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Analysis

The ICT/electronics question: Structural change and the rebound effect

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ABSTRACT

ICT and related electronic appliances consumed 4% of global electrical energy in 2007, growing to 4.7% in 2012, with projections of continued increase in coming decades. This is despite an average annual increase in energy efficiency of about 30% in ICT/electronics throughout the last 5 decades. Mainstream studies of energy-related rebound effects have yet to produce a conceptual framework that adequately encapsulates a unique feature of ICT/electronics: its tendency to induce changes in social practice and socio-technical structures. This study attempts to fill this gap. Surveying rebound effect literature, it builds on studies which explore 'transformational' change caused by energy efficiency increases. It identifies structural changes in business, education, the military and households caused by energy efficiency increases in ICT/electronics, which lead to a proliferation of ICT/electronic devices and consequently increased energy consumption. It shows the cause-and-effect logic between energy efficiency and energy consumption in ICT/electronics, and tentatively estimates rebound effects ranging between 115% and 161% in eight diverse empirical examples. The history of ICT/electronics shows that energy efficiency increases inevitably lead to increases in energy consumption, hence firm controls on CO_2e emission allowances may offer the best hope of curbing energy consumption and CO_2e emissions in this sector.

1. Introduction

This paper explores the phenomenon of steadily increasing energy consumption in the ICT/electronics sector throughout the world, despite the fact that energy efficiency in this sector has also been steadily increasing for over 5 decades.

It has long been known that consumers often increase their consumption of energy services after an increase in energy efficiency (Khazzoom, 1980; Brookes, 1990). This phenomenon was labeled the 'rebound effect' by Saunders (Saunders, 1992), though the term was being used among practitioners as early as 1983 (Berry and Hirst, 1983). The rebound effect is seen almost universally as a consequence of the response of consumers and producers to lower endogenous energy costs, which result from energy efficiency increases (Schipper, 2000). This is seen to happen directly, indirectly, and on an economy-wide scale.

A rebound effect of X% means that only 100-X% of an appliance's energy efficiency increase is being used to reduce energy consumption, while the remaining X% is used to increase the consumption of energy services (e.g. more km traveled, more computations performed, more goods produced). Most empirical studies of rebound effects estimate their magnitude at somewhere between 0% and 100% (see reviews in (Maxwell and McAndrew, 2011; Sorrell et al., 2009)). Rebound effects above 100% (known as 'backfire'), where more energy is consumed after than prior to the energy efficiency increase, are generally thought to be rare, though not all researchers agree on this (Alcott, 2005; Saunders, 2013; Tsao et al., 2010).

It has also been noted that over the last 200 years, both energy efficiency and energy consumption have steadily increased in tandem (Ruzzenenti and Basosi, 2008b). This does not necessarily imply rebound effects above 100%, as the increase in energy efficiency is not always the cause of the steady increase in energy consumption. For genuine rebound effects to be implicated, a behaviourally induced increase in the consumption of energy services must follow causally from an increase in energy efficiency (Sorrell and Dimitropoulos, 2008).

This paper argues that in the ICT and electronics sector there can be a causal route to such increases in energy services consumption, where this route includes the phenomenon of social structural change. This type of change, it is here argued, results from accumulations of increases in energy services consumption which accrue from increases in energy efficiency in ICT/electronics. At certain points in time and space, accumulations of cheap increases in energy services from these appliances provide opportunities for fundamental rearrangements in social, business, household, governance, military or production structures and practices. These rearrangements lead to further proliferation of ICT/electronics appliances and therefore to step-change increases in energy consumption, rather than just the one-for-one changes in consumption that are often assumed in much rebound effect literature.

In this paper the term 'practices' means the routine things people do in order to meet their needs (Reckwitz, 2003), and 'structures' means the ways different people's practices routinely interconnect with each other (Harré, 1993). Structures are assumed here to be sociotechnical,

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in that they involve arrangements of people and technology in particular configurations and relationships (Guy et al., 2011).

The composite term 'ICT/electronics' is used in this paper to embrace all devices using electronic components rather than just electrical components. An electronic component is a discrete device which can act as either a switch or amplifier. Both its input and output are electrical signals rather than mechanical or thermodynamic work. There are two basic electronic components: the thermionic valve (also called the valve, vacuum tube or tube), invented in 1904, and the transistor, invented in 1947. Transistors today usually come in the form of integrated circuits (also called 'chips' or 'microchips'), which may contain up to 10 billion transistors in a pre-designed circuit. A 1950s transistor is about 2 orders of magnitude more energy efficient than a typical 1950s valve, while a microchip may be many orders of magnitude more energy efficient than a 1950s transistor (Braun and MacDonald, 1978; O'Regan, 2012).

Electronic components are the essential elements in computers, mobile phones, tablets, televisions, radios, missile early warning and guidance systems, robots, GPS systems, timepieces, and built-in control systems for a large range of electrical and mechanical appliances in industry, the household, governance and the military. All devices employing electronic components are called ICT/electronics in this paper. However, the focus of the paper is on the devices which are primarily performing electronics based tasks, such as computing and communications (stand-alone computers, routers, local servers, mobile phones, televisions, server farms, direction finders, etc.), rather than secondary uses such as control systems in manufacturing.

The direct worldwide operational energy consumption of this category of ICT/electronics was estimated at 710 TWh in 2007, or about 4% of total electricity consumption, leading to CO_2e emissions of 620 Mt (Malmodin et al., 2010). This does not include energy consumed in the manufacture of this equipment, which is also not considered in this paper. Using the same methodology, Lannoo (2013) estimated that energy consumption of ICT/electronics grew to 930 TWh per year by 2012, when it accounted for 4.7% of global electricity consumption. This represents an average annual growth rate of approximately 5.5%, compared with 3.0% for the annual growth in global electricity consumption (World Bank, 2014). There is also a large, energy-intensive infrastructure to facilitate the interconnection of ICT/electronic devices, including undersea cables, the launching of rockets and space shuttles for the placement and maintenance of satellite communications, and the building of microwave and other radio linking modules in remote regions (Malmodin et al., 2010; Hertwich and Roux, 2011; Hilty et al., 2011; Moyer and Hughes, 2012; Scharnhorst, 2006; Sutherland, 2009; Somavat and Namboodiri, 2011) but this, too, is not included in calculations in this paper.

It is often assumed that novel ways of increasing the energy efficiency of ICT/electronics will break the trend of continually increasing energy consumption in this sector (Berl et al. 2010, Hartenstein, 2011). The US Energy Star label (http://www.energystar.gov/) and the European TSO certification, of Swedish origin (http://tcodevelopment.com/), are in part motivated by this possibility. It is therefore important to consider rebound effects in this sphere, and to critically question whether continued energy efficiency improvements in ICT/electronics will lead to reduced energy consumption.

The questions being addressed in this paper are:

(a) To what extent have increases in energy efficiency been a cause of the development of ICT/electronics?

(b) In what ways has ICT/electronics development led to changes in practices or structures which have caused increases in energy consumption?

(c) What are the magnitudes of these changes in energy efficiency and energy consumption?

(d) What magnitudes of rebound effects would this imply in particular empirical cases, if these can be called rebound effects?

Section 2 of this paper reviews rebound effect and related literature, to develop a conceptual framework for dealing with rebound effects in ICT/electronics. Section 3 explores the connection between energy efficiency and consumption increases in ICT/electronics and links this to the mathematics of calculating rebound effects in this sphere. Section 4 estimates energy efficiency increases and offers a number of empirical examples of rebound effects in ICT/electronics. The results are discussed in Section 5, and Section 6 concludes.

2. Rebound Effects, Structural Change and ICT/Electronics

The simplest form of rebound effect is the direct case, where an increase in energy services consumption in a particular appliance occurs as a behavioral consequence of an energy efficiency increase in that same appliance (Sorrell and Dimitropoulos, 2008; Berkhout et al., 2000). Money is saved by having to pay less for the same level of energy services as previously, and some of the savings are spent on increasing the level of energy services from the upgraded appliance.

Studies also consider the indirect rebound effect, where a portion of the remaining savings are spent on increasing the level of energy services in other appliances (Chitnis et al., 2013; Druckman et al., 2011; Greening et al., 2000; Yun et al., 2013; Sorrell, 2010). The sum of direct plus indirect rebound effects usually appears to be less than 100%. For example, Gonzales (2010) gives an estimate of around 56–65% for direct plus indirect rebound effects in electricity use in Catalan households.

Although the classification of direct and indirect rebound effects appears to work well for most types of everyday consumer products – cars, washing machines, home heating systems, lighting, etc. – the nature of ICT/electronics does not fit well with this schema. To begin with, the services provided by a computer or mobile phone often include elements of production of further goods. A home computer can be used, for example, to produce spreadsheets for obtaining tax exemptions, freelance articles for magazines, or audio-visual presentations for marketing one's musical compositions. Home computers are often also inextricably linked with users' paid employment and used as an extension of office work. This can also be the case, but to a far more limited extent, with more traditional consumer goods such as lighting or space heating, which make it possible to pursue productive activity after dark or in rooms that would otherwise be too cold (Tsao et al., 2010; Galvin, 2015).

Secondly, 'satiation' of consumer need (Sorrell et al., 2009; Wörsdorfer, 2010) does not seem to occur with ICT/electronics as it does with other products. There is a limit to how far a car owner needs or wants to drive per day or year, or how warm a household would want their home to be, but there does not seem to be a limit to how many Gigabytes of memory, Gigahertz of processor speed or Terabytes of storage a user needs in a home or office computer. Further, while cars, home insulation, washing machines and refrigerators were developed to meet specific human needs which do not seem to have changed radically in the last half-century, ICT/electronics seems constantly to beget new human needs, many of which were not even depicted in pre-ICT-age science fiction.[1]

One possible avenue to explore rebound effects under these circumstances is via rebound effects in industrial production (Saunders, 2013), which can inform economy-wide rebound effect studies (Barker et al., 2007; Barker et al., 2009; Mundaca et al., 2015; Sorrell, 2007). The incorporation of ICT/electronics in production control systems leads to efficiencies of energy, materials, capital and labor (Plepys, 2002), bringing cheaper products and therefore increased demand. ICT/electronics in commerce also brings efficiencies which can lead to structural change and consequent increases in energy consumption, such as with online flight bookings (Dobruszkes, 2009). Although ICT/electronics could potentially save energy in industry and commerce (Moyer and Hughes,

[1] For example, in Isaac Asimov's prolific space-age science-fiction writings, in which computers played decisive roles, there were no text messages, mobile phones, word processors or spreadsheets, and there was nothing resembling the internet.

2012), some research sees it catalyzing increases in energy consumption overall (Plepys, 2002).

However, the focus here is on rebound effects that are more directly associated with equipment that is distinctly ICT/electronic. In this respect a more accessible issue concerns the increases in ICT/electronics energy consumption resulting from changes in social structure and social practice that have come about through the widespread acceptance of ICT/electronics in everyday life, including both the home and office.

This resonates with a branch of rebound effect studies to do with structural change issues. In their comprehensive review of rebound effect literature of the late 20th century, Greening et al. (2000) proposed a four-tier taxonomy of rebound effects. The first three tiers correspond to the direct, indirect and economy-wide categories outlined above. The fourth tier, transformational effects, refers to situations where changes in technology ‘have the potential to change consumers’ preferences, alter social institutions, and rearrange the organization of production’ (op cit. 391). However, they express doubts as to whether there could be either reliable data or suitable methodology to estimate such rebound effects.

Nevertheless, the notion of ‘transformational’ effects can offer a starting point for tentatively exploring rebound in ICT/electronics, as it is clear that consumers' preferences and practices have changed as a result of ICT/electronics, as have many social institutions and structures. For example, in researching for a literature review, academics formerly used paper-bound volumes of cross-referenced keywords, leading to physical searches through printed journals. Now their entire search, find and copy activity takes place electronically, with global interconnectedness. Not only has a social practice changed, but a complex set of new socio-technical structures has emerged to make the practice possible: remote servers for internet searches; digitalisation services for journals; systems of access rights for academic institutions; a local computer server system for a university department feeding into a larger server for a university; the world wide web with its global hardware and sets of technical protocols; remote cloud storage with its associated servers; and all these together with the institutions and personnel who manage and service them, often using further layers of ICT.

There are many other examples where ICT/electronics has clearly led to specific, identifiable changes in social practices and social structures: in such spheres as business, the military, civil service, the home, and education. A type of ‘transformational’ rebound effect, which was seen by scholars at the turn of the century as intuitively feasible but highly problematic to explore robustly, is now easy to identify and describe, at least within the sphere of ICT/electronics. Further, although the energy *services* in such a system may be problematic to quantify, levels of energy consumption and energy efficiency are well documented in many spheres of ICT/electronics (see, e.g. O'Regan, 2012; Malmodin et al., 2010; Sutherland, 2009).

A research program exploring rebound effects in transformational change is offered by Ruzzenenti and Basosi (Ruzzenenti and Basosi, 2008a, 2008b). This uses an ‘evolutionary’ perspective, likening the simultaneous increases in energy efficiency and energy consumption in road freight transport to evolutionary developments in biological organisms over time. As road freight transport becomes cheaper due to energy efficiency gains, points are reached where industry finds it more profitable to become more decentralized, causing step-wise increases in freight distance traveled and therefore energy consumption. This happens successively because firms compete to keep their costs per unit manufactured lower than each other's. Ruzzenenti and Basosi argue that this is analogous to biological cell evolution, in which the organisms which are the most energy efficient consume the most energy.

The biological cell analogy is a key to understanding this approach. When a cell becomes more energy efficient, it could, theoretically, continue to do the same amount of work as previously, with the advantage of less energy consumption. It would then have considerable unused capacity. A competing cell which has also increased its energy efficiency could then get the advantage over it by using its spare capacity to increase its work output. In a competitive biological situation, cells which utilize this spare capacity gain an advantage over less efficient cells. Organisms with these cells can then produce and use more of them at a proportionately lower cost in energy consumption. A kind of evolutionary arms race can ensue, where organisms effectively drive each other to increase the energy efficiency of their cells, utilize all the spare capacity this delivers, and produce more such cells, this increasing their energy consumption.

The suggested link between biology and road freight transport is the survival of the fittest. Gains in energy efficiency make it easier to increase activity levels, and these need to be taken up so that competitors do not get the edge. The notion of competitive advantage or (metaphorical) arms race can be clearly seen in the use of ICT/electronics in commerce. As the energy efficiency of a firm's office computers increases over time through regular upgrading, the firm could use the savings merely to lower the price of its services to consumers, but a point may come when a rival firm uses the reduction in energy consumption per computation to restructure its ICT/electronics system so as to give it greater advantages in areas such as delivery logistics, online advertising, interconnectivity between workers, and web connectivity. This firm's energy bill will increase, but so might its sales receipts. This could put its competitor in the position of having to restructure or die.

The ‘arms race’ metaphor becomes literal in the use of ICT/electronics in the military. The front-runner in purchases of computer equipment through the 1950s was the US military. Braun and MacDonald (1978) show how the US military provided the main financial and research impetus for the development of the transistor, from the crude, unreliable and unpredictable device it was in the early 1950s to the solidly reliable component within integrated circuitry it had become by the mid-1970s (see also Ruttan, 2005). The main spheres of development were in early warning systems, weapon delivery, and surveillance. The Soviets' success in putting a cosmonaut in space in April 1961 gave added impetus to this ICT arms race. A reflection of the ICT/electronics competitive arms race is also seen in the term ‘cyber wars’.

Scheffran (2008) notes that this military ‘technological arms race’ not only involves changes in weapons systems and their components, but also the ‘socioeconomic infrastructure and lifecycle within which weapon systems are embedded, designed, developed, tested, deployed, used, and removed’ (op cit. 15). In other words, as the military's physical defense hardware changes, through the ongoing development of ICT/electronics, its organizational structures are rearranged to accommodate and proliferate the new or different capabilities. This is a further example of social and structural change being induced by the continual increases in efficiency and performance of ICT/electronics.

A feature of the evolutionary model is its recognition of the role played by increases in power (work done per unit time). More efficient organisms do not content themselves with lower energy consumption, but utilize their energy efficiency to produce higher power output at less cost in energy (Ruzzenenti and Basosi, 2008b). Analogously, in ICT/electronics energy efficiency increases are associated with more power output: more computations per second, more communication linkups per minute or more Gigabytes downloaded per hour. As Ruzzenenti and Basosi (2008b) point out, the rebound effect will be under-estimated if the energy services in the calculation do not include the intensity of services consumed per unit time.

With respect to ICT/electronics within private households, people tend to behave cooperatively, rather than competitively (Ruzzenenti and Basosi, 2008b). However, the firms developing and marketing ICT/electronics compete for households' spending, and this plays a large part in driving the innovations which offer households new or improved ways of engaging with ICT/electronics. These innovations often lead to step-changes in social practice and structure. For example, household evenings today are not characterized by all or most members sitting around a radio or watching television together, as they tended to do in the 1950s and 1960s (at least in this author's memory). Instead, individual household members tend to busy themselves with their own computers, mobile phones, television portals and other devices. Further, not to possess these devices can lead to social exclusion, since practices of coordinating with friends and colleagues have become heavily dependent on these devices (Oksman and Turtianien, 2004; Valentine et al., 2002). There are also emerging practices of romantic courting that take place largely via electronic media. Glattauer's popular Austrian novel *Gut Gegen Nordwind* depicts an entire man–woman relationship that emerges, develops and comes to its eventual end through a type of email courting ritual (Glattauer, 2006), with no physical contact between the couple. The practices of electronic courting and social media dependence are also caricatured, in their extreme form, in Eggers's popular novel *The Circle* (Eggers, 2013).

A further change in householders' practice as a result of developments in ICT/electronics is that of styles of working from home. The work brought home is no longer (only) a briefcase full of paper documents, but hundreds of millions of bytes of information on a disk, on the firm's website, on a remote internet server or in the cloud. This requires energy consumption in the home, not to mention more consumption in servers, server farms, and the telecommunications nodes in the relevant data transfer chains.

Based on the evolutionary perspective of Ruzzenenti and Basosi (Ruzzenenti and Basosi, 2008a; 2008b), this paper therefore uses the notion of ICT/electronics causing changes in social practice and social/sociotechnical structure as a framework for explaining how the rebound effect can be conceived to occur in this field. It posits that energy efficiency increases in electronic componentry, which have occurred relentlessly since electronic computers were first built, have led to these changes, which have almost invariably increased the number, power and complexity of ICT/electronic devices in use, both throughout the world and in particular groups of people, thus increasing the direct energy consumption of ICT/electronics. To confirm these causal links, however, we also need to consider whether increasing energy efficiency really is a cause of this phenomenon.

3. What Causes What: The Role of Energy Efficiency in ICT/Electronics

3.1. General Considerations

For a rebound effect to be identified there has to be a clear line of cause and effect between a change in energy efficiency and a change in energy services consumption. Simply to identify a correlation between the two is not sufficient evidence of rebound. Multiple causes might also need to be considered, when increases in energy efficiency go hand in hand with other efficiency increases.

The history of ICT/electronics shows that steady efficiency increases in four key variables – energy consumption, component size, materials utilization and cost – have all have been necessary to produce the type of ICT/electronics that has led to the huge increases in computing utility that have given rise to the social and structural changes seen today (Braun and MacDonald, 1978; O'Regan, 2012).

This is seen in the transition from valves to transistors in computer manufacture in the 1950s, and later in the continual miniaturization of transistors within integrated circuits. The first US computer using ‘Von Neumann architecture’, which virtually all computers use today, was the ENIAC, developed for the US military in the 1940s. It used 18,000 valves, weighed over 30 tonnes, and was 30 m long, 3 m high and 1 m deep. It drew 150 kW of power, not including its cooling system. The desktop computer on which this paper is being written has approximately 3 billion transistors as its active components. If it used the same type of components as the ENIAC, it would draw about 25 GW of power, which is about 70% of average UK demand. If it were left on continuously it would consume about 216 TWh of energy per year, about 60% of the UK's annual electricity production (DECC, 2014). Energy efficiency gains have therefore been an essential element in enabling individuals to have computers of the type that are common today.

Parallel efficiency gains in size, cost and materials have also been essential, otherwise a desktop computer using ENIAC components would weigh 5 million tonnes and be 5000 km long, while the cost of its valves alone would be around 1.5 billion US dollars.

A similar dependence on efficiency gains is seen in developments within the transistor age. The first personal computer, the IBM 5150, produced in 1981, used an Intel 8808 chip containing 29,000 transistors, cost around $US 1500 and drew about 153 W (IBM, 2001). If a desktop computer with today's capabilities used components with the same energy efficiency as the IBM 5150 it would draw about 10 MW of power and consume about 85G Wh per year if left on continuously, about as much as 6000 homes. It would be 50 km long and cost something in the order of $US 160 million.

3.2. The Logic of Efficiency Relationships

Clearly, increasing energy efficiency has been a necessary condition for the development of computers and of ICT/electronics, together with increasing efficiencies of size, cost and materials. An increase in the utility from ICT/electronics therefore implies there has been an increase in all these efficiencies. Expressed formally:

$$\Delta T \rightarrow \Delta \varepsilon \cap \Delta Z \cap \Delta C \cap \Delta M \tag{1}$$

where ε is energy efficiency, Z, C and M are size, cost and material efficiency respectively, and T is utility, i.e. the services obtained from ICT/electronics.

Note that the reverse of this is not necessarily true: an increase in all four efficiencies does not necessarily imply an increase in utility, since there may be other factors, such as depth of programming skills and good matches to human needs (or needs that can be created), required to ensure this utility increase is realized.

By the rules of logic, Eq. (1) implies that:

$$\sim \Delta \varepsilon \cap \Delta Z \cap \Delta C \cap \Delta M \rightarrow \sim \Delta T \tag{2}$$

Hence:

$$\sim \Delta \varepsilon \cup \sim \Delta Z \cup \sim \Delta C \cup \sim \Delta M \rightarrow \sim \Delta T \tag{3}$$

i.e. if one or more of these efficiencies do not increase, utility will not increase. It follows from (3) that:

$$\sim \Delta \varepsilon \rightarrow \sim \Delta T \tag{4}$$

Expressed prosaically, if energy efficiency does not increase, the level of utility does not increase. Hence it is logically robust to assert that energy efficiency increases are a necessary and direct cause of increased utility from ICT/electronics.

From a logic-theoretical point of view, therefore, energy-related rebound effects for ICT/electronics can be calculated from energy efficiency and energy services increases. It is also possible to define ‘materials’, ‘cost’ and ‘size’ rebound effects. For example, the enormous reductions in the amount of material needed per transistor have actually resulted in more materials being mined and processed, since the number of ICT/electronics devices has proliferated as a result of their weight not increasing as their computational power has increased. Discussion related to such issues may be found (Plepys, 2002; Hilty et al., 2006; Penzenstadler, 2013; Robinson, 2009; David, 1990), but the focus in this paper is on energy-related rebound effects.

It may be argued that these can only be called rebound effects if it can be proven that power consumption has impeded ICT/electronics use.[2] In fact, the history of ICT/electronics is replete with examples of this. The motivation for the invention of the transistor was the 'dream' of being able to expand ICT/electronics services without overloading power systems Braun and MacDonald (1978). The same factor was one of the main drivers in the development of integrated circuits (O'Regan, 2012). Some more recent examples are: The energy (in)efficiency of mobile phones causes them to draw excessive power from their batteries which consequently do not keep their charge for long enough to satisfy customer needs. Space travel is limited by the energy (in)efficiency of ICT/electronics circuits, since these require power, which is limited in a space vessel.[3] The energy (in)efficiency of computers' central processing units (CPUs) causes them to draw excessive power, causing them to overheat, which limits the amount and speed of processing power that can be incorporated in PCs, servers, etc. There is a very large branch of ICT/electronics research working to overcome these problems by attempting to develop non-Ohmic[4] circuitry for CPUs, such as 'spintronics', which would be thousands of times more energy efficient than silicon chips. See a review of such research in Chumak et al. (2015), and a popular summary of German research on this in (Röthlein, 2015).

Nevertheless, since this is possibly the first exploration of rebound/backfire in the ICT/electronics sector, and since increases in energy efficiency in this sector are almost always coupled with increases in efficiencies of cost, size and material usage, it may be wise to be cautious and tentative in using the terms 'rebound' and 'backfire' here. A further point is that the diffusion of ICT/electronic devices may depend on a range of additional factors besides increasing energy efficiency. When the terms rebound and backfire are used throughout the paper these qualifications should be kept in mind.

3.3. A Definition of Rebound Effect for Energy Efficiency

This paper uses the definition of the rebound effect most widely accepted in economics literature, namely the energy efficiency elasticity of energy services (Sorrell and Dimitropoulos, 2008; Berkhout et al., 2000). This can be formally expressed as:

$$R = \frac{\partial S}{\partial \varepsilon} \cdot \frac{\varepsilon}{S} \tag{5}$$

where S = energy services consumption and ε = energy efficiency. Since it is often difficult to quantify energy services directly, it is usual to assume these are the product of energy efficiency and energy consumed E, i.e.:

$$S = \varepsilon \cdot E \tag{6}$$

This means that the more intensively a user uses an appliance which has given efficiency, the more utility he or she obtains from it.

Substituting (6) in (5) and using the product rule, an expression for the rebound effect in terms of energy consumption can be derived, namely:

$$R = 1 + \frac{\partial E}{\partial \varepsilon} \cdot \frac{\varepsilon}{E} \tag{7}$$

The general solution to Eq. (7) is:

$$R = 1 + \frac{\ln(B_E)}{\ln(B_\varepsilon)} \tag{8}$$

where B_E is the proportionate change in energy consumption and B_ε is the proportionate change in energy efficiency. For example if energy consumption increases by 6%, then B_E is 1.06.

Eq. (8) will be used in the remainder of this paper to estimate rebound effects in every instance.

With regard to B_E it should be noted that the concern here is with total energy consumption within like spheres. For example, if an increase in energy efficiency leads to growth in the average number of ICT/electronics devices in German households, B_E is calculated on the basis of the total increase in energy consumption of these ICT/electronic devices in these households — not on the basis of changes in energy consumption per electronic device.

It should also be noted that, while the expression for the rebound effect in Eq. (8) is a logarithmic function, further expressions will in places need to be developed for calculating B_E and B_ε. Usually these are implicit power functions, but this depends on the type of data to hand.

4. Empirical Examples

4.1. Defining Energy Efficiency

Energy efficiency is generally defined as the useful output of a process as a proportion of the energy input into the process (Patterson, 1996). Energy efficiency can be given absolute values in situations where a measurable amount of work output is being compared with a measurable amount of work input, such as with a pump or boiler. However, in rebound effect calculations based on Eqs. (7, 8), absolute values are not required since we are always dealing with ratios of change, i.e. $\partial\varepsilon/\varepsilon$ or its inverse (Galvin, 2014). For ICT/electronics, energy efficiency could be loosely defined as the number of useful outputs available per second, divided by the energy required to produce them.

Energy consumption takes place in seven main sections of a computer: its central processing unit (CPU); random access memory (RAM); motherboard; media cards, hard disk drive (HDD), monitor and cooling fan. In general, the energy consumption of all sections except the CPU is affected relatively little by the device's level of computing power. Consumption in the CPU is approximately proportional to its clock speed, i.e. the number of computations it makes per second. This amounts to about 100 W in a typical modern computer, though this consumption is occurring only when the CPU is computing, which depends on the type and intensity of usage. The energy consumption of the remaining six sections together averages around 150 W and occurs continually, except for that of the media cards, which can vary significantly depending on visual or audio demand (games, music, etc.).

Apart from the effect of the clock speed, energy consumption does not vary much with the number of transistors in the circuitry of the RAM, CPU, motherboard and HDD, because the increases in numbers of transistors that has been taking place over the last decades has been accompanied by a corresponding reduction in transistor size — i.e. the chips have remained about the same physical size and therefore consume about the same amount of energy, even though there are more transistors in the chips. This implies that the energy efficiency of a chip is directly proportional to the number of transistors in the chip.

The energy demanded by the monitor and cooling fan also remains approximately constant, though sometimes larger fans are required due to the heat generated by faster CPUs.

Hence a rule of thumb is that the energy efficiency of a computer (and of most other ICT/electronic devices) is approximately proportional to the number of transistors in its circuitry, with a downscaling factor to take account of clock speed. The downscaling factor depends very much on how intensively the device is operated. It should be noted that CPU processing speed doubled every 1.52 years from 1975 to 2011 (Hilty et al., 2011), an average annual increase of 58%.

As a simple comparison, the IBM 5150 (see above) used 29,000 transistors, while a modern high-end desktop computer uses about 5 billion. Disregarding the influence of the CPU for the moment, this would make

[2] I am indebted to an anonymous reviewer for pointing this out.

[3] Once a space vessel has reached its cruising speed its energy consumption is almost entirely for ICT/electronics, since the engines are no longer required to overcome resistance or the pull of gravity.

[4] Non-Ohmic means not producing electric currents in mediums which have electrical resistance, and therefore not causing heating or requiring a large power input.

the modern computer 192,000 times as energy efficient as the IBM 5150, giving an average annual energy efficiency increase of 43%. With clock speed included this would reduce to about half that figure, say 22% per year, if both computers were used intensively, as at that level of usage a modern CPU draws around 100 W, almost doubling the power demand of the computer, while the CPU of the IBM 5150 drew only about 7 W. If both computers were used very lightly, the energy efficiency increase would be close to the top figure of 43%. In the absence of any empirical guidance as to how intensively, on average, users drive their computers, an estimated figure of 30% for average annual increase in energy efficiency would seem reasonable.

As a rule of thumb we therefore use the figure of an average annual increase in energy efficiency of 30% for ICT/electronics in the empirical examples that follow, except where non-computing devices are also involved. This gives a value of B_ε of 1.30.

4.2. ICT/Electronics in German Households 1996–2011

The first empirical example concerns ICT/electronics usage in German households in the years 1996 to 2011. In that period household electrical energy consumed by ICT/electronics increased from 8.99 TWh to 33.95 TWh, an average annual increase of 9.3% (BMWi (Bundesministerium für Wirtschaft und Energie), 2015; Energie-Agentur.NRW, 2012). This gives a value of B_E of 1.093. Using Eq. (8):

$$R = 1 + \frac{\ln(1.093)}{\ln(1.30)} = 1.34 \tag{9}$$

This is a rebound effect of 134%. This means that each marginal proportionate increase in energy efficiency of magnitude x led to a proportionate increase in energy consumption of 0.34×. This would be termed 'backfire', where an increase in energy efficiency leads to an increase in energy consumption rather than a decrease.

4.3. ICT/Electronics in New Zealand Households 1949–2006

In the 1940s the only ICT/electronics device in most New Zealand homes was the valve radio. By 1949 80% of homes had a radio (Statistics New Zealand, 2013). Domestic radios in 1949 had 6 valves and demanded about 40 W (6 W per valve plus 4 W for the AC-DC transformer, speakers and other circuitry).

In 2006 the ICT/electronics in use (excluding devices in storage) in the average New Zealand household consisted of 2.0 televisions, 1.2 mobile phones, 1.0 desktop computer and 0.4 laptop computers (Ministry for the Environment, 2006). Assuming this was reasonably up to date technology at the time, this would have amounted to approximately 500 million transistors. When all these devices were switched on they would have demanded approximately 350 W.

The average annual proportionate change in energy efficiency over the 57 years from 1949 to 2006 is therefore approximately:

$$B_\varepsilon = \sqrt[57]{\frac{500000000/350}{6/40}} = 1.33 \tag{10}$$

This represents an average annual increase in energy efficiency of 33%, only marginally higher than the generic figure of 30% estimated in Section 4.1.

Assuming the devices in 2006 were switched on for the same amount of time as the radio was switched on, the average annual proportionate change in energy consumption over the same period would have been:

$$B_E = \sqrt[57]{\frac{350}{(0.8 \times 40)}} = 1.043 \tag{11}$$

This gives a rebound effect of

$$R = 1 + \frac{\ln(1.043)}{\ln(1.33)} = 1.148 \tag{12}$$

This represents a rebound effect of 115%, somewhat lower than that of the first case.

One reason this is lower is because of the long period from 1949 until transistors became dominant, during which there was little change in energy efficiency or energy consumption. There is also a wider margin of error in this second case, as there are no directly available statistics for household energy consumption due to the radio in 1949 and the ICT/electronics in 2006. It may well be that the devices in 2006 were switched on, on average, for more hours (or fewer) per day than radios in 1949.

4.4. Household Computer Use in the UK 2006–2012

A variation on this method of estimating ICT/electronics rebound effects is to look at the numbers of people who appear to have changed their practice with respect to ICT over a given time period. The proportionate change in this number may be used as a proxy for the proportionate change in energy consumption. In the UK, 22.3 million people are estimated to have used a computer daily in 2006, and 34.7 million in 2012 (Office of National Statistics, 2012). This represents an average annual increase of 7.6%, giving $B_E = 1.076$. Again assuming an average annual increase of 30% ($B_\varepsilon = 1.30$) in computer energy efficiency, a rebound effect estimation would be:

$$R = 1 + \frac{\ln(1.076)}{\ln(1.30)} = 1.28 \tag{13}$$

This represents a rebound effect of 128%, a little less than that for the total ICT/electronics usage in German households in 1996–2011.

4.5. Other Cases

As noted above, estimated global energy consumption of ICT was 710 TWh in 2007 and 930 TWh per year by 2012 (Malmodin et al., 2010; Lannoo, 2013). The annual growth rate of energy consumption was therefore 5.5%, giving $B_E = 1.055$. Again setting $B_\varepsilon = 1.30$, the rebound effect is 1.20, or 120%.

Cremer et al. (2013) estimate ICT electricity consumption per capita per year in the commercial sector in Germany at 0.19 MWh in 2000, growing steadily to 0.30 MWh in 2010. The represents an annual growth rate of 4.7%, giving $B_E = 1.047$. Again setting $B_\varepsilon = 1.30$, the rebound effect is 1.18, or 118%.

Baer et al. (2006) estimate ICT-driven electricity consumption in the US residential, commercial, and industrial sectors combined to be 110T Wh in 2001 and 140T Wh in 2006. This gives $B_E = 1.041$. Again setting $B_\varepsilon = 1.30$, the rebound effect is 1.15, or 115%.

Somavat and Namboodiri (2011) estimate the numbers of personal computers worldwide to have increased from 200 million in 1994 to 1400 million in 2010, an annual growth rate of 12.9%. Assuming the energy consumption of a personal computer in 2010 to be about the same as one in 1994, this would give $B_E = 1.129$. Again setting $B_\varepsilon = 1.30$, the rebound effect is 1.46, or 146%.

The US military is probably the world's biggest user of ICT/electronics, but it is difficult to obtain information about its equipment and corresponding growth rates. However Neuneck (2008), gives figures for the percentage of 'smart' compared with 'dumb' bombs dropped by the US military in four military engagements, from 1991 to 2003. As shown in Table 1, this increased from 10% in 1991 to 65% in 2003.

Although these proportions are significantly influenced by specific military goals, there is a clear trend. If these proportions were used as a rough proxy for the growth of ICT/electronics in the US military, this

Table 1
Percentage of 'smart' compared to 'dumb' bombs dropped in four US military engagements. Source: Neuneck (2008).

Engagement	Year	% 'smart' bombs
Desert storm	1991	10
Kosovo	1999	30
Afghanistan	2001	60
Iraq	2003	65

would represent an average annual increase of ICT/electronic energy consumption of 17%, giving a B_E of 1.17. Again assuming an annual average energy efficiency increase of 30%, this would indicate a rebound effect of 161%. This is high compared to other results, and it may be that there are drivers of ICT/electronics in combat technology that are not so strong in the more purely bureaucratic areas of the military, such as its payroll system.

The above results are displayed in Fig. 1.

5. Discussion

There has been a constant increase in the energy efficiency of ICT/electronics for 5 decades, mostly due to increasing miniaturization of integrated transistor circuits. This has been offset somewhat by an increase in energy consumption within CPUs roughly proportional to their clock speed, so that a fair value for average annual energy efficiency increase is around 30%. Taking into account the increases in total energy consumption in particular spheres of ICT/electronics use, this study has tentatively identified rebound effects ranging between 115% and 161%. Most of these are within or close to the range 120–130%.

In all the cases considered here, the steady increase in energy consumption has occurred because of changes in social practice and/or or social (or socio-technical) structure, which have come about as a result, it seems, of steadily increasing utility from ICT/electronics, made possible by steadily increasing energy efficiency. These efficiency increases have occurred alongside efficiency increases in size, cost and materials usage, but these are always bundled together, such that without the energy efficiency increases, the utility increases would not have occurred.

The notion of rebound effects due to changes in social structure was prefigured in Greening et al.'s (2000) concept of 'transformational' rebound effects. A biological-evolutionary metaphor was developed in Ruzzenenti and Basosi (2008a, 2008b), and this offered an approach to dealing with transformational rebound effects that broke free of the direct/indirect/economy-wide categorization that tends to dominate rebound effect literature. The biological-evolutionary metaphor was developed here in relation to ICT/electronics.

This model includes the notion of an evolutionary 'arms race'. In a more literal sense, the military is engaged in an ICT/electronics arms race, as it has been since at least the 1950s. This is seen in such areas as weapons guidance, early warning, communications, personnel detection, navigation, simulation training, data security and data hacking. All these involve changes in practice and social structure in order to fit with and make the most of the technological innovations.

For business firms the softer metaphor of competition is useful, as each firm needs to take advantage of new technologies relevant to its business goals, so as not to be eclipsed in the market by other firms. This, too, involves changes in social practice and structure. Higher educational institutions also act competitively, as each needs to utilize the best ICT/electronics to facilitate competitive research (and teaching) so as to improve rankings and win funding.

For households the most consistent theme is that of social inclusion. Households and individuals often need to embrace developments in ICT/electronics in order to stay connected socially, to keep up with cultural movements, and to perform basic household tasks effectively, such as shopping, booking travel, and doing regular banking.

Because energy consumption from ICT/electronics is relentlessly increasing, there are continual calls for step-changes in energy efficiency. Energy saving modes and features are increasingly common in computers. The US 'Energy star' label certifies a wide range of electrical products. Computers receive the label if they meet specific standards for 'off' and 'idle' modes, have efficient internal and external power supplies, and meet certain levels of efficiency in their operations. Hartenstein (2011) proposes a range of more radical changes to computer architecture and networking which could conceivably reduce ICT energy consumption more deeply. These include, for example, a complete re-design of computer architecture, away from the binary-based Von Neumann system towards architecture more closely resembling the functioning of the human brain. Meanwhile research in physics is attempting to develop a new generation of electronic componentry which would eclipse the transistor by utilizing spintronics, which, if it turns out to be feasible, would produce CPUs many orders of magnitude more energy efficient than today's integrated circuits (Chumak et al., 2015).

Yet as Hilty et al. (2011) point out, all the evidence to date is that efficiency increases in computing lead inevitably to energy consumption increases. The step-change in energy efficiency between the valve and transistor did not lead to less energy consumption in ICT/electronics but to more, as also with the transition from discrete transistors to micro-transistors embedded in silicon chips. Harnessing the energy-saving potential of efficiency-oriented ICT/electronics would only be possible, Hilty and colleagues maintain, if this efficiency increase 'is not used under conditions of seemingly unlimited resource availability'. Instead, they argue, there need to be 'exogenously imposed framework

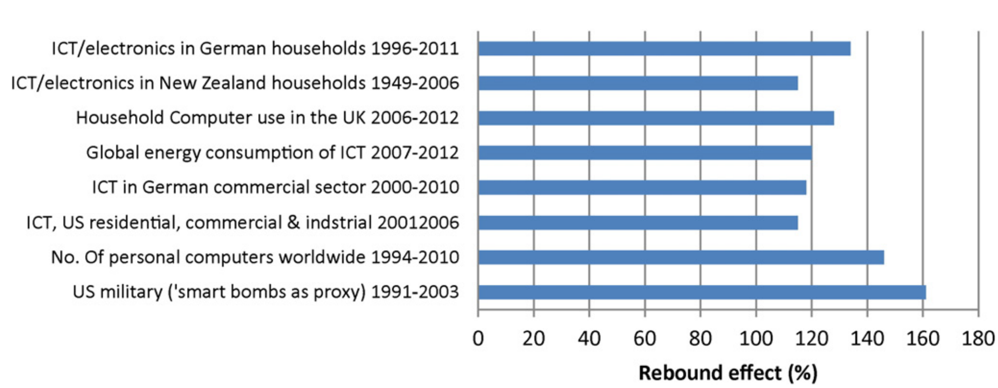

Fig. 1. Rebound effects in various spheres of ICT/electronics.

conditions' on ICT/electronics — regulatory restrictions on how much energy it may consume, within a framework of an effective scheme to put a price on carbon emissions.

6. Conclusions

This study explored how energy-related rebound effects can be conceived and estimated in the ICT/electronics sphere. Although elements of ICT/electronics are now embedded in a vast range of essentially non-electronic appliances, systems and production processes, the study focused on appliances which are first and foremost ICT/electronic devices (except for the military sphere, where bomb guidance systems were used as a proxy). The study argued that energy efficiency increases in ICT/electronics lead to changes in social practice and rearrangements of social and socio-technical structure, which demand or make room for more ICT/electronic appliances.

In the military this can be seen as an arms race, where defense establishments feel the need to develop and adopt cutting-edge ICT/electronics technologies, and restructure their organization and practices to accommodate these, in order to keep ahead of perceived threats. The notion of an 'arms race' is also a useful part of a more general biological-evolutionary metaphor for how increases in energy efficiency in certain spheres can lead to proliferation of more energy-efficient devices.

In the commercial and educational spheres developments in ICT/electronics feed on and enhance competition, where organizations need to continually upgrade and consequently restructure, in order to keep their edge in the market. Part of this market is households, which become targets of this competitive development. Within households themselves, however, competitive analogies do not seem to apply. Instead, developments in ICT/electronics change the technical elements in the socio-technical structures which facilitate interpersonal contact and daily tasks. Households and individuals need to embrace these new and ever more efficient technologies in order to stay socially connected, perform their daily tasks effectively, and keep up with what their culture is offering in terms of entertainment and information.

These social and structural changes lead to a proliferation of ICT/electronic devices, and this paper has tentatively suggested that rebound effects can be calculated based on the total energy consumption increases of these devices in any particular sphere.

The increase in energy efficiency, which has characterized ICT/electronics for over 5 decades, was estimated by a simplified description of how energy is consumed in an ICT/electronic device that uses Von Neumann architecture, which is common to almost all such devices. In reality this figure varies, with an average annual increase of between about 20% and 45%, and the figure of 30% was used in most of the empirical calculations.

All the empirical examples gave rebound effects above 100%, with most around 120–130% and the highest about 160%. As can be seen from Eqs. (7) and (8), the rebound effect will always be greater than 100% ('backfire') if there is an increase in energy consumption caused by an increase in energy efficiency.

Nevertheless, the terms 'rebound' and 'backfire' are used in this study with a degree of tentativeness. Although the proliferation of ICT/electronics, its associated social-structural changes, and its steadily increasing energy demands would not have been possible without large energy efficiency increases, these increases almost always go hand in hand with efficiency increase of size, materials and cost. There may also be further factors to do with diffusion of these devices, which have not been considered in this paper. The important point for policy, however is that increasing the energy efficiency of ICT/electronics is highly unlikely to reduce its energy consumption. In view of climate and energy saving policies, attempts to reduce the energy consumption of ICT/electronics are welcome. However, the history of ICT/electronics strongly indicates that it is an illusion to think that further or even radical energy efficiency increases will lead to reduced energy consumption in this sphere. It would appear that 'transformation' rebound effects, such as with ICT/electronics, require altogether different policy tools. These might include firm controls on permissible levels of energy consumption and CO_2e emissions. A strong, fully enforced carbon pricing system may be the best hope of reducing energy consumption in the ICT/electronics sphere.

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