high tech.

The expansion and growth of technology, and the interplay of these two methods in which infrastructure systems develop has allowed infrastructure to develop from simple, tangible assets to complex, semi-physical systems, reflecting the increasingly complex demands from society. As a result, to predict how the infrastructure systems may change over the next few decades it is important to first identify the new demands being placed on the infrastructure systems, both by society and by the other infrastructure systems – as they are not isolated systems and rely heavily on each other to function.

Sector	Problems facing the system
Energy	Increasing demand Outdated sources Storage problems/Intermittency of supply Geographical mismatch of supply and demand
Communications	Ageing networks Lack of capacity Increasing complexity
Logistics	Higher demand Outdated networks Demand for more efficient systems
Waste disposal	Higher demand Increasing complexity of waste requiring improved recycling/disposal systems

	Outdated capacity

As can be seen, these problems can be generalised into two categories:

Increasing demand – due to higher populations and improved quality of life from economic develop, there will be a higher demand placed upon the capacity of existing infrastructure networks – i.e. a higher demand for the functionality of these systems (as they are also technologies)

Outdated supply/technologies – infrastructure systems are characterised by a difficulty with upgrading and modernising, as a result, much of the capacity is outdated and the technology utilised rather inefficient and old. The supply both needs modernising and an expansion to cope with the increasing demand.

There is one final distinct requirement that is placed on the waste disposal system, and as a result is placed upon all the other systems – and that is of sustainability. Sustainability is defined as the ability to maintain at a certain rate or growth[16], and as a result in order for this to be obtained the waste disposal system must either find new ways to process all of the waste by-products of the other systems or alter the other systems in such a way as that there are minimal by-products. This is because the existence of waste by-products (which cannot be dealt with) is not sustainable as there are finite resources we have to utilise, and if we exploit them in a non-sustainable way, eventually we will either run out of the resource (e.g. as is set to happen with the over-exhaustion of fossil fuels such as coal oil and gas), or have to deal with an excess of the waste by-products and their impacts (e.g. carbon dioxide resulting in global warming). As a result, as well as an expansion and modernising of the capabilities of these systems, they must also increase in sustainability.

The Energy System

Energy is an integral part of life. We use it to cook our food, to keep us warm in the winter, for light, and for communication, among countless other uses. In modern life, it is often impossible to imagine a life without it – just as it is impossible to imagine a life without the technology that it facilitates. We are so accustomed in the UK to the ease of being able to turn up our heating, to switch on our television, to turn the lights on when night draws close, that it is easy to ignore how we have access to this energy, and just to take it for granted. But there is a complex system behind meeting our energy needs – both domestic but also industrial, as it is important to be aware that

[16] (Oxford University Press, 2018)

all of the products we come across in our lives will have needed some energy input along their production cycle before they can be sold and used. Even products which seemingly would need little artificial energy input – such as organic crops – still have to be transported from A to B, and this too requires energy.

When examining the energy system, I am not only looking at what is commonly seen as the energy infrastructure in our country and world – i.e. the generation, distribution and use of electricity throughout our urban and rural areas - but also the extraction, distribution and use of primary energy reserves, such as coal, oil, gas and biomass, which is used either to generate heat, or is converted into a more useful source of energy – secondary energy, that is electricity, which can then be distributed and used in our homes and industries for a wider range of tasks than primary energy resources.

Primary energy resources

Primary energy resources, such as coal, oil, gas and biomass, are straightforward in terms of how they fit into the energy system. These fossil fuels occur naturally in the ground, created over millions of years through a combination of intense pressure, decomposition and dead organic matter. They are extracted from the ground, in a variety of different methods, varying in efficiency and for the type of fossil fuel. They are then transported, often halfway across the globe, to the destination – i.e. where the demand for them is – and are burned, which releases heat energy.

This energy is either used directly – e.g. to heat homes, to power combustion engines which are used for the majority of our transport, or in industry. If not, they are used to generate electricity, again through combustion, which releases energy, which is used to heat water or some other liquid, which vaporises, and turns a turbine connected to a generator, generating an alternating current through Faradays law of electromagnetic induction (i.e. a varying magnetic field induces a current through a conductor). This accounts for 17.5% of the UKs final energy consumption in 2016[17]. Electricity is the prime (but not only example) of a secondary energy resource – a form of energy 'made' (converted) from primary energy resources.

Renewables and other non-primary sources of energy

Other methods aside from burning are used to produce electricity. Renewables use the natural processes of the earth to generate electricity, either by using them to generate an alternating current through electromagnetic induction – tidal and hydroelectric power use water to turn a turbine, while geothermal uses the Earth's natural heat, and wind uses the force of the Earth's wind currents. Nuclear power,

[17] (DBEIS, 2017)

however, uses the heat energy produces by a fission reaction to turn a turbine. This illustrates an important point – that primary energy resources are not always the fuels that need to be extracted from the ground, but also include the Earths processes, which allow for renewable energy sources.

System dynamics

The energy system can be perceived as a relatively linear system, being focused with the pathway of source (where the energy comes from), distribution (i.e. the network that allows for the spatial movement of energy and its resources), and the consumption (i.e. how the energy is used, and what for). Developments in technology will have widespread effects on all levels and processes within the energy system, not only changing characteristics of the categories (i.e. source, distribution and consumption), but also how they relate and interact. Overall it will lead to an increasing complexity of the system.

However, there are various feedback loops existing within the energy system. This is because every event and process in our human/infrastructure systems requires an input of energy. This is no different for processes within the energy system – sources of energy require an energy input in order to be efficiently exploited – this can be the cost of energy of physical extraction, in the case of primary energy reserves such as fossil fuels, or the cost of maintenance and installation of non-consumptive sources, in the case of renewables such as wind turbines or hydro-electric power, which utilise the primary energy resources of natural processes such as the wind or flowing water.

Within the distribution of energy, there is also an energy requirement too. Whether this is in the case of the energy consumption of the logistical medium distributing the primary energy resources – e.g. carrying coal from the mine to the power plant – or whether this is due to the inefficiency of the secondary energy resource acting as a distributor (such as electricity), where energy is lost through the heating of wires through collisions between the current and the atoms of the wire.

As I will go on to explore in my Waste Disposal section, one of the key requirements placed upon all of the other systems (and this is what technology will support) is a reduction in carbon emissions, in order to prevent global warming and complex systematic change of the climate. This particularly applies to the energy system, as this is the route of all emissions – although other systems may account for emissions indirectly, through their energy consumption, it is the energy system that directly accounts for the emissions, and as a result decarbonisation is required in the next few decades if the UK is to meet its (binding) carbon emission targets. The decarbonisation of energy supply can be linked to two interlinked processes:

- The electrification of consumption – where consumption of primary energy such as gas is replaced by electrical input producing the same output (normally heat)
- The decarbonisation of supply – where the energy mix of the UK's energy generation undergoes a transition, from mainly based off of fossil fuels, towards a mix based upon renewables, low-carbon fuels and nuclear power.

Electricity demand – electrification and digitalisation

Electrical peak demand could be as high as 85GW in 2050, compared to around 60GW today.[18] This is due to further inclusion of technologies which require electrical input into our lives – through such measures as the Internet of Things (see communication sector), whereby due to the falling cost and size of electrical microchips and circuits, it is possible to contain sensors in almost every appliance, and for them to communicate with each other to co-ordinate responses. This will work to reduce electrical demand – through saving measures which reduce wastage, through such ways as turning off lights when an occupant leaves the room. However, this will be overshadowed by the cost and energy consumption of the batteries required for these chips – not because of the charge required, but the energy input along the production cycle of the battery. There are a range of other technologies which will become more widespread in the next couple of decades, due to advances in robotics, AI and computing, all of which will increase total energy demand, either directly, through their consumption, or indirectly, through the consumption during their production or maintenance.

Electrification of industries and processes, while it may reduce total energy demand, will increase electrical energy demand whilst decreasing the primary energy demand, as processes normally using gas to produce energy – e.g. central heating units – are replaced by electrical systems, which, depending on the source of electricity, may be more efficient, and will be able to be integrated into home and urban systems through the Internet of Things, leading to smart savings. Electricity demand is expected to grow at more than twice the rate of other final energy sources, comprising a quarter of global energy demand by 2050[19] but there are limits to electrification, and some industries will continue to rely on fossil fuels. Electrification will require major technological reconfiguration[20], particularly in areas such as transport, which comes

[18] (National Grid, 2017)
[19] (World Economic Forum, 2017)
[20] (Royal Academy of Engineering, 2015)

back to the difficulty with evolving technologies and infrastructure – the slow and often incremental change in the system, due to the difficulty in upgrading its capacity.

Furthermore, 'smart grid' technologies such as energy smart meters, which show the total consumption and expenditure on electricity, may contribute to efficiency, as customers, through the price mechanism and awareness of costs, reduce their demand to essentials, and avoid wasting money and electricity. Smart meters will also help energy suppliers, showing power flows within the network, allowing operators to make better asset management and service decision – e.g. it will enable them to be aware of damages to transmission lines and will reduce the time required to fix or service problems like this. The number of sensors in power consuming devices is set to increase six times over by 2020. While it is relatively low at the moment, the ability of energy suppliers and consumers to use the data provided by digitalization exponentially grows with the more connections, and this will translate into further economic savings. Florida Power and Light uses grid data to monitor the status of their grid and operations, and this has contributed to an estimated $30m in savings in 2014[21]. The implementation of 'smart grid' technologies will not only improve efficiency, but also will improve the resilience of the energy system as a whole, through showing bottlenecks and vulnerable areas of the network, and providing real time feedback on the status of the network, reducing maintenance time in the event of a crisis affecting the system.

Demand will also be reduced by the increases in 'direct' efficiency, as the technology which converts primary energy to secondary energy improves, and so power losses are reduced. In 2016, energy losses during the production of electricity and other secondary fuels amounted to 37.4 million tonnes of oil equivalent (435 GWh), 19% of primary energy supply. [22] If this were to be reduces, by the inclusion of newer forms of power plant technology, such as more efficient turbines, through the use of smart materials to make the turbines more aerodynamic perhaps, and thereby improve the conversion of heat energy to electrical energy (i.e. reducing the losses of converting a primary energy resource into a secondary energy resource)

Although demand is set to increase in the next few decades, due to further technological and economic growth, it can also be seen that efficiency within energy consumption and the network will increase also. This is an example of the optimisation of the network – which is defined as the action of making the best or most effective use of a situation or resource[23] - which, as will be seen, is a common

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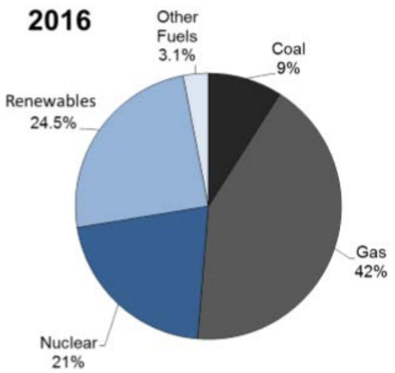
[21] (World Economic Forum, 2017)
[22] (DBEIS, 2017)
[23] (Oxford University Press, 2018)

factor in the development of all infrastructure sub-systems through the next few decades. There will be a transition from consumption based off of primary energy reserves to consumption more focused on secondary energy resources. However, in order to decarbonise the system as a whole requires close attention to how the secondary energy resources are created – which means energy supply must be examined.

Energy supply

In 2016, total UK electricity generation was 338 TWh[24], with this being 17.5% of the UK's final energy consumption, the other 82.5% being comprised of primary energy demand – e.g. central heating and industrial uses of primary energy resources. Of this generation, coal accounted for 31TWh, gas for 143TWh, nuclear generation at 72TWh, Renewable generation at 83TWh, and bio-energy accounting for 30TWh. This does not add up to total electricity generation – as power plants require a portion of the electricity they generate for their own works. This illustrates one of the complexities of energy supply – that the supply is dependent upon itself, it is not a distinct process. At all stages of the energy supply pathway, energy input is required – from transportation, extraction of energy resources, and at generation. It is not a distinct system – and will grow to be even more indistinct, as we shall see.



2 Courtesy DBEIS 2016

There are several key ways that supply is set to change over the next few decades. Due to outdated supply, around half of the UK's nuclear capacity is set to be retired by 2025 – some 10% of the UK's electricity capacity[25] - and as of 2017 only one new nuclear power station, Hinkley Point C, has been given the go ahead, and this will be the UK's first new nuclear reactor since 1995[26]. This illustrates one of the key factors influencing the future energy system – the fact the power plants will continue to become more outdated and must be replaced, in order to modernise the system. Modernisation of the system through replacing outdated or obsolete capacity will lead to efficiency

[24] (DBEIS, 2017)
[25] (World Nuclear Association, n.d.)
[26] (Guardian, 2017)

gains, and thus optimisation of the system. It will also allow for the decarbonisation of supply.

Nuclear power is seen as the bridging step between fossil fuels and a renewable, low carbon energy supply, which is a second way the UK's energy supply will be set to change in the next few decades, as the UK has set itself the target of reducing its emissions of carbon dioxide and other greenhouse gases by at least 80% of 1990 levels, by 2050.[27] Thereby one of the main requirements placed on the energy system as a whole is the reduction of carbon emissions, through the decarbonising of the UK's energy supply, and the reduction of the UK's primary energy demand, through electrification (where processes which were normally met by fossil fuel consumption are met through electrical consumption), the increasing of reliable supply and the decreasing of demand, through energy saving measures such as efficiency.

Decarbonisation of energy supply

One of the requirements on the UK's system is that its output of CO2 and other greenhouse gases must be reduced – in order to mitigate global warming and its corresponding impacts on the world at large. At present, renewables account for around 24.5% of the UK's electrical supply[28], and this will need to increase significantly if the UK is to meet its carbon targets for 2050. In order to decarbonise the UK's energy supply, there must be a transition from power stations and energy supply based off of the consumption of fossil fuels, which release CO2 when combusted, towards a supply based upon renewables and nuclear power, which have a low or zero carbon output whilst running, and only emit carbon through the production/construction process for these plants (i.e. indirectly).

One of the problems however with integration of renewables into the energy system is how they differ compared with traditional fossil fuel-based power plants. These plants require a constant supply of energy resources – there is a constant cost to the operators to keep the plant running and producing electricity. Renewables however, depend on the Earth's processes to generate electricity, through electromagnetic induction, and as such their running costs are incredibly low, although their installation and maintenance costs may be high as they are newer forms of technology. However, this does mean that if around one renewable installation, the Earths processes aren't as strong as normal – e.g. the sunlight is obscured by cloud cover, the wind speed is below that which is needed to turn the turbines – then there is little that can be done to get the installation to generate electricity again, until the weather

[27] (UK Government, 2008)
[28] (DBEIS, 2017)

changes. Their supply is intermittent, and in a system where the supply needs to instantaneously meet the demand nationally, this is not a reliable or efficient system. In order for the supply to decarbonise, there must be a transition to passive harnessing of primary energy resources through renewables, rather than active harnessing of primary energy resources such as fossil fuels, which will spark a change in the requirements placed upon other areas of the energy system - i.e. the distribution system.

A need for the distribution system to change

Distribution of electricity

The distribution of electricity is needed, as electricity production and consumption, while closer perhaps than primary energy consumption and extraction, are still not in the same place. The UK – and indeed all other countries with the capacity to invest in and create an energy infrastructure – has a National Grid – a network around the country of power plants, connecting to domestic and industrial demand, through a series of transmission lines.

3. Courtesy National Grid n.d.

However, electricity travelling through a wire will result in a heating effect, as the electrons in the current collide into the atoms of the wire, losing energy. The method the National Grid uses to get around this is through the use of transformers, which either 'step up' or 'step down' the voltage of the electricity flowing through a wire. Voltage is a measure of the potential energy difference of the circuit and is inversely proportional with the size of the current (how fast the electrons are moving in the wire). If the electrons are moving more slowly, they will lose less energy through collisions with the metal atoms in the wire, and as a result, less energy will be lost through heating in the wire. This way, the energy losses are minimised when the electricity needs to be transported over large distances through the National Grid – the electricity is passed through a 'step up' transformer, which steps up the voltage and lowers the current, is then transmitted through the transmission lines, and is then 'stepped down' before it is consumed.

The National Grid is also connected to the continent via an underground electricity cable – this allows the UK in peak times to buy electricity from Europe, and for Europe in peak times to buy electricity from the UK. There are two connections – one 2000MW high-voltage DC connection with France (indicated), and a 1000MW one with the Netherland, and there are also several in production, connecting the UK to Belgium, Norway and Normandy, France.[29] The interconnection improves the resilience of the UK's energy system by allowing it to 'borrow' from the continent – it avoids the spatial imbalance of energy supply through the distribution of secondary energy resources, whereas previously spatial energy imbalances would be avoided through the transfer of primary energy resources from countries with a surplus (energy producers) to countries with a deficit (energy consumers) via the global economy.

Going back to demand, it could also be reduced by decreasing the losses of energy through transmission and distribution. In 2016, losses accounted for 7.4 percent of the total electricity demand, and comprise three components – transmission losses from the high voltage transmission system (28% of the losses in 2016), distribution losses, which occur between the public supply system network and customers meters, and theft/meter fraud, around 4%.[30] Improvements, through the use of smart materials such a superconductors (provided they don't require a high energy input in order to low the temperature of the material past its transition temperature to where it becomes a functioning superconductor) could help reduce these losses, however the appropriateness of a UK wide roll out of superconducting transmission wires is hard to imagine. There will always be some energy losses after all – as will be explored further in the Waste Disposal section.

Energy Storage

Due to the nature of the Grid – i.e. electricity running along the transmission lines, forming a circuit with the consumption (i.e. essentially components in a massive circuit along the country), demand and supply must be matched instantaneously – i.e. the Grid must be generating at least the amount being consumed at any given point, or else blackouts will occur in parts of the country, as the demand is brought down to level with the supply of electricity. This is rather difficult, predicting the amount of electricity needed instantaneously.

While electricity itself is difficult to store on a large scale – due to various difficulties with the technologies – energy resources are much easier to store, and so the way the UK's energy grid currently solves the problem of needing to increase/decrease supply relatively quickly in order to meet changes in demand is through so called 'peaker plants', which come online when needed and add capacity to the network, and

[29] (World Nuclear Association, n.d.)
[30] (DBEIS, 2017)

through importing electricity from the continent – through the undersea electricity connections to France and the Netherlands. Both of these comprise of stockpiles of energy resources which can be introduced into the system when supply is needed to increase with demand – peaker plants function by taking advantage of a stock of primary energy reserves, while international connections allow secondary energy resources to be bought and sold. However, if the UK's energy supply is to be decarbonised, then stocks of primary energy resources will no longer become a viable way of storing energy.

Inclusion of renewable energy

In order for a significant capacity of renewable energy sources to be introduced into the energy system, there is a requirement for energy storage. This is because the energy supply of renewables is often intermittent and dependent upon the Earths processes – the sun, the wind, the tides, which can vary in magnitude with time. In order for the system to have enough resilience to these changes, ways of storing energy are required. Conventionally, the way the UK stores energy is through stockpiles of fossil fuels, but if the supply is decarbonised then this will no long be viable. Thus, a new form of Utility scale storage is needed.

The exact processes as to how storage plants can store electricity on a large scale varies – the Renewable Energy Association report counts 5 key methods used to store electricity [31] , namely mechanical, electrochemical (batteries), Chemical, high temperature thermal energy, and electromagnetic storage – but in order for the energy system to include a higher capacity of renewable sources, a larger capacity of storage is needed. One of the promising types of storage is chemical – and this will be explored further in the logistics system section – where the electricity at a time where supply exceeds demand is used to create synthetic natural gas or hydrogen through electrolysing water, which then acts as a store of energy, to be used again when demand exceeds supply and supply is required to be increased. Development of battery technologies – such as lithium-ion batteries, which accounted for 96% of new energy storage deployments in It smooths over the peaks and troughs in the generation of electricity. By 2023 Utility scale storage could be a viable alternative to peaker plants, and the cost of storage could reach parity with grid power in the late 2020s.[32]

On a larger scale, in order to also smooth out peaks and troughs in electrical generation, more interconnections with other countries are needed, especially

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[31] (Renewable Energy Association, 2015)

[32] (World Economic Forum, 2017)

countries such as Denmark and Sweden, who have developed their existing renewable energy mix to such an extent that that often produce more energy than they consume. The UK only has limited levels of interconnection, as I explored early – only supplying 5% of the demand over the course of 2015[33], with two interconnection lines to the European grid, with a total capacity of 3.2GW. Better interconnection within the UK Grid and with the European grid, will increase the diversity of the whole system, which will improve resilience, smoothing out the variations in supply.

The inclusion of renewables into the energy system, as well as an increase in effective energy demand, especially as there is increasingly a transition from primary consumption to secondary consumption, will require a radical change in how the energy system distributes energy. Forms of Utility scale energy storage will replace peaker plants, while international connections of National Grids will increase resilience and allow secondary energy resources to be traded.

Summary

Overall, the energy system is set to experience a transition in its functionality, due to the changing requirements placed upon it. The capacity of the energy system to provide for our society's needs will have to grow, fuelled by increasing demand caused by population growth, increasing wealth, and subsequent increases in consumption of technology, whether directly (through technologies which directly require energy input from the system) or indirectly (technologies which require an input of energy through their production cycle). It is important to remember that technology does not only refer to what we think of 'conventional' technologies, mainly focusing on electronics and computing, but any human designed system that provides a functionality, and demonstrates recursiveness.

The source of energy will experience a transition also, as energy sources move from non-renewable, primary fuel-based sources such as fossil fuels to passive, renewable harnessing of the Earth's processes. This is due to the increasing requirement on the energy system to reduce carbon dioxide emissions, in order to prevent large scale change and disruption to the Earth's climate, as CO2 is a waste product which our waste disposal system cannot control. This will spark a change in the distribution system, as large-scale energy storage becomes a requirement in order to cope with the fluctuation in supply from renewable sources, and to maintain the resilience of the network over these fluctuations. International connections will spread the risk of these

[33] (Royal Academy of Engineering, 2015)

fluctuations, allowing secondary energy resources such as electricity (as well as alternate forms of secondary energy resources which may take off, such as hydrogen) to be bought and sold via the global economy.

These three transitions on the demand, distribution and supply will cause the energy system to undergo a radical shift in the way it functions. One of the key ways in which it will change is through decentralization, identified as one of the three trends of the grid transformation in the New Technologies report undertaken by the WEF.[34] Due to the falling installation costs of renewables, plus investment and subsidies by governments in order to support the decarbonisation targets, it has now become viable for consumers to install renewables, mainly PV solar power, into their homes. This reduces their demand on the National Grid due to their own domestic supply, but also increases the supply of the system on a whole, by allowing customers to sell the energy they generate back to the Grid. The WEF Game Changers[35]report refers to this as the fragmentation of the energy system, as the dominance of the system by large players and installations (the typical energy generation, distribution, consumption process undertaken by large energy companies) is reduced by the introduction of a far greater variety of participants, including what it refers to as 'prosumers'. This term is used to refer to consumers of electricity who can also produce and sell electricity back to the grid. This adds increasing complexity to the energy system, through the introduction of bi-direction energy flows, and this is ultimately fuelled by the reducing cost of so called 'microgeneration' technologies – i.e. small scale renewable energy installations such as solar photovoltaic or combined solar thermal technologies (where mirrors are used to focus the sunlight into generating heat and thereby electricity through electromagnetic induction). This, combined with digitalization – another of the three trends identified in the New Technologies report, which will allow for the monitoring and control of energy flows – will lead to a fully smart grid, i.e. a dynamic, two-way system which allows end users to both use and generation power, and to manage their demand efficiently.[36] Thus not only will the component parts of the energy system undergo a transition, but the way in which the whole system functions will also undergo a radical change.

[34] (World Economic Forum, 2017)
[35] (World Economic Forum, 2017)
[36] (Royal Academy of Engineering, 2015)

The Logistics System

As mentioned in the introduction, one of the four key infrastructure systems is the logistical sector. This is a system (by its very nature) entirely focused on flows/connections between nodes in the network. These nodes can be towns, cities, or even smaller places such as streets or houses. The logistical system encompasses both the medium and the method of transportation on that medium.

Logistics is important as due to globalisation and economic development, many products and materials are not directly linked spatially to their demand, so need to be transported. This allows our economies to function efficiently and has led to a growth in trade both in between and inside countries. This is due to the principle of comparative advantage – where one country/area is marginally better at the production of Good X than Good Y, and another is marginally better at the production of Good Y than Good X, and so they each produce the good they have a 'comparable advantage' in production of, sell it on the global market, and buy the goods they don't produce from other countries selling. This leads to the economic specialisation of distinct regions in the economy, both local, national and global, but this is all facilitated by the logistical sector – without it there would be no way to transport all these goods and products.

This is a gross oversimplification of how the global economy works but is useful as a model – due to developments in logistical technology (i.e. improvements in transportation systems, methods of propulsion and so on, such as cargo ships and airplanes) the globe has become increasingly interconnected, forming a global economy, which improves the resilience of the system to local problems – e.g. crop blight etc. – provided the logistical system works efficiently.

It also allows for the movement of people, both domestically – e.g. commuting from home to work- and internationally – whether for work, holidays or other aims. This has led to our world becoming increasingly interconnected, leading to increases in wealth globally, mass market for producers, and new forms of consumption.

It is important to the UK, with an annual turnover of £1 trillion in 2017[37], with 2.3m tonnes of air freight, 17.05bn tonne km goods moved by rail, 9.77m TEUs of containers handled by UK ports, 1522bn tonne km goods moved by HGV. As can be seen, there are three distinct sectors of logistics – land, sea and air based, based off of what medium is used.

37 (Freight Transport Association, 2017)

The logistical system is set to change though, due to increasing demands placed upon it, to become more efficient – in both cost, time, and carbon emissions. The cost of congestion of a HGV carrying freight is £1 a minute[38], and as we see populations increasing, congestion will increasingly become a problem, due to increasing pressure placed upon the existing medium and systems, potentially over the efficient operating capacity. 28% of all carbon emissions are from transport[39], and due to the increasing demands on the waste disposal system to cut carbon emissions, the logistical sector will need to change.

How will it do this? Well there are multiple characteristics of the system which can be changed, and I will examine each one individually in this section. These are a) the type of sub-system – whether it is open or closed – b) the infrastructure of the medium (such as roads and canals), c) the control systems associated with the system, and d) the nature of propulsion of the logistical operators.

Type of Sub-Systems

The sub-systems can be split up two ways, through the medium they operate on and whether the system is open or closed. The three sub-systems based off of the three mediums are:

Land based logistics (encompassing any form of transportation on land ranging from cycling, roads/cars, trains - whether railways or metros)

Key for domestic logistics, and short distance (relative) haulage.

Air based logistics – mainly relating to the transportation via airplane, but also including helicopter, and perhaps the future of logistics, airborne drones. Key for the international transport of people but also to a lesser extent goods.

Sea based logistics – this is key for long distance haulage of goods, products and raw materials. Encompassing mainly cargo ships, this is a bit different to the other two systems due to the existence of bottlenecks in the medium – e.g. the Panama Canal, the Suez, the Straits of Malacca. This is the key logistical medium which connects the world economy, due to cost and capacity – for example, it is 10x cheaper to haul goods by sea than by air per weight[40].

The other way these sub-systems can be split up is into ‘open’ systems and ‘closed systems. Open systems contain a medium in which any form of logistical operator can operate on – i.e. the operator does not need to be fitted to the open system, although

[38] (Freight Transport Association, 2017)
[39] (Royal Academy of Engineering, 2005)
[40] (Raconteur, 2015)

due to the need to control and regulate how the system functions there are often limits on what is and isn't allowed to operate on an open system. By their very nature, logistical sub-systems which operate on an existing natural medium – i.e. air and sea-based logistics – are open systems. As are some types of land-based transportation – roads for example are open systems, as any land vehicle can operate on them.

Closed systems however, require the logistical operator to be designed to fit the medium it operates on, and other operators will not be compatible. The main example of this is the railways – trains must be designed so they function on the tracks, and they cannot be taken out of the system – apart from for maintenance and upgrading. In a closed system, the vehicle and propulsion are part of the system, whereas in open systems, the vehicle/propulsion systems operate on top of the open system.

Infrastructure of the medium

This may seem like an odd characteristic to analyse – considering that two of the mediums are entirely natural (the air and sea) and as a result there is little infrastructure on the medium. More important to take account of however, and what is normally overlooked, is the infrastructure allowing these three sub-systems of land, air and sea, and open/closed systems to interact and function as a whole system. Bridging/adapting points are needed for the whole logistics infrastructure to act as a system – and these are the sea ports, air ports and railway stations that allow a transition between mediums – as there's only so far one medium can transport goods/people, and for the logistical system to be effective it needs to transport goods and people from the point of supply (e.g. the factory) to the demand (e.g. stores and homes), and this will require multiple mediums along the transportation train.

Land is a little bit different, as the mediums are artificial – roads and railway trains are not naturally occurring, and as a result there is a need for infrastructure to create the medium. As technology develops, the cost of creating these mediums will fall, whilst the effectiveness and resilience will increase – for example, in the UK tarmac begins to melt when met with temperatures of over 30 degrees. As a result of global warming and climate change, temperatures will rise, and as a result, roads will require more maintenance – unless new materials are found which are more efficient, through nanotechnology, which will increase the resilience of the system to changes. However, with land-based logistics, there is a limiting factor – the amount of land available for use. Transport infrastructure in the UK only uses 2% of the total land[41], however most of this is in highly populated areas where land is high value. As a result, in order to increase the operating capacity of the medium, an upgrade to the infrastructure of the

[41] (Royal Academy of Engineering, 2005)

medium is needed. One of the key ways this is happening is through the implementation of Mass Rapid Transport systems in urban areas – public transport rather than private. This is often a shift away from open systems – such as the road – to closed systems such as metros, or to semi-closed systems – e.g. roads with a dedicated bus lane to favour public transport over private transport.

Despite some mediums not requiring an infrastructure – e.g. sea logistics – there do exist infrastructures which improve transport times, such as the Panama and Suez Canal, which are in essence artificial short cuts.

Both the infrastructure of the medium and the type of sub-system are unlikely to change – as they would require too high an overhaul and could not be implemented in any achievable time period without large scale disruption and change – aside from in urban areas, towards public transport and mass rapid transportation systems. What will need to change is the ability to co-ordinate and control the flows in the system – currently this is undertaking by regulations and infrastructure such as traffic lights. However, this may change in the future.

Control

Currently, all forms of transportation and logistical systems are operated by humans – i.e. drivers, air traffic controllers, etc. – which operate under a system of rules and regulations in order to allow for an efficient functioning of the whole system, and to avoid any accidents or disruptions to the systems flows, such as the rules of the road, and the requirement of a driving license, gained by the passing of a driving test, in order to drive on the road in the UK.

However, with the advent of more complex systems, there will be a transition to self-control logistics – where the human element of error is cut out in order to implement a more complete and sophisticated system. This will both reduce the number of accidents per year – in the UK road accidents account for over 3000 deaths a year, 8 times as dangerous as the rest of everyday life[42], and 90% of these accidents are caused by human error[43]. The implementation of controlled and autonomous vehicles (CAV – identified as one of the eight great technologies set to be supported by the Industrial Strategy of the UK coalition government in 2010[44]) is the increasing of capacity of the logistics system per unit area. An example of how this will work is through the reduction of congestion (which costs an estimated £15bn each year[45]) through the co-

[42] (Royal Academy of Engineering, 2005)
[43] (Citylab, 2014)
[44] (Science and Technology Select Committee, 2016)
[45] (Royal Academy of Engineering, 2005)

ordination of traffic flows from a central system. This will allow for mechanisms such as the platooning of trucks, due to vehicles being able to travel closer together, which reduce fuel costs and emissions by around 20%[46], with one lorry leading and making decisions for those which follow behind. In total the potential benefit of connected and autonomous vehicles is estimated at £52bn to GDP per annum in the UK by 2025[47], through the improving of traffic conditions, reduction of congestion, and the ability of vehicles to drive closer together, thereby optimising the network.

The benefit is not limited to land-based logistics, however. There is also potential for the application of autonomous marine vessels, and while most of the existing research and develop has been centred on small research and monitoring vehicles, the greatest returns will be through the commercial autonomous operations of vehicles up to the largest new build vessels including ships carrying bulk cargo, as the Rolls Royce parliamentary data explores[48]. Over 90% of the UK's imports/exports pass through the UKs ports after all[49], and sea-based logistics are the key logistical sub-system which underpins the inter-connectivity of the world economy.

In the pursuit of more savings, sea-based logistics have been seeking bigger and bigger ships (mega-ships), limited only by the artificial mediums and chokepoints (e.g. the Panama Canal and 'Panamax' ships – however the Panama Canal is itself undergoing an expansion), however, the cost savings of mega ships are decreasing – approximately 60% of the cost savings of the most recent ships are related to engines rather than scale[50] - and the transport costs due to larger ships will be substantial on existing infrastructure, with further increasing of the maximum container ship size raising transportation costs. Despite this, with a growing demand for trade, savings need to be found in order for the logistical system to stay efficient – and the key way this will be implemented is through connected and autonomous marine vehicles. Rolls Royce estimates the savings due the implementation of this will be around 20% of the total cost (£400bn in freight costs per year), i.e. £80bn in savings[51]. This will be realised through reduced crewing costs (this is the highest cost overhead per voyage), reduced capital costs (allowing the vessel design to be simplified), and increased efficiency of ships.

[46] (Science and Technology Select Committee, 2016)
[47] (KPMG, 2015)
[48] (Rolls Royce, 2016)
[49] (Royal Academy of Engineering, 2005)
[50] (International Transport Forum, 2015)
[51] (Rolls Royce, 2016)

However, in both cases, there is a requirement placed upon the infrastructure systems – changes to digital and physical infrastructure, and indeed the whole way the system is designed and functions (the system architecture). Ports will require changes to their infrastructure in order for fully autonomous vessels to operate. There will need to be a change in traffic management, to allow full benefits to be realised. It is still an early, growing technology, and comes with many ethical as well as systematic requirements – e.g. as with Googles self-driving car in development, who is culpable for when something goes wrong?

A perhaps even more important question to consider is not just what systematic changes automation technologies will bring, but also how the transition will be managed. A key part of any 'smart infrastructure' is the adaptability of a system, where it can meet future needs and absorb future technologies with much less replacement and expensive re-engineering[52], and this is one of the reasons why our infrastructure systems are outdated and ageing. It is difficult, especially with the logistical system, which is constantly in use, to implement changes. Infrastructure can take many years to be implemented, while the parliamentary cycle is 5 years, and there is an issue in upgrading systems which are so intensively in use[53]. There is also issues with how connected and autonomous systems will deal with the unpredictability of human-controls operators on the same logistical sub-system, and until CAV is adopted on a large enough scale this will perhaps cause more of an increase in congestion rather than a decrease (Atkins estimated that the likely tipping point for the proportion of CAVs on the road to produce major traffic flow optimisations is between 50 and 75%[54]).

Overall, the effectiveness of a shift in control of the logistical sub-systems will be determined by the growth and efficiency of the communications infrastructure system – as explored in the next section.

Propulsion

Typically, as with any other type of energy consumption, logistics has been reliant on fossil fuels – in particular oil and its by products through breaking down/adding up of its molecules (e.g. aircraft fuel). In the coming years we will see a further development in the accessibility and aptness of alternative sources of fuel and therefore propulsion – from the well-known, such as electric cars and other types of vehicles, to technologies which utilise the existing system but are perhaps cleaner (e.g.

[52] (Royal Academy of Engineering, 2012)
[53] (Raconteur, 2015)
[54] (Atkins, 2016)

biofuels and other 'zero-carbon' fuels which can be burnt with minimal net carbon output), or a completely different system – e.g. using hydrogen as a store of electricity. As examined in the chapter on the energy system, the endpoint of which form of propulsion will have a huge impact on the requirements of the logistical system on the energy system.

Currently, the propulsion of the existing logistical system is mainly based off of the combustion of primary energy resources- in particular oil and its by-products. As a result, transport accounts for 28% of CO2 emissions[55], which are a by-product of the combustion of carbon-based fuels. However, due to the requirements placed upon the waste disposal system, we as a society are seeking to decrease our carbon emissions.

This means that transportation, in particular, will need to be decarbonised to some extent in order to effectively cut our carbon dioxide emissions. What level depends on the requirements placed by political and social pressures on the waste disposal system – but ideally it would be as close to zero as possible, with minimal carbon dioxide emissions, as utilising a primary fuel such as oil for transportation is not a sustainable basis for the logistical system, due to a) exhaustion of supplies, and b) the build-up of carbon dioxide, enhancing the natural greenhouse effect and causing global warming and climate change.

One of the widely touted solutions to excess emissions, above the international targets set by the IPCC/Paris Accords is an increase in efficiency. Why both reducing the carbon emissions when you can improve the utility per tonne of carbon dioxide emitted? It is true that as technology improves, we see an increasing efficiency in the logistical system – for example with new mega-ships approximately 60% of the cost savings are due to the improving efficiency of the engines[56], and new engine architecture and materials are set to improve airliner efficiency over the next 20 years[57]. Automation will also have the subsequent effect of improving efficiency through the elimination of congestion, and as a result, less time spent with the engine idling. Going back to platooning, this will reduce emissions by around 20%.

However, efficiency is not a complete solution. While efficiency will lead to further savings, due to increasing global and national pressures on the logistical system, the increase in demand for logistics and subsequent increased carbon emissions may exceed the savings from efficiency – Boeing estimate a need for 38,000 new airlines over the next 20 years[58], at an estimated value of $5.6 trillion. Over the past 30 years,

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[55] (Royal Academy of Engineering, 2005)
[56] (International Transport Forum, 2015)
[57] (Raconteur, 2015)
[58] (Raconteur, 2015)

air traffic has increased by a factor of 5 – and demand could treble by 2050[59]. As a result, while efficiency will help, another solution is needed – and this is the transition away from oil-based propulsion (and subsequent carbon emissions) in the logistical sector.

There are two effective ways to do this. One of these methods is to adopt so called zero-carbon fuels, such as 'biological' oil such as ethanol, to be combusted in the same combustion engines as normal oil would. This wouldn't require a large-scale change to the logistical system – indeed it would perhaps only require a slight retrofitting of engines to cope with biofuels – or to the energy distribution system – ethanol could be transported and distributed in the same way as oil is, just from a different source. However, this is an ineffective replacement form of fuel, due to the shift that would be required to produce ethanol on an industrial scale, enough so to replace oil usage as a fuel. This is because ethanol is extracted from organic matter – i.e. crops – and as a result, with a growing population on a finite earth, it would be impossible to grow enough crops on such a scale as to both provide food and fuel – especially as personal wealth continues to increase and whole populations shift from a plant-based diet with minimal meat to a meat-based diet, which requires more land on an order of magnitude higher than a plant-based diet.

The other method is through transitions from oil-based primary fuels to a logistical system based off of a secondary energy resource. There are two viable candidates for this role – electricity, and hydrogen, and both require a primary energy input in order to fulfil their purpose as a secondary energy resources. As a result, there is a risk of just shifting the carbon output away from the logistical system to the energy system, if the energy is not sourced from a decarbonised or low carbon source – such as renewable energy, nuclear power or zero-carbon fuels such as bioethanol (although this comes with the same problem as if we were using it directly in engines). I will focus mainly on electricity and its potential as an alternate source of propulsion in the logistical system – mainly as hydrogen is still experiencing some safety and effectiveness issues, as with any new form of technology, and it suffers from the early adopter problem of demand/supply – there will be not distribution systems for hydrogen fuel without demand from vehicles, but there won't be demand from vehicles without a distribution system for hydrogen fuel. However, aside from that, it is an equally viable form of alternative fuel.

Electricity on the other hand, already has a distribution system – the national grid. However, this is not directly applicable to electric vehicles or aircraft so the system

[59] (Royal Academy of Engineering, 2005)

will need to be modified to cope with increased demand from electric vehicles. There also exist three limiting factors[60] to the implementation of electric vehicles – due to a lack of research into batteries, there is a limit of range and relatively long recharging times, as well as a lack of availability of charging stations, all of which need to change if electric vehicles are able to compete with their internal combustion engine fuelled competitors. Currently, Tesla is the leader in electric car production, with 22,500 sold in 2013 (0.03% of 82.8m vehicles sold in the US), increasing to 50,000 sold in 2017 (0.9%), and continuing to grow. The range on a typical tesla is 265 miles on a lithium ion battery pack[61], and they are investing $5bn between now and 2020 on a new battery factory. Currently electric vehicles do not have the strength to compete with oil-fuelled transportation – as it is still a relatively small, growing industry, with support from subsidiaries, but as oil prices begin to soar due to falling reserves and growing environmentalism pressure, electric vehicles will begin to replace oil-based logistical vehicles, first on the roads and railways, but also on the sea and in the air.

Summary

Essentially, of the four categories we examined (type of sub-system, infrastructure of the medium, control and propulsion), the type of sub-systems are unlikely to change in the future – we already are using all of the mediums possible (bar space-based systems, although this will perhaps have to wait even longer until it is commercially viable and safety focused), the only change will be perhaps between how much of the logistical system each sub-system comprises of, and this is a relatively zero-sum game. However, all are set to increase, due to increasing pressures placed upon the logistical system by a growing population, both in size and in wealth.

The infrastructure of the medium is unlikely to experience a drastic change; aside from on land where due to increasing urbanisation we will see a transition from road-based open systems to closed or semi-closed mass rapid transportation systems (such as Metros or bus routes with dedicated bus lanes) in order to optimise the efficiency of the network, as in other mediums are all natural and so have limited infrastructure. The only distinct change we will see to the infrastructure of the medium is through control infrastructure (see below), and transition nodes between the different types of systems (e.g. ports and airports), which will become increasingly more important as the logistical system grows more complex.

It is with the control of the logistical sub-systems and the fuel of the vehicles that will experience the most change – and the extent they will both change depends on, and

[60] (Citylab, 2014)
[61] (Citylab, 2014)

influences, the change to the energy and communications systems of infrastructure. It is also influenced by the waste disposal system, due to the requirements placed upon in in the decarbonisation of the logistical sector, and indeed the energy and communication sectors.

The control of the logistical sub-systems will switch from human-based to automated – although the extent to which they are automated, and how the transition from a human-controlled system based off of rules of the medium (e.g. the road) to an automated system will depend entirely on public attitudes towards the adoption of these technologies. This will lead to the elimination of accidents – 90% of which are caused by human error – and a reduction in emissions due to increased efficiency. This will place new requirements on the communications system.

The fuel of the logistical sub-systems will also change, in order to decarbonise. It is unlikely that net zero-carbon fuels such as bioethanol will fulfil more than a bridging or niche function, due to the high land cost, which is limited and could instead be used for crops to fuel our growing populations demand. Instead we will see a shift to secondary energy resources – such as hydrogen and electricity – though this will require a large-scale development of the distribution infrastructure, and as a result will put new pressures on the energy system.

These two changes could indeed work in tandem to completely change how we see transportation – at least land-based logistic – as explored in the ReThinkX Sector Disruption report[62], which visualises a fleet of on demand autonomous electric vehicles, not privately owned (Transport as a Service). They estimate it will account for 95% of US passenger miles by 2030 (based on 20-25% of rural users remaining non-adopters) and will reduce energy demand by 80% in the transport sector.

It will do this through exploitation of the fact that individually owned cars are only used 4% of the time, and a result will provide a platform for individuals to rent a car only when it is needed, and this will mean that each car is used at least 10 times more frequently than privately owned cars, and as a result there will be 70% fewer cars manufactured each year, lower emissions and increased efficiency. It will benefit from network effects – so the more drivers/passengers using it the more efficient it will become. We are seeing a similar transition, albeit not on the same scale today, due to the growing influence of Uber and ride sharing through Uber – however the difference being the automated nature and dependence on electric vehicles of Transport as a Service (TaaS). This shows the influence that both the communications and energy systems may have on the logistical system, and vice versa.

[62] (RethinkX, 2017)

The Communication Sector

Communication is defined as the imparting or exchanging of information by speaking, writing, or using some other medium[63], and is an intrinsically important part of our modern society – or indeed, any society, as society by its very nature requires co-ordination and organisation of a group of people, which requires communication between individuals in the group. There is a growing need for communication in our modern society, as, through the exchange of information through a medium, it allows for the co-ordination of all other systems in our society – whether that is the base physical infrastructure systems, our complex soft infrastructure systems (i.e. the institutions which exist to maintain and regulate our economy and population), or the social systems we navigate through each day.

It is important to be aware of two distinctions when talking about communication. The first details between who or which operators, the communication is taking part. We often view communication as between two individuals – and this is the most common form of communication in our everyday lives – but communication can also take place between an individual and a system (e.g. a control system for a factory plant), or, as will become increasingly more common, communication between two machines.

The other distinction is to do with the form of communication, and the system structure of the medium. It is important to be aware of the nature of transfer of information – whether it is a direct communication, i.e. direct exchange of information between one individuals/operators of information and, at least, one other individual/operator. This operates off of a closed system – aside from the two operators, there is no way, without hacking into the system, for external operators to be aware of the exchange of information. Examples of direct communication are texts, telephone calls, letters, etc. The other type of communication is naturally the reverse – operating off an open network, where all operators can gain access to the exchange of information. The exchange of information is no longer limited to between two operators – it is from one operator to many. The number of operators it is available to is potentially limitless, only depending on the medium and the accessibility of that medium. An example of this is the written book, the internet, or social networks such as Facebook or twitter.

It is also important to be aware of the convergence of these networks – these are no longer distinct, and there now exist systems allowing for both indirect and direct

[63] (Oxford University Press, 2018)

communications. Despite their existing distinct forms of communication systems, such as landlines, the internet, and mobile phones, they are slowing converging towards a pervasive system based off of one main technology used to access – handheld devices, such as mobile phones and laptop computers, all of which operate off of the existing dual infrastructure systems of the internet and of mobile phone networks, which are slowly amalgamating into one infrastructure system, with obsolete communication networks – such as landlines, and the post – slowing being cut out of the market.

Information and Data

But in order to accurately understand why these communication networks are so important – and thus analyse them systematically to see how they may change in the future – it is important to have a working definition of information and data, and thus what can be done with this information and data – i.e. what functionality it provides.

Information is defined as 'Facts provided or learned about something or someone[64]', while data is defined as 'facts and statistics collected together for reference or analysis[65]'. From these definitions we can see the subtle difference between the two – information is just facts provided/learned about a certain topic or person, while data is facts collected together for reference/analysis, thus data is a collection of information on a particular topic, collected for reference/analysis.

From the Cisco white paper[66], which explores how and why information is useful to us, we can understand that data comes together to form knowledge, which is information that people are aware of, and thus can act on. Knowledge, when combined with experience, forms wisdom, which again can be used to optimise decision making. We can see that there is a correlation between the input of data and the output of wisdom – thus, the more data, the more knowledge, and thus wisdom.

Why is this important when talking about the communication system? This is because the basis, the *raison d'etre* of the communication system is the transfer of information and data. However, this transfer is not the reason in itself of the communication system – the transfer of data is needed in order to improve the knowledge and wisdom of operators in the system, and thus optimise the decisions they make. One of the key market failures of the economy (and thus the inefficiency of it as a technology in providing its functionality) is that of imperfect information – consumers and producers lacking information on the state of the market, their product and price

[64] (Oxford University Press, 2018)
[65] (Oxford University Press, 2018)
[66] (Evans, 2011)

levels, and thus making less than optimal market decisions, which leads to inefficiency in the market, which translates to losses. As a result, if the transfer of information is improved to market operators, they will be able to make more optimal market decisions, based off of the knowledge and wisdom they have gained from the communication system, and as a result, the economy will be more efficient in its functionality – the allocation of goods and services from producers to consumers.

This leads us onto Metcalfe's law, which states that the value of a network is proportional to the square of the users/nodes. This can be translated onto the communication system, as the larger the capacity of the communication system, and the more efficient its flows (i.e. methods of transfers of information, realised by technology) between nodes, the more valuable the communication system is to the users, as there is more information which can be provided, and thus turned into valuable knowledge and information, which can then be applied to optimise market decisions, and thus optimise the technology that is the economy.

Brief History of Communication Technologies

Naturally, the first communication technology was not an artificial technology, but a natural one – the human language. This developed through evolution, as we began to form social structures and hierarchies, and is essentially what all the other artificial technologies – mobile phones, social networks, the post etc – operates off of. Without language there is no communication, as language allows for the direct, face to face exchange of information, which is the key to creating social groups, and then, from that, a functioning society.

The next step in the communication story was the creation of a written form of language – the written word. This allowed, for the first time, indirect communication, through writing. And this is the way it stayed, for almost two millennia, with communication systems barely passing past the point of the written word. We developed more efficient networks, based off of physical writing – such as the postal system.

The next step was, of course, the telegram. And from that, landlines and the radio, leading toward mobile phones, operating off of radio technology – and then finally, towards the end of the 20th century, the real key part of communications technology – the computer, leading to closed private and governmental networks, which then gave way to the internet and the world wide web. Which is where we stand now – with new technologies based off of the internet, and social networks operating on top of the internet, being on the rise.

The Internet

When looking at the internet, it is important to draw a distinction between the internet, and the World Wide Web, as these terms are often used interchangeably; and although they have a significant overlap there is a strong distinction.

When we talk about the Internet, what we are referring to is the physical network made up of switches, routers and other hardware, with a primary function of transporting and distributing information between computers[67]. The World Wide Web, on the other hand, is the application layer operating on top of the internet architecture; it provides an accessible interface to operators to use the internet. The internet has not changed much over the years – apart from an extension of capacity in order to meet the ever-increasing traffic needing to pass through the internet, the actual system architecture has not changed so much, and neither has its functionality – as a means to transport information. In essence, the internet is just a logistical sub-system, with a task of transporting information, rather than products, people or services.

The web, however, has gone through several development phases[68]. It initially started out in it research phase as ARPANET, a governmental, closed system of networked computers. Its second phase however, occurred (referred to as brochure-ware by the Cisco white paper) when the internet was opened up, from a private closed network, to a public, open network, and there was a demand/need for almost every company to share information on the internet, accessible to its customers. This led to a huge increase in market information for the consumer, allowing them to make more efficient economic decisions. The third evolution took the web from providing a functionality of static data to providing the ability to buy and sell products and services through transactions on the internet, and that finally led us to the development phase of the social web, where social networks such as Facebook and Twitter operating on top of the internet, have grown rapidly, by allowing people to communicate, connect and share information. It has become almost a requirement to be on these social networks.

Movement from wired to wireless systems

An important thing to be aware of when considering the future of communication systems is the transition, from wired connectivity to wireless connectivity. This can be seen, both in the telecommunications system, and in connectivity to the internet.

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[67] (Evans, 2011)
[68] (Evans, 2011)

Initially, the landline reigned supreme – this is one of the reasons that now in the UK almost every house has a landline, or access to one, provided the tenants purchase a landline subscription. This allowed for long range, direct and vocal communication between two people at a low cost. However, in the early, mobile phones began to phase in – operating off of a system of mobile phone masts through the sending and receiving of electromagnetic radiation, they provided a more mobile, faster connection than landlines. This was the start of constant connectivity – we can see this now, where it is almost a given that someone has a mobile phone, in particular a smart phone. The mobile phone network also increased the capacity of the telecommunications network, to such an extent where now 95% of the world's population is covered by at least a 2G network, and 69% is covered by 3G or better.[69]

The same development can be seen with internet access – initially, access to the internet was through a wired connection – dial up internet, and then Ethernet. This meant that, like with the landline, there was a bottleneck – a limit on the amount of communications, due to the access port, i.e. the wired device. However, this was replaced by wireless connectivity – i.e. WIFI, which has become an accepted part of our modern-day society, to the point where often we feel lost without it. However, WIFI still depends on part on the wired connection – a WIFI router is required to be connected via the Ethernet to the Internet, and then sends/receives signals through electromagnetic radiation.

These two systems also experienced a convergence, through smartphones and 3G technology, which allows access to the internet wirelessly through the mobile phone network, by integrating the mobile network into the internet. We are seeing the connection speeds and capacity of this grow already – we are on 4G technology and are preparing to implement 5G in the future.

However, it is important to note, that despite these developments in communications technologies, there is still a significant proportion of the world's population without access to these communication networks – some 4 billion people do not use the internet[70], and while good fast connectivity reaches almost 70% of the population, it reaches less than 30% in rural areas (through either broadband or 3G).[71] Although it is not the function of this report, it is important to note that the communication system requires some development in terms of accessibility and affordability until the whole

[69] (WEF, 2017)
[70] (WEF, 2017)
[71] (WEF, 2017)

world can be connected, and there will still be a significant inequality in connectivity and technologies unless something is done about this.

Future of wireless connectivity – 4/5G

Technologies for 5G, and future generations of connectivity, when deployed in the 2020s, will provide higher bandwidth (range of frequencies within a given band, which controls the maximum capacity of a network link transmitting bits of data per second) and lower latency (delay before a transfer of data begins following the instruction for its transfer) than current generation technology.[72] Thus this will increase the capacity and speed of the mobile phone network, aiming to reach estimated data rates of 10s Mb/s for 10,000s of users, and over 100Mb/s for metropolitan areas[73], thus increasing the speed and capacity of the mobile internet network to handle flows of data.

Mobile phones are an example of a pervasive technology among consumers – in 2016, over 1.5 billion smartphones were sold.[74] A new generation of mobile network has appeared approximately every 10 years – 1G in 1982, 2G in 1992, 3G in 2001, and 4G in 2012. This, in conjunction with developments in technology of the actual mobile phones themselves, has created a convergent system, with mobile phones developing from simple phones which could do little more than transmit voice communications, to smartphones which can navigate the web, handle photos, videos and many other applications – essentially operating as a mini hand-held computer. As the well-known fact goes, the Apollo rockets which took Astronauts to the moon had less computing power than the mobile phones we now carry around in our pockets.

But it's not only faster connectivity and capacity through the use of mobile phones that 5G will facilitate. It will also help to facilitate the internet of things, by providing a further mode of wireless connectivity.

The future – the Internet of Things.

The internet of things is a world where up to 50 billion things/devices are connected to the internet by 2020 (the equivalent of 6 devices for every person on the globe).[75] The expected benefits of this are $11 trillion per year by 2025[76] to the global economy. It will do this by provides accurate, real time information to consumer and producers alike, allowing for more informed market decisions, and increased savings by

[72] (IEEE)
[73] (IEEE)
[74] (IEEE)
[75] (Evans, 2011)
[76] (Evans, 2011)

improving the efficiency of processes ranging from the energy consumption of houses to the processes used by heavy industry to produce steel.

It will do this by the creation of a network made up of the 50 billion sensors embedded in devices/things, which will provide real time data, through connection to the internet, via either WIFI, Ethernet or mobile phone networks, although it is most likely that the connections will be via wireless networks such as 4/5G or WIFI. It is described as a 'self-configuring wireless network of sensors whose purpose would be to interconnect all things – either as a source of information or as a consumer[77]. Thus, not only could these nodes in the network function as sensors – as described in the ATOS white paper, through a passive mode of connection, where the object carries identification and just stores information, which is passed on – but they could be connected in an active mode, not only functioning as sensors through measuring something, but as presenters, presenting the information to a human or other machine, or gateways, enabling communication between devices, or actuators, receiving commands via gateways from somewhere else in the network and acting on those commands. Furthermore, these active objects could be multipurpose – not only functioning as one of the categories, but of multiple, measuring, sending and receiving data. This could allow for real time responses, by either a program or a human, to changes observed by the sensor, allowing for more efficient responses to changing conditions in a network or system.

However, the Internet of Things will require significant changes, both in hardware and software, in order for its benefits to be realised. It also follows the same trend – a movement away from a direct system, to an indirect one (information is available to more than just the two nodes communicating in the system), from a wired to a wireless system (the sensors will need to be wireless as it is not feasible for all the sensors to be wired into a network), and from a closed system to an open system.

Hardware requirements

The Internet of Things will require significant improvements in technology in order for its effects and benefits to be sufficiently realised – not only in the hardware which dictates our current communication network (i.e. the internet and web, on top of/through which the Internet of Things will run) but in the technology for the sensors which play such an integral part in the Internet of Things, that will be embedded in devices and objects around the globe, in homes, public spaces and in workplaces. This sensor technology allows for the collection of an enormous amount of data[78], which

[77] (ATOS, 2012)
[78] (Peter Evans, 2012)

can then be analysed through the software developed to realise the benefits of this sensor technology.

The three main requirements placed on these sensors in regards to hardware are a sufficient energy source, hardware size, and radio connectivity. Associated technologies to fulfil these requirements, such as wireless tech, miniaturisation, and batteries, all of these which are now mature and cost-effective enough for implementation and will continue to drop in price and improve in maturity in the next few months.

In regards to the sensor energy source, sensors will need to be self-sustaining as the vast majority will not be directly connected to a power source, and the battery technology has not developed to such a scale of miniaturisation and efficiency that we can provide enough power to a sensor sending and receiving information in real time for several decades – as another requirement on the energy source is that it won't need changing regularly, as this would be grossly inefficient. Thus, the most efficient way for these sensors to be powered is through self-sustainability – the ambient energy harvesting from external sources, such as kinetic, solar or thermal energy from outside sources[79]. This is an example of decentralization of supply– the development of the complexity of the system, moving away from the typical source-distribution-consumption model that our existing energy system is mainly based off of.

Our existing network infrastructure will need a significant development and investment in order for the internet of things to be realised, as machine to machine communication will bring an unprecedented level of network traffic[80], and thus the existing infrastructure will need to be adapted and modernised. It will require such a larger scale of computing power due to its real time nature, as around 50-100 trillion objects would share data. Vastly parallel systems capable of performing calculations orders of magnitude higher would be required – and cloud computing would enable dynamic distribution of workload, which will mean that the system will be able to scale rapidly to meet the growing demand in terms of storage and computing power[81].

Demand for data processing is more than doubling every two years and will have increased 20 times by 2020[82] - up to a 40x increase in demand by 2025. This will not only place a much larger requirement on computing power and subsequent infrastructure but will also have the subsequent impact of a vastly larger energy consumption. Currently the energy consumption of all total computing power is

[79] (IEC, 2014)
[80] (ATOS, 2012)
[81] (ATOS, 2012)
[82] (Peter Evans, 2012)

around 130GWh per year, equivalent to about 2.5 times the energy consumption of NYC. However, by 2025, this will grow to the equivalent of between 9 to 14 megacities worth of energy consumption – a magnifying of at least one order of magnitude[83]. This will place further requirements on the energy system.

Software requirements

There is little software needed for the system of the Internet of Things - the system just provides the data, it will be up to consumers to generate the software required to process and analyse the data provided. This will require a lot of automation, and may lean quite heavily on AI, an example of a changing system, from human based decision making to decisions informed, and potentially made, by machine learning programs – i.e. AI. To what extent this is realised depends on public attitudes to AI and how AI is regulated, which is not covered by this report. But it is important to note that AI and the Internet of Things are significantly linked, as AI will provide the processing power, software and machine learning tools required to interpret and act upon the real time data provided by the Internet of Things.

The one significant requirements in terms of software that the Internet of Things will require is due to the fact that the internet is not designed to support a huge number of low-power devices that interact with the physical world[84]. Indeed, it is having problems with the scale of devices connected to the internet even now, in the present day and age, as the internet is running out of unique IP addresses (an Internet Protocol address, a 32-bit numerical label assigned to each device connected to a computer network which uses the Internet Protocol for communication). As a result, IPv6 has been developed, using 128-bits for the IP address, thus providing up to 2^{128} possible addresses, an increase from the 2^{32} data points from IPv4 (approximately 5 billion unique addresses) which will meet the needs of connecting 50 billion devices to the Internet by 2025, with bonus space for tens of billions of data points[85].

Impacts/benefits – i.e. functionality

The main benefit that the Internet of Things will bring, as with any communications system, is vastly unparalleled amounts of data. The collection of this data, as well as the analysis and application of the analysis of the data, will be used to improve machine performance[86], and as a result will inevitably increase the efficiency of the systems and networks which the machines operate in. It will lead to a vast

[83] (Peter Evans, 2012)
[84] (CCC, 2015)
[85] (IEC, 2014)
[86] (Peter Evans, 2012)

optimisation of networks ranging from supply chains, to home energy networks, to even the infrastructure systems we have been exploring. Indeed, logistics and energy will see a vast optimisation in their networks, and as a result will become far more efficient.

The improvement is not limited to just network optimisation and efficiency however. It will also optimise the maintenance of system, through facilitating optimal, low cost maintenance across fleets and systems, in response to real time damages and problems[87], improving the resilience of all systems. It will lead to intelligent decision making, through gathering enough information from intelligent devices and systems to facilitate data driven learning, which will enable a subset of operational functions to be automated, which is essential as the complexity of systems increase.[88]

The optimisation of networks, automation of some functions and reduction in maintenance costs will have a significant economic impact, on a large scale. By 2025, 5G capacity by itself – without even the Internet of Things which it will facilitate – could have an estimated 110 billion euros per year, in just 4 key sectors, which are automotive, health, transport and energy[89]. The Internet of Things, however, has an estimated $11 trillion per year by 2025[90], and the application of the Internet of Things to industry (the so called 'Industrial Internet' as explored in the report) could be worth up to $82 trillion in extra value by 2025, which is just under half of the global economy in 2017[91]. The development of the communications system will have significant economic benefit.

It will also impact on the other infrastructure sectors.

Logistics in communications

The logistics sector will be optimised through the flow of goods, vehicles and people. This will be implemented either through stationary sensor networks (either on vehicles or part of the traffic infrastructure), or through floating sensor networks (where individual vehicles operate as the sensors)[92] .

Management of the increasing complex traffic flows – especially as CAVs (controlled and autonomous vehicles) become wider spread – relies on the accurate measurement of the traffic flows. Wireless technology may be beneficial in reducing deployment

[87] (Peter Evans, 2012)
[88] (Peter Evans, 2012)
[89] (IEEE)
[90] (Evans, 2011)
[91] (Peter Evans, 2012)
[92] (IEC, 2014)

costs compared to wired sensors, but the real benefit will be turning the vehicles into sensors (through the implementation of wireless sensors, connected to the Internet of Things), which will accurately measure traffic flows, particularly within cities, where it is becoming increasingly critical to manage the ever-increasing flows of people, goods and vehicles, in a closed space.

This was touched upon in the Logistics section, but the 'Logistics Internet' could be developed – the application of a cloud computing approach to logistics, with empty warehouse space being dynamically filled when demand is high and there is space capacity, as a result optimising the logistics sector. The Internet of Things could take this optimisation further, through urban consolidation centres – warehouses just outside the city where all goods destined for the city are consolidated and then shipped with an optimized routing, through careful analysis and planning of the traffic flows within the city, through the floating sensor networks.

Energy

The demand for improved reliability and quality of the power grid is increasing, as is the dependency on electric power. The implementation of a smart grid – providing the capacity to integrate more renewable sources, electric vehicles and distributed generators into the network, will deliver power more efficiently and reliably through demand response, and comprehensive control and monitoring capabilities, using automatic grid reconfiguration to restore outages, and access to improved control of consumers consumption, all facilitated through the Internet of Things and a developed communications system.

The Internet of Things can also reduce losses of energy in the source-distribution-consumption pathway – of the theoretical energy in the fuel, 2/3rds is lost in generation and another 9% is lost in transmission[93], and as a result of the primary energy only 30% is available as electricity at the point of use. The Internet of Things can solve this by providing real time monitoring, and enable a valid management of the whole process, and as a result this will lead to optimisation and improved efficiency of the conversion of energy. The 'Industrial Internet' is also expected to reduce energy consumption – both through savings in the logistical sectors (14% of global transportation fuel demand can be reduced by the Industrial Internet[94]), and savings of direct use of energy (for example in the industrial sector, the heavy industry energy consumption could be reduced by up to 20% through the Industrial Internet[95]).

[93] (IEC, 2010)
[94] (Peter Evans, 2012)
[95] (Peter Evans, 2012)

Summary of how the communication system will change

From this section it can be seen that the communications system is an integral part of our everyday life – so many of our tasks in everyday life are facilitated by the transmission of information and data, whether that is from old forms of communication such as books and the written word, to more high-tech methods of communication such as the internet, and mobile phones. However, the communications system, much like the other systems, is set to change and develop as new technologies form through the process of combinatorial evolution, and are normalised and integrated into the economy, creating a ripple effect upon the communications system and thereby the rest of the economy.

The main changes will be through the implementation of the next generation of connectivity, through 5G, which will result in a larger bandwidth, and lower latency, which will lead to increased data transmission speeds, thereby increasing the quantity of data available. This will facilitate the implementation of the Internet of Things, where billions of devices/objects will be interconnected and share data, providing a huge amount to be analysed and thus acted on. This will improve market decisions by solving the problem of imperfect information, thus optimising market decisions. This will reduce costs and improve efficiency, both in the systems and networks that comprise industries in the economy, and in the economy as a whole, providing a significant increase in revenue, and growing the economy. As the new technologies that will make up the communications system are integrated into the economy, and make it more complex and improve its functionality, this will impact on the other infrastructure systems which make up the basis of the economy, as they are all interconnected, and will lead to the optimisation of their functionalities also.

The Waste Disposal System

Waste is defined as 'Unwanted or unusable material, substances, or by-products'.[96] However, it is also defined as an act or instance of using or expending something carelessly, extravagantly, or to no purpose[97]. As we shall see, both of these definitions are applicable to the context of the waste management system.

In pretty much every industrial or technological process, there is waste – both in the sense of unwanted/unusable materials, and in the sense of a lack of efficiency leading to the use/expenditure of something carelessly or extravagantly. It is important to be

[96] (Oxford University Press, 2018)
[97] (Oxford University Press, 2018)

aware of the distinctions between the two – the former definition and application describes unwanted by-products of the process, which potentially cannot be used, while the latter is mainly related to energy wastages as a result of a lack of efficiency in the process. They are two sides of the coin – one is related to the process itself, and the other to the outcome of the process. We will see that both are applicable to the waste management system, and place different requirements on it. They are also interlinked – energy wastages lead to unwanted by-products created in the processes required to produce that energy. They are not mutually exclusive.

Both can be minimised; however, it is impossible to achieve a fully 'zero waste' system, just as it is impossible (due to the 2nd law of Thermodynamics, that the entropy of any system always increases, thus isolated systems spontaneously evolves towards thermal equilibrium, where the heat energy is spread equally over all of the system) to achieve a 100% efficient system, in terms of energy. This is because energy will always be lost through heat transmission (although the energy is not technically 'lost' from the system, as the first law of thermodynamics states, energy is not created or destroyed – the total energy in a system is always constant. The energy is 'lost' in the sense that it loses it utility as heat, it becomes spread over the environment and thus is 'lost' in terms of the process.

The goal then, is to minimise the waste created – to ensure that it is as close as possible to a sustainable level.

Sustainability – a goal for our society

Sustainability is a word which is often thrown around a lot in our day and age. There are several difference applications of the word, but the basis of sustainability is to provide for the needs of the present (i.e. current consumption levels), whilst not impacting on the ability to provide for the needs of the future. This is one of the main requirements placed upon the waste disposal system by our society – in order to improve the sustainability of our society on a whole.

This is because waste products and sustainability are opposing concepts – a truly, 100% sustainable society would have zero waste. The Earth is a finite and closed system – the raw natural resources available can and will be used up and are not replenished from an outside source (ignoring the new materials brought through meteorites), and thus in order to be completely sustainable, unwanted waste products (which may be unusable) must be minimised.

Nature has evolved as a system to do this – a circular system. This is where the waste products of one process (the output) becomes the input of another process, and thus the overall balance is regulated in the large natural system that is the biosphere (the collection of all of Natures living things). The prime example of this is in carbon dioxide – which will become increasingly relevant further on in this section – is the emission and use of carbon dioxide. Carbon dioxide is released as a waste production in respiration, the basic process of life in every living thing, which is the reaction of glucose and oxygen to produce energy. The other by-product is water. However, in every plant, a counter reaction, called photosynthesis takes place, where through an input of solar energy, water and carbon dioxide react together to form glucose (which is then used for respiration), and oxygen (which is emitted). This is a prime example of a circular system – where the total waste is zero.

However, it is only through millions of years of evolution that nature has created this circular system, and it is fragile, particularly to human impact. Our processes and systems aren't nearly so balanced, as technology has only been around for several millennia, and we have not yet come to terms with the need for a circular system, as waste products have not (globally at least), built up to a significant scale that it causes us problems. Thus, our technology exists within the reverse of a circular system – a linear system. This is where the waste products are not recycled at all – they are just left as an output. This is a significant problem, not only because of the lack of efficiency in a linear system versus a circular system, but because we use the environment and nature as a dumping ground for those waste products. Although nature does absorb the waste products of our technological processes into its circular system, this can often take many decades or centuries, and through the development of increasingly complex materials with non-organic complex molecules, we may reach a point where Nature is no longer able to cope with our waste. This is why there is a such a large requirement placed upon the waste disposal system, and by proxy placed upon all other systems, not limited to infrastructure, in our economy, to develop more efficient ways of reducing, recycling and dealing with waste.

Waste hierarchy – methods of dealing with waste

An important way to examine how the way waste management will have to change in the future is by examining how it currently operated, and some of the problems/changes that will be placed upon waste management stakeholders and operators in the future. An important tool to refer to is the waste management hierarchy [98], which lists the prioritisation of waste management techniques by efficiency and overall impact;

1. Waste reduction – if waste products are avoided/or prevented from being formed, through the avoidance of unnecessary waste, then there is zero need

[98] (ISWA, 2009)

to dispose of said waste. Thus, no raw materials are wasted, there are no waste by-products, and the process is more efficient, meaning that there is less wastage of energy and the process is then more efficient.

2. Re-use – the re-use of products delays the end of the lifecycle, thus increasing the time before products become waste that must be disposed of. This has a similar affect as waste reduction in that it reduces the demand for raw materials for input, and thus reduces the energy wastage through reducing the manufacture/processing of those raw materials into the product
3. Recycling – this reduces the demand for raw materials and eliminates the need to dispose of the waste products, by following natures example by turning waste into an input. However, this increases energy losses as it requires an energy input, although this is often below that needed to make new products from raw materials[99]
4. Incineration – conversion of waste products into energy through combustion. However, this can create new waste products that are potentially more harmful, especially if complex materials are incinerated, and naturally, as with any combustion reaction, it results in an output of carbon dioxide, which is one form of waste which the waste disposal system has not yet developed to deal with.
5. Landfill – the last resort option, this is the sequestering away of waste until it decomposes. This can take potentially hundreds of years and relies on Nature to turn the linear system of waste we operate under into a circular system, by processing the waste in landfill back into useful products and re-introducing them to nature. However, this has three limitations; 1) of space, due to the long decomposition times of some types of waste if the other approaches are not used due to our consumer-centric society which is exponentially growing in population we may run out of space to use as landfill, 2) this can produce an output of methane, a greenhouse gas several times as potent as carbon dioxide, and which lasts longer in the atmosphere, and 3) as the complexity of materials increases, the ability of Nature to break down these materials will diminish. It is not a sustainable approach.

Waste by-products and products

It is important to be aware that there will always be waste products produces in any system or process, no matter how efficient or high-tech the process is – at least, products which are unwanted in the context of the process. One of the lessons of

[99] (ISWA, 2009)

Nature and its circular system is that no material or substance is truly unusable, although it may well be unwanted – circular systems function by making the output of one process the input of another. Another concern is not of waste by-products but of waste products themselves, which have reached the end of their usable life and thus are left to be disposed by the waste disposal system.

If we look at the waste hierarchy, we can see that the top three approaches – reduction, re-use and recycling – are all approaches which make our linear process-based system, which creates waste, more circular. They do this by either reducing the waste products produced, which essentially is just an optimisation of the process which creates the waste, which will improve the efficiency of the process, or re-using products which extends the lifetime utility of the product, pushing away the time when the product becomes a waste product by losing its utility, or through recycling, which through an input of energy turns the waste products or by-products back into useful materials, essentially 'de-wasting'.

Why is it important to examine these approaches of waste management? It is because of the requirements placed upon the waste management system to be as sustainable as possible. If we examine the 5 approaches, we can see that the 3 examined above can be considered to be sustainable, even considering the input of energy needed to recycle, as this is often a much lower energy cost required than fabricating new materials from scratch. The other two approaches – incineration and landfill – are not as sustainable, especially with how waste is set to change, as landfill just moves the problem onto Nature to solve, and this can often take centuries for nature to deal with, and incineration while reducing solid waste, can create more dangerous types of waste.

However, incineration can be the preferable and more sustainable option compared to landfill, as it turns waste products or by-products into energy. It can be considered a renewable energy resource – if waste is continually created through our linear systems then there will be a constant output of waste – and the energy contained in this resource can be harnessed through incineration processes, resulting in an output of energy. This has an economic advantage over other primary energy resources as there already exists an established infrastructure to collect waste and deliver it to an energy plant. In 2006 post-consumer waste provided more than 1400PJ, which is enough energy to supply 140m average European consumers[100]. Incineration, while not necessarily sustainable, is a preferable option to landfill – in the case of solid waste which is combustible and does not produce by-products which are harmful.

[100] (ISWA, 2009)

Waste Development

The waste by-products we create are in a constant state of flux. For the first few millennia of human activity and exist, all the waste our civilizations created were primarily organic, meaning that the waste could be broken down by nature. Landfill in this case, was a sustainable approach (although it has to be said that they probably weren't thinking of that in the Middle Ages). However, with the advent of the Industrial revolution, and the revolutions that followed, more complex, non-organic waste was created by the technologies and industrial processes which the Industrial Revolution introduced and developed. As with any change in technology, this resulted in a changing requirement placed upon the other systems of technology – primarily on waste management, which was a new idea to society, being relatively present thinking rather than future thinking, which changed with the introductions of technology which reduced distance and improved life expectancy.

However, as technologies involved with waste management and disposal developed, so did technology in general. It can be observed that, due to lack of foresight, our waste disposal system does not fulfil the requirements placed upon it by society, especially in the case of waste products or by-products of increasing complexity. Both the scale and the type of waste is set to change in the future, due to the increasing spread and development of technology across the globe – without significant change to the linear nature of our processes, the amount of waste we produce will continue to increase, and the ability of conventional systems to deal with it will begin to fall due to the increasing complexity of the waste produced. An example of this is E-waste.

E-waste is defined as old electronic equipment which have outlived their lives – e.g. outdated appliances, mobile phones etc. They contain metallic and non-metallic elements, alloys and compounds, which if discarded in the open can cause severe environmental/health impacts. A total of 20-50m tonnes of e-waste is generated worldwide every year[101], a total of over 5% of all total solid waste generated, and the volume is expected to increase at a rate of 300% per annum in developing countries, due to the spread of technology globally and the growth and development of technology which facilitates this. In 2016 44.7m metric tonnes were created, and only 20% of this E-waste was recycled[102], showing an inability of the waste disposal systems to cope with the E-waste created. Not only will the other 80% end up at landfill and take potentially centuries to be broken down, but electronics is made up of complex and rare earth metals, compounds and alloys, and thus the lack of recycling of E-waste

[101] (Waste Management and Research)
[102] (Baldé, 2017)

represents a significant loss in economic terms of the raw materials present in the E-waste – the total value of all materials in E-waste wasted was estimated at approximately €55bn in 2016, which is larger than most economies in the world[103].

E-waste represents a turning point in terms of waste – it is made up of complex materials which will take centuries or millennia to be broken down by Nature, and the waste disposal systems do not have the infrastructure in place to cope with the expected volume of waste produced, which leads to the E-waste going directly to landfill or dumped in Nature and left to rot, which not only causes environmental damage and degradation but is a significant economic loss to the global economy, and forces us to rely on conflict-strewn regions of the world in order to attain the rare earth metals and minerals which our electronics requires. Waste is only set to become more complex, and as a result there will be increasing requirements placed on the waste disposal system to recycle or manage in other ways these complex forms of waste – as landfill or incineration may cease to be an option, due to the inability of Nature to process this type of waste, and the potentially harmful chemical by-products that could be created by sending complex forms of waste to incineration – even now, incinerator emissions are a major source of fine particulates, toxic metals and of more than 200 organic chemicals, including known carcinogens, mutagens and hormone disrupters[104], and due to new forms of complex forms of waste being created in the future, this could worsen.

There is thus an important requirement placed on the development of the waste disposal system, in order to both cope with the volume of waste in the future, and the changing type of waste in the future, both of which will require huge changes in the technology and systems involved in waste disposal.

Reducing waste: why energy efficiency is needed

Even in the event where the 'best' approaches to waste management were used, to change our systems into the closest possible form of a circular system, through the introduction of waste recycling, reduction and re-use, where the waste by-products were thus minimised, there would still exist a wastage in the system, and this is that of energy costs.

Energy, as we looked at in the section on the energy system, is an integral part of day to day life; all interactions, processes and systems are governed by it, even those where we cannot see what we would consider a typical energy input cost or a relationship with energy. As was explored in the logistics section, all logistics requires an energy

[103] (Baldé, 2017)

[104] (BSEM, 2008)

input to move a product or a service from point A to B, and thus all processes where there is a spatial imbalance in the inputs or outputs of the process takes up energy. The same can be explored in the communications system – communication is just the transmission of information from A to B after all, and thus requires energy too. It can be seen that everything is dependent on energy, because of its nature it governs all reactions, as all reactions are just energy changing forms or type.

But why is energy important in relation to the waste disposal sector? This is because our energy sector is dependent upon the exploitation of primary energy resources to generate more useful forms of energy (secondary energy sources – e.g. electricity – which can then be used to undertake more tasks and provide a wider range of functionalities). Primary energy resources, on the most part, take the form of fossil fuels – such as coal or gas. The energy in these fuels is exploited through the combustion of these primary energy resources with oxygen to release heat, which results in an output of carbon dioxide and water.

Natural cycles exist for both carbon dioxide and water, which regulates the balance of these in our Earth system. Water, whilst unwanted, can be considered less of a waste product as it is quickly absorbed into the hydrological system (the system of flows and stores of the water on Earth) and thus is quickly given a 'use' again.

Carbon dioxide however, stays in the air, as the carbon cycle is a less dynamic system and the flow of carbon through the system is on a whole much slower than that of water. It is important to be aware that carbon dioxide – or any other greenhouse gases - is not inherently bad. They are actually incredibly useful, as they act as a blanket around the Earth, ensuring the variance in temperatures due to the day/night cycle and the season's cycle (and the subsequent changes in sunlight) are not too extreme, and are so modulated. They do this by letting heat as sunlight in, but not letting all of the heat back out again – like a greenhouse. The Earth absorbs the heat from the sunlight and re-emits it as radiation, but the majority of this isn't able to leave the Earth's atmosphere as it is absorbed/reflected back by the greenhouse gases.

So why is Carbon dioxide as a problem then? This is because although the greenhouse effect is needed, and greenhouse gases are needed, it's a delicate balance. Any disruption to the amount of greenhouse gases in the atmosphere will trigger a change in the amount of heat absorbed, and this will change climates across the globe drastically. And, through human activity, we are putting more carbon dioxide into the air, and thus enhancing the greenhouse effect, which leads to 'global warming'. Since the pre-industrial era, atmospheric concentrations of CO2 have increased by 35%[105].

[105] (ISWA, 2009)

This isn't sustainable – as global warming will lead to drastic changes in the climate across the globe, which will result in extinctions of species, an increase in extreme weather, and widespread social and economic impacts, potentially even creating 'environmental refugees'.

This is why there is a need to improve energy efficiencies and reduce the wastage of energy throughout all systems and processes; as not only is it a wastage in itself and thus leads to a lack of optimisation in the systems/processes, leading to a loss of value and increasing costs, it also results in an increase of waste in the other sense – that of unwanted or unusable by-products. This definition could be taken slightly further, as carbon dioxide is unwanted due to the adverse effects it will have on the world as a whole, due to the enhancing of the greenhouse effect and subsequent impacts on the world and its climate.

Summary

It can be seen that, due to the nature of our society, it is inevitable that waste will be created. It is impossible to reduce waste away to zero – there will always be some form of wastage in our system, whether that is through unwanted by-products, products which have reached the end of their useful lives, or wastages in energy in the processes which exist in our society. Therefore, there will always be a need for a waste disposal system, and a need for waste management techniques, such as reducing, re-using, recycling, incineration and landfill, to deal with the waste our society produces.

However, it is important that these waste management techniques are applied in a sustainable fashion, in order to transition our systems from linear systems (which take an input and produce waste output along with the desired output), into a circular system (where waste is minimised by turning waste output into an input for another process). The most sustainable forms of waste management are the 'triangle' of reusing, reducing and recycling, and these will continue to be viable even despite the ever-increasing complexity of waste over time – to the extent where landfill and incineration are not viable approaches as they will either lack the capability to deal with future types of waste. Nature may no longer be able to absorb waste that we can't process and thus just dump at landfill, and incineration may result in increasingly harmful emissions if we continue to rely on it as a waste management technique. The waste disposal system needs to be developed if it is able to sustainably cope with the future scale and type of waste – however this will not necessarily be a cost, as waste, especially more complex forms, holds a huge amount of economic potential. In the future, it may be seen as a commodity to be re-processed through recycling back into raw materials available for production and will then make our society all the more sustainable.

Author: Luke Hatton, Summer 2018

There will also be pressures placed upon the other sub-systems of infrastructure to change, by the waste disposal system. The two main ways that they will change are interlinked with two key management techniques – reduction and re-use. By changing the systems that produce waste, there will be a smaller requirement placed on the waste disposal system to deal with said waste – whether that is a reduction in waste by-products or re-use of products, thereby extending their lifecycle and preventing them from becoming waste products. However, this also applies to wastage in energy terms too – as one of the big concerns is waste by-products that are emitted into the atmosphere and enhance the greenhouse effect. The primary waste by-products here is Carbon dioxide (although there exist a range of other greenhouse gases which can be produced as waste) which is emitted through the combustion with oxygen of fuels, which is the primary way in which energy is generated. Thus, energy efficiency and carbon dioxide emissions are intrinsically linked, and by improving energy efficiency, less carbon dioxide will be emitted, and thus it can be prevented from escaping into the atmosphere and resulting in climate change. Due to increasing energy consumption, as a result of the increasing development of technology, carbon emissions and wastage of energy through lack of efficiency will increasingly become a concern, and as a result the other systems will have to change to reduce these emissions, through optimisation and decarbonisation.

Conclusion to this study

In the introduction it was examined that technology is a multipurpose word, being used on a variety of levels to describe the harnessing of natural phenomena in order to fulfil a human need or purpose, through a sequence of operations and physical hardware which realises these operations. In essence they offer a functionality – they are executable, they provide a purpose. And they are also recursive in natural – they're made up of components which, by themselves, are technologies, sub-systems operating under a system to provide the functionality of the technology.

This is important to be aware of, as it means that things which conventionally we wouldn't refer to as technologies – such as the economy, or the built infrastructure – are by their definition technologies, and a result will change radically in the next couple of decades, as we experience rapid technological growth, in what some would call the Fourth Industrial Revolution, as the economy and our society experiences a 'wave of creative destruction' fuelled by the new 'radical' technologies which are set to become mainstream through normalisation.

The built infrastructure was split down to the essential areas of energy, logistics, communication and waste management in this report, and, as has been seen, these areas (or sub-systems of the large scale system of the built environment) will experience a radical shift in the way they function and are structured, both caused by and exacerbated by the future development in technologies, and the growing requirements placed upon technologies to provide for our society.

As examined in the main sections, the energy system will experience an increase in demand, mainly fuelled by a transition from primary to secondary consumption. As a result, this will require an increased capacity of supply, but due to the requirements of the waste disposal on all our systems, both the existing and new sources of energy must be decarbonised, resulting in a change in the distribution system, with the implementation of large scale power storage caused by the potential fluctuations in supply of renewables.

The logistics system will experience a drastic change in the method of control and the fuel of the vehicles – with a transition from human-based control to CAVs (Controlled and Automated Vehicles), which will remove the human error aspect, reduce accidents, and optimise the functionality of the network by increasing the efficiency of the network. This will reduce emissions. The propulsion method for vehicles will also transition, in order to decarbonise, and will experience a shift to consumption of secondary energy resources such as hydrogen or electricity, or sustainable primary fuels such as biofuels. This is due to the waste disposal system again placing requirements on the other systems – but the development of the logistics system will also place new requirements on the energy system (infrastructure required for a shift to secondary-based propulsion) and on the communications system (due to the implementation of CAVs).

The communications system will change due to the implementation of the next generation of connectivity, through 5G, which will result in improved speed of transmission of information. This will facilitate the Internet of Things, where billions of devices can be connected, providing data to be acted on to optimise any and all systems or processes involving technology in our society, from areas as wide range from heavy industry to domestic energy consumption. This will also result in increased pressures on the energy system due to increased energy consumption on a whole to support this massive increase in data and the processing power required.

The waste disposal system will need to improve the way it operates, in order to cope with the increasing complexity of new forms of waste, caused by the developments in technology that are set to be experienced, such as E-Waste. The aim of this system is to make our society into as much of a circular system as possible, by reducing waste as close to zero as possible – however achievable this may be – through the expansion of recycling, reducing and re-using approaches to waste management, as Nature will no longer be able to cope with the waste we can't process. It places a requirement on all other systems to become as efficient as possible, to reduce the wastage of energy and thereby limit the emission of carbon dioxide and other greenhouse gases into the atmosphere, in order to maintain the sustainability of our society, which is the key goal of the waste disposal system.

This report set out to examine the ways in which the built infrastructure systems will change in response to the development in technologies in the next few decades, and the requirements placed upon them by society, by taking a systematic view of infrastructure. Through systematic thinking (i.e. examining the sub-systems not in isolation, but taking into account external factors that may modify the development of the sub-systems) this report has examine the main overarching structure of the infrastructure sub-systems, in order to anticipate how (and why – technologies will not just be implemented into these systems for no reason, they must contribute to the functionality of the system as a whole) they will change in the next few decades. It has examined the ways in which the sub-systems interact and place requirements upon each other – they're not isolated, they're tightly linked in how they function – it could be said that they are dependent upon each other to provide their functionality, and subsequently society as we know it is by definition dependent upon the interaction and function of these systems, as they make up the infrastructure, which comprises of all the technologies necessary for the functioning of a country and the delivery of essential services. This report tried to focus on the UK but indeed these systems are present in every country – although they vary slightly in quality and how they function due to local factors such as wealth, governance and natural constraints.

However, the extent to which this report is able to examine the ways in which these systems interact is limited – although it has tried to avoid an isolation-based thinking which treats each sub-system as individual and isolated from the environment, it is impossible to be aware of and examine each and every influence that the environment and other systems will have on the sectors of the built infrastructure. This links to a branch of systems thinking interlinked with complexity, called Complex Adaptive Systems[106] .

Although this report has touched upon complexity, it has not actually given a definition. Complexity refers to the state or quality of being intricate or complicated[107],

106 (Chan, 2001)
107 (Oxford University Press, 2018)

and results from the inter-relationship, interaction and interconnectivity of elements, both within a system and between a system and its environment[108]. Complex Adaptive systems are systems which are characterised by complex behaviours that emerge as a result of often nonlinear interactions among a large number of component systems at different levels. This links with the definition of technology being a recursive system, made up of many different levels of component sub-systems which are technologies in their own right, and interact to provide the functionality of the technology as a whole. Thus, it can be seen that technologies are Complex Adaptive Systems, and then by their nature the infrastructure systems are CASs also.

This results in one of the inherent difficulties in analysing the extent to which technological change will affect or change the infrastructure sub-systems, due to their nature, as a complete understanding of the individual parts does not automatically convey an understanding of the whole system, as CASs form out of dynamic networks of interactions, both within the system (e.g. with differing parts of the energy system placing differing requirements on each other) or in-between the system and the environment (e.g. external requirements placed on the energy system). As a result, it is not only difficult to understand and analyse the functioning of these systems, it is also difficult to predict how these systems will change over the next few decades – exacerbated by the unpredictability of future technologies produced through combinatorial evolution, and the extent to which differing technologies are normalised or absorbed into the economy and society as a whole. This will be governed not only in how the technologies function and operate but also attitudes to their use and implementation – which is often the key factor in how/to what extent technologies are normalised or become absorbed into everyday lives.

In systems thinking this outcome is referred to as the emergent behaviour or order – where the overall outcome, behaviour or result pattern of the system has properties that the individual parts do not have, due to the interaction between its parts (and the interaction of the system and the surrounding environment). These outcomes are often difficult or impossible to predict simply by looking at the individual parts or interactions[109], and as was examined earlier, it is difficult to analyse and be aware of all of the external influences and requirements placed on the systems, which influence the emergent complex behaviour.

As a result, it is difficult in principle to predict, with any significant degree of accuracy, the way the sub-systems that comprise the built infrastructure – energy,

[108] (Chan, 2001)
[109] (The Health Foundation, 2010)

communications, logistics and waste disposal – will change over the next few decades, due to the influence of new technological growth, under what some experts are calling the fourth industrial revolution. Other sub-systems of infrastructure could potentially be included under the whole system of the infrastructure – the line between what can be considered the 'hard' built infrastructure and 'soft infrastructure (comprising institutions which are critical to the functioning of a country, such as government) is often blurred and unclear, and which sectors are included ultimately depends on what you qualify as necessary for a country. The CPNI [110] counts 13 total national infrastructure sectors, with some of these sectors having distinctly defined sub-sectors. However, this would be a long report indeed if the effect of technology on all of these sectors was to be examined and would throw up a number of interactions of an order of magnitude several times higher between the systems to analyse, and as a result this report limited the sub-systems of infrastructure to what it considered the four critical systems of energy, communication, logistics and waste disposal.

However, although it is difficult to accurately predict the way in which the sub-systems of infrastructure will change, by analysing systematically the way in which their systems are organised and function, what can be predicted is the overall change in the emergent behaviour of the systems. In the context of technology, this is the functionality that the technology provides – the resultant purpose of the technology. The energy system will meet the consumption levels of the future, drawing from an efficient, secure, and decarbonised energy mix. The communication system will see an increase in speeds of data transmission, which will provide a larger (by many orders of magnitude) amount of information to consumers and producers alike. The logistics system will increase the capacity to transport goods, people and services alike, and will potentially transition to systems which require less human input and produce less carbon emissions. And the waste disposal system will develop new ways of processing increasingly complex forms of waste.

Overall, the method in which these systems achieve or realise these future functionalities is uncertain. This report has worked to analyse these systems in order to best estimate how they will change in the next few decades, due to new technologies, and suggested some ways in which future technologies may fit into these systems and as a result radically reshape them. However, as can be seen, all of these systems are in fact examples of complex adaptive systems, and as a result their emergent behaviour, caused by the interaction among the large number of component systems that make up these sub-systems of the built infrastructure, is complex and often unpredictable. It is impossible to analyse these systems to such an extent that

[110] (CPNI, 2017)

every external and internal interaction can be modelled and put together to form a picture of how these systems will change. Even if that was feasible, due perhaps to the increasing computing power and data transmission speeds facilitated by the development of the communications system, it is impossible to predict some of the future technologies, as the way they operate or the functionality they provide may be impossible for us to understand at this present point in time, and as a result the impact they will have cannot be analysed. This report has anticipated some of the possible ways these systems will change – but these are not certainties, nor are they set in stone. What can be predicted is that these systems will change, and their emergent behaviour and functionality they provide will develop to meet the needs human society places upon them.

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