The Transition from a Fossil-Fuel Economy to a Knowledge Economy

Roger Fouquet and Ralph Hippe

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Abstract

The purpose of this chapter is to show economic growth in history was driven by the development of energy markets (and boosted by energy transitions), particularly between the eighteenth century and 1973, and driven by the development of information, human capital and knowledge (and related transitions), which have also been underway for a long time but is becoming more dominant today. Thus, there has been a very long run shift from energy resources to knowledge as a fundamental driver of economic growth.

Keywords: Transitions, Knowledge, Energy, Green Growth, Economic Policy.
JEL Codes: N33, N93

1. Introduction

Green growth entails the redirection of the economy onto a more sustainable long run trajectory (World Bank 2011, Bowen and Fankhauser 2011). Given the environmental impact and degradation of natural capital stocks of current economies, conventional growth is unlikely to be sustainable in the long run. In particular, the intensification of climate change due to increased fossil fuel use over the next century – if the latter is allowed to happen – is likely to impose escalating and irreversible impacts and costs on the economy and society (Wagner and Weitzman 2015). Therefore, in the long run, green growth can be seen as an attempt to avoid a potential environmentally-triggered economic and social collapse (Diamond 2005).

One of the key structural transformations sought in the pursuit of green growth is a reduction in carbon dioxide emissions. The most obvious way to achieve this is through a transition away from high carbon-emitting energy sources towards low carbon energy sources (Grubb et al. 2008, Foxon et al. 2008, Stern and Rydge 2012). Another proposed solution is to maintain our dependence on fossil fuels, yet reduce emissions through carbon capture and storage (IEA 2008). An alternative (yet, potentially complementary) way would be through a radical reduction in the use of material and energy resources by increasing the share of the 'weightless' economy (Quah in Chapter 20, Hepburn and Bowen 2013).

Perez in Chapter 19 and Quah in Chapter 20 argues that an increasing share of modern economies will reside in dematerialised or weightless knowledge products as a result of the ICT revolution. All goods and services that can be expressed in digital form (i.e., encoded in bits), such as telecommunications, financial services, news and media entertainment, computer software and algorithms, electronic databases and libraries, and all other goods and services that can be delivered via the internet, are dematerialised products, which have the same properties as knowledge. That is, they are non-rival (i.e. use by one person does not hinder another person's consumption), infinitely expandable and not geographically constrained. Once created, they are reproducible at (virtually) zero marginal cost. Furthermore, growth triggered by such dematerialised products is likely to impose substantially less pressure on natural capital assets (including resource stocks, such as energy, and ecosystem services, such as the atmosphere). And, because of its special characteristics, ideas need not be subject to diminishing returns, so GDP growth may be sustainable with the use of non-renewable resources tending to zero and the use of eco-system services tending to a sustainable asymptote.

With this alternative perspective for green growth in mind, it would be valuable to develop a deeper understanding of the foundations of the weightless or knowledge economy (Powell and Snellman 2004). The 'knowledge economy' rests on four key pillars, according to the World Bank (2008): first, a broad institutional and legal structure of property, business and trade; second, human capital formation (e.g., education and skills); third, information and communication technology (ICT) and related infrastructure; and, fourth, an innovation system (including an advanced process of research and development for producing knowledge, and a specific institutional and legal structure for intellectual property rights). Mokyr (2002) and Jacob (2014) argue that this 'knowledge economy' has been gradually developing over several hundred years.

Both aspects of green or sustainable growth, i.e. climate change on the one hand and knowledge creation on the other, have to be seen together – particularly in a long-run perspective. Indeed, this fact was highlighted by the Nobel Prize committee, which jointly awarded the Nobel Prize in Economics 2018 to key representatives of both areas: to William Nordhaus ("for integrating climate change into long-run macroeconomic analysis") and Paul Romer ("for integrating technological innovations into long-run macroeconomic analysis"). Both authors have addressed, according to the committee, "some of our time's most basic and pressing questions about how we create long-term sustained and sustainable economic growth” […] “by constructing models that explain how the market economy interacts with nature and knowledge” (Nobel Prize 2018).

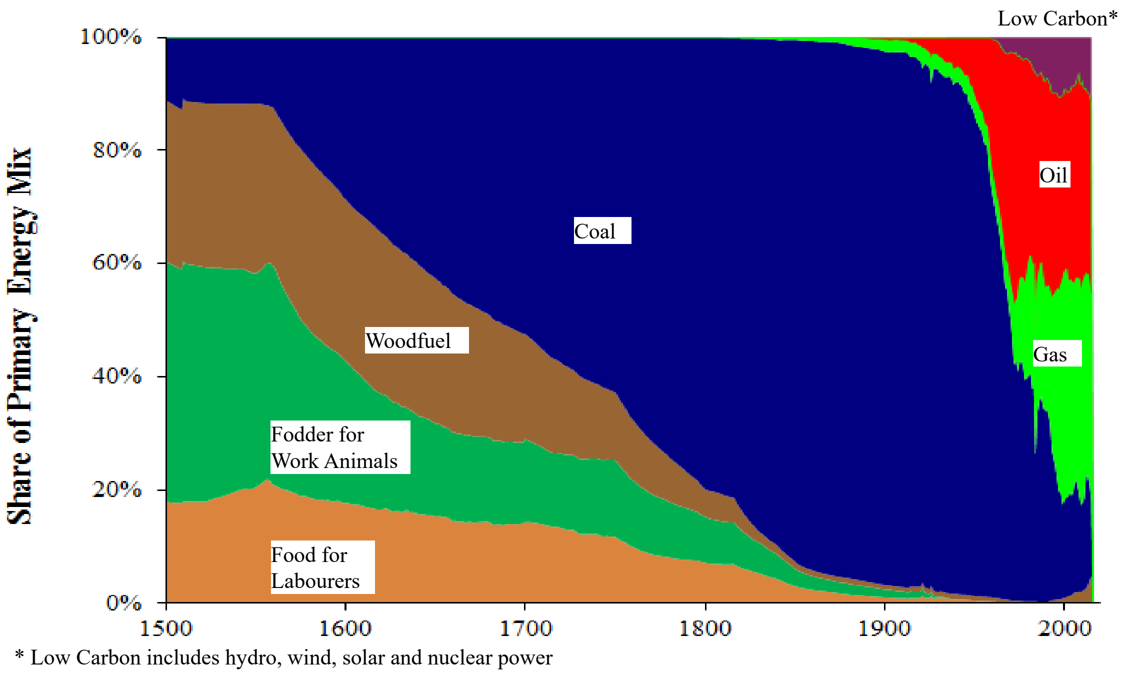
In line with this reasoning, this paper investigates the long run process of the dematerialisation and informatisation of economic growth, by identifying the historical transformation from an economy dependent on energy – and fossil fuels, in particular – to a knowledge economy. In addition to the decline in energy intensity, this piece considers the transition towards high levels of human capital, of communication and information, and of knowledge production. The ability of economic activity to shift away from megatonnes to megabytes is critical to the long run potential to generate green growth.

2. Industrial Development and Energy Transitions

The history of economic development has depended upon an economy’s abilities to reduce the costs of production, distribution and consumption of goods and services in order to meet the appropriate demands at particular levels of economic development (Easterlin 1981). Industrial production offered the opportunity to generate increasing returns to scale, driving down prices, thus, helping to increase per capita income. Now, numerous industrial activities have tended to depend on heating (particularly for metals) and power. However, traditionally, woodfuels for heating competed with agricultural products for land use. Thus, in many regions, access to forests and woodfuel constrained rapid expansion of industrial activity.

The introduction of mineral fuels in Britain reduced the burden imposed by a constrained land on a growing population. Traditionally, coal had been seen as an undesirable commodity because of the impurities it generated during industrial production, and its smoke. As a result, coal use was limited to local markets – for instance, at the end of the fourteenth century, coal output in the North-East of England, the main region of coal production, has been estimated to have been only 45,000 tons (Hatcher 1993 p.29). However, as the price of woodfuels rose in London, and a more entrepreneurial spirit opened more coal mines, shipments down the East coast to the capital increased. Between the fifteenth century and end of the seventeenth century, the coal mining industry expanded from a niche business to one of the major generators of wealth in the North-East of England (Hatcher 1993). Britain began its long transition from renewable energy sources to fossil fuels (see Figure 1).

Figure 1 Share of primary energy consumption in the UK



Source: Fouquet (2010).

As demand grew in the seventeenth century, however, coal supply struggled to follow and prices started to rise, which in turn led to developments that helped transform the coal industry into one of the pillars of the British economy. First, the development of pumps to remove water from mines enabled much greater depths to be achieved. This was first done using horses and then accomplished most successfully with the use of the steam engine in the eighteenth century. For decades, steam technology was limited to the coal mines, because engines required large quantities of fuel to provide power. Yet, experimentation improved its energy efficiency to the point that it became profitable to introduce them in the textile industry. This, in turn, generated a huge new demand for heating fuels, which could only be met with the expansion of the coal industry.

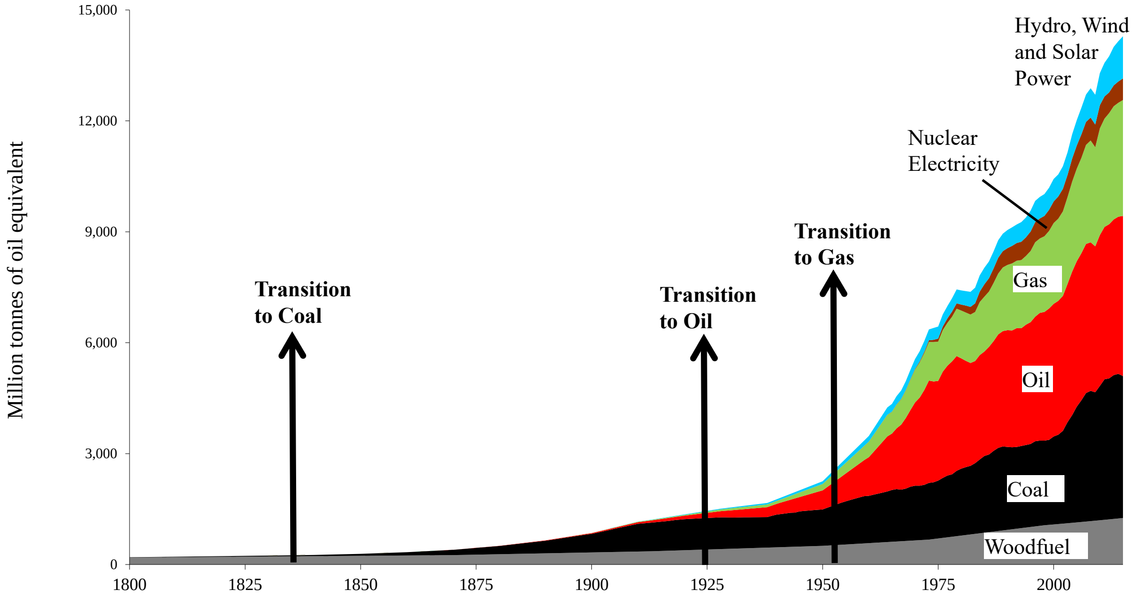
Second, Britain also discovered that its vast energy reserves were not limited to the North-East. A number of regions started to compete with the Newcastle trade. The coal industry transformed itself from a localised business to one of the leading sectors of the economy. Third, transport routes were dramatically improved. The improvements to rivers and building of canals enabled industrial regions to reduce the cost of heating services. Along the coast economies of scale were achieved by increasing the size of ships carrying the goods (Hatcher 2003).

During the nineteenth century, however, a continually growing price-inelastic (domestic and international) demand for coal coupled with antiquated extraction techniques, more powerful trade unions and attempts towards collusive behaviour amongst large suppliers put upward pressure on prices (Church 1987). This created concerns about the scarcity of coal. One of the problems associated with the production and supply of energy resources was that they often require long term investments. For the coal industry, there was, at times, a delay between the signal of scarcity and the change in flow of resources resulting from higher investment in extraction, from hiring more miners and finding new seams. Consequently, during the second half of the nineteenth century, the average coal price in the United Kingdom exhibited increased volatility, generating uncertainty for investors and harming economic growth (van de Ven and Fouquet 2017). Stanley Jevons (1865) highlighted the issues of resource availability, the threat of rising prices and its importance in Britain's economic supremacy.

Another problem associated with the growing use of coal was air pollution. The rise in smoke concentration has been linked with the rapidly soaring mortality rate attributed to bronchitis - from 25 deaths 100,000 inhabitants in 1840 to nearly 300 in 1890. A conservative estimate of the annual health damage caused by coal production and consumption at the end of the nineteenth century was £(2000)20 billion and close to 20% of the British GDP (Fouquet 2011). Yet, the smoke abatement movement in the Victorian era faced politicians' belief that legislation would harm business and industry. When government did regulate, it provided weak legislation and limited enforcement. It took around one hundred years, and the introduction of the Clean Air Act of 1956, to introduce the necessary legislation (Fouquet 2012).

Despite these environmental pressures, the ability to emit smoke and ultimately externalise the costs of coal combustion allowed households and industry to use fossil fuels. The use of fossil fuels enabled economies to expand far more than would have been possible if heated by woodfuel and powered by crop-eating animals, as well as by a few rivers. Within a few decades during the second half of the nineteenth century, numerous European economies, the USA and Japan made the transition to coal.

Figure 2. Transition in Global Energy Consumption



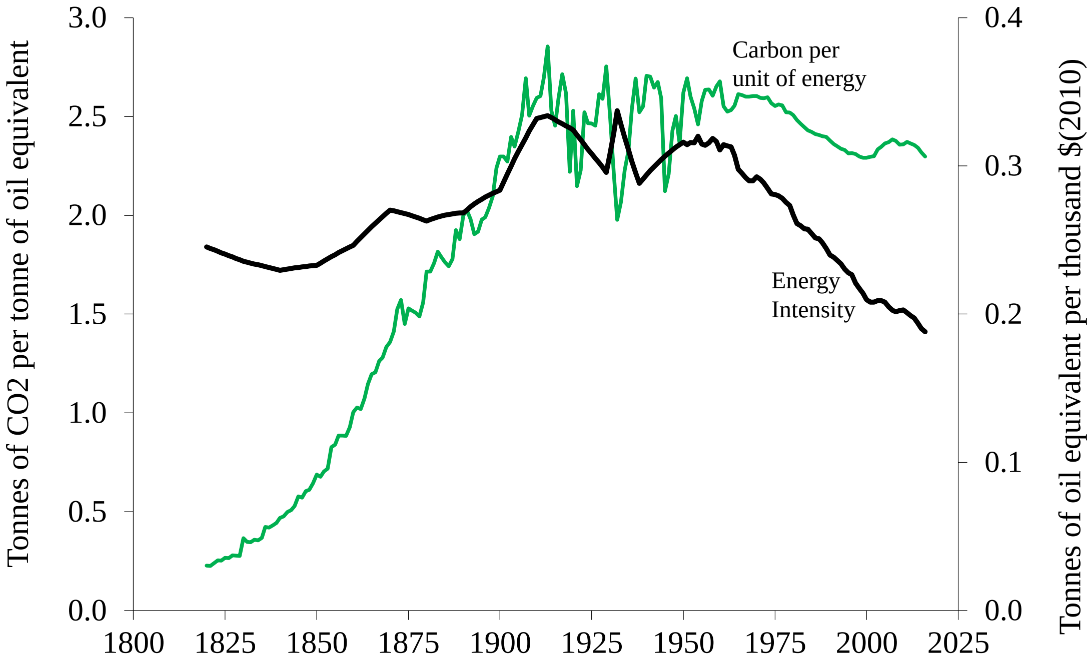
Source: Fouquet (2009), BP (2017).

Taking a global perspective, global energy consumption exploded over the last two hundred years (see Figure 2). There have been three major energy transitions since the beginning of the nineteenth century - here, the transition is identified to have begun when the energy source has reached 10% of the total global primary energy consumption. The first transition was the transition to coal at the middle of the nineteenth century, the second one was to oil at the end of World War I and the third one was to natural gas from the mid-1950s. It is evident that each transition has led to a higher level of energy consumption. Therefore, Fouquet (2010) notes that a transition to renewable energies (and thus to low-carbon energy) might possibly not cause a decrease in the consumption of high-carbon energy. In its place, it might serve to increase overall consumption.

Nevertheless, two important trends reflect the move towards generating greener growth. First, since 1950, the global economy has used substantially less energy per unit of GDP produced (see Figure 3). In the last sixty years, there has been a 40% decline from 0.32

tonnes of oil equivalent per unit of GDP in 1956 to 0.19 tonnes in 2016. Second, during the twentieth century, roughly 2.5 tonnes of carbon dioxide have been emitted for each tonne of oil equivalent consumed. Since the 1970s, there was a modest decline. In the first decade of the twenty-first century, this carbon (per unit of energy) intensity increased – reflecting China's use of coal. Between 2013 and 2016, this carbon intensity has started to decline again. This is a promising trend that needs to be followed carefully.

Figure 3. Global Carbon per Unit of Energy and Energy Intensity, 1800-2016

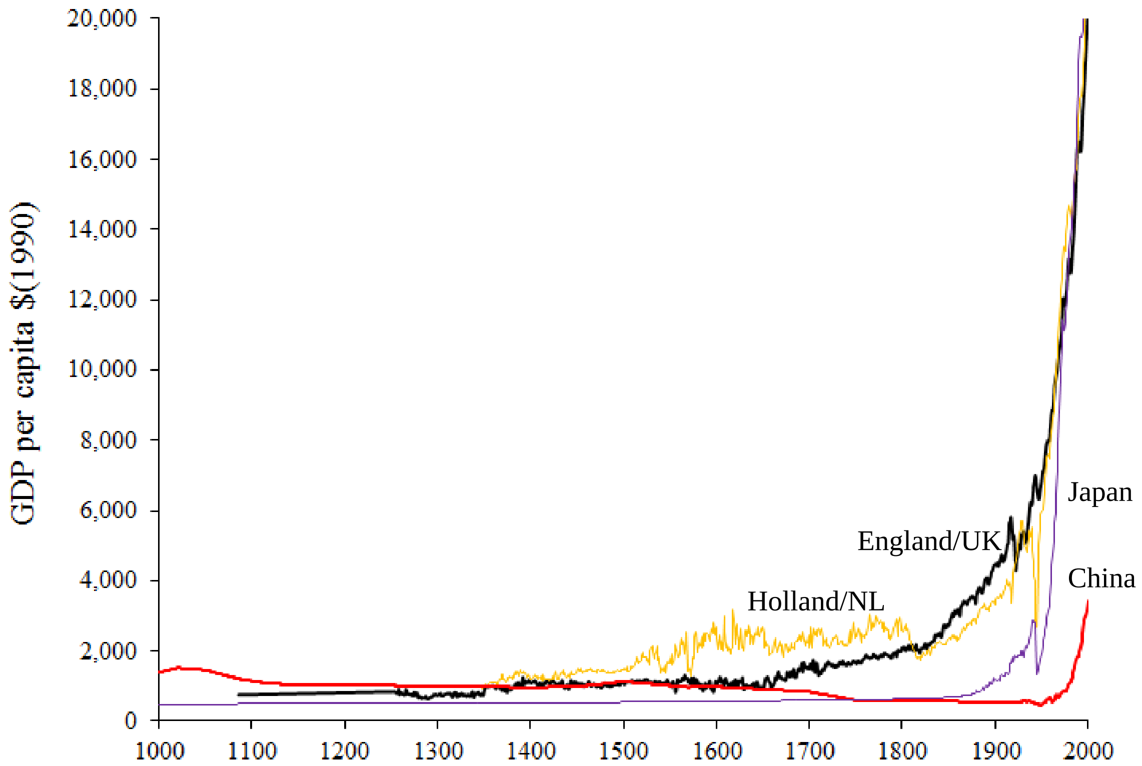


Source: UN (2017), World Bank (2017), BP (2017), Maddison (1995, 2003) and Etemad (1991)

3. Economic Transitions

Now, the energy transitions fueled the dramatic increases in industrial production and improvements in income levels during the late nineteenth century and twentieth century (see Figure 4). Of course, rising GDP per capita was the result of numerous factors, including the development of technologies, financial capital and human capital, and the integration of markets, as well as better institutions. Nevertheless, energy played a critical role in enabling these factors to unfold and the economic expansion to take place.

Figure 4. Long-run trends in GDP per capita in European and Asian countries

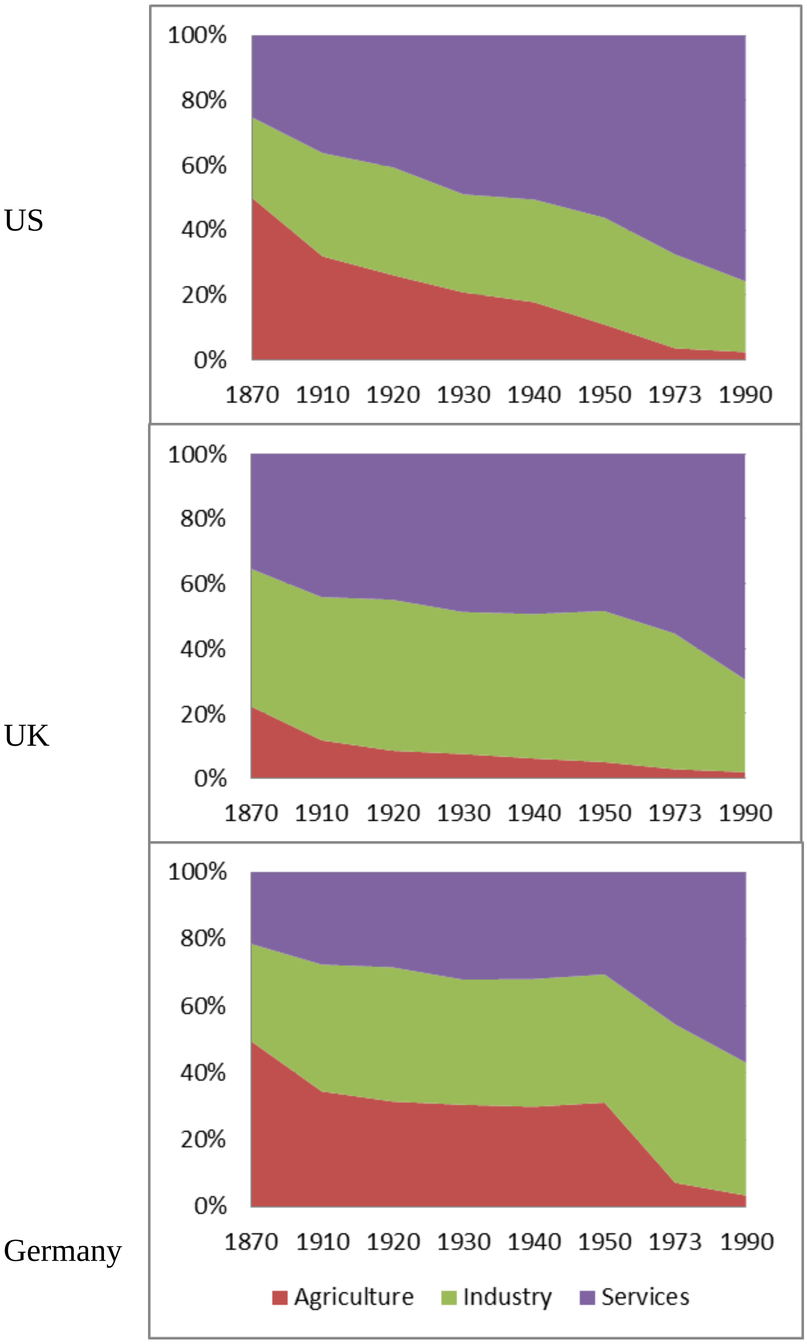


Source: Maddison/Bolt and van Zanden (2014)

The economic transition from an economy based on agriculture before the Industrial Revolution to an economy based on manufacturing and increasingly services can be demonstrated by using Broadberry's (2009) data for the United States, the United Kingdom and Germany (Figure 5). Note, however, that the sector share of agriculture in employment was historically even much higher before the Industrial Revolution. For example, it has been estimated that the share of agriculture in male employment was up to 75% in England in 1500 (Shaw-Taylor and Wrigley 2013). For this reason, the figure shows only the second part of the transition.

Still, the figure illustrates that the evolution in the US was advancing slowly and progressively over many decades. Agriculture's share declined and service's increased, while the manufacturing sector had a relatively constant share. In addition, in the UK employment had already moved out of agriculture to a large extent by the end of the nineteenth century. The shares of manufacturing and services were relatively balanced until World War II. Subsequently, services began to emerge as the main employment sector in the UK. The case of the US and the UK contrasts with the experience of Germany. In Germany, the share of agriculture was almost stagnant during the first part of the twentieth century. The same can be said of the share of industry and services because the share of services did not increase significantly. A rapid decrease of agriculture took only place after the First World War while the share of industry still remained at the same level at the end of the twentieth century as in 1910. The decrease in agriculture was matched by a comparable increase in the share of services. The move towards the service sector and the decline of industry has been much more pronounced in the US and the UK whose economies now focus on the service sector.

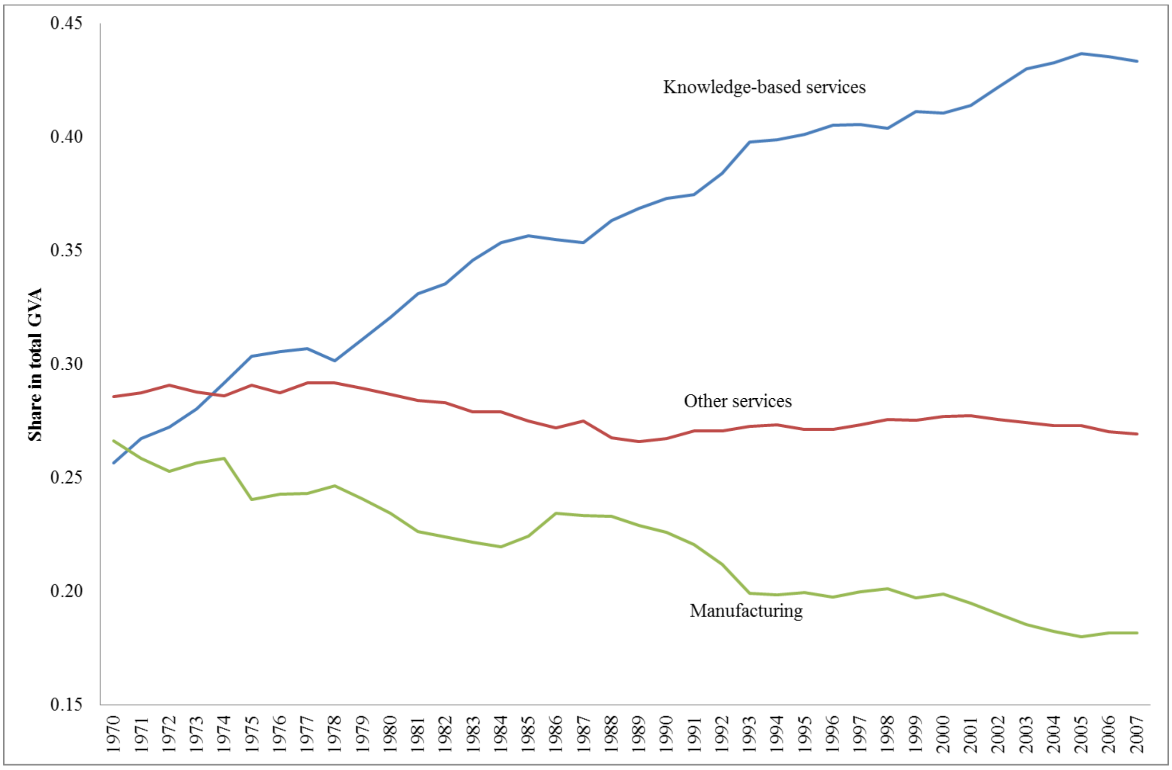
Figure 5. The transition of employment sectors in the US, the UK and Germany



Source: Based on data by Broadberry (2009).

However, the ‘service sector’ is a very large sector, comprising many different sub-sectors that have not very much in common. If we consider the EU15 (i.e., the former 15 members of the European Union) over the last few decades and distinguish those service sectors that are partly based on knowledge and those that are not, we see that knowledge-based services have been the main driver of the growth of the overall service sector.[1] This evolution becomes particularly apparent if we consider gross valued added (Figure 6). Similarly, the EU refers to knowledge-intensive services, and estimates that they have been growing over the last years, representing 46% of total valued added in the EU25 countries in 2005 (European Commission 2009).[2] The 'knowledge economy' might, therefore, be an important driver for future economic growth and Green Growth.

Figure 6. The transition towards knowledge-based services in the EU15



Source: Authors' own calculations, data by EU KLEMS database (2011).

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[1] Knowledge-based services include communications, financial services, business services, education and health, as proposed by the OECD (1999) (see also The Work Foundation 2011).

[2] Knowledge-intensive services are water and air transport; post and telecommunications; financial intermediation; real estate, renting and business activities; education; health and social work; and recreational, cultural and sporting activities (European Commission 2009). EU25 are the EU 15 countries plus the ten East European countries that became members in 2005.

A similar idea has been developed by Florida (2012a) who, alternatively, distinguishes among different social classes. He defines the following social classes by their employment: the agricultural (farming, fishing, forestry), working, service and creative classes. The working class includes the work done by blue-collar workers who operate in sectors such as maintenance, construction and transportation. In addition, the distinction between the creative and the service class needs some clearer specification. Florida defines the creative class as "workers in science and technology, arts, culture and entertainment, healthcare, law and management, whose occupations are based on mental or creative labor" (Florida 2012b) and the service class as being constituted by those individuals who "prepare and serve food, carry out routine clerical and administrative tasks, provide home and personal health assistance, do janitorial work, and the like" (Florida 2012b). It appears that his distinction between the creative class and the service class is in some respects similar to the one distinguishing knowledge-based and other services. However, it includes additional parts of the population that are 'creative' and work in fields such as arts and entertainment.[3] Furthermore, the working class as proposed by Florida appears to be a larger category than just the traditional industrial sector.

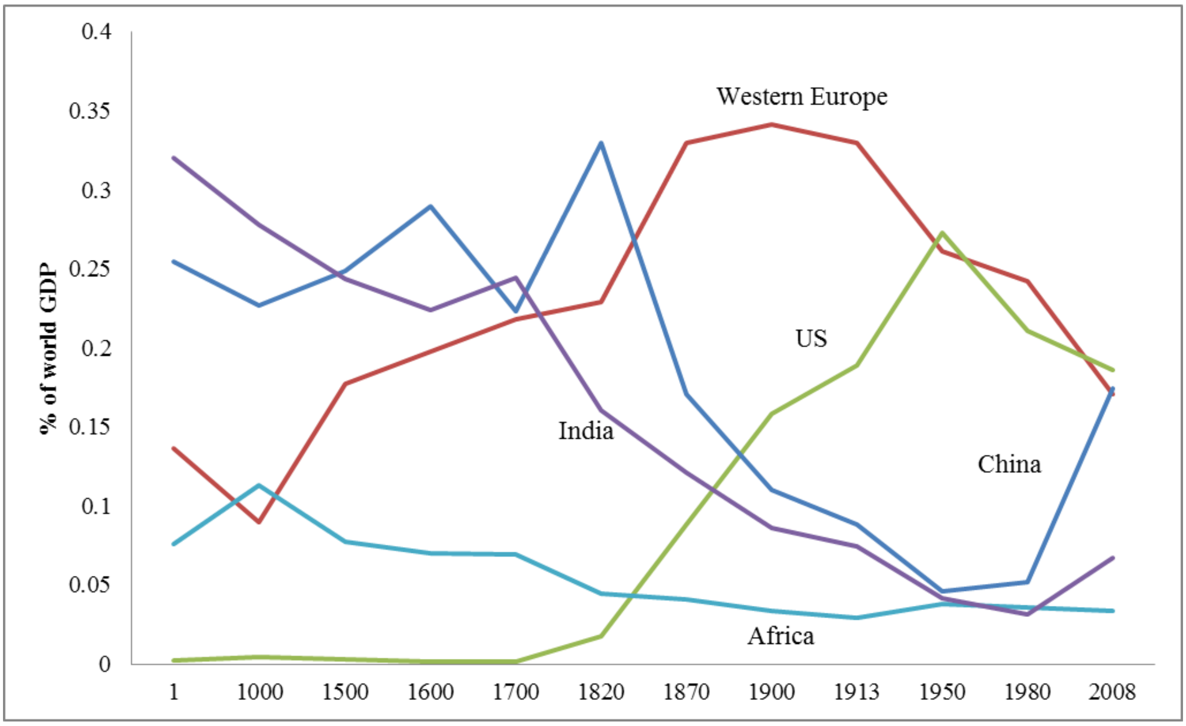
Still, the author provides some useful long-run trends in employment of these four categories of classes in the United States for the last 200 years. The broad trends are in some respects similar to those highlighted by Broadberry's (2009) data. The prolonged time dimension and the new class distinctions, however, allow some additional insights. In particular, the rise of the working class, or in Marxist terms of the proletariat, is clearly

[3] Florida explains that the "[m]embers of the Creative Class engage in complex problem solving that involves a great deal of independent judgment and requires high levels of education. Interestingly enough, however, the Creative Class is not simply another name for the college educated. While nearly three quarters of college graduates belong to the Creative Class, four in ten of its members do not have college degrees, but still engage in work that is creative by definition" (Florida 2012b).

visible between the 1820s and 1850s. More precisely, the working class increased its share in total employment from about 20% to roughly 55% in three decades of industrialisation. The share of the working class then remained more or less stable (with some variations) for about one hundred years until the 1950s, when the service and creative classes reached higher shares similar to those that the last held in the 1820s (about 30% and 20%, respectively). Since then, the working class has drastically been reduced to currently only about 20% of total employment, whereas the service and creative classes rose to new heights with about 45% and 30%, respectively. Thus, the long-run trends suggest that the service and creative sectors may become still more important in the future. And, according to Florida (2012), it will be the creative class that will have a major impact on future economic growth and development. In addition, he argues that it will be important to upgrade the jobs in the working and service sectors. Adding creative skills to these jobs will give the opportunity to increase productivity and demand even further in this new economy.

Moreover, Florida's evidence, and those presented further above, show that the share of agriculture has decreased throughout the last 200 years. The causes and consequences of the initial move out of agriculture have been widely analysed. Industrialisation has not only led to lower shares of agriculture in the leading countries of the Industrial Revolution but also to their rapid increased importance at the global economic level. However, one could say that we also see a new transition to an older order of relative word shares of country groups in the world during the last years. Historically, both China and India may have made up the major share of world GDP (see Figure 7). Over the centuries, Western Europe became increasingly an economic world power and Asia's share declined. The most decisive period might have been the 19th and 20th centuries. Western Europe reached its peak share of about 34% of world GDP around 1990. At the same time, the US rose to become the major driver of world GDP by the 20th century, with a share of up to 27% in 1950. Only during the last decades, there appears a reversal of this tendency. Most importantly, China has been increasing its share of world GDP very rapidly and has again attained levels previously held in the 1870s (about 17%). India is only beginning to rise slowly. On the other hand, Africa does seem to stagnate at historic low levels.

Figure 7. Evolution of shares in world GDP



Source: Based on data by Maddison (2007).

4. The Transition to the Knowledge Economy

4.1 The knowledge economy

The 'knowledge economy' has recently become a key term. Rooney et al suggest that whereas "[k]nowledge is people doing things, knowledge economies are people doing things with better outcomes for more people" (Rooney et al 2012, p. 1). The emerging 'knowledge economy' can also be measured by indexes. For example, the World Bank has constructed the 'Knowledge Economy Index' (KEI). The KEI and GDP per capita are quite strikingly correlated. The KEI comprises various indicators of the four pillars that make up the knowledge economy. These pillars are the economic and institutional regime, education and skills, information and communication infrastructure and the innovation system (World Bank Institute 2008).[4] We will focus here roughly on pillars 2 and 3 of the KEI. Although according to the World Bank the knowledge economy includes some further important pillars and dimensions, the KEI does emphasise the relevance of human capital, ICT and knowledge in the present and probably in the future.

4.2 Human capital transitions

Human capital has been defined in many different ways. We may first note the definition of Becker, who received the Nobel Prize for his work on human capital: “the knowledge, information, ideas, skills, and health of individuals” (Becker 2002, p. 3). Whereas knowledge, information, ideas and health may be more or less clear terms, the notion of ‘skills’ is more ambivalent. For this reason, let us refer to the OECD which states that “abilities and capacities people have to perform tasks that are in demand in the workforce … [which] are usually acquired through education, training and/or experience” (Martinez-Fernandez et al 2010, p. 31). In fact, skills can be subdivided into three different categories: “[b]asic skills are those more generic and routine skills that can be found in occupations present in most industries and organisations. Advanced skills have a higher component of knowledge intensity and can be found in technical occupations and management positions but also refer to social and communication skills needed for team work and specific language

[4] More specifically, these indicators are tariff and non-tariff barriers, regulatory quality and rule of law (economic and institutional regime), adult literacy rate, gross secondary enrolment rate and gross tertiary enrolment rate (education and skills), telephones per 1,000 people, computers per 1,000 people and internet users per 1,000 people (information and communication infrastructure) and royalty payments and receipts in US$ per person, technical journal articles per million people, patents granted to nationals by the U.S. Patent and Trademark Office per million people (innovation system) (World Bank Institute 2008, p. 3).

and cultural skills that are of growing importance in certain multicultural working environments. Converging skills require several of the other skills plus some specific skills" (Martinez-Fernandez et al 2010, p. 31).

The authors also refer to the idea of 'green skills' that may be needed in the future economy. These 'green skills' are converging skills which are composed of both traditional and new skills.[5] The potential future transition to Green Growth might importantly affect the demand for skills. For example, Bowen (2012) (referring to a study by ILO/CEDEFOP 2011), notes three different areas. First, a 'green restructuration' of the economy might lead to increased demand for particular skills in some industries and decreased demand in others. This structural change may lead to the creation of new jobs. Many of these jobs will be rather jobs with higher requirements for generic skills. Still, sectors such as the renewable energy sector and those related to improvements of energy efficiency might be based relatively more on lower or unskilled labour. This circumstance might imply that there will be no clear move towards higher skill jobs. Instead, skills requirements might be relatively diverse in these green jobs. Second, we might see be the emergence of new occupations. Third, it appears important to note that not only new occupations and jobs are created but also the job profiles, i.e. the content, of job that are already existing will change. Thus, the overall changes brought about by such a green transition might be quite significant. Different hurdles have to be overcome for a successful transition, in particular the issue of skill shortages in a variety of areas. These questions reveal once again the importance of considering human capital and skills in the context of Green Growth.

[5] To give a clearer definition of green skills, these skills are "[s]pecific skills required to adapt products, services or operations due to climate change adjustments, requirements or regulations (e.g. water purification and site remediation planning/engineering in mining, solar panels installation, wind turbines design, green management, carbon capture and storage techniques)" (Martinez-Fernandez et al 2010, p. 31).

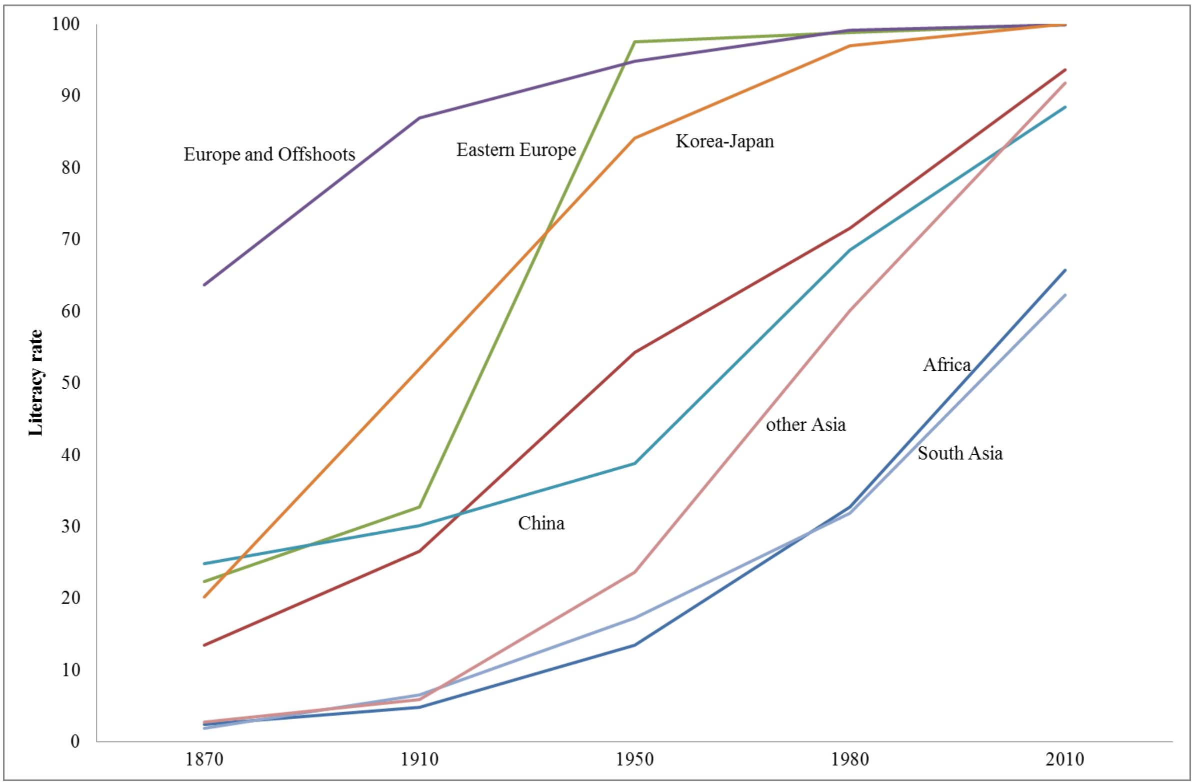
Let us now consider human capital in the context of transitions. The theory on transitions indicates that transitions typically follow an S-shaped curve. Indeed, this S-shaped curve has also been found in the development of human capital (Meyer et al 1992, Patrinos and Psacharopoulos 2011). More precisely, Patrinos and Psacharopoulos (2011) show that there has been an S-shaped curve for the transition of average years of schooling in the most developed countries over time. Several phases can be distinguished: a phase of low educational levels, when progress is also relatively slow. Then the take-off and the acceleration phase with much higher rates of progress. Finally, at high levels of human capital, the increases are once again relatively small. For this reason, the human capital transition follows the ideal scheme of transitions. In the case of education, this scheme has also to do with the inherent characteristics of the measure employed (Meyer et al 1992). In fact, the variable is characterised by a lower and an upper bound. In addition to average years of schooling, other evidence also suggests an S-shaped curve, or at least parts of such a shape. For example, Hippe (2012) shows that increases in numeracy in cross-regional data of several European countries are lower the higher the numeracy values are in the 19th century. However, he finds that countries with low numeracy may show quite high slopes. Still, we have to take into account that these data are only cross-section data and do not permit to evaluate the evolution of a region or a country over time.

How can we now model the human capital transition around the world? Wils has analysed the length of the human capital transition. More specifically, she has considered literacy rates from 130 countries between 1970 and 1999, taking literacy defined as all individuals older than 15 years. She finds that generally “the education transition takes 3-5 generations to proceed from 10 to 90 percent literacy […]. A more detailed statistical analysis by Wils and O’Connor (2002) shows that 67 percent of a subset of 45 countries … from around the world were on a 55-100 year trajectory. All of the remaining 33% were proceeding more slowly" (Wils 2002, p. 11). There was no transition that took less than 55 years in her study on literacy, which emphasises the long-run character of human capital transitions.

What about other educational indicators? In the same paper, Wils also refers to primary, secondary and tertiary education. She collected data from the 1996 UNESCO Statistical Yearbooks and used the age-specific characteristics of the data to take them as an indicator of the increases in school enrolment over time. More specifically, she uses 10 year birth cohorts in the age range 15 to over 65 years. In this way, she uses a similar approach to the one commonly employed when estimating numeracy with the age heaping method (e.g., A'Hearn et al 2009, Hippe 2012, Hippe and Baten 2012, Hippe 2013, Baten and Hippe 2017). She summarises her findings by stating that "[a]s with literacy, the time between a cohort in which 10 percent has attended no primary to a cohort where 90 percent have primary education averages about 75 years. Secondary education follows along with a remarkably similar delay – about 30 years – and a remarkably similar slope for all the countries included. Tertiary education increases much more slowly than the other levels" (Wils 2002, p. 13).

Does this S-curve also characterise the *long-run* human capital transition in the world? Data by Morrisson and Murtin (2013) suggest that we can find such a curve also by looking at the last 140 years. Considering literacy data, the S-curve is not as evident as in the earlier examples but still identifiable (see Figure 8). Particularly in Eastern Europe and Korea-Japan a rapid transition can be perceived. But also the phases 2 (i.e., take-off) and 3 (acceleration) can be interpreted to be perceivable in the curve of Latin America, China and other Asian countries. The initial pre-development, the take-off and the unfolding acceleration phase appear relatively clearly in Africa and South Asia.

Figure 8. Evolution of literacy in world regions, 1870-2010



Source: Morrisson and Murtin (2013).

In Europe and its Offshoots, only the latter part of the curve, i.e. the later part of the acceleration phase and the subsequent stabilisation phase, can be seen due to the early high literacy rates in this region. One would need to go much further back in time in some of the European countries to find the moment when only 10 % of the population were literate. For example, Cressy (1980) estimates that this threshold was attained around 1540 in England, more than three hundred years before the upper threshold of 90 % literacy was reached. This very long-run and rather slow growth of literacy is probably also typical for other early advanced European countries such as Germany, Switzerland, the Netherlands, Scotland or the Scandinavian countries. The early but slow growth of literacy distinguishes these countries from all other countries in Europe and in the world. The corresponding European differences in literacy from 1850 onwards are also depicted by Johansson (1977). Whereas the before-mentioned countries had literacy levels close to 100% already in 1850, different groups of regions followed, in particular England and Wales, then France, Belgium and Ireland, followed by Austria-Hungary and subsequently Spain, Italy and Poland. The lowest literacy levels were common in Russia, the Balkans and Portugal. These findings are further confirmed by Diebolt and Hippe (2017, 2018a, 2018b) and summarised by Diebolt et al (2018) and Hippe (2019). Similar results have also been found by Hippe and Baten (2012) for regional patterns of numeracy in Europe.

We generally find that transitions occur more rapidly over time. In the early advanced countries, the human capital transition (as indicated by literacy) took place much earlier than in other countries and regions but necessitated several centuries to reach the upper limit of the threshold. Literacy values may illustrate this phenomenon. Whereas the transition in Latin America took roughly about 150 years (with a lower limit reached about 1850), the transition was much quicker with in the other Asian countries, taking less than 100 years (lower limit reached in 1915).

As a caveat, we have to mention that Morrisson and Murtin's (2013) data show that the other Asian countries were at similar (low) levels as South Asia and Africa until the beginning of the 20th century but transformed their human capital levels in the following decades much more rapidly than the two latter regions. Therefore, it is possible that both South Asia and Africa will need more time to accomplish their human capital transition than the other Asian countries and thus more than a 100 years. Still, the strong commitment to education for all and new technologies such as the internet may potentially speed up their literacy transitions. Furthermore, one has to consider that the transition of individual countries may be more rapid than the one of a whole continent. The focus on a whole continent or a larger group of countries may blur the experience of individual countries because, to take an extreme case, the transition might have been accomplished in some countries of a continent when it has not even started in others. Mixing these countries results in much longer transition phases. Therefore, Wils' (2002) above-mentioned analyses for rather recent average transition periods of a number of countries should be kept in mind when considering larger geographical areas.

A better understanding of the human capital transition is crucial for estimating the future evolution of human capital in general and population more generally. Lutz et al (2008) have estimated the future evolution of the population in different regions of the world according to their level of education. First, they suggest that in Europe, North America and China there will be a stabilisation of the population until 2030. In Europe and North America, the size of the population in 2030 will be more or less the same as in 2000. In China, the size will only stabilise from 2015 onwards. Taking a glance at the educational distribution, it is clear that the forecast indicates that overall education will increase in all regions. The number of individuals with no education is supposed to fall in all regions but Sub-Saharan Africa. In addition, the number of individuals with (only) primary education will decrease in Europe, North America and China, whereas it will increase in South Asia and Sub-Saharan Africa. Secondary education is assumed to stagnate in Europe and North America but to increase in all other regions. Finally, tertiary education is estimated to be increasing in all considered regions until 2030. These estimations suggest that higher forms of human capital as measured by secondary and tertiary education will play an even more important role in all regions in the future. They may also hint to a gradual increase of importance of the knowledge economy not only in the most developed countries but also in developing countries.

4.3 The information and communication revolution

Let us now turn to another key pillar of the knowledge economy, information and communication. What is information? Evidently, there are numerous definitions available (see Zins 2007). According to Chen (1994), we can define information as "what creates or transforms a representation in a relation which links a system to its environment" (Chen 1994, p. 16). In line with this definition, materials that support information are not themselves information. For example, newspapers are not information but only information support. In addition, the techniques that process information have become increasingly sophisticated through time, from bamboo and other materials to current digital means. We also need to better understand what is meant by 'representation' in the above definition. Representation can also be called 'knowledge'. In order to generate knowledge, information needs to exist and to be circulated. Therefore, while information is considered to be a flow, Chen (1994) affirms that knowledge is a stock.[6] Likewise, information is inherently linked to technology, as technology is based on specific techniques that are themselves founded on knowledge. Therefore, information and knowledge contribute to technological progress.

In consequence, the ability to generate, exchange and accumulate information has been revolutionised, most recently, by a series of electrical and digital technologies – including the mobile phone and the internet. Yet, prior to these end-of-the-twentieth-century developments, a series of important advancements related to mail coaches, railways, the telegraph and the telephone enabled communication rates to increase dramatically from the Victorian era.

Figure 9 shows the dramatic increase in communication since the mid-nineteenth century. A crude estimate indicates that under 50 Gigabytes of information were communicated in the United Kingdom in 1800. This had soared to nearly 2,000 Gigabytes in 1900. By 2000, there were a little more than 40,000 Gigabytes. This estimate suggests communication (via postal services, telephone, mobile phone, text messaging, and emails) in 2015 was equivalent to 85,000 Gigabytes of information in the United Kingdom.

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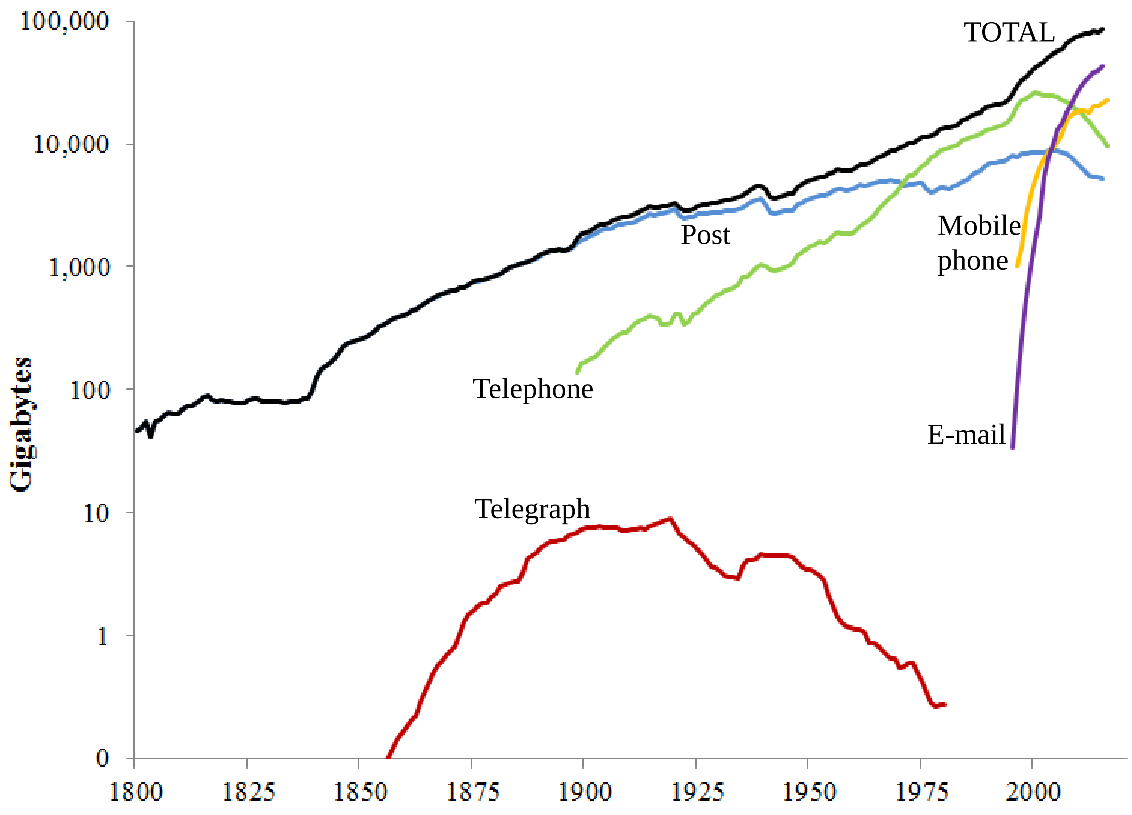
[6] In contrast, Foster (2014, p. 214) does not see knowledge as a stock but as a 'virtual structure'

The estimates are based on a conversion rate of messages and minutes of conversation from individual means of communication into bytes of useful information. For instance, letters were often 200 to 500 words long, thus, equivalent to 800 to 4,000 bytes. Instead, telegraph messages were often very short – generally 15 words or less. Likewise an average minute of telephone or mobile phone conversation generated about 40 words, or close to 160 bytes. Similarly, most emails are short, consisting of 80 words. Naturally, this ignores the large quantity of superfluous information sent with each email. This method also ignores the variation in the efficiency of individual words at conveying the desired message – for example, a telegraph is much more efficient than many letters or telephone conversions.

Figure 2 The use of communication technologies in the UK, 1800-2015



Source: authors' own

Still, this implies there was a more than 1,000-fold increase in the 'average' British person's communication services use between 1700 and 2015. Furthermore, annual growth rates of communication use at the end of the twentieth century and beginning of the twenty-first century were broadly similar to the growth rates throughout the nineteenth century.

So, despite the dramatic growth rates, communication and information use is not a new phenomenon, and goes far back in time. In fact, the use of information and communication has always played a crucial role for any civilisation. For this reason, early civilisation already developed means to improve the exchange of information and communication and provide a sufficiently stable and reliable basis for it. Lampe and Ploeckl (2014) highlight how messenger services were developed in the Persian and Roman Empires. However, these early systems were installed for government purposes, and only few wealthy private individuals were able to use them. Later, the Habsburgs took initiatives to create a stable communication system within their large empire. The beginnings of the post system can be traced back to these political intents.

In addition to letters, the post system increasingly exchanged also other forms of information, such as newspapers and later parcels. The speed of transmission was dependent on the transport system, e.g. the use of human, animal and machine power. The Industrial Revolution fundamentally increased the speed of transmission by the use of new machines. However, the post system is only one dimension of the exchange of information and communication. New technological developments allowed this exchange in increasingly diverse ways. For instance, the Industrial Revolution also enabled the use of electricity for communication. The invention of the electric telegraph was an early breakthrough in the 1840s. Bell’s telephone followed in the 1880s. The invention of radio and television followed in the 20th century. Yet another well-known breakthrough came with the development of computers and finally the internet, the most recent means of transmission of information and use of communication.

Thus, unsurprisingly, the use of information and communication technologies has increased over time. If we consider the computer as a means of using, modifying and disseminating information, Nordhaus (2007) shows that computers have increased their calculating power exorbitantly in the last decades. While the growth of calculating devices, such as the early abacuses, was very limited until the 20th century, it has since taken off. An important breaking point was the Second World War, after which the increases were particularly dramatic.

Furthermore, ICT are often perceived to be an important driver of growth in the economy. Historically, Lampe and Ploeckl (2014) show that the flow of information is related to the flow of trade. In the First Wave of Globalisation before the First World War, an increase in the use of information is related to higher trade volumes. On the other hand, Nordhaus (2007) states that the tremendous increases in computer power have not been matched by similar increases in economic welfare. Although increases in economic welfare have been certainly important, the real contribution of computer power only came at the end of the 20th century.

Nevertheless, a number of recent contributions in the literature show a clear indication of the important role of ICT on economic growth. From a theoretical perspective, endogenous growth models have long emphasised the importance of ideas, information and knowledge for the growth of innovation and ultimately economic growth (e.g., Romer 1990). In this context, ICT appear fundamental in the diffusion of information, technological adoption and the generation of knowledge spillovers, bringing about higher productivity, innovation and economic growth (Quah 2002). This may particularly be the case for the more recent broadband internet infrastructure technology (Czernich et al 2011).

There has also been a large empirical literature on the relationship between ICT and growth. Different strands can be identified (Vu 2011). First, firms and individuals may be more productive thanks to the use of ICT, resulting in higher growth rates (e.g., Stiroh 2002, Brynjolfsson and Hitt 2003, Jensen 2007). Second, authors using the growth accounting framework (e.g., Jorgenson 2001, Oulton 2002, Jorgenson and Vu 2011) conduct analyses for one country or a range of countries. Cross-country regressions have also been popular (e.g., Hardy 1980, Roller and Waverman 2001, Koutroumpis 2009). These studies generally show the importance of ICT (or of individual technologies that are part of ICT) for economic growth.

In consequence, international organisations have also considered the relevance of ICT for economic prosperity. For example, the World Bank (2012) suggests that increasing internet connectivity by 10 % increases the growth of GDP by about 1.4 %. For this reason, international organisations such as the World Bank recommend the further diffusion of ICT and promote the active involvement of governments to achieve these goals.

Similarly, researchers such as Ahmed and Ridzuan (2013) and Antonopoulos and Sakellaris (2009) equally show that ICT are a crucial factor for economic and TFP growth, studying the cases of developing and developed countries (see also Jímenez et al 2014). In fact, the internet has particularly attracted the attention of researchers. Differential internet access within countries can be explained in part by gross national income (Goldfarb and Prince 2008, Orviska and Hudson 2009). In reverse, GDP per capita may partly explain internet growth in the OECD (Kiiski and Pohjola 2002). Internet access is also dependent on socio-economic differences, bringing about the “digital divide” (Orviska and Hudson 2009). Interestingly, once controlled for internet access, less educated and low income individuals are longer online than others. Therefore, the characteristics of internet usage are different to those for internet access. The value of time may explain this pattern (Goldfarb and Prince 2008). The way time is spent online is also dependent on education in some EU countries (Pantea and Martens 2013).

4.4 The knowledge explosion

Thus, we can see that ICT and knowledge are important for economic growth. Indeed, the spread of knowledge has accelerated impressively. In fact, it has been estimated that "[t]he sum total of humankind's knowledge doubled from 1750-1900. It doubled again from 1900-1950. Again from 1960-65. It has been estimated that the sum total of human knowledge has doubled at least every five years since then… It has been further projected that by the year 2020, knowledge will double every 73 days" (Appleberry 1992, see Breivik 1998, p. 1). While the foundations of such estimations are certainly quite debatable, they still may give a hint of the direction of knowledge production over the longer run.[7] To give an illustration: if one takes these estimations literally[8] and combines them with estimations of world GDP (or more exactly, the gross world product, GWP) by DeLong (1998) until 1990, worldwide knowledge and GDP have risen in a manner that world knowledge increased but less than the growth rate of world GDP. Only in the last decades does world knowledge take off and should have increased even much more rapidly since 1990. In this sense, 1990 would be the turning point in this history of economic growth and knowledge growth since 1750 and the Industrial Revolution. It might once again suggest the important role knowledge might play in future growth.[9]

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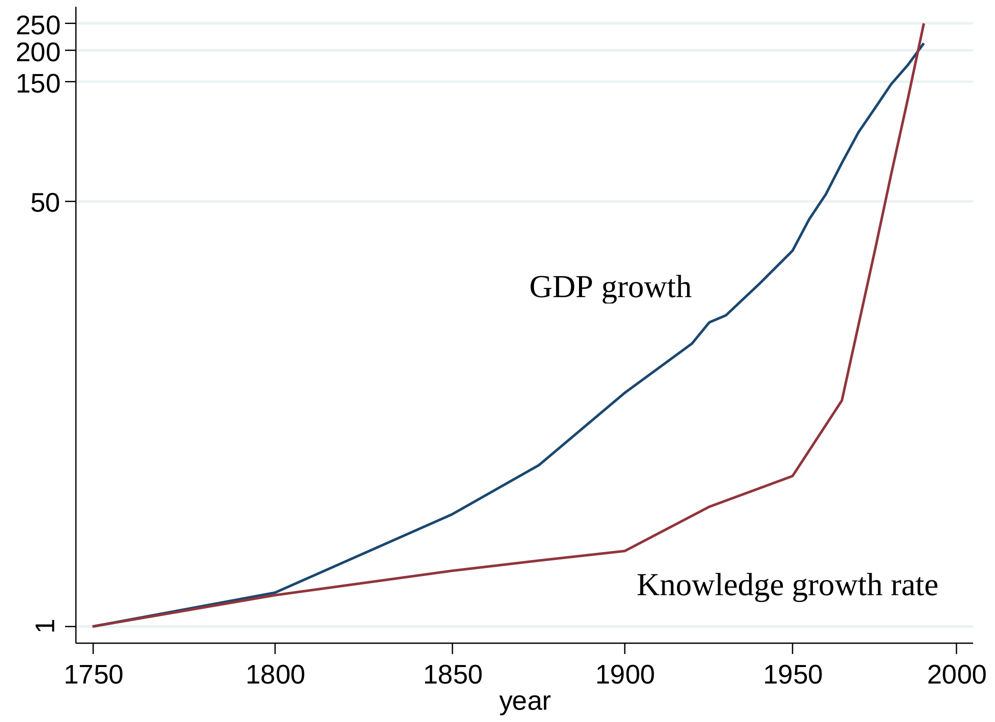
[7] These data are possibly based on Buckminster Fuller (1981) and the idea of a 'knowledge doubling curve'.

[8] It is assumed that a doubling occurred during 1950 and 1965, the citation being not absolutely clear for the period 1950 to 1960.

[9] But, still, these estimations are very rough so that no definite conclusions can be taken.

Figure 3 Long-run growth of worldwide knowledge and GDP



Source: own calculations, based on Appleberry (1992) and DeLong (1998).

5. The Connection between Energy and Knowledge

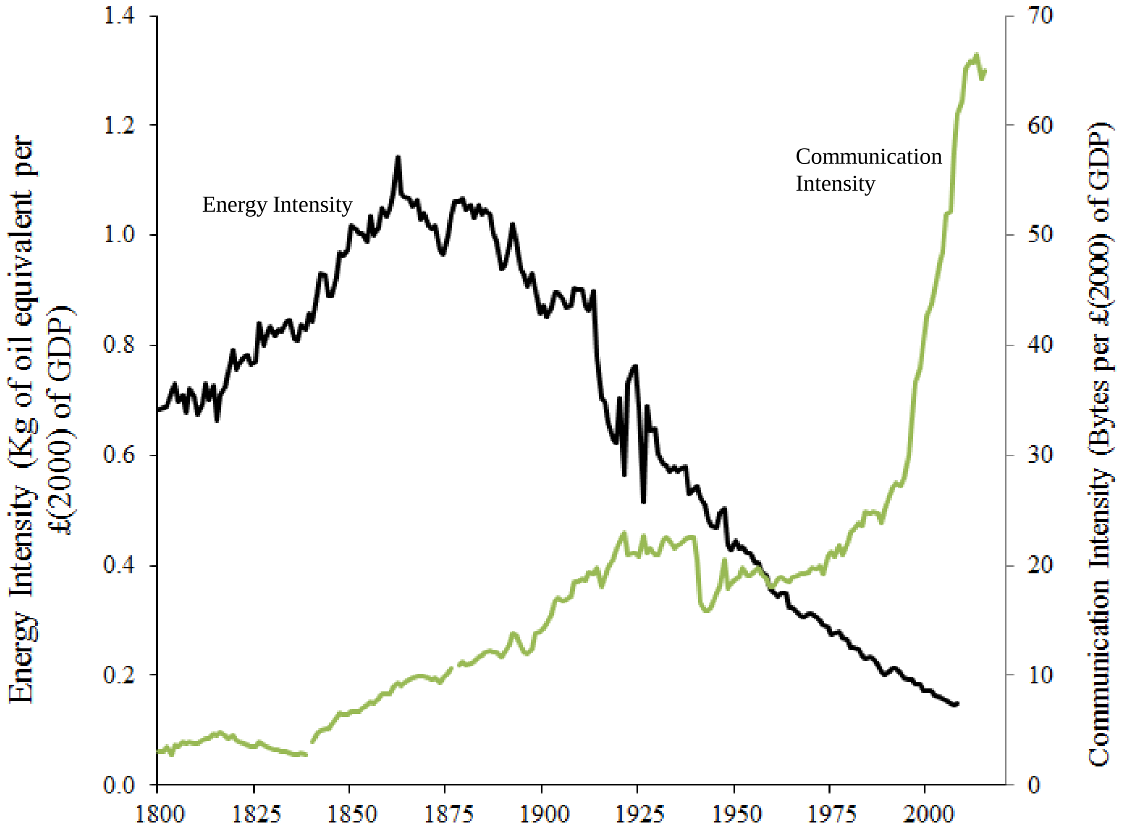
Information in general, and ICT in particular, and thus knowledge is fundamentally linked to energy. However, their exact relationship has been controversial, as some see information as a kind of energy and others see energy as a form of information. In contrast, Chen (1994) argues that information is fundamentally different from energy because it is non-material, inexhaustible and does not adhere to the same laws of physics. While in the first stage both are complementary (e.g., activities linked to information need energy consumption), they have a relationship of substitution in a second stage. This substitution is based on the law of entropy, i.e., the second law of thermodynamics. That is, all systems tend towards disorder. The entropy degradation can be reduced by information and the increased use of information can reduce energy consumption (or given a certain consumption of energy, can lead to higher economic value).

This is not a new phenomenon. While the information-energy nexus has become popular during the last years of the 'information revolution', long-run history shows that human societies and economies have continuously evolved towards the substitution of energy by the use of information (Chen 1994). In other words, "the direction of history has been towards a progressive substitution of 'intellectual and symbolic activities' for 'physical and energetic activities', of 'symbols' for 'things' and of 'intellect' for 'hand'" (Chen 1994, p. 21 referring Cloutier 1983), leading to a progressive dematerialisation of the economy. Increasing energy prices and falling ICT equipment prices have also been accelerating this shift. Technology is becoming increasingly complex while work is increasingly transformed into the abstract world. A historical comparison may illustrate this trend towards the dematerialised economy. In the Industrial Revolution, muscles were replaced by machines in an era of mechanisation. Today, computerisation means that production processes are optimised so that less energy and capital are needed alongside raw materials. In this way, we may be moving from an energy (and material) intensive epoch to a new age of high information intensity. This energy-information substitution happens in different ways: by incorporating information in capital, in labour, in the organisation of production, in energy, and finally, in material (Chen 1994). For example, we can think of more sophisticated knowledge of workers when they perform a certain technical task with specific technical equipment. But also more available information and its analysis are crucial in this respect, as illustrate the recent explosion of information and the debates on 'Big Data'. Furthermore, recent newly created ICT allow a better management and communication of information, which may be the foundations of more efficiently organised work organisations.

Given the crucial and fundamental role of information and energy, the economic system can also be viewed by using these two elements (plus materials). This, however, cannot be done using the standard, conventional methods of economics. These methods are based on the factors of production and their particular characteristics. Their characteristics are divisibility, substitutability, complementarity and independence. In contrast, information cannot be understood as a factor of production because its properties are not compatible with this approach. In other words, information cannot be divided, and it is not additive nor independent nor exhaustible. Still, the mistake of treating information as a factor of production is committed rather often (Chen 1994). The energy-information substitution does not come about as a substitution of factors of production, but by incorporating information in the factors of production and the respective combinations of these factors.

Just to reflect this trade-off, Figure 11 compares the energy intensity and the communication intensity in the United Kingdom. Energy intensity (that is, primary energy consumption relative to GDP) has been on the decline in the United Kingdom since the mid-nineteenth century. This can be contrasted with the rise in communication intensity (Gigabytes of information relative to GDP) during the second-half of the nineteenth century and from the end of the twentieth century. In other words, communication (as well as information, human capital and knowledge) form a much greater component of the economy today than in the past.

Figure 4 Energy and communication intensity in the UK, 1800-2015



Source: authors' own

An alternative perspective can be gained from the paradigm first established by Solow (1956) and advanced by endogenous growth theory (e.g., Lucas 1988, Romer 1990). Foster (2014) claims that these theories are ahistorical and cannot explain the historical shift in the aggregate production function. He considers entrepreneurship, innovation and skills adoption to be the fundamental drivers of economic growth (following Baumol 2002). Foster favours evolutionary macroeconomic models which do not use the idea of a production function. Instead, they use innovation diffusion curves which may explain what happens when knowledge accumulates and new energy sources become available. Thermodynamics, and in particular the law of entropy, are central in these models. Exactly this physical dimension is lacking in standard models, and material flows are not considered (Warr and Ayres 2012).

In this alternative view, economic systems are dissipative structures and become ever more complex (Foster 2014).[10] Economic growth is the consequence of the accumulation of useful knowledge and radical new ways of using knowledge can lead to growth spurts until the new created market or niche is satisfied. Therefore, the 'knowledge gradient' in its economic dimension has increasingly become crucial to economic growth.[11] The individuals at the core of the reduction of this gradient are entrepreneurs whose actions lead to creative destruction. The particular importance of uncertainty in the area of entrepreneurship also means that traditional economic methods of using constrained optimisation do not apply. At the same time, there is an 'energy gradient' that the dissipative structures seek to reduce (Schneider and Sagan 2005, Foster 2014). The Industrial Revolution can serve as an example. The Industrial Revolution was spurred by the use of new energy sources and the application of novel knowledge. Therefore, both energy and knowledge were at the heart of the Industrial Revolution (see also Mokyr 2002, Allen, 2009, McCloskey 2010; Foster 2014). New capital goods were generated that catalysed knowledge given the restrictions of the energy gradient. Accordingly, economic growth is seen as a co-evolutionary process where new knowledge acts as a complement to higher energy use. In other words, when energy is saved this surplus is used together with new knowledge for new applications. Substitution of labour by machines (and today computers) enables a higher rate of knowledge production which together with the employment of new free energy allows the production of more goods (Foster 2011). Similarly, Ayres and Warr (2012) propose a model

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[10] In these dissipative structures, free energy is used to provide work and specific services, generating possibilities of consumption. In addition, investments are undertaken that increase the degree of complexity and allow a greater production of goods by employing more energy or the same amount of energy in a more efficient manner.

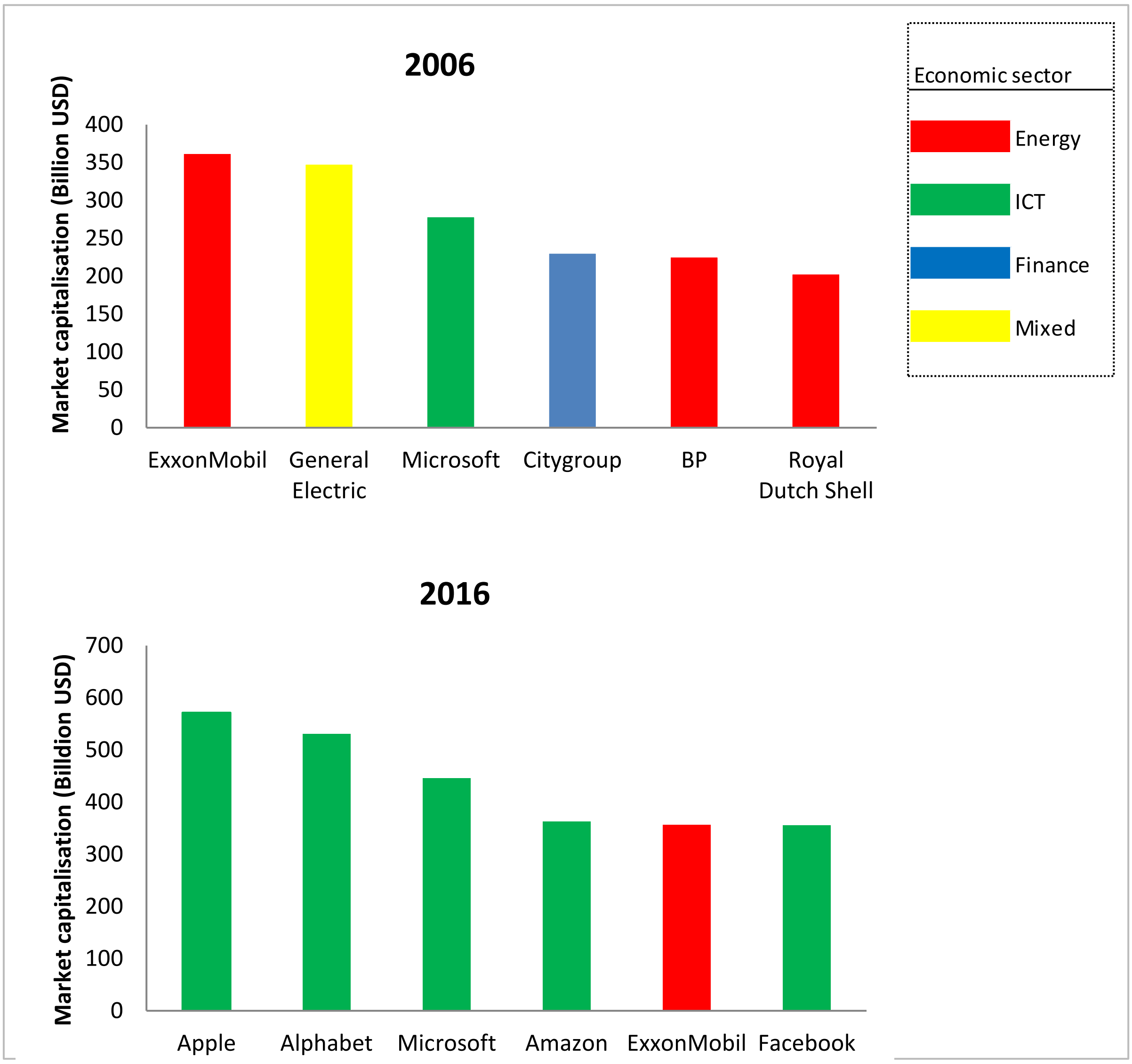
[11] Note that Foster emphasizes that not all information and knowledge is equally important for growth. Similarly, Warr and Ayres stress that "those [from knowledge derived technologies] pertaining to energy productivity provide the greatest productivity enhancements and spillover potential" (Warr and Ayres 2012, p. 93).

that does not use the classic factors of production but considers an economy which is characterised by a system that processes materials, including extraction, conversion and finishing of goods until their consumption. This system is governed by the law of physics. For this reason, it presents an alternative system approach to the neo-classical standard model, including waste flows that can have a negative environmental but eventually also economic effect.

Thus, while energy has been a historical driver of growth, the role of information, knowledge and ICT may be even more important in the future. While energy conversion technologies, such as the steam engine, the combustion engine and electricity, have been General Purpose Technologies (GPT) that were important drivers of productivity and growth increases, ICT will increasingly be the next fundamental GPT in this long-run perspective (Ayres and Warr 2012). Why? Because ICT increase energy efficiency. In addition, ICT allow an increasing direct connection between producers and consumers of energy. Intermediaries in many economic activities will be less needed, thus reducing inventories and waste. Finally, ICT allow lower energy intensities and move forward the general trend towards consumption patterns that are less energy intensive (Walker 1985).

In this vein, there has also been a recent shift among the largest companies worldwide: while in 2006 three out of six companies with the highest market capitalisation worldwide were operating in the energy sector, only one energy company (ExxonMobil) still remained in this list a decade later (see Figure 12). The exact opposite case occurred in the ICT sector: only Microsoft was big enough for this list in 2006, while all companies but ExxonMobil were from ICT in 2016, with Apple being the worldwide leader.

Figure 12. Worldwide largest companies, 2006 and 2016



Source: FAZ/Statista (2016). Data for 2016 refer to August.

Therefore, the internet is also seen as the core of a third industrial revolution, together with renewable energies (Rifkin 2012).[12] Rifkin lays out the five pillars of this new

[12] Rifkin lays out the five pillars of this new revolution. These pillars are "(1) shifting to renewable energy; (2) transforming the building stock of every continent into micro–power plants to collect renewable energies on-site; (3) deploying hydrogen and other storage technologies in every building and throughout the infrastructure to store intermittent energies; (4) using Internet technology to transform the power grid of every continent into an energy internet that acts just like the Internet (when millions of buildings are generating a small amount of renewable energy locally, on-site, they can sell surplus green electricity back to the grid and share it with their continental neighbors); and (5) transitioning the transport fleet to electric plug-in and fuel cell vehicles that can buy and sell green electricity on a smart, continental, interactive power grid" (Rifkin 2012).

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Similarly, Castells suggests that the current revolution in information technologies is "at least as major an historical event as was the eighteenth-century industrial revolution, inducing a pattern of discontinuity in the material basis of economy, society, and culture" (Castells 2009, p. 29).[13] He argues that information technology is at the heart of this new revolution, similar to the key importance of new energy sources in the industrial revolutions.

However, he points out that this statement may not be confounded with the fact that the creation of new knowledge was also essential to these earlier revolutions. In particular, "[w]hat characterizes the current technological revolution is not the centrality of knowledge and information, but the application of such knowledge and information to knowledge generation and information processing/communication devices, in a cumulative feedback loop between innovation and the uses of innovation. […] For the first time in history, the human mind is a direct productive force, not just a decisive element of the production system" (Castells 2009, p. 31).

[13] Even more broadly, Toffler has argued that the information society is the third wave of economic revolutions, after the agricultural and the industrial revolution (Toffler 1980).

In addition, whereas previous revolutions spread relatively slowly across space, the new revolution connects the different regions of the world quickly. The ultimate consequences will still need to be seen, but they could potentially be relatively radical and ground breaking.

6. Conclusion

The purpose of this chapter is to show how historical economic growth was driven by the development of energy markets (and boosted by energy transitions), particularly between the eighteenth century and 1973, and driven by the development of information, human capital and knowledge (and related transitions), which have also been underway for a long time but is becoming more dominant today. Thus, there has been a very long run shift from energy resources to knowledge as a fundamental driver of economic growth.

An important feature of the history of economic growth since the Industrial Revolution has been based on the externalization of costs of production and consumption (Fouquet 2008). By passing on or spreading those costs, more opportunities were available for production and economic growth. For example, British industrial supremacy depended on the use of coal and the emission of vast quantities of smoke and sulphur dioxide, with external costs around 20% of GDP by the end of the nineteenth century (Fouquet 2011). Experience also shows that, for a number of reasons, principally related to the industrialists' position of influence, legislation to protect environmental standards or compensation for the victims was rarely successful (Fouquet 2012). Yet, minimizing the externalization of the costs of production (associated with passing them on to the workers, society or the environment) might imply lesser opportunities for the costs of production to fall and, thus, for economic growth. So, based on past experiences, one has to wonder about the potential for green (that is, internalized) growth.

Crucial for future economic growth will be for the economies to follow a path that is economically successful without damaging social or environmental structures. One example of this might be the weightless economy, where material and energetic resources are not as central to production and consumption as they have been (Hepburn and Bowen 2013, Perez in Chapter 19, Quah in Chapter 20). Human capital and ICT have seen stark increases over the last centuries and even the last decades, and they may play a major role in this future economy. Thus, it will be interesting to see whether this type of economic growth does manage to substantially reduce the material and energetic content of economic activity, helping to achieve greener growth.

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