Which Role for ICTs as a Productivity Driver Over the Last Years and the Next Future? (*)

Gilbert CETTE (**)
Banque de France;
Aix-Marseille University (Aix-Marseille School of Economics);
CNRS; and EHESS

Abstract: This paper deals with the role of ICTs in the recent productivity slowdown, and with their possible future impact on productivity in developed countries: the United States (US), the Euro Area (EA), the United Kingdom (UK) and Japan. Few papers analyze the recent slowdown of the ICT contribution to productivity growth, and these papers, which concern only the US, disagree, as it will be stressed, on some important aspects. Some of the main outputs of our analysis are the following: i) A dramatic productivity slowdown has happened in the U.S. and other developed areas since the early 2000s; ii) This productivity slowdown seems to be at least partly linked to a decrease of ICT, and more precisely of chip performance gains, and to the end of the ICT increasing diffusion as a factor of production; iii) A growing attention given by chip producers to reduce heat (or, in other words, power consumption) could have contributed to the chip performance (in terms of clock speed) slowdown; iv) Some big ICT improvements will happen in the future, the next operational probably being the 3D chip; v) Large productivity gains could also be generated from an extension of the use of available chip capacities in a lot of areas, since 2005 this development being called by ITRS the 'More than Moore' process; vi) Benefits from technological changes and from the 'More than Moore' process will partly depend on institutional appropriate changes, for example concerning regulations on the labor and product markets.

Key words: ICT, productivity, growth, innovation.

(*) This paper takes elements from the previous publication of CETTE (2014).
The author would like to thank, without implicating, Antonin BERGEAUD, Remy LECAT, Jimmy LOPEZ and Carole LY-MARIN for their help.

(**) The views expressed in the paper are my own and do not necessarily reflect those of Banque de France.

A productivity slowdown in all advanced countries from the mid-2000s [1], before the current crisis, is stressed by numerous papers. [2] Productivity growth is now very low, even nil in some countries, and, if it lasts, this situation will be alarming for a lot of reasons (for example for the difficulties to consolidate public finances). This productivity slowdown raises the question of a possible simultaneous one concerning Information and Communication Technologies (ICTs thereafter) productive performances. This link is strongly suggested by several empirical facts, as for example the slowdown of the decline of ICT price relative to GDP price (CETTE, 2014).

The next Section comments on productivity growth developments in the US, the EA, the UK and Japan from 1891 to 2013 with a specific focus on recent years. The following Section stresses the question of a possible responsibility of the slowdown of ICT performances on the productivity slowdown observed since the mid-2000s. Te 4th Section gives some elements of debate on ICT performance developments. The last Section concludes by raising the question of the future of productivity growth in developed countries and of the role of ICTs.

■ An impressive labor productivity slowdown since the mid-2000s

Different productivity indicators can be considered to characterize productivity growth, for example labor productivity (LP) or total factor productivity (TFP). We have chosen a LP indicator for two reasons: i) To make it simpler; ii) TFP indicator has suffered from particular fragilities in recent years from difficulties to evaluate the capital stock in the context of the current crisis. Nonetheless, the main stylized facts we are going to comment on would be the same with a TFP indicator. The LP indicator here considered is an hourly one, calculated by dividing the GDP by the total number of hours worked, itself corresponding to the product of the total employment by the average working time per worker. Data used are from

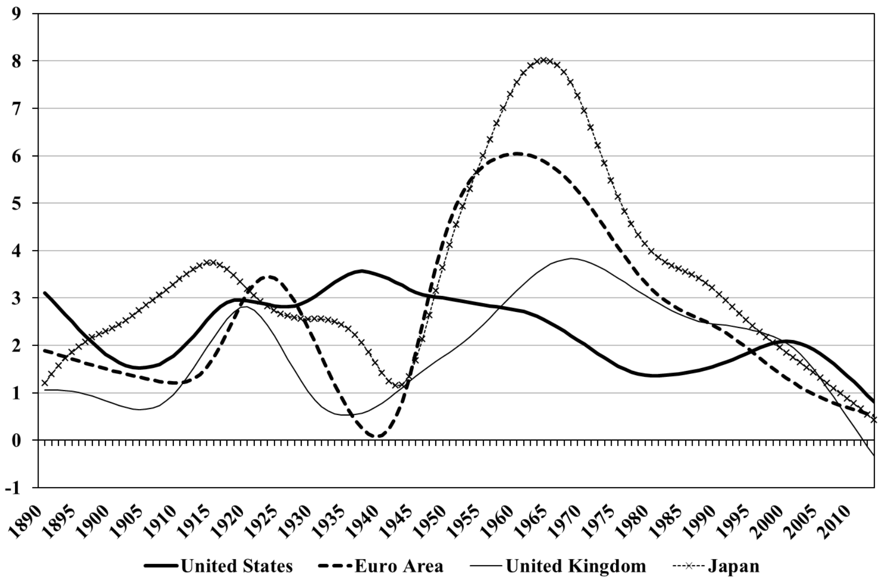
1 The productivity has accelerated in Spain from 2008, the beginning of the current crisis, for very specific reasons (see BERGEAUD, CETTE & LECAT, 2014).

2 See for example for the United States, GORDON (2012, 2013, 2014) or BYRNE, OLINER & SICHEL (2013), and for all advanced countries CRAFTS & O'ROURKE (2013), or BERGEAUD, CETTE & LECAT (2014).

BERGEAUD, CETTE & LECAT (2014).[3] These data allow us to characterize productivity growth and levels at the macroeconomic level in the main industrialized countries and areas over a long period, more precisely from 1890 to 2013.

Figure 1 represents the smoothed labor productivity (LP) growth of the US, the EA, the UK and Japan over the period 1891 to 2014. Over this long period, the stylized facts are well characterized by smoothing the growth of the LP indicator with a Hodrick-Prescott filtration (HP). To focus on long cycles, a value of 500 is chosen for the lambda coefficient of this HP filter. Table 1 gives the average annual growth rate of labor productivity per hour in the US, the EA, the UK and Japan on different sub-periods.

Figure 1 - Average annual growth rate of labor productivity per hour in the United States, the Euro Area, the United Kingdom and Japan
Smoothed indicator - Whole economy - 1891-2014 - In %



Smoothed indicator through Hodrick-Prescott filtering (λ = 500)

The Euro Area is here the aggregation of Germany, France, Italy, Spain, the Netherlands, Belgium, Portugal and Finland. These eight countries represent together, in 2010, 93¼% of the total GDP of the Euro Area (16 countries in 2010).

Data source: BERGEAUD, CETTE & LECAT (2014).

[3] See this paper to get more details on stylized facts commented hereafter.

Table 1 - Average annual growth rate of labor productivity per hour in the United States, the Euro Area, the United Kingdom and Japan
Whole economy - 1891-2014 - In %

	United States	*Euro area*	*United Kingdom*	*Japan*
1890-1914	1.59	1.32	0.77	1.91
1914-1950	3.20	1.94	1.57	1.98
1950-1974	2.45	5.54	3.07	7.10
1974-1994	1.45	2.87	2.76	3.54
1994-2004	2.31	1.31	2.25	2.03
2004-2014	1.19	0.75	0.35	0.87

The Euro Area is here the aggregation of Germany, France, Italy, Spain, the Netherlands, Belgium, Portugal and Finland. These eight countries represent together, in 2010, 93¼% of the total GDP of the Euro Area (16 countries in 2010).

Data source: BERGEAUD, CETTE & LECAT (2014).

In the U.S. we observe the following stylized facts:

- At the end of the 19th century and the beginning of the 20th century, a productivity slowdown. It corresponds to the end of the 1st industrial revolution, itself mainly characterized by the increase of the use of steam energy in numerous industries (manufacturing, transportation…).

- During the 20th century, a long productivity growth wave of approximately ¾ of a century, corresponding to the 2nd industrial revolution, which was named "the one big wave" by GORDON (1999). The ascending part of this wave is affected by a transitory slowdown corresponding to the Great Depression, before WW2. GORDON (2012, 2013, 2014) characterizes the 2nd industrial revolution by four major aspects: the increase in the use of electricity for lighting and for powering motors, the increase of the use of the internal combustion engine in manufacturing and transportation, the development of chemicals, with petrochemicals and pharmaceuticals, and the development of communication and information innovation with telephone, radio, movies…

- At the end of the XXth and the beginning of the 21st century, a shorter wave of approximately three decades corresponding to the 3rd industrial revolution. The 3rd industrial revolution is related to the production and the increase in use of ICTs. This productivity improvement from ICTs has been stressed by numerous papers, for example by JORGENSON (2001) or JORGENSON, HO & STIROH (2006, 2008). The top of this productivity growth wave is located at the end of the 20th century and the productivity slowdown starts at the beginning of the 2000s, before the Great Recession, this fact already being stressed by previous studies, as for example BYRNE, OLINER & SICHEL (2013). The productivity growth impact of this

3rd industrial revolution appears to be shorter and smaller than the 2nd industrial revolution one.

What do we observe in the other main advanced economic areas? It appears that the productivity growth wave corresponding to the 2nd industrial revolution is interrupted in the EA, the UK and Japan from the 1930s and during WW2, but becomes higher than in the U.S. afterwards. In these three areas, the little wave, apparent in the U.S. and corresponding to the 3rd industrial revolution (the ICT one), is absorbed in the previous one corresponding to the 2nd industrial revolution or is too small to be visible. As in the US, productivity slows down and the smoothed productivity growth becomes even lower than in the U.S. from the end of the 1990s or the beginning of the 2000s. The 2nd productivity wave is bigger in the three areas than in the US, from a productivity level catching-up process during the golden age corresponding to the four decades following WW2.

The stylized facts commented above seem to give complete credit to the story proposed by GORDON (2012, 2013, 2014). The productivity improvements from the ICT technological shock would be smaller than the one from the technological shock associated to the 2nd industrial revolution. Furthermore, the 3rd industrial revolution would be declining, if not over. [4] These facts raise the fundamental question of a possible end of the productivity impact of the 3rd industrial revolution linked to the ICT technological shock. Such a perspective would have heavy consequences for the growth perspectives in these countries.

[4] Intangible capital improvements are sometimes associated to the third industrial revolution mainly linked to ICTs. Some components of intangible capital, as for example "Computerized information", could be considered as very close to ICT ones, but it is less the case for others as "Scientific R&D", "Other innovative property", "Market research & advertising", "Training" or "Organizational capital". We do not consider here these capital intangible components as part of the third industrial revolution, as they are not mainly technological. Growth behavior of these capital components differs to the ICT one: intangible capital does not slowdown during the 2000s, in the U.S. and European countries, and we observe on the contrary a huge decline of ICT capital from the early 2000s in these two economic area (see below). On intangible capital, see among others CORRADO *et al.* (2013).

End of the ICT spread and sharp slowdown of the ICT performances?

A technological shock as the ICT one may impact labor productivity in the medium to long run through different channels (see JORGENSON, 2001 or CETTE, MAIRESSE & KOCOGLU, 2005, for a detailed presentation). First, it can accelerate the capital deepening process in the ICT user industries if it decreases the investment to output relative price. This channel can be reinforced by an enlargement of the ICT diffusion as a production factor, this enlargement being itself incented by the decline of the ICT relative price. Secondly, it can improve the TFP in three different ways: i) in the ICT producer industries, from the decrease of the output price, meaning that a same output value corresponds to more output volume; ii) in the ICT user industries in case of mis-measurement of the ICT production factor volume or of the output volume, or also in the case of mis-specification of the production function. This impact would correspond to what ABROMOVITZ (1956) named concerning TFP: "a measure of our ignorance"; iii) in both industries from externalities, network ones in particular, this impact being by definition "Manna from heaven", to use the expression from HULTEN (2000).

A candidate to explain the productivity slowdown commented in the previous section could be a sharp slowdown of the ICT capital deepening process from the early 2000s. [5] This sharp slowdown could have two consistent components: a lower decrease of the ICT relative price and a slowdown of the ICT diffusion as a factor of production.

If the productive performance of the investment is taken into account through the split of the investment value into investment price and investment volume, then the quality improvement of the investment should correspond, for a similar investment value, to a higher investment volume and a lower investment price. Quality improvements of investment are at least partly evaluated in national accounts through hedonic or matching methods. This is mainly done for ICTs, these investments benefitting more than others from performance improvements. From this, the investment price has declined relative to the output price over the last decades. [6]

---

5 BYRNE, OLINER & SICHEL (2013) show that the share of ICT producers in the U.S. economy declined since the early 2000s. This could have contributed also to the productivity slowdown, through the 3rd TFP channel evoked before.

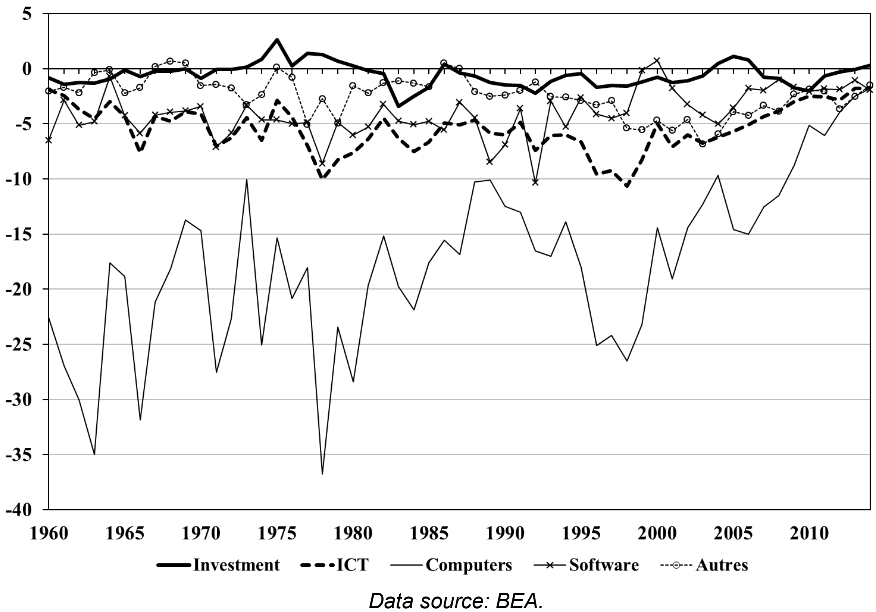
6 ICT price decreases play a large role to explain productivity growth from the end of the 20th century but are not specific to this period. For example, FERGUSON & WASCHER (2004,

Table 2 - Average annual growth rate of investment price relative to GDP price in the United States - 1959-2014 - In %

	1959-2014	*1959-1974*	*1975-1995*	*1995-2004*	*2004-2014*
Investment	-0.59	-0.48	-0.54	-1.05	-0.44
ICT	-5.49	-4.61	-6.17	-7.67	-3.35
Computers	-17.96	-22.70	-18.37	-18.99	-8.31
Software	-4.07	-4.45	-5.29	-2.96	-1.89
Others	-2.46	-1.31	-1.93	-5.01	-2.94

Calculation of the author from BEA original data

Figure 2 - Annual growth rate of investment price relative to GDP price in the United States - 1960-2014 - In %



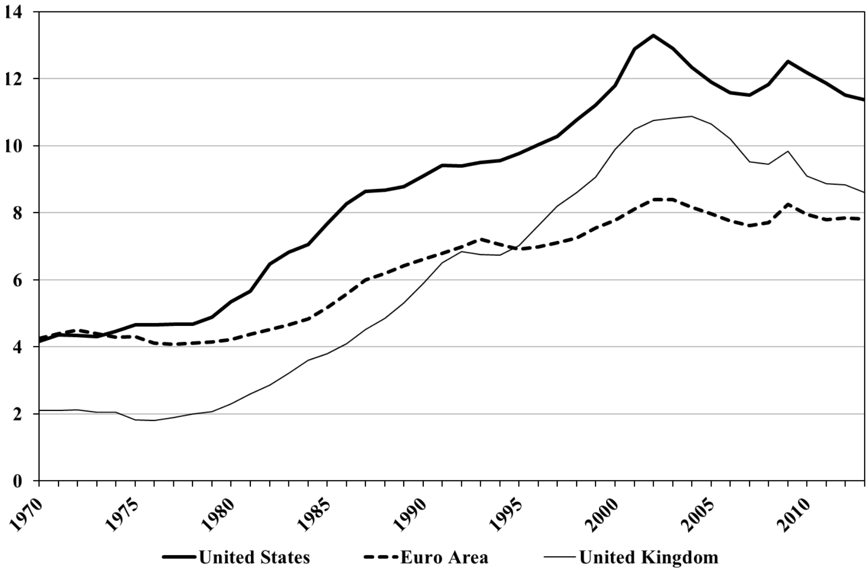
Data source: BEA.

Figure 2 and Table 2 report the average annual growth rate (in %) of investment price relative to GDP price, in the US, over the period 1959 to 2014. It appears that the investment price relative to the GDP price has

p. 8) relate that during the second half of the 19th century, "[…] telegraph aided the expansion of railroads by improving the coordination of rail traffic. But the ability to send messages rapidly over long distances also proved valuable in many other industries. Initially, sending a telegram was relatively expensive, with rates between New York and San Francisco averaging $7.45 for ten words or less in the late 1860s. By the late 1880s, rates for the same message had fallen to as little as $1.00." This telegram price change corresponds on average to an annual decrease of about -9.½% over two decades!

declined, on average, by 0.59% per year. This decline is mainly due to ICTs. It means that the technological shock corresponding mainly to ICTs has been the source, through its capital deepening impact, of an improvement of U.S. productivity over the period 1959 to 2014. And the global ICT impact on growth adds to this capital deepening channel effect the impact acting through the TFP channel, also from the ICT relative price decline. But the decline of the investment relative price is not constant: on average, it is per year -0.54% from 1974 to 1995, -1.05% from 1995 to 2004 and -0.44% from 2004 to 2014. These changes seem mainly due to the changes of the ICT relative price growth. Within the last sub-period 2004-2014, it appears that the investment relative price and the ICT relative price decreases continue to slowdown. It suggests that the productivity slowdown from the slowdown of ICT performances is quite continuous from the mid-2000s.

Figure 3 -Trends in the ICT capital coefficient in the United States, the Euro Area and the United Kingdom - 1970-2013 - In %



The capital coefficient is the ratio of ICT capital stock to GDP in current prices.

Source: CETTE, CLERC & BRESSON (2015) from OECD data.

The diffusion of ICTs is proxied here by the capital coefficient, defined as the ratio of ICT capital stock to GDP. This indicator can be constructed in value or in volume. Figure 3, from CETTE, CLERC & BRESSON (2015), gives the ICT capital coefficient in value in the US, the EA and the UK. [7] We observe that after the rather stable decade of the 1970s, the ICT capital coefficient in value rose in the 1980s and 1990s in the three areas. This rise means a growth in ICT diffusion which is linked to an increase in the use of these productive technologies. The ICT coefficient reached a maximum at the beginning of the 2000s and then stabilized in the EA, decreasing slightly in the U.S. and declining more in the UK. The peak at the beginning of the 2000s suggests a spurred investment effort associated with the fear of Y2K. The stability of the nominal ICT capital coefficient since the beginning of the 2000s has already been raised by CETTE & LOPEZ (2012). CETTE, CLERC & BRESSON (2015) confirm this result and show that the stagnation persisted during the crisis. The diffusion of ICT as a factor of production appears to have been stabilized for more than a decade, which is consistent with the productivity slowdown observed in the 2000s. The ICT capital coefficient in volume terms continuously increased over the entire period, the stabilization in value since the early 2000s being consistent with an increase in volume because of the relative ICT price decrease, even small these last years.

The stabilization of the ICT capital coefficient in current prices is at different levels depending on the country. ICT diffusion in the U.S. settled at a higher level than in the EA and the UK. The lag of ICT diffusion is considerable. By 2012, the U.S. had an ICT capital coefficient that was 30% and 25% higher than the in EA and the UK. Earlier analyses support this hierarchy of ICT diffusion. [8] Numerous studies provide explanations for these international differences in ICT diffusion, including the level of post-secondary education among the working age population as well as labor and product market rigidities. For example, an efficient use of ICT requires a higher degree of skilled labor than the use of other technologies. The required reorganization of the firm for effective ICT adoption can be constrained by strict labor market regulations. Moreover, low levels of competitive pressure, resulting from product market regulations, can reduce the incentive to exploit the most efficient production techniques. Numerous empirical analyses have confirmed the importance of these factors. [9] Among others, CETTE & LOPEZ (2012) show, through an econometric approach,

---

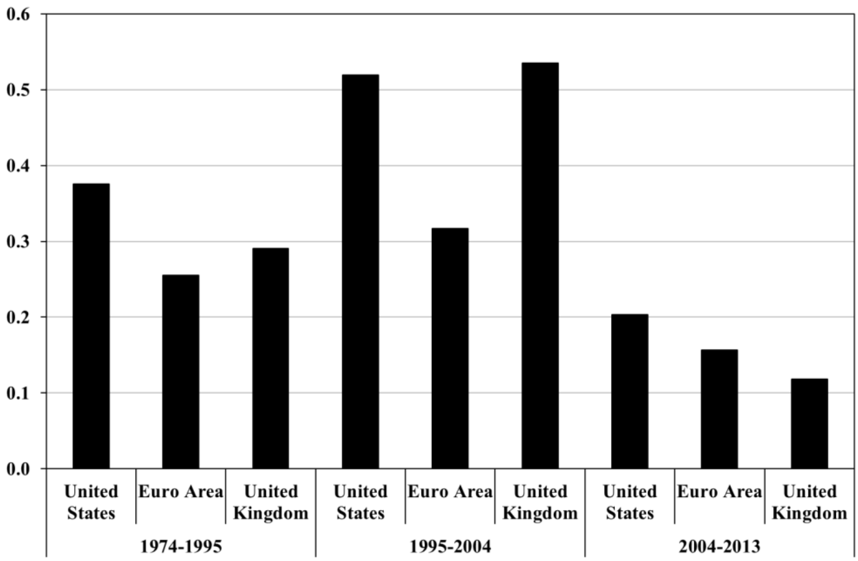
[7] From particular uncertainties, data concerning Japan are not commented in this study.

[8] See SCHREYER (2000), COLECCHIA & SHREYER (2001), PILAT & LEE (2001), van ARK *et al.* (2008), TIMMER *et al.* (2011), and CETTE & LOPEZ (2012).

[9] See AGHION *et al.* (2009), GUERRIERI *et al.* (2011) and CETTE & LOPEZ (2012) who use country-level panel data, as well as CETTE *et al.* (2013) who employ sectoral-level panel data.

that the U.S. benefits from the highest level of ICT diffusion because of a higher level of post-secondary education among the working age population and less restrictive product and labor market regulations. Using a growth accounting approach, CETTE, CLERC & BRESSON (2015) propose an evaluation of the ICT contribution to the productivity growth through the capital deepening channel. It appears that the 1995-2004 sub-period shows the largest contribution of ICT to labor productivity growth (Figure 4). The literature frequently emphasizes the large increase in the ICT contribution originating in the middle of the 1990s. [10] The increase is linked to the acceleration of the growth rate of ICT capital in volume, which is connected to ICT capital in value and to the relative price of ICT with respect to GDP.

Figure 4 - Contribution of ICT capital intensity to labor productivity growth in the United States, the Euro Area and the United Kingdom
1974-2013 - Average percentage points per year



Source: CETTE, CLERC & BRESSON (2015).

The decrease in the ICT contribution to labor productivity growth over the last 2004-2014 sub-period has been discussed for the U.S. by BYRNE *et al.,* (2013). It has also been observed in the EA and the UK (Figure 4). This decline is explained by a slowdown in the growth of the volume of ICT

10 See for example JORGENSON (2001), JORGENSON *et al.* (2006), or BYRNE *et al.* (2013), for the US, and CETTE *et al.* (2009), van ARK *et al.* (2008), or TIMMER *et al.* (2011) for different advanced countries.

capital, which is linked to both the stabilization of the ICT capital coefficient in value and to a smaller decrease in the relative price of ICT compared to GDP. This smaller decrease may signify, as noted earlier, a gradual exhaustion of the rate of improvements in ICT performances. So, this gradual exhaustion could have contributed to the productivity slowdown observed since the 2000s, before the Great Recession.

■ Elements of debate on ICT performance developments

The ICT performance improvements are mainly linked to semiconductor chips, which are intermediate components used in hardware and communication equipment. And among semiconductors, microprocessors are the most used ones. The performance of a microprocessor is usually appreciated through the number of transistors located on it. As the size of transistors decreases, this number can increase. Gordon MOORE, a cofounder of Intel, predicted in 1975 that the number of transistors located on a microprocessor would double every 2 years. This prediction is usually named 'Moore's Law'. [11]

PILLAI (2011) shows the performance improvement of microprocessors produced by Intel and AMD over the period 1971 to 2009. It appears that this improvement is quite regular until the beginning of the 1990s, when an acceleration happens. This acceleration ends at the beginning of the 2000s, and since, the improvement is back to its pre-acceleration path. The analysis of PILLAI (2011) ends in 2009 and cannot really perceive a possible new slowdown of Moore's Law since the mid-2000s, which would be consistent with what national account data tell us concerning ICT price growth over the very recent years.

AIZCORBE, OLINER & SICHEL (2008) and BYRNE, OLINER & SICHEL (2013, 2015) stress that the decline of the ICT price decrease, since the early 2000s, could be, at least partly and for microprocessors, a consequence of statistical mis-measurement. On semiconductor detailed data from Intel, BYRNE, OLINER & SICHEL (2013, 2015) use a hedonic approach to evaluate the semiconductor price changes. Their results are a

[11] Gordon MOORE expresses the principle of the continuous increase of the transistor number located on a chip already in 1965 (see MOORE, 1965). In 1975, he evaluates this increase to be a factor 2 (more precisely 1.96) every two years (see MOORE, 1975).

faster price decrease, since the beginning of the 2000s, than the price indicator calculated by the BLS by a matched approach-, that is used in national accounts. The explanation given for this difference is that, by the discount price behavior of Intel, chips are sold at a price below the catalogue price used to implement matched approach evaluation. [12] BYRNE, OLINER & SICHEL specify that the price index calculated from a hedonic approach is now in use, since March 2013, in the Federal Reserve calculation of industrial production indexes. From these results, they conclude that the improvement of ICT remains a strong engine of growth. [13] But their measure of chip quality is not limited to clock speed and includes several components.

These analyses are truly convincing about the slowdown of the chip price decrease observed from the early 2000s in the U.S. national account statistics, and which would mean a deceleration of the chip and ICT performances, being in reality, at least partly (in unknown proportions), related to a chip price mis-measurement.

Nevertheless, it has to be noted that a growing part of the research on spending in the chip industry has been devoted since the early 2000s to reducing the heat generated by the chips (or, in other words, to reducing the chip power consumption). This aspect is raised for example by the ITRS (2013b) [14] report or by BYRNE, OLINER & SICHEL (2013). [15] The growing

---

12 "[…] existing chips are being sold at a discount relative to the constant list price that widens when new models are introduced. Thus, to the extent that significant chip sales are taking place at transaction prices that fall ever further below the list prices, a standard procedure that relied on those list prices or other similar prices reported by manufacturers would be biased. Our hedonic index, which only uses prices at the time of each new chip's introduction, provides a very rough way of avoiding this potential bias." (BYRNE, OLINER & SICHEL, 2013, p. 32).

13 "Our results have important implications for understanding the rate of technical progress in the semiconductor sector and, arguably, for a broader debate about the pace of innovation and its implications in the U.S. economy. Notably, concerns that the semiconductor sector has begun to fade as an engine of growth appear to be unwarranted." (BYRNE, OLINER & SICHEL, 2015, p. 27).

14 "The heterogeneous integration of multiple technologies in a limited space (e.g., GPS, phone, tablet, mobile phones, etc.) has truly revolutionized the semiconductor industry by shifting the main goal of any design from a performance driven approach to a reduced power driven approach. In few words, in the past performance was the one and only goal; today minimization of power consumption drives IC design". (ITRS report, 2013b, Executive Summary, p. 3).

15 "However, as speed continued to increase, dissipating the gen¬erated heat became problematic. In response, Intel shifted away in the early to mid-2000s from increases in clock speed and boosted performance instead by placing multiple copies of the core architecture on each chip – a change enabled by smaller feature size – and by improving the design of those cores." (BYRNE, OLINER & SICHEL, 2015, p. 7).

attention given by chip producers to reduce heat could have contributed to a chip performance (in terms of clock speed) slowdown.

The ICT contribution to productivity growth must have also slowed down from the early 2000s because of the end of the ICT increasing diffusion in all advanced economic areas, if we evaluate this diffusion as above through an ICT capital coefficient indicator calculated in current prices. This diagnosis can be only slightly affected by the uncertainties in ICT price evaluation. Note again that this stabilization of the ICT capital coefficient in current prices corresponds also to a slowdown of an indicator calculated in constant prices since the early 2000s, when the decrease of the ICT relative price to GDP price itself slowed down.

■ To conclude: what future role for ICTs as a productivity growth engine?

The previous sections of this paper have raised several facts: i) A dramatic productivity slowdown has happened in the U.S. and other developed areas since the early 2000s; ii) This productivity slowdown seems to be at least partly linked to a decrease of ICT and more precisely of chip performance gains, and to an end of the ICT increasing diffusion as a factor of production; iii) A growing attention given by chip producers to reduce heat (or, in other words, power consumption) could have contributed to the chip performance (in terms of clock speed) slowdown. The question is of course: what to expect in the future concerning ICT performances and, consequently, productivity growth?

The contribution of ICTs in future productivity growth, let's say over the two next decades, is very uncertain. For this reason, optimistic or pessimistic scenarios are both realistic. GORDON (2012, 2013, 2014, 2015), for example, is very pessimistic and for him this contribution will be very low. BYRNE, OLINER & SICHEL (2013) propose two steady-state scenarios. In the first lower-bound one, ICT performance improvement, measured by ICT relative price growth, could keep about/almost? The same path as the one observed on average during the 2004-2012 sub-period. It means a slowdown of the ICT performance improvement compared to the 1995-2004 sub-period but also, slightly, compared to the 1974-1995 sub-period. But it also means an acceleration in comparison to what we have observed in the more recent years. In the second upper-bound scenario, ICT performance improvement could adopt a path intermediate to the one observed in the 1974-1995 long sub-period and to the one observed in the 1995-2004 favorable sub-period. The contribution of ICTs to future productivity growth (both from ICT capital deepening and from TFP in ICT producing sectors) differs by ¼ to ½ of a percentage point between these two scenarios. This gap is not so wide, and we could imagine more pessimistic scenarios than the lower-bound one (like GORDON proposes) but also more optimistic scenarios than the upper-bound one.

To add to this uncertainty, we can make both a pessimistic and an optimistic remark:

- The pessimistic remark is that, as shown by PILLAI (2011), in respect to the two-year option of Moore's Law over the last decades, the R&D spending in semiconductor manufacturing has grown at an impressive average rate. This evolution corresponds to an increase of R&D spending in the semiconductor industry by a factor 2,500 from 1970 to 2008. Such a progression could not remain sustainable, which means a slowdown in the future. This slowdown would have, as a consequence, a slowdown of Moore's Law and thus of the ICT performance improvement.

- The optimistic remark is that the semiconductor producers consider that some big improvement steps will happen in the future (see ITRS, 2013a, 2013b). The next operational one could be the 3D chip, which will allow fast ICT performance improvements for many years. [16] It has already started to be in process. [17] Other improvement steps, further in time and still more uncertain, could be quantum computing and biochips. Even only from the first step, the future contribution of ICT to productivity growth could be more favorable than the upper-bound scenario of BYRNE, OLINER & SICHEL (2013), and the U.S. could benefit from a second ICT productivity growth wave.

Beyond that, large productivity gains could be generated from an extension of the use of available chip capacities in a lot of areas. This development, called in 2005 by ITRS the 'More than Moore' process, has

---

[16] "By fully utilizing the vertical dimension, it will be possible to stack layers of transistors on top of each other and this 3D approach will continue to increase the number of components per mm² even when horizontal physical dimensions will no longer be amenable to any further reduction." (ITRS, 2013a, p 2).

[17] "The Flash 3D bit layer model was updated in 2013 to align with the recent introduction of a 24-layer 3D NAND device, processed at a relaxed 64nm process point. The 3D NAND range of layers was also updated, along with the anticipated trend of relaxed process technology reduction going forward." (ITRS, 2013b, Executive Summary, p. 9).

numerous potentialities, as stressed by ITRS (2013b), [18] CARBALLO *et al.* (2014) or INEMI (2015). PRATT (2015) gives some emphasis to the potential improvements for robotics and MOKYR *et al.* (2015) to the gains in research efficiency. The main future impact of ICTs on productivity growth will be driven, for these authors, by these potentialities. This explains also the optimistic approach from BRYNJOLFSSON & McAFEE (2014) who nevertheless emphasize the necessity of adapted institutions to get the real benefits from these potential gains. FERNALD & JONES (2014, citation from p. 48) suggest also that a possible acceleration of innovation could happen within the next decade, from "[…] the rise of China, India and other emerging economies countries, which likely implies rapid growth in world researchers for at least several decades."

In the non-U.S. advanced countries, the productivity growth could also be positively influenced, in the future, by a possible catch-up of the higher ICT diffusion level observed in the US. This catch up needs the implementation of structural reforms. From this, structural reforms may have a large impact on productivity growth, in the U.S. and also in other advanced countries (for recent analyses see for example BAILY, MANYIKA & GUPTA (2013) [19], for the U.S. and CETTE, LOPEZ & MAIRESSE, 2014, for the most advanced countries). It means that the future of productivity will depend, in all advanced countries, on technological progress (for example the productive use of the 3D chip), on the 'More than Moore process' but also on institutional changes from these structural reforms. [20] More precisely, benefits from technological changes and from the 'More than Moore' process

[18] "By nature, the More than Moore domain is multidisciplinary, involving expertise from many different areas, such as electrical and mechanical engineering, materials science, biology and medical science." (ITRS, 2013b, Executive Summary, p. 8).

[19] "Technological opportunities remain strong in advanced manufacturing and the energy revolution will spur new investment, not only in energy extraction, but also in the transportation sector and in energy-intensive manufacturing. Education, health care, infrastructure (construction) and government are large sectors of the economy that have lagged behind in productivity growth historically. This is not because of a lack of opportunities for innovation and change but because of a lack of incentives for change and institutional rigidity." (BAILY, MANYIKA & GUPTA, 2013, p. 3).

[20] CETTE, FERNALD & MOJON (2015) propose also a specific story concerning Italy and Spain. In these two countries, very low real interest rates from higher inflation rates than in other large Euro area countries, as Germany and France, was the source of capital miss allocation and low productivity growth from the 1990s to the Great Recession. Real interest rates are, since the Great Recession, comparable or even higher in these two countries than in Germany and France. From that, Italy and Spain could benefit from favorable capital reallocation and higher productivity growth. It seems that this process is already observable in Spain, which is the only one large developed country which benefits from an increase of productivity growth, and is starting in Italy.

will partly depend on institutional appropriate changes, for example concerning regulations on the labor and product markets. These changes have a large potential role to play to reduce some brakes on productivity, to tackle some headwind productivity threats and, concerning the non-U.S. countries, to help to catch up with the U.S. level of ICT productive capital diffusion. This gives room for economic policies to play an essential role for the future of productivity growth.

References

ARK, B. van, O'MAHONY, M. & TIMMER, M. (2008): "The Productivity Gap between Europe and the United States: Trends and Causes", *Journal of Economic Perspectives* 22 (1), pp. 25-44.

ABRAMOVITZ, M. (1956): "Resource and output trends in the U.S. since 1870", *American Economic Review*, Vol. 46, pp. 5-23.

AGHION, P., ASKENAZY, P., BOURLÈS, R., CETTE, G. & DROMEL, N. (2009): "Education, Market Rigidities and Growth", *Economics Letters* 102 (1), pp. 62-65.

BAILY, M. N., MANYIKA, J. & GUPTA, S. (2013): "U.S. productivity growth: An optimistic perspective", *International Productivity Monitor*, n° 25, Spring, pp. 3-12.

BERGEAUD, A., CETTE, G. & LECAT, R. (2014): "Productivity trends from 1890 to 2012 in advanced countries", Banque de France, Working paper, n° 475, February, forthcoming in the *Review of Income and Wealth*.

BRYNJOLFSSON, E. & McAFEE, A. (2014): *The second machine age – Work, progress, and prosperity in a time of brilliant technologies*, Kindle Edition.

BYRNE, D. M., OLINER, S. D. & SICHEL, D. E.:

- (2013): "Is the information technology revolution over?", *International Productivity Monitor*, n° 25, Spring, pp. 20-36.
- (2015): "How fast are semiconductor prices falling?", NBER Working Paper No. 21074, National Bureau of Economic Research, Cambridge, MA.

CETTE, G. (2014): "Does ICTs remain a powerful engine of growth", Presidential Address at the Annual Conference of the AFSE, *Revue d'Economie Politique*, Vol. 124, n°4, Juillet-Août, pp. 471-489.

CETTE, G., CLERC, C. & BRESSON, L. (2015): "Contribution of ICT diffusion to labour productivity growth: the United States, Canada, the Eurozone and the United Kingdom, 1970-2013", *International Productivity Monitor*, n° 28, Spring, pp. 81-88.

CETTE, G., FERNALD, J. & MOJON, B. (2015): "The pre-global financial crisis slowdown in productivity", mimeo, September.

CETTE, G., KOCOGLU, Y. & MAIRESSE, J. (2009): "Productivity Growth and Levels in France, Japan, the United Kingdom and the United States in the Twentieth Century," NBER Working Paper No. 15577, National Bureau of Economic Research, Cambridge, MA.

CETTE, G. & LOPEZ, J. (2012): "ICT demand behaviour: an international comparison", Economics of Innovation and New Technology, *Taylor and Francis Journals*, Vol. 21(4), June, pp. 397-410.

CETTE, G., LOPEZ, J. & MAIRESSE, J.:

- (2013): "Upstream product market regulations, ICT, R&D and productivity", Working paper No. 19488, National Bureau of Economic Research, Cambridge, MA, Forthcoming in the *Review of Income and Wealth*.
- (2014): "Product and labor market regulations, production prices, wages and productivity", Working paper No. 20563, National Bureau of Economic Research, Cambridge, MA.

CETTE, G., MAIRESSE, J. & KOCOGLU, Y. (2005): "ICT and potential output growth", *Economics Letters*, Vol. 87, Issue 2, pp. 231-234.

CARBALLO, J. A., CHAN, W.-T. J., GARGINI, P. A., KAHNG, A. B. & SIDDHARTHA, N. (2014): "ITRS 2.0: Toward a Re-Framing of the Semiconductor Technology Roadmap", Proc. Intl. Conf. on Computer Design, 2014.

COLECCHIA, A. & SCHREYER, P. (2001): "ICT Investment and Economic Growth in the 1990s: Is the United States a Unique Case?", OECD Science, Technology and Industry Working Papers 2001/07, OECD.

CORRADO, C., HASKEL, J., JONA-LASINIO, C. & IOMMI, M. (2013): "Innovation and intangible investment in Europe, Japan and the United States", *Oxford Review of Economic Policy*, 29(2), pp. 261-286.

CRAFTS, N. & O'ROURKE, K. (2013): "Twentieth Century Growth", Discussion Paper Series, CEPR, n° 9633, September.

FERGUSON, R. & WASCHER, W. (2004): "Distinguished lecture on economics in Government: lessons from past productivity booms", *The Journal of Economic Perspectives*, Vol. 18, n° 2, Spring, pp. 3-28.

FERNALD, J. & JONES, C. (2014): "The future of U.S. productivity growth", *American Economic Review*, Papers and Proceedings, 104(5), pp. 44-49.

GORDON, R. J.:

- (1999): "U.S. Economic Growth since 1970: One Big Wave?", *American Economic Review*, Vol. 89, No. 2, pp. 123-128.
- (2012): "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds", *NBER Working Papers* 18315, National Bureau of Economic Research, Inc.
- (2013): "U.S. productivity Growth: The Slowdown has returned after a temporary revival", *International Productivity Monitor*, Centre for the Study of Living Standards, Vol. 25, Spring, pp. 13-19.

- (2014): "The demise of U.S. Economic Growth: Restatement, rebuttal, and reflexions", National Bureau of Economic Research, Inc, NBER Working Papers, No. 19895, February.

- (2015): "Secular stagnation: a sully-side view", *American Economic Review*, Papers and Proceedings, 2015, 105(5), pp. 54-59.

GUERRIERI, P., LUCIANI, P. & MELICIANI, V. (2011): "The determinants of investment in information and communication technologies", *Economics of Innovation and New Technology* 20 (4), pp. 387-403.

HULTEN, C. R., (2000): "Total factor productivity: a short biography", NBER Working Paper, No. 7471.

INEMI (2015): "International Electronics Manufacturing Initiative 2015 Roadmap".

ITRS:

- (2013a): *International Technology Roadmap for Semiconductors*, 2012 edition update.

- (2013b): *International Technology Roadmap for Semiconductors*, 2013 edition.

JORGENSON, D. (2001): "Information technology and the U.S. economy", *The American Economic Review*, Vol. 91, March, N°1.

JORGENSON, D., HO, M. & STIROH, K.:

- (2006): "Potential Growth of the U.S. Economy: Will the Productivity Resurgence Continue?", *Business Economy*, January.

- (2008): "A Retrospective Look at the U.S. Productivity Growth Resurgence", *Journal of Economic Perspective*s, Vol. 22, Winter, No. 1.

MOKYR, J., VICKERS, C. & ZIEBARTH, N. L. (2015): "The history of technological anxiety and the future of economic growth: Is this time different?", *Journal of Economic Perspective*, Vol. 29, No. 3, Summer, pp. 31-50.

MOORE, G.:

- (1965): "Cramming More Components onto Integrated Circuits", *Electronics Magazine*, Vol. 38, No. 8, April 19.

- (1975): "Progress in Digital Integrated Electronics", IEEE, *IEDM Tech Digest*, pp. 11-13.

PILAT, D. & LEE, F. (2001): "Productivity growth in ICT-producing and ICT-using industries: a source of growth differentials in the OECD?", OECD Science, Technology and Industry Working Papers 2001/04, OECD.

PILLAI, U. (2011): "Technological progress in the microprocessor industry", *Survey of Current Business*, February, pp. 13-16.

PRATT, G. A. (2015): "Is a Cambrian explosion coming from robotics?", *Journal of Economic Perspective*, Vol. 29, No. 3, Summer, pp. 51-60.

SHREYER, P. (2000): "The contribution of Information and Communication Technology to Output Growth: A Study on the G7 Countries", OECD Science, Technology and Industry Working Papers 200/2, OECD.

TIMMER, M., INKLAAR, R., O'MAHONY, M. & ARK, B. van, (2011): "Productivity and Economic Growth in Europe: A Comparative Industry Perspective", *International Productivity Monitor* 21, Spring, pp. 3-23.