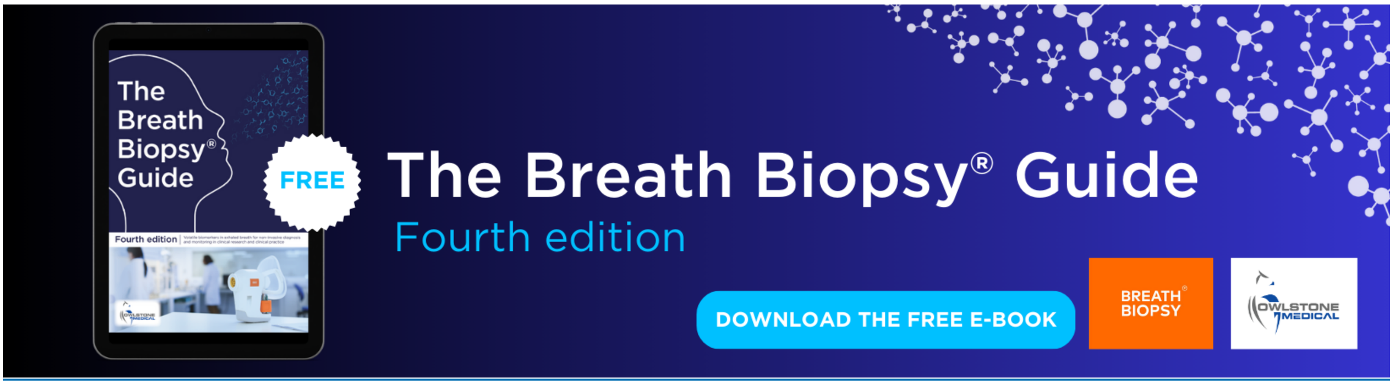
ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The digitalisation, dematerialisation and decarbonisation of the global economy in historical perspective: the relationship between energy and information since 1850

To cite this article: Roger Fouquet 2024 *Environ. Res. Lett.* **19** 014043



ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
12 June 2023

REVISED
16 November 2023

ACCEPTED FOR PUBLICATION
1 December 2023

PUBLISHED
13 December 2023

LETTER

The digitalisation, dematerialisation and decarbonisation of the global economy in historical perspective: the relationship between energy and information since 1850

Roger Fouquet

Energy Studies Institute, National University of Singapore (NUS), Singapore 119620, Singapore
Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science (LSE), London WC2A 3PH, United Kingdom

E-mail: fouquet@nus.edu.sg

Keywords: digitalization, decarbonization, global economy, historical, energy intensity, information and communication technologies (ICT)

Supplementary material for this article is available online

Abstract

To better understand the processes of digitalisation, dematerialisation and decarbonisation, this paper examines the relationship between energy and information for the global economy since 1850. It presents the long run trends in energy intensity and communication intensity, as a proxy for total information intensity. The evidence suggests that, relative to GDP, global economic production has been reducing energy and increasing information use since 1913. The analysis indicates that it initially required little information to replace energy in production and that the ability to substitute away from energy and towards information has been declining. The result implies that the global economy is now reducing energy and increasing information at a substitution rate of 0.2 kB per kWh of conserved energy or 0.8 GB per tonne of carbon dioxide mitigated. As the price ratio of energy to information is currently higher than this marginal rate of substitution, there are incentives to further substitute information for energy. However, one conclusion is that (without the long run escalation of carbon prices) substitution away from energy and towards information is likely to cease within the next few decades and, beyond that, digitalisation will play a declining role in the decarbonisation process.

1. Introduction

The global economy is in the middle of a structural transformation involving digitalisation, dematerialisation and decarbonisation (Grübler 1998 p 281, Nakicenovic *et al* 2021, Creutzig *et al* 2022). These transformations are associated with transitions in the use of energy and information to generate output and wealth. A pivotal question to ask is: will digitalisation play a role in the global decarbonisation effort?

This question can be examined by analysing the long run dynamics of the relationship between energy and information, which underlie the process of dematerialisation, decarbonisation and digitalisation (Lange *et al* 2020). The role of energy in the history of economic development has been investigated in detail (Cipolla 1962, Allen 2009, Kander *et al* 2013, Otojanov *et al* 2023). Grübler (1998 p 277) reminds us that 'there is no unique and universal 'law' that specifies an exact relationship between economic growth and energy use.' Similarly, the historical development of information and communication technologies (ICT) and knowledge has been charted (Mokyr 2002, Dudley 2008, Dittmar 2011, Hidalgo 2015). Hidalgo and Hausmann (2009) have proposed that economic development results from increasing and re-structuring information in order to produce higher value and more complex products. Despite the fundamental role energy and information have played in global economic development, they have rarely been analysed together.

Energy and information (or knowledge[1]) can be seen as two factors of production for generating economic output. Although mainstream economic analysis tends to use labour and capital as the factors of production, labour can be measured in terms of workers' physical effort or energy, human capital or workers' skills and know-how effectively incorporates stored information and knowledge, and physical capital can be seen as embodied technical information or knowledge. Thus, an analysis of the factors of production in historical economic development could focus on the substitutability and complementarity of energy and information (Spreng 1993, 2015, Chen 1994).

Each ICT wave has offered opportunities to replace energy in production (Williams *et al* 2022). Most recently, enhanced information management systems have improved the coordination of energy production, harnessing big data. Digital sensors and smart meters have emerged, empowering real-time energy monitoring and providing tools for demand-side management. ICT facilitates the integration of decentralized energy sources like solar panels into local energy markets via blockchain technology. In parallel, smart meters can enable peak power reductions and behavioural changes that lead to energy savings (Fouquet 2017). Thus, information in the broad sense—including investments in knowledge (e.g. patents, software), human capital and education, as well as reading material and audio-visual information—has great potential to replace energy in production processes (Hippe and Fouquet 2018).

Grübler (1990 p 256, 1998 p 322) started the empirical analysis by exploring the long run trend in communication in France, comparing it to the trend in transport services, and finding a complementary relationship, with both trends rising. Machado and Miller (1997) observed that the US economy became less energy intensive and more information intensive between the 1960s and 1980s, proposing a substitution between the factors of production[2]. Fouquet and Hippe (2019) used historical statistics on the consumption of different ICT to produce a single metric of communication (in Terabytes) and an indicator of information intensity of the economy, and compared it to the trend in energy intensity. Fouquet and Hippe (2022) indicated that, for five European economies, a coevolution of energy and communication intensities existed during the early phase of industrialisation, followed by a divergence associated with the development of high tech and ICT.

The purpose of this paper is to examine the relationship between energy and information (as proxied by communication) of the global economy (as well as an international panel of economies from each global region) since 1850. Analysing the relationship between energy and information requires the separation of the two channels of impact: first, there is the substitution away from energy and towards information, and, second, there is the role of information in generating economic growth, which stimulates the demand for energy (and emissions). This paper focuses on the first channel and isolates it by using energy intensity and communication intensity, which implies the economic growth channel (i.e. GDP) is controlled for in the analysis. By using this approach, *this paper offers the first analysis of the historical substitution away from energy and towards information of the global economy*.

This analysis can reveal the rate of substitution. That is, how many kB are required to replace one kWh of energy and mitigate one tonne of carbon dioxide emissions? It can also indicate whether there is a trend in the rate of substitution. By using fundamental tools of economic analysis (i.e., isoquants and isocost curves), it is possible to formulate an explanation for the trend. This trend and framework enable projections to be made about the potential for the global economy to continue substituting away from energy and towards information in the future. Hence, *this paper offers a structured understanding of the role digitalisation is likely to play in the global decarbonisation effort*.

Before embarking on this analysis, two clarifications are needed. First, due to data limitations, information is proxied by a specific type of information, communication. The implication of using this proxy is discussed in the penultimate section. The evidence indicates that overall information may not have increased as much as communication, yet

[1] Ackoff (1989) defines and clarifies the distinction between data, information, knowledge, understanding and wisdom. Data can be defined as symbols representing the properties of objects and events. They are observable, but are not necessarily in a usable format. Information is data in a useful format (Hidalgo 2015). Information systems generate, store, retrieve and process data. Information can be converted into knowledge and understanding through analytical and synthetic thinking. Information answers questions that begin with such words as who, what, when, where, and how many; knowledge offers instructions as answers to how-to questions; understanding provides explanations, answering why questions (Ackoff 1989). This creates a 'knowledge pyramid' where data is transformed into information to knowledge, understanding and potentially wisdom through the use of careful judgement (Hippe and Fouquet 2018). In this paper, 'information' will be the term used, although the differences in the relationship between energy and these distinct terms deserves further consideration.

[2] It is important to note that this evidence does not take account of imported goods and deals only with territorial energy use. There may well be a correlation between increases in information intensity and imports of energy-intensive goods and warrants further research. Even when embodied energy in imported goods is accounted for, it is not fully accounted for since estimates tend to only include the last stage of production, not the energy used to build capital goods (Andrieu *et al* 2022). Equally important in the analysis is the indicator used to measure the size of economic activity, such as GDP, as the choice of the variable can alter the results (Semieniuk 2024).

communication intensity and broader information intensity followed similar trends. Thus, the analysis using communication as a proxy for overall information appears to be broadly valid.

Second, while the substitution channel of impact has been isolated in the analysis, the evidence cannot identify a causal relationship. This would require a deeper statistical analysis based on quasi-experimental conditions, which is not possible with the data. Nevertheless, this paper offers a first analysis of the relationship, which will hopefully inspire future research to identify causal impacts.

The next section of the paper presents the global trends in energy intensity and communication intensity, and examines the relationship between energy and communication by constructing an isoquant for the global economy. This isoquant reveals the marginal rate of technical substitution (MRTS). In section 3, this is compared with the isocost curve via the ratio of the energy and communication prices. Section 4 repeats the isoquant exercise for twenty economies around the world (in Europe, North and South America, Asia–Pacific and Africa)—five economies from each region are selected on the basis of the size of their GDP. Section 5 discusses some limitations of this exercise, as briefly highlighted above. Section 6 offers a conclusion about the long run role of digitalisation in the global decarbonisation effort.

2. The rate of substitution of information for energy in the global economy

The energy intensity (i.e. energy use relative to GDP) of the global economy has been declining for the last one hundred years. Figure 1 presents primary energy consumption[3] in kWh per $ of GDP (in 2020 dollars). In 2020, the global energy intensity was a third of the level in 1920. The industrialisation of Western economies during the nineteenth and early twentieth centuries was very energy intensive. However, since World War I, energy consumption has risen less rapidly than economic activity. For instance, since 1950, while energy use rose six-fold, the global economy grew thirteen-fold.

Meanwhile, global communication consumption increased 112-fold since 1950, and nearly 20 000-fold since 1850—averaging more than 6% per year (see figure 2). These estimates are based on a method developed in Fouquet and Hippe (2019, 2022), and are discussed in more detail in the supplementary material. Given the communication consumption grew faster than GDP, communication intensity has increased since 1850, most notably between 1890 and 1910 and since the mid-1970s (see figure 2).

[3] The estimates of primary energy consumption include biomass and animal draft (Malanima 2020).

Figure 3 suggests that the global economy followed a co-evolution of energy and communication up to 1913, then a phase of rapid substitution away from energy and gradually towards communication, followed by a phase of gradual substitution away from energy and rapid shift towards communication[4]. This result is consistent with the long run relationship between energy and communication observed in a number of European economies (Fouquet and Hippe 2022).

Figure 3 represents an isoquant curve for the global economy. An isoquant curve indicates the quantities of factors of production used while keeping production constant. Here, a constant production is assumed by using energy intensities and communication intensities, rather than absolute values of energy and information inputs. The tangent or slope of the isoquant curve reveals the MRTS between the two factors of production. Although the results should be interpreted with caution given the strong assumptions (to be discussed below), from 1913, the data shows a nearly ‘textbook isoquant’ with declining MRTS between energy and information.

Figure 4 presents (in black) the trend in the MRTS. Despite some volatility, at low levels of information (1913–1949), the rate of substitution was very low (on average, 0.0002 kB per kWh); as information increased (1950–1987), the marginal rate of substitution rose (on average, 0.009 kB per kWh); as information increased further, so did the marginal rate of substitution (on average, 0.08 kB per kWh); and, finally, at high levels of information (2008–2015), the marginal rate of substitution was also relatively high (on average, 0.2 kB per kWh). Thus, on average across the global economy, it initially required little information to replace energy in production, however, the ability to generate output using information rather than energy has been declining and, now, requires greater quantities of information to conserve energy.

3. Price incentives for digitalisation to decarbonise the global economy

This global substitution might reflect changing price incentives. The assumption in economic analysis is that the equilibrium mix of two factors of production

[4] As mentioned in the introduction, this assumes that energy and information are factors of production. Here, information is proxied by communication as one-to-one information provision. Also, there is considerable discussion about the complementarity and substitutability of energy and information, and how these factors of production should be represented in the production function (Spreng 1993, Chen 1994). Thus, here, the assumption is that both energy and information are exhaustible, divisible, substitutable, complementary and independent factors of production (see Fouquet and Hippe 2022 for further discussion on the assumptions).

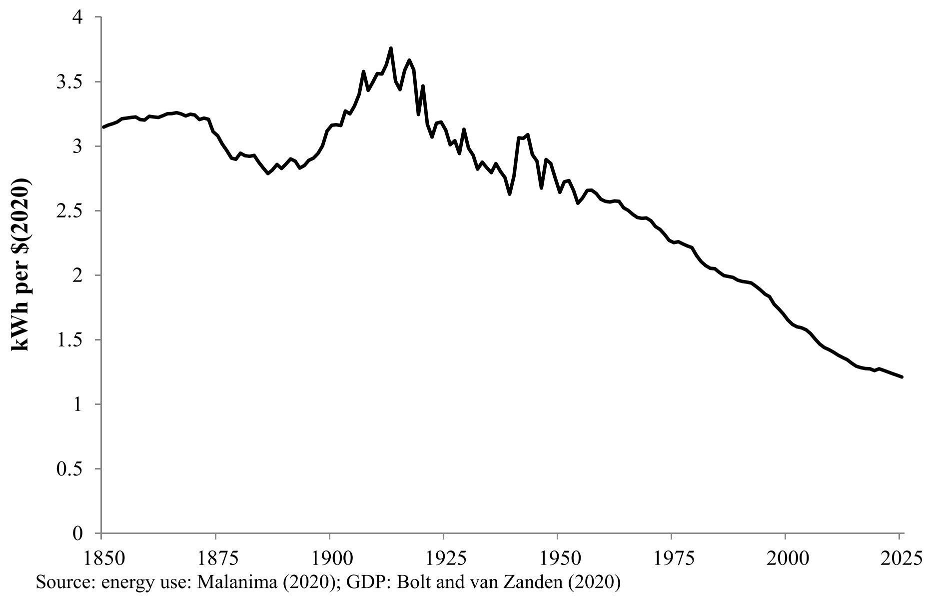


Figure 1. Global energy intensity, 1850–2018.

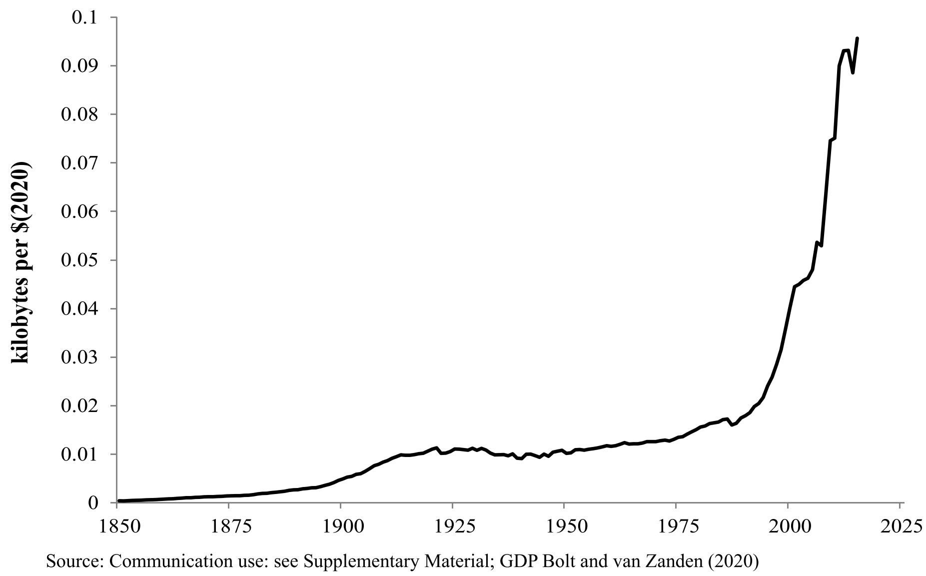


Figure 2. Global communication intensity, 1850–2015.

is determined by the point of tangency between the isoquant curve (i.e. the MRTS) and the price ratio of the two factors of production. Thus, a moving equilibrium for the global economy might be the result of a rising price of energy relative to information.

With price data for the United Kingdom (Fouquet 2011) as a proxy for the global average, it is possible to examine the incentives to substitute between energy and information. Figure 4 shows (in red) that there was a gradual decline in the price of energy relative to information (to $0.05 per kB per $1 per kWh) with the introduction of the telegraph and the telephone, which were faster and better quality but more expensive forms of communication per kilobyte. Afterwards, it stayed broadly constant until the 1950s, when the trend in the price ratio started increasing gradually. The rise in the price ratio accelerated due to the 1970s Oil Shocks. Since 2000, the ratio has increased about eight-fold (of $0.5 kilobyte per kWh) with advent of new ICT.

Figure 4 also indicates that (apart from the late 1990s) the price ratio of energy to information was higher than the MRTS from information to energy. Here, the MRTS indicates the benefits of producing using an additional unit of energy rather than information (e.g., as mentioned above, in 1973, it was averaging 0.009 kB per kWh). The price ratio indicates the cost of producing using an additional unit of energy rather than information (e.g. in 1973, it was 0.05 kB per kWh). The costs of using additional energy

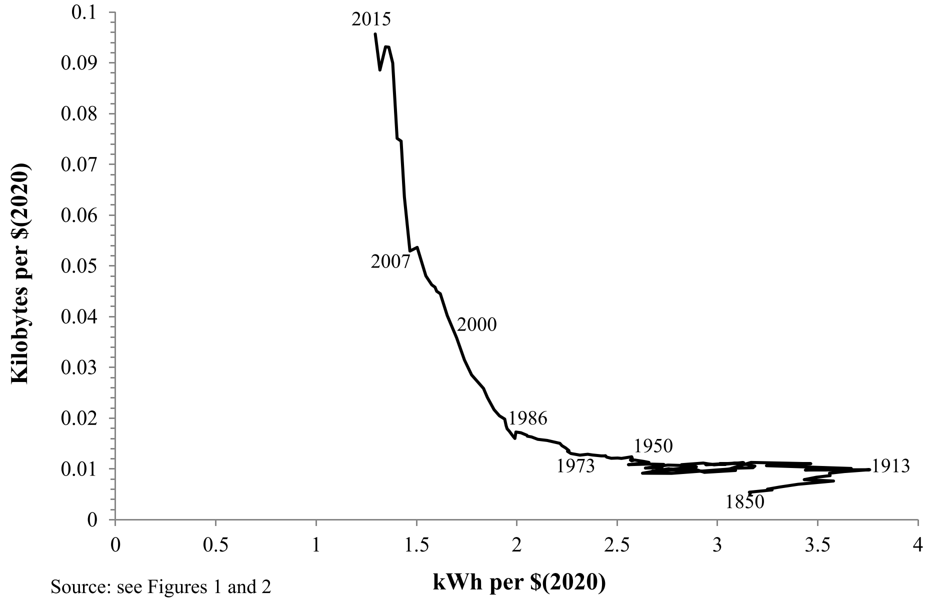


Figure 3. Global communication intensity relative to energy intensity, 1850–2015.

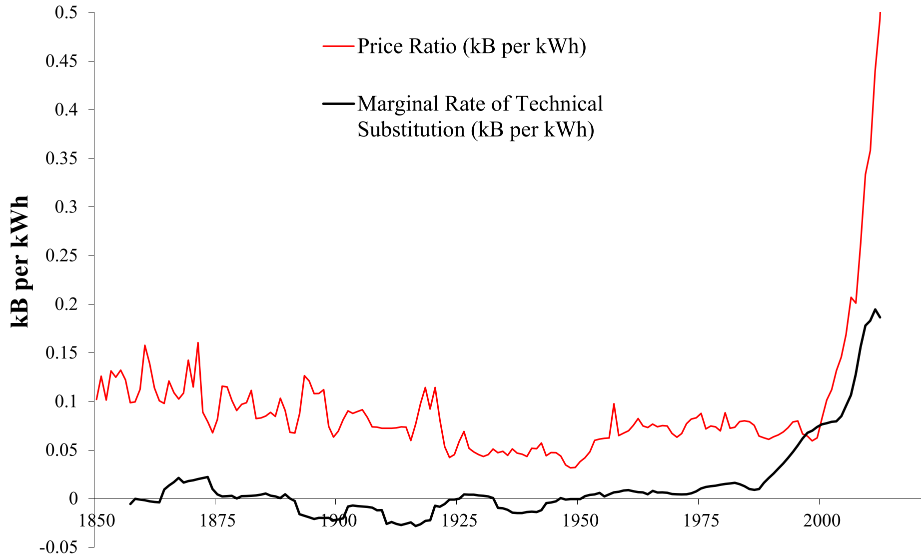


Figure 4. The marginal rate of technical substitution (MRTS) of energy for communication and the energy-communication price ratio, 1850–2015.

rather than information were almost always greater than the benefits. The only exception was in the 1990s, when the price of energy fell, weakening the incentives to replace energy with information. Thus, there was nearly always an incentive to use less energy and more information in production.

Crucially, the current price ratio (of $0.5 kB per kWh) is higher than the MRTS (of 0.2 kB per kWh). This implies that there is likely to be further substitution away from energy and towards information. Looking ahead, as long as the price ratio (of energy to information) is greater than the MRTS, the global economy will have the incentive to substitute away from energy towards information.

Being interested in climate stability, this relationship can be presented in terms of carbon dioxide mitigated. The marginal rate of substitution was 0.002 GB per tonne of CO_2 reduced between 1913 and 1949, 0.05 GB per tonne of CO_2 mitigated between 1950 and 1986, 0.36 GB per tonne of CO_2 mitigated between 1987 and 2007, and 0.82 GB per tonne of CO_2 mitigated between 2008 and 2015 [5].

[5] The carbon dioxide emissions are calculated by multiplying the primary consumption from each energy source in Malanima (2020) by the carbon coefficient for each energy source (BEIS 2020). Thus, for each year, a one kWh reduction in global energy consumption is associated with a specific reduction in carbon dioxide emissions, reflecting the global economy's carbon intensity.

The idea that less than 1 GB of information would be required to mitigate one tonne of CO_2 seems a cheap trade-off. Afterall, one tonne of CO_2 costs around $100 per tonne in the EU in 2023 (Trading Economics 2023). However, the implication of the analysis is that, given where the global economy is on the isoquant, it will require increasing investments of information to conserve energy and reduce carbon dioxide emissions. Furthermore, the incentive to continue up the global isoquant curve (in figure 3) will depend on further reductions in the price of information relative to energy. This will depend on continuously cheaper ICT and higher energy prices. Rising carbon prices in the long run will be one way to maintain the incentives for economies to shift towards ICT to reduce CO_2 emissions.

4. Country-level relationships between energy intensity and communication intensity

Despite the distinct pattern at the global level, it is worth exploring variations across regions and countries. Here a selection of economies from Europe, North and South America, Asian–Pacific region and Africa is examined since 1850. Five countries are chosen from each region on the basis of the size of their GDP (Bolt and van Zanden 2020). Supplementary material outlines how the energy intensity and communication intensity trends are estimated.

The national-level data offers a more nuanced picture of the relationship between energy and communication intensity. As expected given their key role in driving global economic change in the nineteenth and first half of the twentieth centuries, results for the European economies are quite similar to the global trend, with a positive relationship followed by a negative one, as energy intensities declined and communication intensities rose (see figure 5(a)). The high energy intensities of early industrialisers with abundant coal reserves, the United Kingdom and Germany, imply the change in the relationship between energy and information was more pronounced in those economies.

The USA and Canada saw only declines in energy intensities which implies they experienced a substitution towards information for the whole period (see figure 5(b)). For Latin American economies, the relationship is less notable because of the much smaller variation in energy intensity. However, a close look shows that there is a positive relationship between energy and communication intensities. This might reflect the co-evolution of the energy and communication industries. Alternatively, it might indicate that energy intensity is closely related to industrialisation, whereas communication intensity is more related to technological development.

The Asia–Pacific economies experienced a degree of switching from the positive then negative relationship (see figure 5(c)). However, the relationship is far less clear with a large number of data points at low levels of communication intensity. Japan and Australia appear to be gravitating towards an equilibrium level of energy and communication intensities. Instead, for China, Indonesia and India, the most salient observation is a lack of relationship with little variation in energy intensities and large increases in communication intensities.

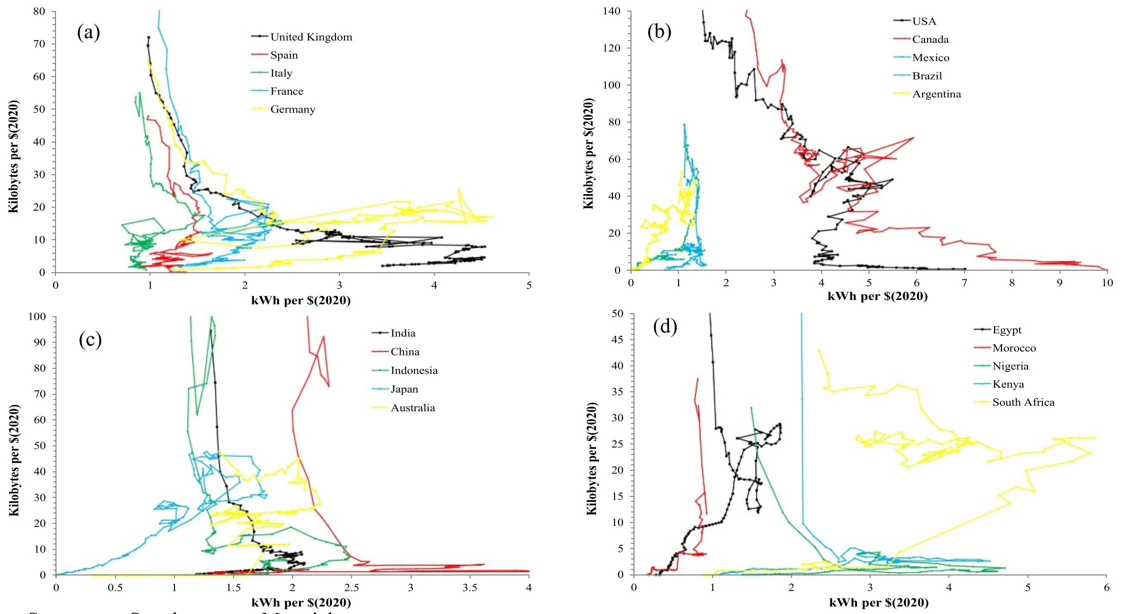
This large increase in communication intensity and little change in energy intensity is a dominant feature for a number of African economies. In addition, the opposite also appears in the early part of these economies' development—little change in communication intensity and substantial increases in energy intensity. Both features reflect a lack of a relationship. Only South Africa follows the trends associated with early industrialisers.

For recent industrialisers, two factors explain the differences. First, there may have been some complementarity of energy and information at low levels of economic development (as in figure 3 before 1913). Second, in the nineteenth century, industrialisation required large quantities of energy, and effective ICTs were limited. Today, ICTs are well developed and offer an alternative way to industrialise, not possible in the nineteenth century (Pearson and Fouquet 1996). In principle, industrialising economies could select either an energy-intensive or information-intensive path (which implies a form of substitution—it would require a counterfactual analysis to identify the substitution rate) to optimise social welfare (combining economic growth, consumption and avoided emissions). Either way, late comers have more options in terms of their development path (van Benthem 2015).

In sum, the overwhelming evidence indicates that the experiences of later industrialisers did not follow the same trajectory as Europeans or the global trend (see figure 3). Certainly, the global historical relationship between energy and information appears to have been dictated by the early industrialisers in Europe, North America and Japan. However, especially since the 1950s, other economies have industrialised. More recently, China and now India are industrialising, and they will increasingly influence the future of the global relationship between energy and information.

5. Limitations on the analysis of the relationship between energy and information

This is a highly stylised analysis of the relationship between energy and information, based on some critical assumptions. First, information is proxied by communication, which is a specific type of



Source: see Supplementary Material

Figure 5. Communication intensity relative to energy intensity in European countries, 1850–2010 (a); North and South American countries, 1850–2010 (b); Asia–Pacific countries, 1900–2020 (c); African countries, 1900–2010 (d).

information. Communication is information sent as one-to-one information. One-to-many dissemination of information incorporates reading material (e.g. books, newspapers, academic papers, parts of the internet, etc) and audio-visual information (e.g. radio, television and other parts of the internet, such as spotify, youtube, etc). Measurement of the use of audio-visual information is more challenging because of the lack of statistics on the behavioural aspects related to audio-visual and internet use, and only cover a small period (BARB 2023). One could also include information in the creation of knowledge, such as 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). Hidalgo and Hausmann (2009) argues that the structuring of information creates knowledge and value, rather than information itself. Thus, this paper is part of a bigger research programme aiming to investigate the relationships between energy and information.

Noting that communication is a proxy for a broader set of information might clarify one conundrum—the global economy followed a global co-evolution of energy and communication intensities up to 1913. Perhaps, using total information, the evidence would show a more modest growth than GDP, implying a substitution towards energy, because energy (i.e. coal) was relatively cheap. Certainly, a preliminary analysis for the United Kingdom indicates that, in 1850, the quantity of communication (in TB) was equivalent to 1% of the written disseminated information (e.g. books, newspapers, internet 'read'), remaining the same in 1900, falling to 0.6% in 1950, then increasing from the mid-1960s to 7% in 2000 and up to 25% in 2015. This suggests that, despite the increased availability of reading material since the introduction of the internet, the growth rate of (one-to-one) communication is higher than the rate of (information) reading—although people still read three times more information. Overall information may not have increased as much as communication and, therefore, the marginal rates of substitution for information might be lower since the mid-1960s. Nevertheless, based on these preliminary estimates, communication intensity and information intensity followed similar upward trends, and the intensity of the sum of communication and reading-related information increased more than 200-fold in the United Kingdom between 1850 and 2015. Thus, communication as a proxy for overall information appears to be broadly valid.

Second, energy and information are not the only factors of production. Just as using capital and labour is simplistic, so, is using energy and information. The period between 1850 and 1913 shows that there was no substitution between energy and information at the global level. Instead, the factors of production appear to be complements. This implies that they are replacing a third factor of production. For instance, land was often assumed to be a key factor of production in nineteenth century economic analyses. The declining importance of land in production might explain the coevolution of energy and information prior to 1913.

Third, traditionally, isoquants present the marginal rate of substitution between factors of production while keeping production and technology constant. Underlying the creation of figures 3 and 5(a)–(d) are major technological changes, and this needs to be remembered.

Fourth, at this stage, it is important to not attribute a causal relationship between energy and information based on these empirical observations. The relationship could be driven by another factor. To formally identify a causal impact would require quasi-experimental conditions. Also, despite isolating the substitution channel, there are reasons to believe that causality could run in either direction—that is, increases in energy and information use tend to boost economic growth, and economic growth can drive the demand for energy and information. Thus, attempts to identify the causal channels require future research.

6. Conclusion

With the goal of gaining insights about the role digitalisation might play in the global decarbonisation effort, the purpose of this paper was to examine the relationship between energy and information (as proxied by communication) of the global economy since 1850. While the global economy grew 90-fold since 1850, global energy consumption increased 36-fold and global communication soared by almost 20 000-fold. Despite some variation across economies and regions, the broad trend of the more rapid growth of communication use than energy consumption holds true for all economies examined.

Analysing the relationship between energy and information requires the separation of the two channels of impact: first, there is the substitution away from energy and towards information, and, second, there is the role of information in generating economic growth, which stimulates the demand for energy (and emissions). This paper focused on the first channel and tried to isolate it.

At the global level and for many (but not all) economies, the evidence revealed a clear historical connection between energy and information. From the early twentieth century, there was a phase of rapid substitution away from energy and gradually towards communication, followed by the more recent phase of gradual reductions in energy intensity and rapid increases in communication intensity. In 2015, this substitution mitigated one tonne of CO_2 for every 0.82 GB of communication.

The substituting relationship appears to be most prevalent in the industrialised economies. Other economies did not follow this pathway—for some, there appears to be little relationship between energy and information. Thus, the tendency only applies under certain circumstances, and there are severe limitations with relying exclusively on a global analysis.

Furthermore, it is important to stress that there are no claims of causality in this paper. Correlation does not imply causality. Other factors may explain the apparent substitution trends. It is important to push forward this research, providing a more detailed and robust analysis of the relationship between energy and information.

Nevertheless, this historical evidence reveals that the apparent rate of substitution has been rising for more than one hundred years. If this relationship continues in the same direction, then the rate of technical substitution would rise further. If the relationship maintains a similar change in the rate, then broadly every 30 years, the MRTS would increase by one order of magnitude—that is, around 2040, the rate would be 2 kB per kWh; by 2070, 20 kB per kWh; and, by 2100, 200 kB per kWh[6]. Thus, it is appropriate to anticipate limits to the potential substitution away from energy and towards information.

Furthermore, without price incentives, the mix between energy and information in the global economy would reach an equilibrium. To avoid this stasis, the price ratio needs to remain above the MRTS (as shown in figure 4). Given the rising MRTS, this would require a rising price of energy or a declining price of information. Either way, the price ratio would need to continue rising to create the incentives to move up the isoquant curve. Otherwise, ICT would cease to play a role in the dematerialisation and decarbonisation of the global economy.

Historically, the relative price did change by one order of magnitude in the last two decades (see figure 4). However, this only occurred once since 1850. In addition, the economic limits of the rise in the long run price of energy (Fouquet 2011) and perhaps the technological limits on the decline in the price of information put constraints on the dynamic incentives for substitution. The only force that could maintain this rising relative price is the continued internalising of an exponentially rising social cost of carbon (Kunnas *et al* 2014, Rickels *et al* 2023). However, this implies the social cost of carbon would need to rise by orders of magnitude every few decades and increase 1000-fold (i.e. $100 000 per tonne of CO_2) by 2100. This implies huge climate damages. Thus, given the historical shape of the isoquant curve

[6] Primary electricity consumption (e.g. renewable and nuclear power) are estimated using the 'partial substitution' or 'input-equivalent' method. This method 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 (BP 2021). Compared with the direct equivalent method, which is used by the IEA, this method generates higher values for primary electricity compared with fossil fuels, and should be considered when looking at the transitions towards low carbon energy sources (Koomey *et al* 2019, Semieniuk and Weber 2020). Historically, the role of primary electricity has been minor relative to fossil fuels. Looking forward, this difference in the method is likely to have an impact on the estimates of the substitution from energy to information

and the constraints to the rise in the relative price of energy to information, it could be concluded that the substitution away from energy and towards information is likely to cease within the next few decades, and digitalisation will play a declining role in the decarbonisation process.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.lse.ac.uk/GranthamInstitute/profile/roger-fouquet/#data. Data will be available from 1 January 2024.

Acknowledgments

I would like to thank Charlie Wilson and three anonymous referees for their valuable comments that significantly improved the piece, and also comments during the Oxford Symposium on Technology and Global Change, including Arnulf Grübler, Nuno Bento, Frank Geels, Jonathan Koomey and Greg Nemet. Naturally, responsibility for any errors rests with me. Also, I gratefully acknowledge support from the UK Research and Innovation through the Centre for Research into Energy Demand Solutions (CREDS), Grant Reference Number EP/R 035288/1, the ESRC Centre for Climate Change Economics and Policy (CCCEP) Grant Reference Number ES/R009708/1 and the Grantham Research Institute on Climate Change and the Environment at the London School of Economics for the data collection.

References

Ackoff R L 1989 From data to wisdom *J. Appl. Syst. Anal.* **16** 3–9

Allen R C 2009 *The British Industrial Revolution in Global Perspective* (Cambridge University Press)

Andrieu B, Vidal O, Le Boulzec H, Delannoy L and Verzier F 2022 Energy intensity of final consumption: the richer, the poorer the efficiency *Environ. Sci. Technol.* **56** 13909–19

BARB 2023 Viewing data (available at: www.barb.co.uk/viewing-data/)

BEIS 2020 UK government GHG conversion factors for company reporting (available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020)

Bolt J and van Zanden J L 2020 *Maddison Project Database: Maddison Style Estimates of the Evolution of the World Economy. A New 2020 Update* (Groningen Growth and Development Centre. University of Groningen) (www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2020?lang=en)

BP 2021 Updated methodology for converting non-fossil electricity generation to primary energy (available at: www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/using-the-review/methodology.html#accordion_renewable-energy)

Chen X 1994 Substitution of information for energy: conceptual background, realities and limits *Energy Policy* **22** 15–27

Cipolla C M 1962 *The Economic History of World Population* (Pelican Books)

Creutzig F *et al* 2022 Digitalization and the anthropocene *Annu. Rev. Environ. Resour.* **47** 479–509

Dittmar J E 2011 Information technology and economic change: the impact of the printing press *Q. J. Econ.* **126** 1133–72

Dudley L 2008 *Information Revolutions in the History of the West* (Edward Elgar Publications)

Fouquet R 2011 Divergences in long run trends in the prices of energy and energy services *Rev. Environ. Econ. Policy* **5** 196–218

Fouquet R 2017 Make low-carbon energy an integral part of the knowledge economy *Nature* **551** S141

Fouquet R and Hippe R 2022 Twin transitions of decarbonisation and digitalisation: a historical perspective on energy and information in European economies *Energy Res. Soc. Sci.* **91** 102736

Fouquet R and Hippe R 2019 The transition from a fossil-fuel economy to a knowledge economy *Handbook on Green Growth* ed R Fouquet(Edward Elgar Publications)

Grübler A 1990 *The Rise and Fall of Infrastructures: Dynamics of Evolution and Technological Change in Transport* (Physica-Verlag)

Grübler A 1998 *Technology and Global Change* (Cambridge University Press)

Hidalgo C A and Hausmann R 2009 The building blocks of economic complexity *Proc. Natl Acad. Sci.* **106** 10570–5

Hidalgo C 2015 *Why Information Grows: The Evolution of Order, From Atoms to Economies* (Basic Books)

Hippe R and Fouquet R 2018 The knowledge economy in historical perspective *World Econ.* **18** 75–107 (available at: https://www.world-economics-journal.com/Papers/The-Knowledge-Economy-in-Historical-Perspective.aspx?ID=698)

Kander A, Malanima P and Ward P 2013 *Power to the People: Energy in Europe over the Last Five Centuries* (Princeton University Press)

Koomey J, Schmidt Z, Hummel H and Weyant J 2019 Inside the Black Box: understanding key drivers of global emission scenarios *Environ. Model. Softw.* **111** 268–81

Kunnas J G, McLaughlin E, Hanley N, Greasley D, Oxley L and Warde P 2014 Counting carbon: historic emissions from fossil fuels, long-run measures of sustainable development and carbon debt *Scand. Econ. Hist. Rev.* **62** 243–65

Lange S, Pohl J and Santarius T 2020 Digitalization and energy consumption. Does ICT reduce energy demand? *Ecol. Econ.* **76** 106760

Machado A C and Miller R E 1997 Empirical relationship between energy and information segments of the US economy—an input-output approach *Energy Policy* **25** 913–21

Malanima P 2020 World energy consumption: a database 1820–2018 (available at: https://histecon.fas.harvard.edu/energyhistory/DATABASE%20World%20Energy%20Consumption.pdf)

Mokyr J 2002 *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton University Press)

Nakicenovic N *et al* 2021 *The Digital Revolution and Sustainable Development: Opportunities and Challenges* (International Institute for Applied Systems Analysis (IIASA))

Otojanov R, Fouquet R and Granville B 2023 Factor prices and induced technical change in the industrial revolution *Econ. Hist. Rev.* **76** 599–623

Pearson P J G and Fouquet R 1996 Energy efficiency, economic efficiency and future carbon dioxide emissions from the developing world *Energy J.* **17** 1–26

Rickels W, Meier F and Quaas M 2023 The historical social cost of fossil and industrial CO_2 emissions *Nat. Clim. Change* **13** 742–7

Semieniuk G 2024 Inconsistent definitions of GDP: implications for estimates of decoupling *Ecol. Econ.* **215** 108000

Semieniuk G and Weber I 2020 Inequality in energy consumption: statistical equilibrium or a question of accounting conventions? *Eur. Phys. J. Spec. Top.* **229** 1705–14

Spreng D 1993 Possibility for substitution between energy, time and information *Energy Policy* **21** 13–23

Spreng D 2015 The interdependency of energy, information, and growth *ICT Innovations for Sustainability: Advances in Intelligent Systems and Computing* vol 310, ed L M Hilty and B Aebischer pp 425–43

Trading Economics 2023 EU carbon permits (available at: https://tradingeconomics.com/commodity/carbon) (Accessed 9 June 2023)

van Benthem A 2015 Energy leapfrogging *J. Assoc. Environ. Resour. Econ.* **2** 93–132

Williams L, Sovacool B K and Foxon T J 2022 The energy use implications of 5G: reviewing whole network operational energy, embodied energy, and indirect effects *Renew. Sustain. Energy Rev.* **157** 112033