Energy Research & Social Science 91 (2022) 102736

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Twin transitions of decarbonisation and digitalisation: A historical perspective on energy and information in European economies

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ARTICLE INFO

Keywords:
Energy transitions
ICT
Twin transition
Energy intensity
Historical

ABSTRACT

This paper investigates the structural transformation associated with the 'twin transition' of decarbonisation and digitalisation in European economies by placing it in a broader historical perspective. With this in mind, this paper analyses the long run trends in energy intensity and communication intensity since 1850. The evidence indicates that these economies experienced a coevolution of energy and communication intensities during their industrialisation phase, followed by a divergence in the energy and communication intensities associated with the development of high tech and ICT. Overall, this reflects the dematerialisation of these European economies. The paper also analyses the speed of historical energy transitions and communication technology transitions in these economies, finding that communication transitions appear to be substantially faster than energy transitions. The evidence suggests that twin transitions of the decarbonisation and digitalisation of economies are likely to experience a process of imbalanced structural transformation (with ICT continuing to forge ahead). This expectation should guide policy recommendations – increasing the need for low carbon industry to develop and create synergies between the two industries in order to avoid the new industrial revolution being high-carbon.

1. Introduction

Since the beginning of the First Industrial Revolution, global economies have extracted and used 500 billion tonnes of oil equivalent of fossil fuels, leading to 1500 billion tonnes of carbon dioxide emissions [1]. These emissions, along with past other greenhouse gas emissions, have significantly altered the global climate. Past and future emissions risk imposing irreversible consequences to our climate. Thus, the fossil fuel energy system can only be a temporary phase in the history of global economic development.

Signs of a new industrial revolution are emerging [2]. One of the most salient features of this transformation has been the expansion of information and communication technology (ICT). Since the 1970s, this transformation included the transition from mechanical and analog electronic technology to digital electronics, including the adoption of personal computers and mobile phones. In the last couple of decades, this includes the growing use of new technologies - such as artificial intelligence (AI), cloud computing, robotics, 3D printing, the Internet of things, and advanced wireless technologies - promising a new phase of disruption with major economic and social implications.

At the same time, the 2010s decade was a tipping point for renewable energy sources, with dramatic reductions in the costs of generating electricity and increases in investment, capacity and generation – with wind power production rising seven-fold, and solar power rising 60-fold in the last ten years [1]. In fact, the transition to renewables may well be underway – as renewable energy sources have reached 10 % of global primary energy consumption (see Fig. 1). Nevertheless, if low carbon energy technologies align themselves with ICT and become part of an industrial cluster, there is an increased likelihood that the next Industrial Revolution will be green [3]. Thus, a central strategy of long run economic policy should be to ensure 'smart green growth' [4] or the 'twin transition' of decarbonisation and digitalisation of the global economy [5].

As stated by President Von der Leyen, the twin transition is a key priority of the European Commission [6]. To this end, the Commission has set up the European Green Deal, with the intention of "tackling

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https://doi.org/10.1016/j.erss.2022.102736
Received 24 November 2021; Received in revised form 1 May 2022; Accepted 2 July 2022

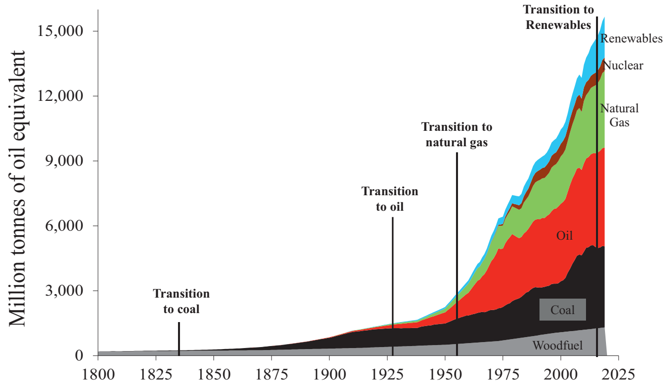

Fig. 1. Global primary energy consumption, 1800–2019.

climate and environmental-related challenges that is this generation's defining task” [7]. The Green Deal's objective is to reach zero net emissions by 2050 and decoupling economic growth from the use of resources and the dematerialisation of the economy. Digitalisation also plays a key role, as “Europe must leverage the potential of the digital transformation, which is a key enabler for reaching the Green Deal objectives” [7]. To make this a reality, the European Commission has also set up the Digital Education Action Plan (2021–2027), to enhance the digital competences of European citizens and boost the digital ecosystems in education [8].

With this in mind, the central question of this paper is whether the ‘twin transition’ will exhibit a process of structural transformation associated with balanced growth in which these two industries will create synergies and co-evolve (promoted by Roseinstein-Rodan [9]) or will they experience unbalanced growth, in which one industry forges ahead and the other develops less swiftly (argued by Hirschman [10]). The answer to this question will offer insights into the types of policies that will be required for promoting a successful ‘twin transition’. For instance, if the evidence suggests that we can expect a balanced twin transition, it will be essential to develop policies that focus on addressing potential coordination failures. Instead, if an unbalanced twin transition is expected, it will be key to develop policies that promote the lagging industry to expand and that interconnect the two industries in order to generate synergies. Indeed, a major risk is that the lack of complementarities between industries leads to a high-carbon digitalisation of the global economy [11].

To better understand the potential for low carbon energy sources to align themselves with ICT, it is essential to analyse the changing structure of the economy and the speed of transitions within the two industries. Given the rare and protracted nature of economic structural transformations and of transitions,[2] a historical or long run analysis is needed. To achieve this broad objective, *the first aim of this paper is to investigate empirically the changing structure of the economy by comparing the changing role of energy (and its decarbonisation) and ICT (and its digitalisation) in European economies*. This investigation will take the form of an analysis of the long run trends in energy intensity and communication intensity in a selection of major European economies since 1850. This will reveal broader lessons about the rate and timing of structural transformations.

The second aim of the paper is to analyse the speed of historical energy transitions and communication technology transitions. Given that communication transitions that have occurred in the last 30 years have been digital transitions, this analysis will highlight any differences between analog and digital communication transitions. Furthermore, a comparison of the speed of energy and communication transitions will help understand some of the challenges associated with aligning low carbon energy sources with ICT. This will reveal insights about the potential twin transition of the decarbonisation and digitalisation of economies.

The next section will present the role of industrial development in structural transformation, which forms the motivation for this analysis. Section 3 discusses the relationship between energy and information or communication. The fourth section will outline the data used for the analysis. This will be followed by an analysis of the long run trends and transitions in the energy markets and communication services. In light of the analysis, the penultimate section will discuss the potential twin transition of decarbonisation and digitalisation of the global economy. The final section draws conclusions.

2. Structural transformation and industrial development

Economists and economic historians have identified a set of factors important in driving structural transformations [13]. North [14] noted the importance of developing institutions that protect economic agents' rights to produce, exchange and consume. Olson [15] and more recently Acemoglu and Robinson [16] argued that limiting the power of vested interests is critical for economic development. Meanwhile, McCloskey [17] argued for the promotion of a culture of enterprise and commerce, including a willingness to seize or create new opportunities. In sum, institutions that protect rights while minimising powerful groups to maintain the status quo and encouraging opportunities to be taken are critical for creating incentives to ensure that economies can change and transform structurally.

In addition, certain theories of structural transformation and long run economic development, as exemplified in the formal analysis of Romer [18] and Murphy et al. [19], modelled the interaction between specific industries. The interaction between industries is central to the ideas of Rosenstein-Rodan [9], which emphasise the importance of industrial complementarities, and Hirschman [10], which advocated sectorally unbalanced or uneven growth. Rosenstein-Rodan [9] stressed the importance of coordination amongst sectors and industries – and the lack of coordination being a barrier to economic development. If only a number of industries would decide to invest and expand at the same time, they might generate the virtuous cycle of demand and income to lift the economy out of its lower development equilibrium towards a socially more desirable outcome. The source of the coordination failure is the existence of complementarities, or pecuniary externalities [20]. That is, the returns to each industry depend positively on the number of industries in the economy (and their levels of development). Each industry forms its expectations about its demand and profits on the basis of industrial development in the economy, and will wait for others to develop first. While they wait, profits and workers' incomes remain low. Thus, government is seen as an ideal agent to provide the ‘big push’ and coordinating signal to change firms' expectations and incentives [21].

Certainly, Freeman and Louça [22], Geels and Schot [23] and Kander et al. [24] conceptualized energy systems as part of industrial clusters or development blocks, in which the success of an energy source, and its growth in use was linked to the complementarities with other technologies and industries. Past energy systems (such as the coal block, consisting of coal, steam engines and the iron industry, and later, the internal combustion engine-oil block and the electricity block) created mutual markets for each other's products, achieving economies of scale and declining costs. As Kander et al. [24] put it, the implications of energy transitions and the associated structural transformation depended on the market suction and market widening created by the links between, for example, oil demand and the car, and oil demand and oil tankers, respectively. Thus, the structural transformation depended on the co-evolution of the energy sources and the related industries.

Meanwhile, Hirschman [10] stated that it is not always possible for

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[2] ‘Transition’ refers to changes in the socio-technical energy system, while ‘transformation’ is a particular pathway in which regime actors are dominant in the process and refers to a broader change of socio-ecological systems [12]. Here, specifically, the main focus will be on energy and communication transitions, and the transformations of economic systems.

different industries to grow in parallel. He highlighted the importance of leading sectors being able to forge ahead due, say, to technological innovations combined with the demand for their products at a particular stage of development, that can then stimulate higher levels of income and demand. This might occur through market conditions, if technological innovations reduce costs and prices sufficiently, or might be triggered by directed government policy. He argued that growth in a sufficiently important sector could create profit opportunities in downstream industries and a dynamic pressure for them to grow at a later stage. In fact, he proposed that unbalanced growth and the dynamic tensions it creates have the potential to accelerate economic development (although this remains unproven). However, there is a risk that the economy will suffer from a tiered structure, where one industry is successful and the others are in its shadow. Faced with unbalanced growth, it is essential that governments ensure that lagging industries develop.

Having outlined two potential types of structural transformation, it is important to understand what type twin transitions are likely to occur. As explained in the introduction, the evidence will provide the foundation for determining what policies will be most important to promote a successful twin transition.

3. Dematerialisation, decarbonisation and digitalisation: substitution between energy and information

Underlying any structural transformation are the factors of production that generate economic growth. The standard classification of factors of production focus on labour and capital. However, labour in the traditional sense refers to the workers' time providing physical effort or energy. In addition, skilled labour is enhanced by the worker's investment in human capital incorporating stored information and knowledge. Similarly, physical capital can be seen as embodied information or knowledge, combined with energy and materials. Indeed, both the Solow [25]-Swan [26] standard model of economic growth (which identifies the central role of technology in the growth process) and Romer's [18] endogenous growth model (which explicitly analyses the role of scientists in the production of technology) highlight the role of information or knowledge creation as pivotal to economic growth. Thus, a reduced form analysis could present an alternative economic growth model in which energy and information (or knowledge) are the factors of production used to convert materials into an output.

Certainly, Cipolla [27], Allen [28] and Otojanov et al. [29] have noted the critical role energy played in industrialising economies. Mokyr [30] emphasised the stimulating force of ideas and innovation for improving production, exchange and consumption. Hidalgo and Hausmann [31] argue that economic growth and development result from increasing and re-structuring information in order to learn how to produce higher value and more complex products. Thus, information (structured to create knowledge) and energy have been identified as central factors needed to achieve long run economic growth.

With this in mind, this section briefly discusses the relationship between energy and information (which will be proxied by communication as one-to-one information provision) in economic activity. Information in general, and digital information and communication in particular, are closely linked to energy, offering a potential way to improve the dematerialisation and decarbonisation of the economy, but also creating increasing demands for energy [5,32].

Spreng [33,34] proposes that there is a three-way relationship between energy, information and time (i.e., workers' time or labour). Although this is a potentially helpful separation, workers' time can be split into the labour providing physical effort and the human capital incorporating stored information and knowledge. Similarly, physical capital can be seen as embodied information or knowledge, combined with energy and materials. Thus, a reduced form analysis could present energy and information as the factors of production used to convert materials into an output.

Chen [35] focusses explicitly on the relationship between energy and information. He argues that, at one level, there is a complementary relationship given that all information activities require energy. At another level, they are substitutes as information can help make better decisions and reduce energy consumption. However, Chen [34] argues that information is fundamentally different from energy (and other factors of production, such as capital and labour) because it is non-material, inexhaustible and does not adhere to the same laws of physics. He argues that the implication of having these characteristics is that information cannot be incorporated in a standard production function – since factors of production need to be exhaustible, divisible, substitutable, complementary and independent. He goes onto to argue that 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.

Despite these concerns, it is helpful to examine empirically the relationship between energy and information. For instance, Spreng [33] examines the amount of energy, labour and information used in different industrial activities. He finds that pre-industrial activities tend to use a great amount of labour. By contrast, classical industrial activities (e.g., textile, iron and steel production) need energy, labour and information. Finally, high-tech industries require mostly information. Machado and Miller [36] show that the US economy became less energy intensive and more information intensive in the 1963–1987 period. They argue that they found a possible substitution relationship between the evolution of information activities and the use of energy. Their results suggest that information became less dependent on energy, while energy became more dependent on information.

Looking at more recent developments, the introduction of ICT has radically changed the relationship between information and energy. ICT has altered and will continue to alter energy systems. Meanwhile, the dramatic growth of ICT is creating its own dependence on electricity, which could alter information and communication systems. Thus, there is the potential for major synergies between the two industries.

The first direction of causality is that ICT is greatly influencing energy systems. ICT is transforming the energy supply industry. Better information management systems are improving the coordination of energy production. Increased computing power enables the use of big data, analysing greater amounts and complexity of data on infrastructure used to generate, transform, store, trade, transport or control energy [37]. In parallel, the use of digital sensors in electricity networks for supply monitoring and the installation of smart meters for analysing consumers' demand are providing new system management tools. For instance, smart meters provide demand-side management opportunities, such as peak clipping, load shifting and strategic conservation – possibly combining information and dynamic pricing – that could increase the flexibility of energy systems, especially in the context of intermittent renewable power sources [38]. Indeed, the reduction of the 'digital gap' in terms of the technical needs for systematic market integration is enabling grid contributions from decentralised units such as photovoltaic plants and home-based storage systems via local, regional and national energy trading markets [39]. Similarly, blockchain technology is instrumental in the development of digital certificates for these decentralised low carbon energy sources, through the verification and exchange of certificates [39]. As a result, digital technologies - such as artificial intelligence, the Internet of things, blockchain and cloud computing – are increasingly facilitating the transition to a more resource-efficient and low carbon economy by lowering the barriers to the large-scale deployment of greener business models [40]. Thus, ICT is pivotal in improving the efficiency, reducing the costs and lowering the carbon content of energy systems.

ICT is also affecting conventional energy demand. As mentioned above, demand-side management via smart meters is starting to provide pricing or energy information feedback, which has the potential to decrease peak power demand and move consumption from peak to valley periods [38]. Sovacool and Del Rio [41] identify hundreds of home technologies with the potential to alter the management of energy usage. Especially in industrial settings, the Internet of things is seen as a source of energy savings [42]. Similarly, Gosnell et al. [43] show how better management practices (assisted by ICT) can substantially reduce work-related travel energy consumption. Thus, for specific activities, ICT could be expected to lead to energy savings.

ICT is also changing broader behaviour, which has major energy demand implications. In relation to tele-working, Hook et al. [44] note the key energy savings are associated with a reduction in average vehicle distance travelled – O'Garra and Fouquet [45] indicate this could be as high as 24 % from voluntary reductions in commuting. There could also be possible energy savings through reductions in office energy consumption. However, there is evidence that tele-working does not necessarily reduce energy consumption, either because of additional travel behaviour and energy consumption in the home – for instance, Gubins et al. [46] found inconclusive evidence in a Dutch study, while De Abreu and Melo [47] found an increase in energy consumption amongst UK tele-workers. Indeed, in a systematic review of the literature, Hook et al. [44] find that, while two-thirds of studies concluded that teleworking reduces energy consumption, amongst studies accounting for the full energy consumption only half of them found reductions in energy consumption due to teleworking. In relation to e-commerce, Wunnik et al. [48] noted that, although car travel may decline, freight transport is likely to rise. Thus, Jorgensen et al. [49], Koomey et al. [50] and Horner et al. [51] emphasise the major uncertainties related ICT both in the direct effects and the indirect (e.g., rebound) effects that e-commerce or teleworking create.

Pulling together the evidence on the role of ICT on energy is challenging. One early study [52] concluded that, in the US, one kWh of direct electricity used by ICT equipment led to an average 10 kWh in energy reductions due to efficiency and substitution. However, recent studies put this conclusion in doubt. For example, the potential greater efficiency of power systems is reducing the price of the service consumers face, which increases the consumption of energy services, implying direct rebound effects. Coroama and Mattern [53] argue that in some contexts (e.g., automated vehicles, entertainment services) the rebound effects are likely to be large, but, in other markets, the rebound effects may only be moderate (e.g., when the rebound activity is less resource intensive than the original activity, when there is a financial and physical limiting factor, and when the market is saturated). Thus, there is great variability in the impacts of ICT on energy consumption and the broad consensus is that, overall, digitalisation has increased energy consumption, because the energy-reducing effects due to direct efficiency improvements and sectoral shifts have been less important than the direct effects and economic growth impacts of digitalisation [54].

In the other direction, the ICT industry is dependent on electricity and its consumption has been increasing. Koomey [55] notes the growing use of energy associated with the broader ICT infrastructure and data centers, in particular – although this has sometimes been exaggerated [56]. While possibly an over-estimate, Jones [11] proposed that, in 2014, the energy use of global ICT was equivalent to 2000 TWh of electricity, of global data centers was 200 TWh and of bit coin mining was 20 TWh – compared with a global electricity consumption of 20,000 TWh. Irrespective of the precise numbers, demand for information management, computing, exchange and storage is rapidly increasing and this creates upward pressure on energy demand. Forecasts of the use of electricity associated with internet are likely to double (or potentially quadruple) over the next decade [57].

Yet, the energy demand of ICT is also affected by dramatic improvements in the energy efficiency of ICT equipment over the last thirty years [58]. Galvin [59] suggests that the efficiency of ICT has improved by as much as 30 % per year. For example, bit coin mining has become highly sensitive to the cost of electricity – with some miners shifting the location of their operations according to the price of electricity at particular times of year and more efficient devices being introduced on the market almost every month [60]. Williams et al. [61] discuss the major improvements in energy efficiency of communication from one technological generation to the next - with the recent 5G networks responsible for a ten-fold efficiency improvement. However, given the high demand for computing services, it is important to consider the rebound effects. Hargreaves et al. [62] argue that efficiency improvements on devices are outweighed by energy-intensive forms of demand. Galvin [59], using a series of case studies, concludes that the rebound effects of ICT are generally very large - between 120 % and 130 %. Meanwhile, looking at computing and entertainment together, Chitnis et al. [63] find a direct rebound effect of 91 %; however, the indirect rebound is negative (−103 %) and larger than the direct rebound, leading to a negative combined rebound effect (−12 %). Thus, there is still substantial uncertainty about the impacts of energy efficiency on the ICT market.

At a broader macroeconomic level, there is possible evidence that the increased investment in ICT is leading to a reduction in energy intensity of economies [64]. Looking at the United Kingdom over more than two hundred years, Fouquet and Hippe [65] show how energy intensity has been declining and communication intensity has been increasing since the mid-nineteenth century. Indeed, despite his concerns, Chen [35] stated "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'" (p. 21), leading to a progressive dematerialisation of the economy. Inevitably, this process of digitalisation and dematerialisation also has an impact on the decarbonisation of the economy.

A key question is how these two factors of production (i.e., energy and information) change at different levels of economic development. It might be that they are essential at all levels. However, it is possible and even probable that their importance changes at different levels of economic development. Therefore, it might be valuable to look for transitions in their influence on economic growth (using their intensity of use as an indicator). In addition, there may well be interaction between factors, which may change with economic development. Thus, an analysis of how these factors change and interact in long run economic growth will be important in maintaining economic growth in the long run and, possibly also, in ensuring inclusive, equitable and green growth.

4. Data

This section outlines the data used to analyse the relationship between energy intensity and communication intensities. As a reminder, energy intensity measures the quantity of energy used in an economy divided by Gross Domestic Product (GDP), as presented in Fig. 2. The data on GDP (and population, which is used to produce per capita estimates) starting in 1850 is available from the Maddison Project [66], which is based on a large set of original sources [67–70]. For 2019, the data was updated using Eurostat [71].

The historical primary energy consumption data by energy source for Germany, France, Italy and Spain comes from Kander et al. [24]. The data for the United Kingdom comes from Fouquet [72]. These have been updated using BP [73]. Throughout the paper, the data on 'renewable energy' will refer to most forms of renewable energy sources except woodfuel for heating, which will be presented separately. To be precise, it includes all water and wind power for mills and electricity generation, geothermal and biomass for electricity, and biofuels for transport; human and animal power are not included – for more detail, see [24,72,74].

The energy values for primary electricity sources (e.g., renewable and nuclear power) are calculated based on the 'partial substitution' or 'input-equivalent' method, which assigns value based on the equivalent amount of fossil fuel input required to generate that amount of electricity in a standard thermal power plant - rising from 36.0 % in 1965 to 40.2 % in 2020 [75]. Compared with the direct equivalent method, which is used by the IEA, this method generates higher values for

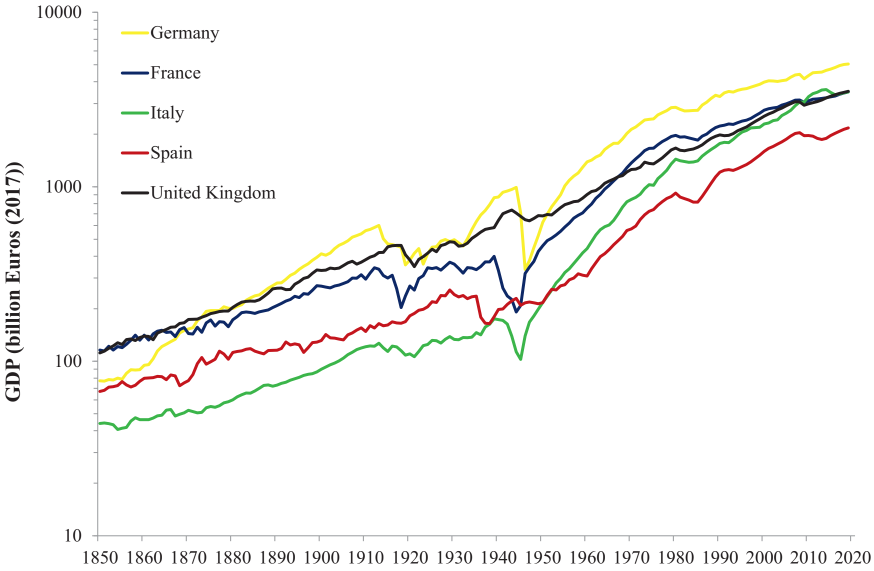

Fig. 2. GDP in selected European countries, 1850–2019.

primary electricity compared with fossil fuels, and should be considered when looking at the (arguably accelerated) transitions towards renewable and nuclear power below [76,77].

The estimates for communication use and intensity in this paper are based on collecting statistics on the number of letters, telegrams, text messages and emails, and on the minutes of telephone, mobile and mobile 'app' conversations. The historical postal statistics (in number of letters), telegraph statistics (in number of messages) and telephone statistics (in number of calls) are from Mitchell [78]. This data is also available from and updated by CNTS [79]. In addition, mobile phone and SMS text messaging is available from ITU [80] – the ITU website also provides the original telephone and telegraph statistics back to 1849.

Trends in emails and mobile app calls and texts made are not directly available. As a result, estimates are generated. For emails, it starts with an estimate of the daily number of emails sent, excluding the number of spam messages sent in the Germany, France and the United Kingdom in 2021, which accounts for just under 90 % of total emails in European countries and the USA, and 98 % in China and Russia [81]. Dividing these estimates by the population enables the estimation of emails sent per person in these countries in 2021 - ranging from 12 to 16 messages per day. For Italy and Spain, in the absence of data, emails sent per person are assumed to be the average of in Germany, France and the United Kingdom. There are also estimates of the trend in global emails sent and the global number of internet users back to 2017, providing a trend in emails sent per user [81]. The rate of increase per person in 2017 of 5 % is used to calculate the rate in previous years. This rate of change is applied to individual countries going back to 1990, when email messaging began. The share of each country's population using emails are available between 2005 and 2020 from Eurostat [82], which are linearly extrapolated back to zero in 1990 and are multiplied by the country's population and the average messages sent per person to generate estimates of annual emails sent between 1990 and 2020.

For mobile app calls and text messages, the estimation process starts with the share of the population using individual apps [83]. This includes Apple Messenger, Discord, FB Messenger, Google Hangouts, IMO, Skype, Snapchat, Telegram, Threema, Viber and WhatsApp. These are combined with the trends in global usage for the specific mobile apps [81]. This generates the number of messages sent and calls made, which can be multiplied by the average minutes per call [84], to estimate the minutes per call.

These messages and conversation minutes are converted into bytes of information using the method developed in Fouquet and Hippe [65]. The method is explained here, with Table 1 showing the assumptions made. For instance, letters were often 100 to 500 words long. Here, the assumption is that the average letter is 200 words, and that there are four characters per word [85], thus, equivalent to 800 bytes. Instead, telegraph messages were often very short – generally 20 words or less – the assumption is that the average message was 15 words. Similarly, most emails are shorter than letters, but longer than text messages – a survey of emails indicated, the average email consisted of 80 words, which can be converted into bytes in the same way. Likewise, an average minute of telephone or mobile phone conversation generated about 40 words, or close to 160 bytes. Based on comparing statistics of the minutes of phone conversation and the number of phone calls made, the average conversation is close to 3 min long – hence, the assumption made, as shown in Table 1. These assumptions enable the conversion of different communication technologies into a single indicator of one-to-one information sent and received.

Prior to this study, the closest dataset on long run trends in communication was Perkins and Neumayer [86], who compared international growth rates of mail, telephone and internet use. However, their data ends in 2003 prior to the dramatic increases in mobile phones and the internet, and does not combine the different forms of communication into a single measure.

To proceed, a few clarifications are necessary. First, as a reminder, one 'bit' is a binary unit of information – i.e. 0 or 1. One byte is equivalent to eight bits. Generally, eight bits are required to encode one character. Thus, one byte is equivalent to one character, and this is the assumption used throughout this study. Second, it is worth noting that this study focusses on the amount of information in messages, and is not comparable to the size of computer files. For example, a 500-word Word document might be 200kB (i.e., 200,000 Bytes), even though the information content measured here would be 2000 Bytes (i.e., 500 * 4, assuming four characters per word – since the average length of a word in English is 4 letters long [85]). The difference between the two is associated with the document template, meta-detail and formatting, which is itself additional specific information unrelated to the content of the message.

Also, it is important to stress that this is about the quantity of information communicated rather than any estimate of 'meaning'. In other words, this does not try to measure the efficiency of communication provision. For instance, the telegram tended to be used in an efficient way - given its cost, senders prepared short messages focussed on meaning. Letters sent by postal services tended to be less expensive (per

Table 1
Conversion of communication into bytes of information.

	Post letter	Post card	Telegraph message	Telephone conversation	Mobile/app conversation	SMS/app message
Minutes				3	6.2	
Words	200	30	15	120	120	10
Bytes	800	120	90	480	480	40

Source: see text.

word) and, therefore, less focussed on brevity – as a consequence, they probably did not have the same efficiency of communication. However, estimating the 'meaning' and efficiency of communication is a daunting task, which will not be attempted here.

Finally, this study estimates the quantity of information sent in one-to-one communication. This is separate from one-to-many 'dissemination' of information, which includes books, newspapers, radio, television and the internet. A preliminary estimate for the UK indicates that one-to-one communication accounts for a little under half of the communication and dissemination[3] information in 2019. Of the total estimate of information, 97.5 % of it was in digital form. Thus, based on this preliminary evidence, the digitalisation of information is practically ubiquitous in the second decade of the twenty-first century.

Arguably, estimates could also incorporate information in the creation of knowledge, which would include technology (information in physical capital, often outlined in patents), software, human capital (information in workers' skills and expertise) and organisation (information about the labour-capital relationship). As Hidalgo [87] explains, it is how the information is structured which creates the knowledge and the value, rather than information itself. Whether including information in knowledge or not, this paper should be seen as part of a bigger project associated with assessing the full relationship between energy and information.

5. Long run trends in energy consumption: carbonisation, decarbonisation and dematerialisation

5.1. Growth and convergence in energy consumption

This section reviews the evolution of energy use since the mid-nineteenth century in Europe. Here, the focus will be on France, Germany, Italy, Spain and the United Kingdom. These economies were chosen because they have had the largest population and GDP in Europe. The United Kingdom was the first economy to industrialise from the end of the eighteenth century, Germany and France followed in the second half of the nineteenth century. Italy and Spain industrialised in the first half of the twentieth century – for further detail, see [24].

Although absolute consumption levels are important to assess environmental impacts, Fig. 3 presents the long run trends in per capita primary energy consumption for comparison across countries. Average consumption increased roughly ten-fold between 1850 and 2019 – for most countries, from 240 to 330 kgoe (kilograms of oil equivalent) to 2500–3600 kgoe. By 1850, the average person in the United Kingdom consumed 1500 kgoe as the economy had already begun its industrialisation process, which included the use of coal to heat and transport its population. Germany and France's average energy consumption increased rapidly during the second half of the nineteenth century, as did Italy and Spain's consumption in the second half of the twentieth century. The trends show the convergence in energy usage across countries, which began at the end of nineteenth century and culminated in the early twenty-first century. This convergence suggests that 'post-industrial' lifestyles have diffused across these European countries and are prevailing.

5.2. Energy transitions

However, when consumption by source is examined in Fig. 4, considerable differences exist across countries. First, it is important to note the dominance of coal use in Germany and France for 150 years. In Italy and Spain, coal only dominated the energy mix from the early twentieth century. Despite the transitions to coal, per capita woodfuel consumption declined only gradually, indicating that coal did not fully replace woodfuel consumption, instead it was added on-top-of woodfuel, enabling better standards of living [88]. The delayed transition to coal implied that woodfuel remained more important in Italy and Spain than in Germany and France until well into the twentieth century.

Second, it is also worth highlighting that, prior to their role in electricity generation, water and wind power were not main sources of energy – however, as noted in Fouquet [72], they may have played a crucial role in key industries by reducing the cost of grain-crushing and of textile-fulling and, thus, the price of food and clothing. In Germany, where coal was readily available, the need for hydropower for electricity was less acute and remained relatively lower than in France, Italy and Spain – although geographical factors influencing the hydropower potential may also be at play.

Third, coal's dominance of the energy mix ended in the second half of the twentieth century. Crucially, though, total per capita coal consumption has only declined modestly, except in France - with major air and atmospheric pollution implications. Oil and natural gas became the main energy sources in the second half of the twentieth century.

Fourth, low carbon energy sources (i.e., woodfuel, other 'renewables sources' (see the data section for details) and nuclear power – as opposed to higher carbon energy sources, including coal, oil and natural gas) have begun to play an important role in the energy mix since the third-quarter of the twentieth century. Nuclear power increased rapidly in Germany, France and Spain, though it only became a main energy source in France. Renewable energy sources associated with power generation have grown rapidly in the early twenty-first century. This is particularly the case in Germany and Spain, where per capita renewable electricity consumption is over 500 kgoe in 2019; while, in France and Italy, per capita consumption is 375–420 kgoe. Although past energy developments and transitions were market-led, the transition towards low carbon energy sources is heavily influenced by political decisions. Given the climate-related targets, and the limited success of nuclear power, it will be interesting to see whether renewable energy sources become the main sources of energy over the next few decades and, crucially, whether they replace fossil fuels or are added on-top-of fossil fuels, as this will have major implications for climate stabilisation strategies.

Finally, thus, at present, energy consumption is highly diversified with different energy sources meeting different energy services (e.g., heating mostly from natural gas; power being met by coal, natural gas, nuclear and renewables, and transport from oil).

To analyse the energy transitions in more detail, Table 2 provides a summary of the speed of dominance and speed of decline of specific energy sources across countries (the UK is also included to provide additional evidence). The 'speed of dominance' (in the first three columns) refers to the shortest duration in years from the year that the energy source was below 5 % of the total energy mix to the year it reached 50 % of country's energy mix. In Fouquet [89], the speed of historical energy transitions was measured from 5 % to 80 % or the peak

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[3] The estimate related to the internet is only including text-based content, rather audio or visual content.

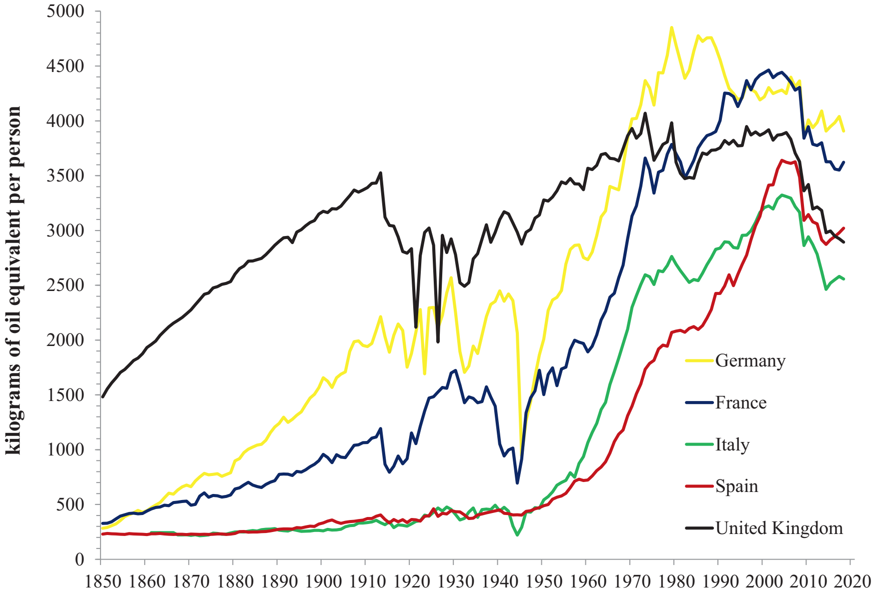

Fig. 3. Energy consumption per capita in selected European countries, 1850–2018.

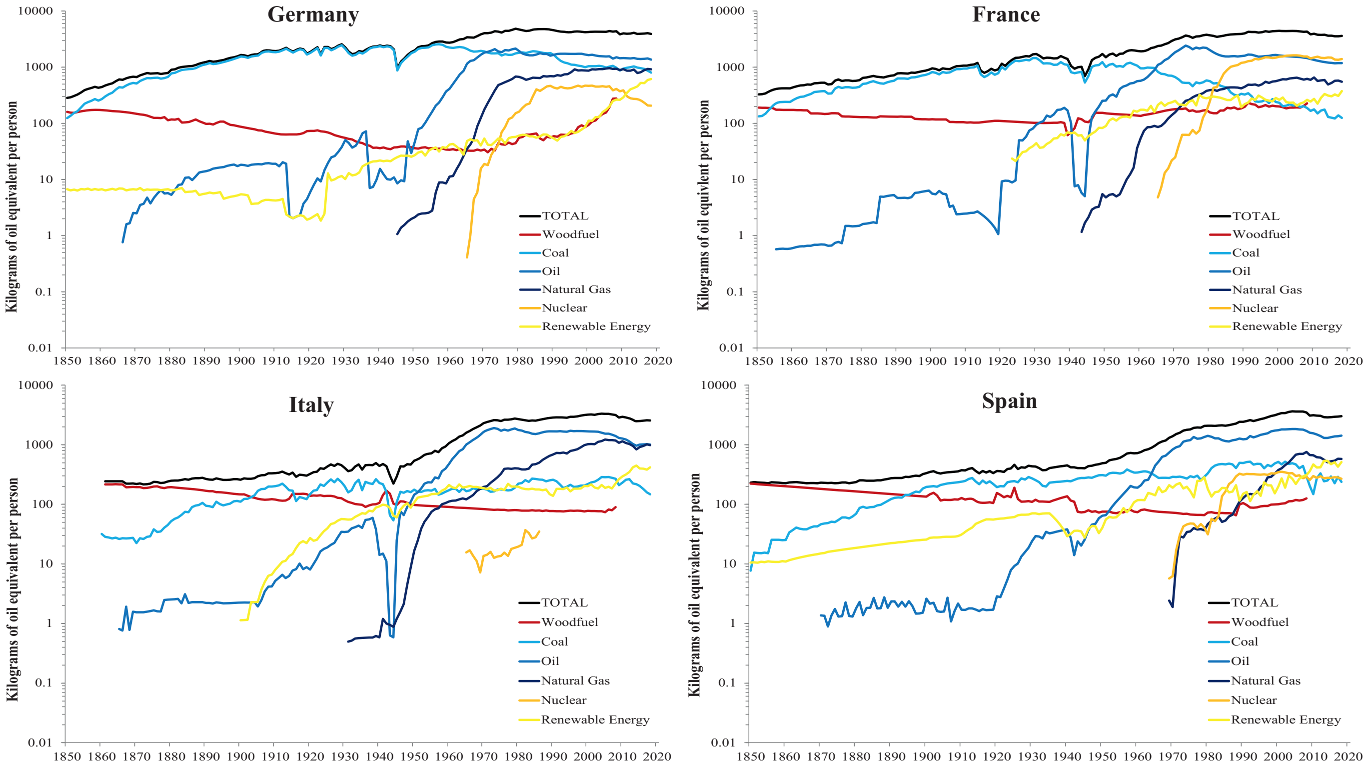

Fig. 4. Primary energy consumption per capita by source in selected EU countries, 1850–2018.

percentage - however, in too many cases in the current study, 80 % was not reached and, therefore, 50 % was used instead – Sovacool [90] notes that this selection does affect the measured speed of transition. The important point for the current study is that a common metric is used.

Coal was the slowest energy transition. It took on average 72 year; excluding the UK's protracted experience in the fifteenth and sixteenth centuries [89], the average length was still 49 years – suggesting that the speed of energy transitions may be affected by economic development. The transition to oil was faster, averaging 33 years and coinciding with the post-World War II expansion. This average was affected by the fastest individual uptake of an energy source was for oil in Germany – taking 20 years from 5 % to 48 % of the energy mix. Removing this remarkable but incomplete transition, the average was 37 years for oil to reach dominance. With a small coefficient of variation (4.1 %), a little under 40 years could be used as an indicator of the duration of a rapid energy transition.

For other energy sources, the transitions were incomplete. For instance, natural gas averaged 41 years, but no countries analysed here experienced the dominance of natural gas – this average was affected by Spain's introduction of natural gas, which was rapid at 19 years but it

Table 2
Transition speed: Dominance/peak and decline of energy sources (in years).

	Dominance	Dominance	Dominance	Decline	Decline
	Coal	Oil	Natural gas	Woodfuel	Coal
United Kingdom	161	35	40[a]	210	49
Germany	39	20[a]	40[a]	51	49[b]
France	55	38	41[a]	122	37
Italy	59	36	66[a]	65	78
Spain	46	38	19[a]	78	61
Average EU-4	**49.8**	**33.0**	**41.5**	**79.0**	**56.3**
Average Europe	**72.0**	**33.4**	**41.2**	**105.2**	**54.8**
Standard dev.	17.0	7.6	16.7	64.3	15.5
Coef. of variation	30.3 %	22.8 %	40.4 %	61.2 %	28.3 %

Notes: (i) 'the speed of dominance' refers to the shortest duration in years from the technology being at (or below) 5 % of the total market to reaching 50 % (or more) of the total market; (ii) 'the speed of decline' refers to the shortest duration in years from the technology being 50 % (or more) of the total market to being 5 % (or below) of the total market; the 'coefficient of variation' is the standard deviation divided by the average (i.e., mean).

[a] The energy source did not reach 50 % of the country's energy market (for oil, in Germany, the peak reached 48 % of the energy mix; in the UK and Italy, natural gas peaked just below 40 %, whereas in Germany, France and Spain, its peak was below 25 % of the energy mix).

[b] The energy source did not decline below 5 % (i.e., coal in Germany, which in 2019 remained above 15 %). For additional details, the authors can be contacted.

only reached 22 % of the energy mix.

As a comparison, the French nuclear programme took 34 years to peak at 41 % of the energy mix. The UK and German nuclear power programmes peaked after 17 years, although only reaching 10 % and 11 % of the energy mix, respectively. The Spanish programme was rapid going from 5 % to 13 % in 6 years. Meanwhile, the Italian nuclear power remained below 1.5 % of the energy mix.

Similarly, the Italian hydroelectric programme took 18 years to expand from 5 % to 15 %. The Spanish programme spent 38 years to reach 18 % of the energy mix. The French programme expanded to 10 % over 28 years. As mentioned earlier, the UK and Germany had large coal reserves to depend on, and there was probably less impetus to find alternative ways to generate electricity.

The 'speed of decline' - which indicates the shortest duration in years from the technology being 50 % (or more) of the total market to being 5 % (or below) of the total market - averaged 105 years for woodfuel and 55 years for coal. Thus, the declines associated with energy transitions are even more protracted than the rise to dominance. This may reflect the social and economic implications of substituting away from an energy source. If these slow declines (compared with the rises to dominance/peaks) are generalisable, the transition away from high-carbon energy sources is likely to take many decades, leaving a 'long tail' of carbon dioxide emissions.

5.3. *Carbonisation and decarbonisation of the energy mix*

There is also great interest in the decarbonisation of the economy. However, it is also important to discuss first the carbonisation of the economy. Fig. 5 shows a dramatic increase in the carbon intensity (i.e., the amount of carbon dioxide emissions per unit of primary energy consumed) due to the rise of coal and reduction of low carbon energy sources in the total energy mix during the nineteenth century.

For the UK, where the coal industry had already developed by the mid-nineteenth century [72], the carbon intensity was near the maximum – 3.96 kg of carbon dioxide per kg of oil equivalent (kgoe). For Germany and France, low carbon energy sources (e.g., woodfuel, watermills and windmills, etc.) still provided a lot of the energy requirements. With the development of stationary and moving steam engines, coal was used increasingly for power and transport services, as well as in heating processes, such as iron and steel production [24]. In other countries, particularly Italy and Spain, woodfuel remained an important source of heating. Nevertheless, by 1900, the carbon intensities of these European economies approached the carbon intensity in the UK. The inevitable consequence was a dramatic increase in air pollution and carbon dioxide emissions.

This dominance of high-carbon energy sources continued with the transitions towards oil and natural gas, although they emit less carbon dioxide per unit of energy (see Fig. 5). Only in the third quarter of the twentieth century was there a reduction in fossil fuels in the energy mix. This decarbonisation process began with the introduction of nuclear power and accelerated in the twenty-first century with the development of wind and solar power [1]. Economies use one-fifth to one-half low

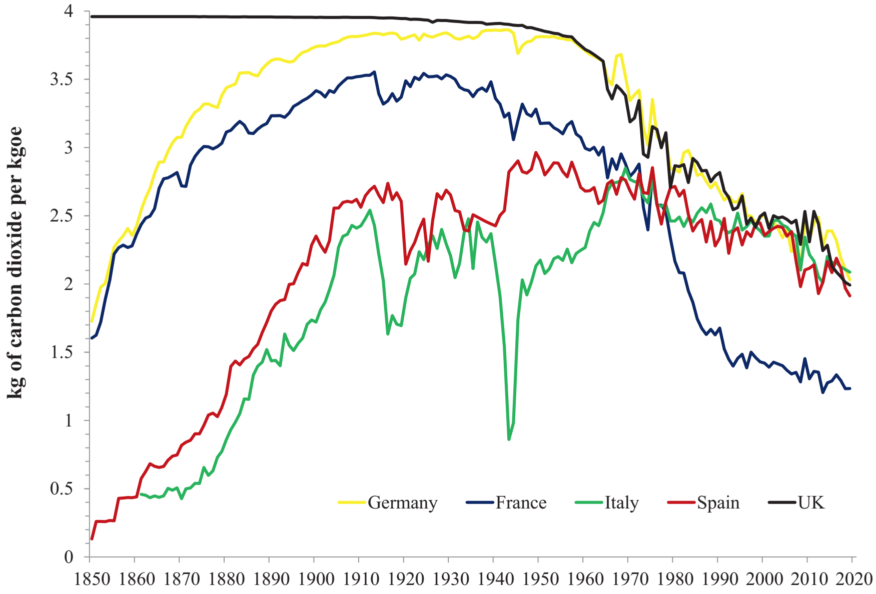

Fig. 5. Carbon intensity in selected European countries, 1850–2018.

carbon energy sources at the end of the second decade of the twenty-first century – implying that their carbon intensities are around 2 $kgCO_2$/kgoe.

Looking at the main services energy provided, only power is being decarbonised [1]. The French experience reveals the challenge of decarbonisation. It is close to the share of decarbonisation experienced in 1850. In France, most of the electricity is generated from low carbon sources and they account for just over half of all the primary energy used in the economy. In other words, full decarbonisation of the power sector would probably enable other countries to roughly double their share of low carbon energy sources in the mix. However, the other half of the energy mix would be provided by fossil fuels. Thus, major efforts need to be made to find solutions to decarbonise transport and heating, if economies seek to return to the shares of decarbonisation experienced in the early nineteenth century (or mid-seventeenth century in the case of the UK) – if electric vehicles diffuse swiftly and renewable energy sources can meet the additional power demand, then the much of transport could be low-carbon within 30 years, given historical experiences. The same could apply to space and water heating. However, there are hard to decarbonise transport services (such as heavy goods vehicles, water-based freight and airplanes) and heating (including industrial high-temperature processes) which may take many more decades to decarbonise.

5.4. *Dematerialisation: trends in energy intensity*

As well as the decarbonisation of the economy, it is important to look at the dematerialisation of the economy. Energy intensity measures the amount of energy used for each unit of economic value generated (i.e., kgoe per € of GDP). It offers a broad indicator of the economy's reliance on energy and a crude measure of the energy efficiency of the economy (see Saunders et al. [91] for further discussion).

Looking at energy intensity, four patterns emerge. First, Fig. 6 shows considerable variation in energy intensity across economies and over time. In the mid-nineteenth century, the United Kingdom was using four times the amount of energy per unit of GDP compared with other economies. Its coal industry was highly developed, and its economy was very energy intensive and arguably highly energy inefficient. Italy was the second most energy intensive economy, although it was dependent on woodfuel. Germany was able to exploit large coal reserves and became the second most energy intensive economy. Spain remained the least energy intensive until the late twentieth century.

Second, energy intensity tended to rise with industrialisation. By the late nineteenth century, Germany became the second most energy intensive as it expanded its economy fuelled by the development of its coal industry. France also developed a coal industry and became as energy intensive as Italy by the early twentieth century. Although less dramatic, largely because it did not have large coal resources to exploit, Italy's energy intensity increased with industrialisation in the first half of the twentieth century. Spanish industrialisation started in the mid-twentieth century and this is reflected in the rising. This correlation between industrialisation and energy intensification is, in large part, a result of the rise in the demand for heating, power and freighting in the production and distribution of goods [92]. Fouquet [93] stresses that this process of industrialisation can lock economies into energy intensive pathways, especially when large stocks of resources are available (as in the case of the UK and Germany) that became hard to escape, with potential negative implications for the long run prosperity of the economy, increasing its vulnerability to energy price shocks, inflation, trade balance deficits, political pressures from energy companies and environmental pollution.

Third, the evidence also shows that energy intensity has tended to decline at higher levels of economic development. For the United Kingdom, the decline in energy intensity began from the 1860s. For Germany and France, energy intensity rose until the 1930s and then began to decline. For Italy, energy intensity had declined since 1850, apart from two brief periods of industrialisation in the 1910s–1920s and 1960s–1970s. Spain has kept a relatively stable energy intensity and shows that the tendency to decline at higher levels of economic development is not universal. This reduction in energy intensity reflects a broader trend in the dematerialisation of the economy.

An important factor driving the trends in energy intensity was the role of international trade. In the nineteenth century, the United Kingdom and then Germany were major exporters – and evidence indicates that their energy intensities would have been substantially reduced without these exports [94]. However, in the second half of the twentieth century, this effect has been reversed. In the mid-twentieth century, this involved the appropriation of natural resources (especially oil) from developing economies [95], which boosted energy intensity. Then, since the 1960s, these European economies have outsourced industrial production, importing goods from industrialising economies. This industrial production was associated with energy-

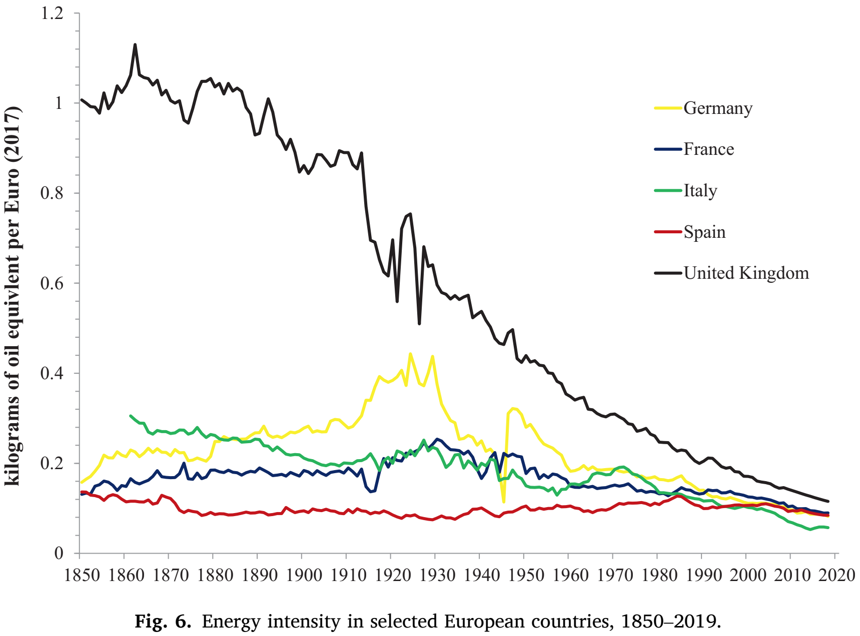

Fig. 6. Energy intensity in selected European countries, 1850–2019.

intensive activities, imposing ecological damage and responsibility on developing countries [96]. A new development in this process of international trade is the import of primary materials essential for the production of renewable energy technologies – for instance, two-thirds of the world's cobalt production (used in wind turbine magnets) originates in the Democratic Republic of Congo, while half of all rare earth metals (used in wind turbines and electric vehicle motors) and 70 % of graphite (used in the production of solar panels) come from China [73] – with considerable environmental impacts [97].

Finally, similar to per capita energy consumption (see Fig. 3), the energy intensity of individual economies converged in the second half of the twentieth century. This convergence may reflect common modes of production and lifestyles diffusing across these European countries. It is tempting to anticipate a continued decline in energy intensity and dematerialisation of these economies over the next few decades, especially given that energy scarcity pressures are not likely to be relieved with a transition to low carbon energy sources and that economies are shifting away from heavy and energy-intensive industries towards lighter and information-rich services.

6. Long run trends in communication use: expansion and digitalisation

This section investigates similar patterns for communication. It examines the transitions in communication technologies, the broader digitalisation of communication services, and the associated increases in communication per capita and in communication intensity.

6.1. Communication transitions

Fig. 7 presents the uptake of different communication technologies in Germany, France, Italy and Spain. This offers a comparison of economies that industrialised from the nineteenth century, such as Germany and France, and those that developed economically in the twentieth century.

To examine the transitions associated with communication technologies in more detail, Table 3 provides a summary of the speed of dominance and of decline of specific technologies across countries. As in Table 2, the ‘speed of dominance’ indicates the shortest duration in years from the technology being at (or below) 5 % of the total market to reaching 50 % (or more) of the total market. In the case of mobile phone in all countries and mobile apps in certain countries, the technology did not reach 50 % of the total market. For mobile phones, the peak ranged from 32 % for the UK, 34 % in Germany to 44 % for France. For mobile apps (principally Whatsapp), the technology reached more than 50 % of the total communication in Italy and Spain, but is 37 % in France, 47 % in Germany and 49 % in the UK in 2020.

On average, it took 56 years for the telephone to reach dominance, replacing mail as the main source of communication – note that, although the telegraph may have offered value for certain businesses that depended on rapid communication, the scale of communication using the telegraph (measured in bytes) was relatively limited. The evidence indicates that telephone was slower to reach dominance in the early industrialising economies (UK, Germany and France). The countries that industrialised in the twentieth century (Italy and Spain) were able to adopt the new technology more quickly. On average, it took 18 years for the mobile phone to peak and only 8 years for mobile apps to dominate/peak. While the evidence is not completely comparable, given the lack of dominance in some cases, there is a clear acceleration in the speed of adoption and dominance, and a reduction in the coefficient of variation.

‘The speed of decline’ refers to the shortest duration in years from the technology being 50 % (or more) of the total market to being 5 % (or below) of the total market. On average, it took 43 years for postal services to decline from 50 % to 5 %, whereas it took on average 16 years for the telephone to decline by an equivalent share. Again, there is evidence of an acceleration in the speed of transition, as well as a decline in the coefficient of variation in the speed across countries. In addition, the coefficient of variation appears to be substantially smaller for declines than for the rise to dominance of a technology. In other words, it is easier

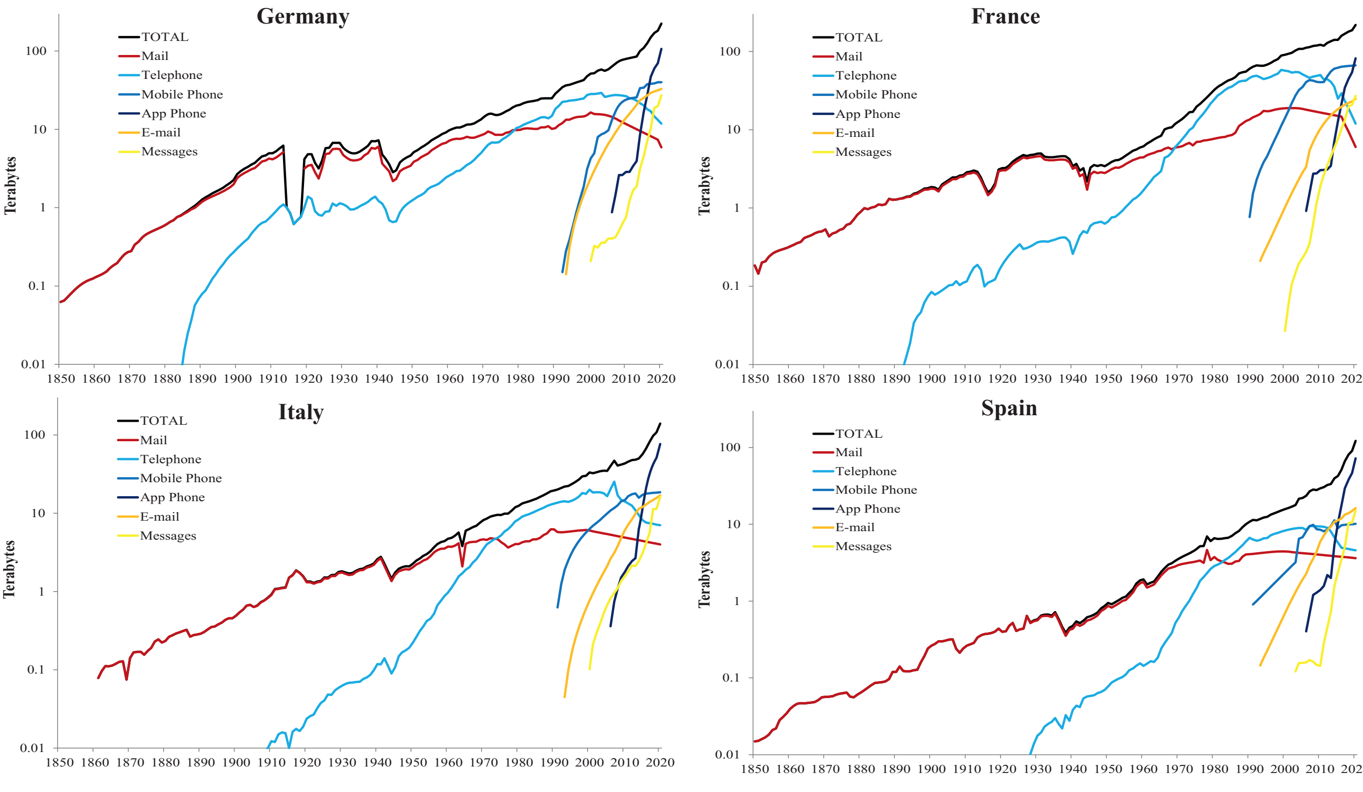

Fig. 7. Communication consumption by technology in selected EU countries, 1850–2019.

Table 3
Transition speed: Dominance/peak and decline of communication technologies (in years).

	Dominance	Dominance	Dominance	Dominance	Decline	Decline
	Telephone	Mobile	Mobile apps	Digitalisation	Mail	Telephone
United Kingdom	75	14[a]	10[a]	14	47	15
Germany	69	15[a]	6[a]	19	39	17
France	58	22[a]	6[a]	14	50	17
Italy	33	22[a]	8	18	44	13
Spain	46	18[a]	8	18	36	16
Average EU-4	**51.5**	**19.3**[a]	**7.0**[a]	**17.2**	**42.3**	**15.7**
Average Europe	**56.2**	**18.2**[a]	**7.6**[a]	**16.6**	**43.2**	**15.6**
Standard dev.	17.0	3.8	1.7	2.4	5.7	1.7
Coef. of variation	30.3 %	20.7 %	22.0 %	14.5 %	13.2 %	10.7 %

Notes: (i) 'the speed of dominance' refers to the shortest duration in years from the technology being at (or below) 5 % of the total market to reaching 50 % (or more) of the total market; (ii) 'the speed of decline' refers to the shortest duration in years from the technology being 50 % (or more) of the total market to being 5 % (or below) of the total market; the 'coefficient of variation' is the standard deviation divided by the average (i.e., mean).

[a] The technology (e.g., mobile phone and mobile apps in certain countries) did not reach 50 % of the total market (for mobile phones, the peak ranged from 32 % for the UK and 44 % for France). For additional details, the authors can be contacted.

to anticipate the speed of decline than the speed of dominance.

Having examined the speeds of transitions of communication and energy, it is worth comparing the two. When looking at Tables 2 and 3 together, the first point to note is that there is generally an acceleration in the speed of dominance and of decline. The fact that the oil transition was faster on average than the partial natural gas transition indicates that this cannot be taken as a rule but a tendency.

Second, communication technologies appear to dominate and decline more quickly than energy sources. A note of caution is also due since the transitions did not occur at the same time. Since the first point is that the timing (or perhaps level of economic development) appears to matter, the transitions are not directly comparable. In fact, the closest comparison in time as probably the oil transition with the telephone and the oil's rise to dominance was faster than the telephone's transition. Furthermore, the mobile and mobile apps occurred in the last thirty years. Having said that, the transition to renewable energy sources is occurring at the same time, and is unquestionably slower, if it does occur. In addition, it is hard to anticipate the rise to dominance of an energy source in less than 18 years (as in the case of the telephone) and certainly not in less than 8 years (mobile apps), because of the major infrastructure changes and capital replacement that is likely to be required. Thus, as a guide to the future, the evidence suggests cautiously that communication transitions tend to be faster than energy transitions.

6.2. *Digitalisation of communication*

A broader transition that has been underway since the 1990s is the digitalisation of communication. Fig. 8 shows the rapid rise of digital technologies in the overall communication mix – here, digital technologies include mobile phones conversations and texting (here, it is assumed that all mobile phone communication was digital even though early mobile phones were analog, but they would have accounted for a small amount of the total communication), mobile phone and computer apps (such as Skype, WhatsApp) and emails. Using the criteria of a transition in Tables 2 and 3 (i.e., 5 % to 50 %), the digitalisation transition took 15 years – roughly from 1995 to 2010. The adoption rate of digital technologies continued to rise in the 2010s. In 2020, 92 % of all communication was digital.

Digitalisation of communication and information systems more generally is likely to have major implications for the economy. For instance, it is probable that the digitalisation has increased the ability of much of the workforce to work remotely during the Covid-19 pandemic. Without this digitalisation, it is possible that a larger share of the labour force would have had to commute to their workplace to continue their jobs, forcing a more difficult public health decision about whether to work and commute or not work – leading to a greater reduction in GDP. Thus, the digitalisation of communication increased the economy's resilience to the pandemic.

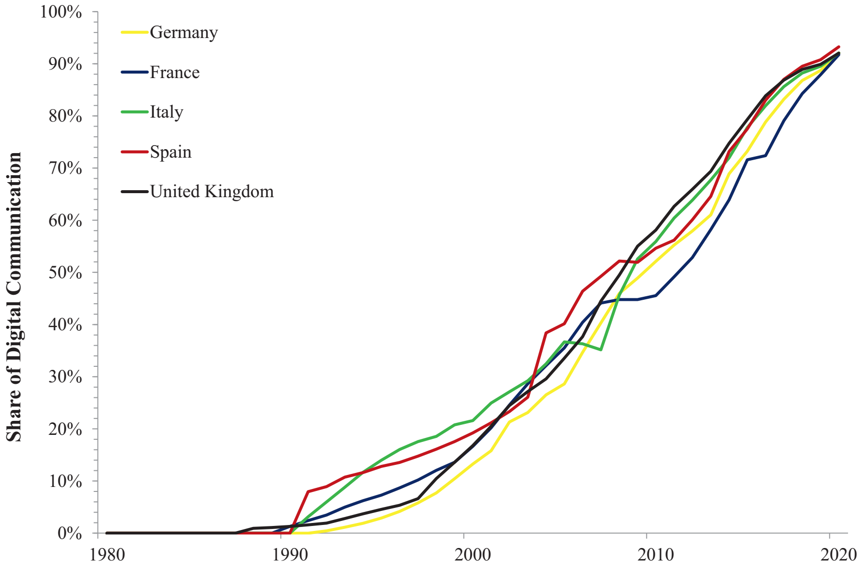

Fig. 8. The share of digital communication in the communication mix.

One important question to explore is whether the digitalisation of ICTs is associated with a reduction in energy consumed by the provision of communication and information services. Related to this question are two factors. First, per byte provided, how much energy is used? Digital technologies may require less energy than horse-drawn mail coaches, (coal-fuelled or electric-powered) train-carried letters and possibly analog telephones. Second, digital ICT has stimulated more communication and information, which in turn have increased energy consumption. Certainly, as discussed earlier in this paper, Hook et al. [44] in a meta-analysis indicate that around half of the (rigorous) studies find reductions associated with teleworking.

Nevertheless, these studies focus on the direct or local impacts of the digitalisation process. Harder to measure are the broader and longer-term transformations of the economy and society that digitalisation creates. For example, the digitalisation reduces the relative cost of teleworking encouraging the expansion of industries and services that can make use of these types of work-modes. At the same time, the pandemic has undoubtedly reduced the incentive to work and live in urban centers, thus, potentially leading to work and housing relocations, with both positive and negative impacts on transport use and associated energy consumption. Thus, the key questions are overall (i) has the digitalisation of ICT reduced or increased energy use? (ii) what has been the associated benefits (or costs) of the carbon dioxide saved (or emitted)? and, (iii) what has been the net benefits to individuals, society and the economy from the digitalisation process? These are questions beyond the scope of this paper – and warrant future research.

6.3. *The rise in communication consumption*

To offer a comparison in the levels of consumption across time and across countries, it is helpful to divide estimates by the country's population. Fig. 9 presents estimates of communication per capita by technology for the four countries. The broad trend in the uptake of specific communication technologies is similar. However, there has been substantial variation across countries. For instance, the average German and French person was sending the equivalent of nearly 50kB of letters (i.e., 12,000 words, assuming four characters per word) in 1900, while the average Italian and Spaniard was sending 15kB (i.e., less than 4000 words). Later, by 2000, the French were especially keen on the telephone conversing 1000kB per person (i.e., close to 250,000 words), while it was less than 500kB per person in the other three countries. Nevertheless, the telephone became the dominant source of communication in the 1960s–1970s for all four selected countries. In all four countries, the new communication technologies (mobile phone, texting, email, mobile apps) were adopted quickly.

Looking across time, it is clear that communication per person expanded greatly (see Fig. 10). In the mid-nineteenth century, the average 'EU' person (i.e., excluding UK) communicated 1–5 kB of information per year. This increased to 15–50 kB by 1900, to 35–90 kB in 1950, to 400–1600 by 2000 and reached 2400–3500 kB in 2020. Assuming the average word includes four characters, in 1850, the average person in the EU (and Europe) sent roughly 500 words per year using communication technologies and, in 2020, this increased to about 750,000 words per year (or 2000 words per day). Thus, individual average communication increased 1500-fold in the last 170 years, with a convergence across countries.

6.4. *Trends in communication intensity*

Fig. 11 reveals a steady rise in the communication intensity (which refers to the total amount of communication (in kB) per €(2017) of GDP) of the economy between 1850 and the 1920s. This was followed by a stabilisation and even decline in intensity after World War II. A possible explanation is that globalisation increases the role of information in an economy, and the period post-1913 until the 1960s was relatively autarkic. Since the 1960s, communication intensity has risen greatly, especially in France. This suggests that the French economy has been more informational intense than other economies (or at least that their society is more dependent on communication).

The evidence indicates that industrialisation appears to be associated

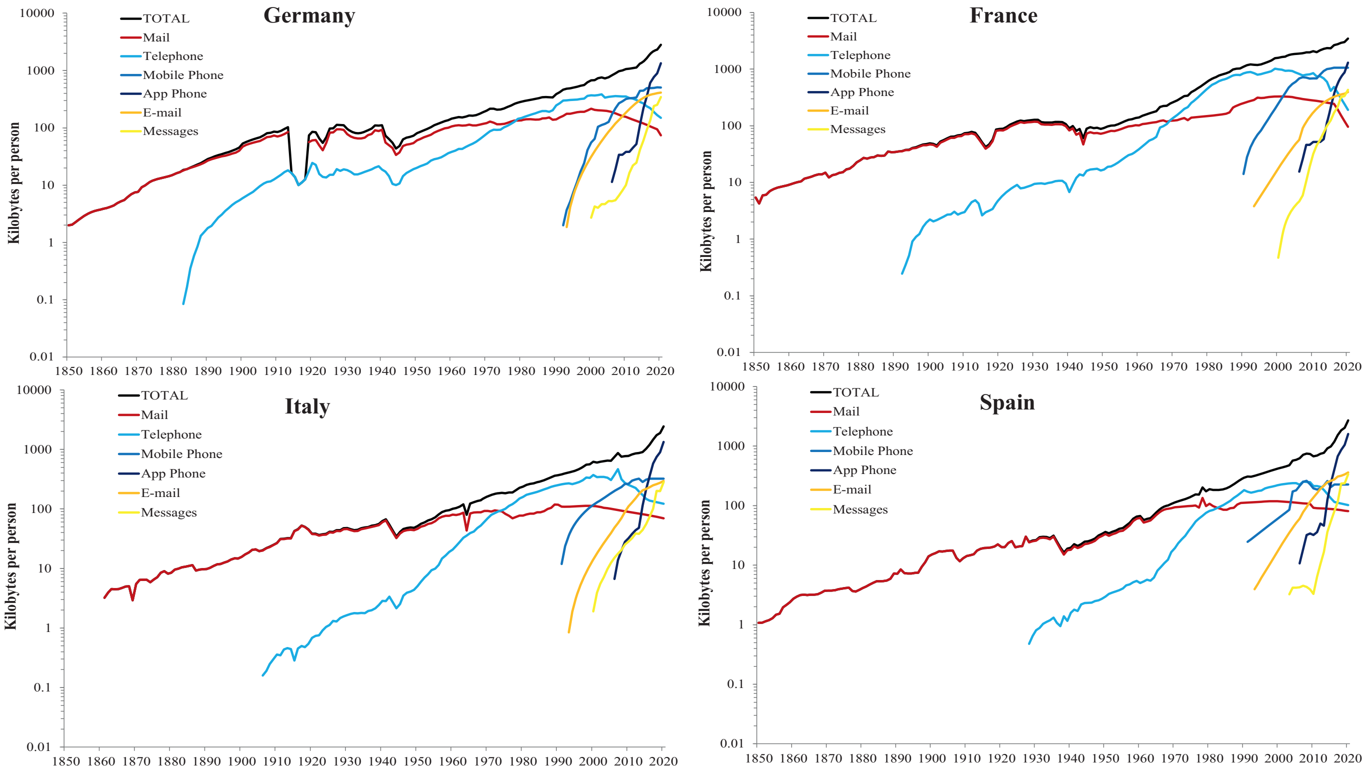

Fig. 9. Communication consumption per capita by technology in selected EU countries, 1850–2019.

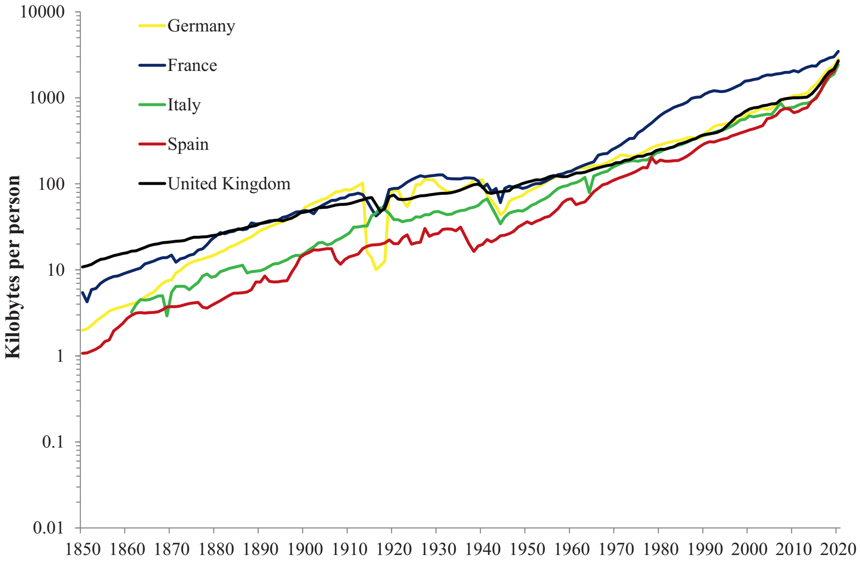

Fig. 10. Communication consumption per capita in selected European countries, 1850–2019.

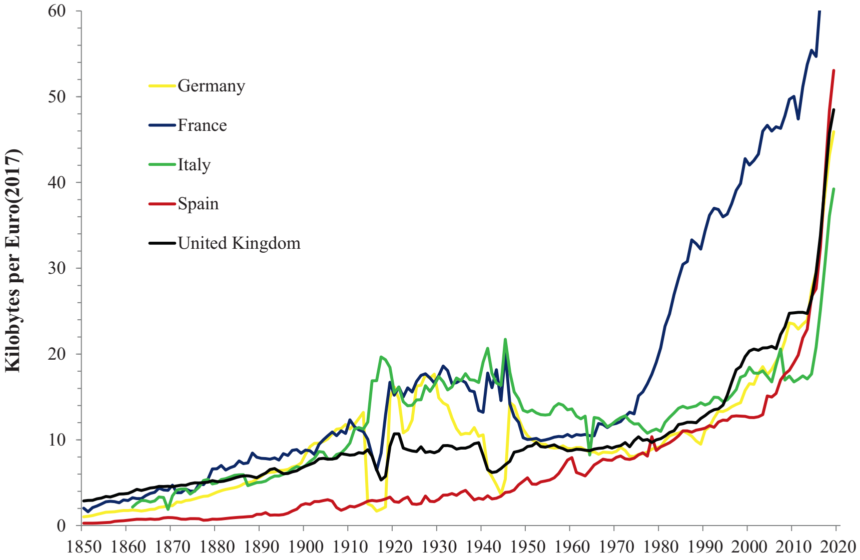

Fig. 11. Communication intensity in selected European countries, 1850–2019.

with rising communication intensity. Certainly, Spreng [33] noted that heavy industries used considerable amounts of information and that lighter industries required even more information. Furthermore, industrial activities and trade require a high degree of coordination and, therefore, depends on communication. Hidalgo and Hausmann [31] explained how increased communication and information reflects a rising complexity of the economy. According to their analysis, greater and better arranged information enables higher value and more complex goods and services to be supplied. In other words, the theory and evidence indicate that the value of the economy is increasingly dependent on informational content (and communication offers our first evidence of this tendency).

One of the challenges associated with analysing intensity trends is identifying the separate role of economic development (e.g., industrialisation, post-industrial development) and technological diffusion. This is especially challenging as there may be a causality between phases of economic expansion and technological diffusion. Future research should seek to identify causal impact of these different channels on communication (or information) intensity.

7. The relationship between energy and communication intensity

In this section, energy intensity and communication intensity will be compared across countries. These indicators offer evidence on the extent to which an economy is becoming more energy or communication intensive. It is worth remembering that the communication intensity can be used as an indicator of the broader information and possibly even the knowledge intensity of the economy. This is of interest as there is considerable debate about the information or knowledge economy. Thus, this section offers evidence on the timing of the growth of the information or knowledge economy.

The ‘knowledge economy’ refers to an economic system structured around four key pillars: the economic and institutional regime, education and skills, information and communication infrastructure and the innovation system [98,99]. Re-structuring the economy towards the ‘knowledge economy’ has been seen as an opportunity to create a new era of economic prosperity and achieve fundamental changes to the way the future economy might work [2,100]. A conduit for stimulating the knowledge economy is to drive down its costs, including the costs of communication, information dissemination and storage, computing and knowledge production. The most effective way to achieve these cost reductions is through digitalisation of these processes. Thus, digitalisation stands as the central strategy to move towards the ‘knowledge economy’ and a new era of economic development.

Fig. 12 compares the energy intensity and communication intensity in France, Germany, Italy and Spain - note that the scales are different for each country. For Germany and France, the intensities trends follow similar paths between 1850 and the 1960s (i.e., rising up to 1929 and then modestly declining until the 1960s) and then, from the 1970s, the energy and communication intensities diverge. Italy followed a similar path, except that its industrialisation and its rise in energy intensity started in the early 1900s. From 1929, both intensities decline in Germany, France and Italy. However, in the 1970s, energy intensity continues to decline, whereas communication intensity starts to rise. Although Spain appears to have followed a slightly different course, the main difference is a delay in the industrialisation process, the associated rise in intensities trends, the decline in energy intensity which occurred in the 1980s and the rise in communication intensity which has been rising since the 1940s. In sum, for most of countries, there are two important findings: first, the coevolution and then divergence of intensities, and, second, the existence of critical junctures.

The first observation is the existence of a co-evolution of energy and communication intensities. This suggests a possible complementarity relationship. This is compatible with Spreng's [33] finding that classical industrial activities require energy, labour and information. Certainly, the process of industrialisation tends to stimulate an increase in energy intensity. Indeed, energy industries have been part of broader industrial clusters, in which complementarities with other technologies and industries were pivotal in their industrial development [22,24]. It also appears to have been associated with an increase in communication intensity, no doubt due to the demands for coordination. This was then followed by a divergence between energy and communication. Again, this holds with Spreng's [33] result that high-tech industries depend principally on information. Certainly, a structural transformation towards high-tech industries that are predominantly information-guided would lead to the observed divergence. A crucial question is whether the trends (or parts of the trends) are (i) causally connected (uni-directional or bi-causal), (ii) confounded by another factor (e.g., economic development, technological innovation) that influences both intensities or (iii) just a spurious correlation? This is not a question that can be answered in this paper, but it is an invitation to address this question [5,101].

Also noted was the existence of critical junctures. The three critical junctures are (i) the beginning of industrialisation in each country, (ii) the crash of 1929, and (iii) the shocks of the 1970s. First, the process of industrialisation triggered in each economy an increase in both energy intensity and communication intensity, in-line with Spreng's [33] evidence on heavy industries requiring energy and information. Second, it appears that there was a culmination of energy and communication intensities which ended after the Great Crash in 1929 in France and Germany, leading into the Great Depression. This is precisely what Perez [102,103] argues in her long run analyses of the relationship between financial markets and technological revolutions. She noticed phases of two to three decades of financial development, which triggers technological innovation and diffusion, culminating in a major bubble that inevitably collapses. The Great Crash could thus be considered a “point of no return”, a turning point not only in the economic, financial and political history of these countries but also of their energy history; indeed, it seems be a ‘turning point’ towards a less energy intensive economy.

Third, in the 1970s, a new critical juncture appeared. The higher price of oil and other energy sources triggered a major shift in energy consumption and energy policy. The ensuing crisis may well have encouraged these European economies to invest in high-tech industries, creating the structural transformation towards a higher information and lower energy economy.

To compare the two trends directly, Fig. 13 presents the ratio of the communication intensity to the energy intensity. The evidence shows

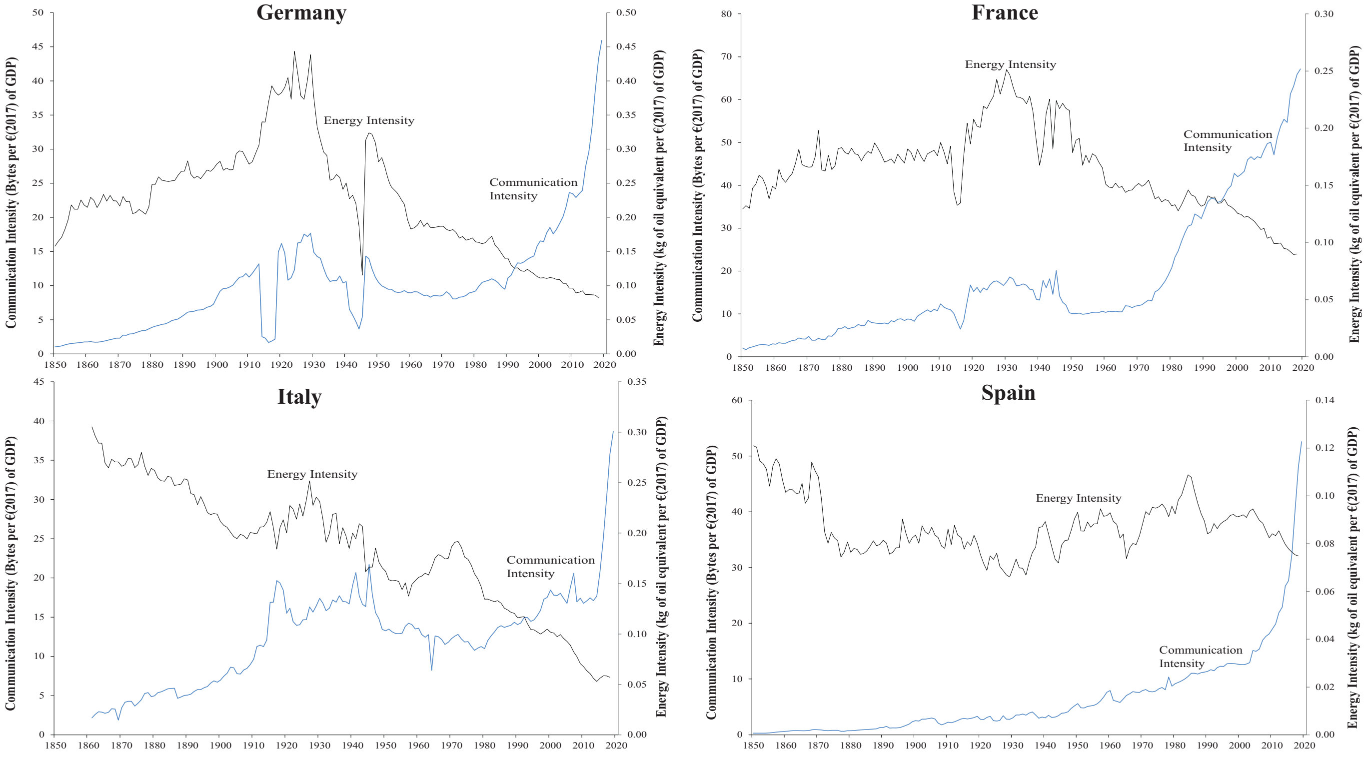

Fig. 12. Communication intensity and energy intensity in selected European countries, 1850–2019.

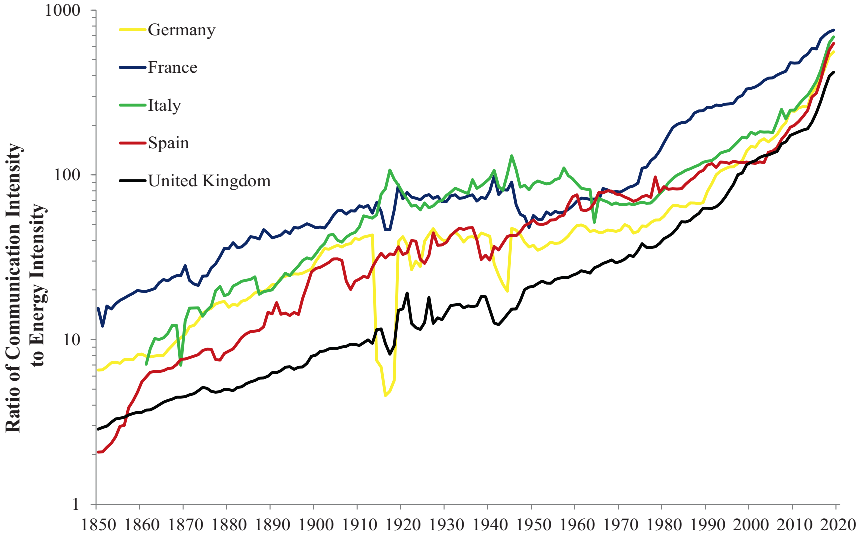

Fig. 13. The ratio of communication intensity to energy intensity in selected European countries, 1850–2019.

that there has been a near-continuous increase in the communication-to-energy ratio. This is in-line with Chen's [35] statement that there has been a long run substitution of information for energy and a broader dematerialisation of the economy. As expected by the decline of heavy industries and the expansion of high-tech industries, the rate of dematerialisation has accelerated since the 1970s and the Oil Shocks.

It is interesting to note that the ratio falls during wars. This drop was pronounced in Germany, France and the UK. It was oddly reversed in Italy during the first World War. The Spanish experience offers support for the hypothesis that wars affect the ratio – Spain remained neutral in both wars and the ratio appears to be unaffected by the periods 1914–18 and 1939–45, however, it was affected in the period 1936–39, when it experienced a civil war. An explanation could be that, during wars, while industrial production and especially war-related activities must continue whereas communication becomes less essential, except for strategic purposes.

Finally, it is tempting to predict that the 2007–2008 financial crisis and the Covid-19 crisis will act similar critical junctures and even 'turning points' in the transformation of the global economy. Evidently, it is highly speculative at this point, but it could be imagined that for energy, the latest crisis could possibly mark a decisive move towards renewables or in favour of fossil fuels (given much lower energy consumption in 2020, leading to even negative crude oil prices during the peak of the crisis in April 2020). In the end, this could lead to a radical digitalisation of energy production and consumption. This could have a long-term effect of enabling much higher energy consumption levels. However, higher energy consumption levels would go hand-in-hand with lower CO_2-intensity, given the use of renewables and the international commitment towards a more climate-neutral economy [7]. Nevertheless, this should not be confused with a direct more environment-friendly production of energy (given the resource-intensity of producing and recycling batteries and other involved production materials).

In the case of communication, Covid-19 would not be a 'turning point', but rather an acceleration point (given the partial replacement of physical meetings by online videoconferences, email and chat communication, etc.) towards much higher communication levels. Certainly, the global economic shutdown triggered by Covid-19 has encouraged a shift towards digital communication and information services [104].

8. Conclusion

This paper investigated the changing structure of the economy and the speed of transitions underlying this changing economic structure in order to better understand how twin transitions of decarbonisation and digitalisation might unfold.

The first aim of the paper was to analyse the long run trends in energy intensity and communication intensity in major European economies since 1850. The evidence showed that European economies experienced a coevolution of energy and communication intensities, in which both increased during their industrialisation phase, which was associated with heavy industries. This co-evolution ended with the Great Crash of 1929, which was a critical juncture for economic activity, financial markets, technological development and energy consumption. For a number of economies, almost 50 years passed between the end of co-evolution period in 1929 and the beginning of the divergence period in the 1970s. The 'in between' period was a time of crisis leading to the Great Depression of the 1930s and World War II, as well as a return to greater autarky. Nevertheless, the post-World War Golden Age was an opportunity for rebuilding and may have set the foundations for the subsequent transformations. The Oil Shocks of the 1970s ushered-in an era of divergence in the energy and communication intensities, which was associated with the development of high tech and ICT.

This analysis helps to isolate the timing and nature of structural transformations of economies. Looking forward, a continued decline in energy intensity and dematerialisation of European economies is likely over the next few decades – although this is likely to depend on further imports of energy-intensive goods [105–107] and may not be the case in developing economies [101]. This dematerialisation is intensified by advanced economies shifting away from heavy and energy-intensive industries towards lighter and information-rich services, and energy scarcity pressures continuing with a transition to low carbon energy sources. The role of critical junctures in re-directing the economic system is especially relevant at present, given that we face the largest crisis since the 1930s, and one can speculate that there is the possibility that 2020 was a year in which European economies were pushed towards a new phase of restructuring.

The second aim of the paper was to analyse the speed of historical energy transitions and communication technology transitions. The evidence offers a few key insights. First, the evidence suggests tentatively that transitions accelerate with economic development, which is promising. Less promising is the tendency of declines away from the old energy sources to be slow, hinting that the transition away from high-carbon energy sources will take many decades, leaving a 'long tail' of carbon dioxide emissions.

Second, the demand for certain services is harder to decarbonise, and the transition to low carbon energy sources can only begin once viable low-carbon substitutes exist. The implication is low carbon power is leading the way; if the transition is rapid by historical standards, then the transition to low carbon power could be completed within two decades. If electric vehicles take-off and renewable energy sources are able to meet the additional electricity requirements, then a substantial share of the transport sector could be low-carbon within 30 years, based on past transitions. Similarly, if electric space and water heating become popular, then three decades is realistic. Nevertheless, certain hard-to-decarbonise transport services (such as heavy goods vehicles, water-based freight and airplanes) and heating (including industrial high-temperature processes) may delay the completion of the transition to low carbon European economies by several more decades. Thus, the full low carbon transition in Europe might be possible by 2100 with the current economic and political momentum.

Third, the evidence indicates that the communication transitions, at similar levels of economic development, tend to be substantially faster than energy transitions (see Fig. 14). In particular, the digitalisation transition took 15 years to reach dominance (i.e., over 50 %) and 25 years to reach near-ubiquity (i.e., over 90 %). This suggests that there may be fundamental differences between communication and energy markets (most probably including the lifetime and turnover of the technologies and the structure of the supply chains). This latter highlights a potential challenge about aligning low carbon energy sources with ICT, as Fouquet [3] recommended. Communication and energy markets may operate and transform at different speeds. Thus, it becomes crucial to consider how to accelerate low carbon energy transitions to align them with changes underway associated with ICT. This may help to achieve the twin transition of the decarbonisation and digitalisation of economies.

In particular, the digitalisation transition shows that, with the correct incentives, markets can achieve rapid transitions [90]. Governments will most probably need to continue to regulate certain energy markets to create the correct incentives. Yet, the take-off of renewable energy sources indicates that when incentives are introduced, they do tend to stimulate innovation and transitions [108–110].

In addition, the discussion has hinted at potential benefits from transitions. Most saliently, the economic response to the Covid-19 pandemic showed that the digitalisation of communication increased the economy's resilience to shocks - by enabling a larger share of the workforce to work remotely compared with the potential for such adaptive behaviour pre-1990 and the digital era. Indeed, this flexibility is offering an opportunity to shift behaviour following Covid-19 restrictions [45]. In a broader context, Fouquet [88] estimated the net benefits to the economy and society from past energy transitions, which were especially large associated with transport and lighting energy transitions. While it is hard to anticipate the scale of the potential impacts of a transition beforehand [5], it is probable that the avoided economic and social costs associated with a decarbonisation transition will be very large and should be a central governmental priority - along with the continuation of the digitalisation transition, which is likely to include AI and big data, driving the knowledge economy to new heights.

Crucially, unchecked, the digitalisation process will advance without decarbonising. This imbalance in twin transitions creates a need to formulate policies that enable the lagging industry (i.e., low carbon energy) to develop [111]. These policies must be conscious of the risk of powerful vested interests holding back the development of the low carbon industry [112]. Also, this imbalance suggests a lack of synergies between ICT and low carbon industries. In turn, this absence implies a need to promote linkages and complementarities between the leading industry (i.e., ICT) and the following industry (i.e., the low carbon industry). Ultimately, policies focussed on developing synergies will increase the likelihood of successful twin transitions.

Finally, twin transitions will be crucial in minimising the environmental impact of economic growth. Here, the emphasis has been on the structure of the economies, rather than on their scale. This focus risks detracting from the absolute environmental impact of these economies. An important question, beyond the scope of this paper, is whether a shift in the structure of individual advanced economies will be sufficient to avoid a climate crisis – especially if these economies depend on importing energy-intensively produced goods [105–107]. An even bigger question is whether the eventual shift in the structure of the global economy will be sufficient to avoid a climate crisis. Key to answering this question is whether economic growth [113–115] is the problem or the solution to the climate crisis.

Declaration of competing interest

Roger Fouquet

My research related to this project was funded by the European Commission's Joint Research Centre (JRC) for the analysis, and the UK Research and Innovation through the Centre for Research into Energy Demand Solutions (CREDS), grant reference number EP/R 035288/1, for the data collection, as well as support from

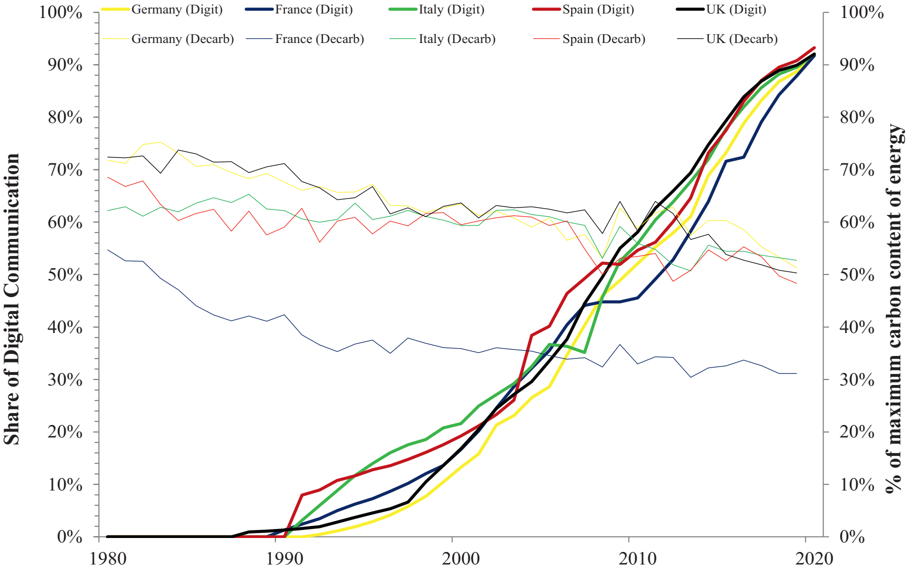

Fig. 14. Twin transitions: the digitalisation and decarbonisation of selected European economies.

the Grantham Research Institute on Climate Change and the Environment, at the London School of Economics, and the ESRC Centre for Climate Change Economics and Policy (CCCEP) grant reference number ES/R009708/1.

I have not received any additional financial support from any interested parties.

I do not hold paid or unpaid positions in any relevant entities.

This paper does not involve the collection of data on human subjects and I therefore have not obtained Institutional Review Board approval.

Ralph Hippe

My research related to this project was not funded.

I have not received any additional financial support from any interested parties.

I do not hold paid or unpaid positions in any relevant entities.

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Acknowledgments

We would like to thank Claude Diebolt, the editor, Benjamin Sovacool, and three anonymous referees for their valuable comments. We gratefully acknowledge support from the European Commission's Joint Research Centre (JRC) for the analysis, and the UK Research and Innovation through the Centre for Research into Energy Demand Solutions (CREDS), grant reference number EP/R 035288/1, for the data collection, as well as support from the Grantham Research Institute on Climate Change and the Environment, at the London School of Economics, and the ESRC Centre for Climate Change Economics and Policy (CCCEP) grant reference number ES/R009708/1. We have not received any additional financial support from any interested parties, and do not hold paid or unpaid positions in any relevant entities. The substantial part of the work was conducted while Ralph Hippe was a scientific officer at the JRC Human Capital and Employment Unit.

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