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Are we entering the age of involuntary degrowth? Promethean technologies and declining returns of innovation

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A R T I C L E I N F O

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A B S T R A C T

Any reflections on an eventual transition towards a degrowth society have to take into account the current crisis in the dominant system and question whether the latter will be able to grow again or not. In order for the latter to happen, the role played by technological innovation is crucial. This paper starts by reconsidering Georgescu-Roegen's definition of Promethean Techniques and Tainter's principle of Declining Marginal Returns, with the aim of providing – within the common framework of the theory of complex systems - a sound theoretical basis for the analysis of the rise and fall of complex societies. The main purpose is to verify whether, after the last Promethean revolution, a "Great Wave" emerged or not. The second part of the paper presents an initial investigation into this hypothesis, using Total Factor Productivity growth as an indicator of (marginal) returns on innovation (1750–2015). Despite the limitations implicit in the use of this indicator, data show three cycles of innovation, corresponding to the first, second and third industrial revolutions, but of different magnitude and duration. In particular, the whole cycle that began with the first industrial revolution in England around 1750, reached a peak in the U.S. in the nineteen-thirties and later declined, following a trend that basically confirms the Great Wave hypothesis. Even recent innovations resulting from the ICT revolution, however considerable, do not seem capable of counteracting this long-term trend. Data on returns on innovation seem, therefore, to be coherent with evidence provided by research in other fields (energy, mineral resources, agriculture, health, education and scientific research), showing that advanced capitalist societies have entered a phase of declining marginal returns - *or involuntary degrowth* - with possible major effects on the system's capacity to maintain its present institutional framework.

1. The two contrasting meanings of degrowth

The term "degrowth" was coined as a provocative slogan in order to indicate a project for an alternative society, opposed to the dominant model based on unlimited growth (Latouche, 2014). However, the expression has since also been used as a synonym for recession, and decline, often with the aim of denigrating its advocate. Although Serge Latouche (2014) was quick to clarify that "degrowth does not mean negative growth", it is true that the two meanings currently coexist, creating inevitable confusion.

However, the fact that detractors of degrowth may use the expression in a different, negative sense does not signify that the idea of involuntary degrowth is without important analytical significance. Involuntary degrowth, by undermining the system's very capacity to sustain itself, creates the necessary conditions for opening up various possible scenarios (Bonaiuti, 2014), including that of "voluntary" (or serene) degrowth. Therefore, however disparate these two meanings of degrowth may be, the related processes remain very closely linked.

According to the declaration issued in Paris in 2008, degrowth signifies "a voluntary transition towards a just, participatory and ecologically sustainable society". It is precisely this "voluntary" process which has become the focus of debate and has also been covered in this Journal (Schneider et al., 2010, p. 511; Sekulova et al., 2013). On the other hand, all those processes (whether of a bio-physical or of a socio-economic nature) that restrict or slow down the continuous and stable growth of the system, increase its costs or reduce its benefits, can be considered the typical causes of trends of *involuntary* degrowth. When Georgescu-Roegen first used the term *décroissance* in the title of his 1979 book, he clearly intended the latter meaning. System dynamics, (Forrester and Forrester, 1971; Meadows et al., 1972), Ivan Illich's theory on (social) counter-productivity (1973), the analysis of societal and ecosystem

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metabolisms (Giampietro et al., 2011; Sorman and Giampietro, 2013) and Tainter's works (1988, 2006) on diminishing returns of past complex societies all offer important contributions to this perspective. Bonaiuti's book (2014) on the diminishing marginal returns (DMR) of today's capitalist societies can be considered a first attempt to sum up these contributions and draw some initial conclusions in this regard.

2. Promethean techniques and expansion phases

According to standard economics (in Georgescu-Roegen, 2011 sense), technological change is basically a continuous, uniform process (Solow, 1956; Romer, 1986). Innovation,[1] like nature, *non facit saltus*, as Alfred Marshall's (1961) motto states in the introduction to his *Principles of Economics*. This point of view, i.e. that technological progress is a continual flow wherein there is little point in distinguishing the characteristics and extent of every innovation, has recently become commonplace. Because after the Second World War indices have shown continual and stable growth, economists such as Maddison (1991) assumed that theories around long-term business cycles belonged to the past.

However, if we extend our outlook to the entire social-economic history following the First Industrial Revolution, it is hard to deny the idea that periods of rapid expansion are generally followed by slack phases. According to Joseph Schumpeter, behind these long-term phases of expansion there are always some epoch-making innovations (Schumpeter, 1939),[2] that is to say, innovations that cannot be obtained through incremental variations on what previously existed. In this regard, Georgescu-Roegen (2011, p.161) used to recall his mentor's illuminating metaphor: "Add successively as many mail coaches as you please, you will never get a railway [engine] thereby".

A new way of combining inputs, a new method of production or the application of a new scientific discovery all boast the characteristics of the *novelty* and *irreversibility* that lie at the root of a process of innovation. This phenomenon is known in complex system theory as the "principle of emergence[3]".

The subsequent imitative processes (on the part of both other entrepreneurs and consumers) give rise to positive feedback, which is followed by a phase of exponential growth.

It was not, therefore, merely by chance that when the young Georgescu-Roegen arrived in Harvard in 1934, he was to catch the attention of Schumpeter precisely for his studies on the "cyclical components of a phenomenon" (Bonaiuti, 2011, p. 6). Forty years later, Georgescu-Roegen would return to this intuition of his master's, transferring it to the field and scale appropriate to bioeconomic processes with his notion of Promethean Technique. What characterises a Promethean Technique is, indeed, its capacity to open up a new phase of expansion.

In order to be defined as such, an innovation has to exhibit the following characteristics:

1) it permits a (new) qualitative transformation of energy (i.e. from chemical energy to mechanical work);
2) it generates positive feedback that permits it not only to maintain its own material structure but also to produce a surplus of (accessible) energy.

According to Georgescu-Roegen (2011, p. 154–7), during the evolutionary history of mankind only very few innovations seem to reflect these characteristics: the mastery of fire, the adoption of agriculture[4] and the conversion of fossil fuel into mechanical work.

Nowadays it is widely recognised that the controlled use of fire was a breakthrough: it provided small groups of hunters and gatherers with a means of cooking, producing warmth and light and gaining protection from predators. "The hominid fossil record suggests that cooked food may have appeared as early as 1.9 million years ago, although reliable evidence for managed fire use does not appear in the archaeological record until after 400,000 years ago" (Bowman et al., 2009, p. 481). Despite the fact that the later use of fire for making tools, thus changing the structure of various raw materials (first clay, then metals), along with the effects of this on population growth, has so far been poorly documented (Brown et al., 2009), the use of fire remains unique to man and, at the same time, has led to an increase in the complexity of socio-technical organisation.

The second Promethean innovation was the development of agriculture. The adoption of agriculture around 10,000 years ago brought about a leap from small, social hunter-gatherer groups to more complex forms of social organisation (ultrasociality) based on the widespread division of labour. There is evidence that this coincided with an exponential increase in population: "Between 6000 and 4000 BCE the earth's population increased from about 7 million to over 30 million and may have reached 100 million by 2000 BCE". Although it was initially less efficient than the previous way of procuring food, and accompanied by major negative consequences (Diamond, 1997), the implementation of agriculture proved capable of producing a greater surplus of available energy (Gowdy and Krall, 2014, p. 182; 2015).

There is little doubt that the third innovation, the conversion of fossil fuel into mechanical work, marked a fundamental discontinuity in the evolutionary history of humankind. The exploitation first of coal, then of oil, opened up a new "entropic watershed" (Rifkin, 1980), making possible what Jacques Grinevald (1976) redefined as the "thermo-industrial" revolution. The population that grew by only 515 million from the beginning of the Common Era to 1750 increased nearly ten-fold in just 265 years from 770 million to 7.35 billion, revealing an unprecedented leap in scale (Biraben, 1979).

A periodisation of three great waves, each marked by the arrival of a new Promethean technology, might seem reductive. Momentous transformations, such as "the cognitive revolution",[5] in fact, do not seem directly related to a greater availability of energy. Yet we should neither attribute to Georgescu-Roegen's approach a determinism that has no part in it nor, even less, conclude that energy availability is capable of explaining the most significant conquests of our species. What the bioeconomic theory states is that more complex forms of social organisation necessarily require greater quantities of energy to sustain themselves (Tainter, 2006). In other

[1] The term 'innovation' has been defined in many different ways. Here it is generally considered a synonym for 'technological or social change'.

[2] Recently, Schumpeter's idea that long-term economic cycles follow the emergence of epoch-making innovations, has received renewed attention. See, in particular, the works of the International Institute for Applied Systems Analysis (IIASA), Ayres (1990), Marchetti (2010), and Perez (2002).

[3] As Anderson states in his 1972 Science paper "More is different", a new type of property emerges for every new level of complexity, and these new properties are as fundamental as the others. We may conclude that laws emerging on higher level of complexity are "new laws" that cannot be deduced from the fundamental laws of the previous level. See also Bonaiuti, 2014, p. 8–10.

[4] In most of his last papers, Georgescu-Roegen (2011) considers only two Promethean techniques: the mastery of fire and the conversion of fossil fuel into mechanical work. However, in what is probably his last paper (1993), he also included agriculture, a proposal that has since been developed by John Gowdy (Gowdy and Krall, 2014).

[5] By cognitive revolution one generally refers to (genetic) mutations that altered the inner wiring of *Homo sapiens* (around 70,000 years ago) enabling him to communicate in a new type of language which could not only convey information but also create imagined worlds (Harari, 2015).

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words, the arrival of a new Promethean Technique opens up a new frontier of possibilities, but does not determine their characteristics. It is, on the other hand, correct to state that the most significant changes in the complexity of social organisations actually occurred precisely after a new Promethean Technology appeared. Recent research has provided important new evidence supporting Georgescu-Roegen's hypothesis (Dunbar, 2014; Goudsblom, 2012; Glikson, 2013).[6]

The clearest proof of the arrival of Promethean technologies is, therefore, that of permitting a *leap in scale* in the complexity of the social and cultural organisations that rely on it (Bonaiuti, 2014, p. 26). The exceptional conditions necessary for this leap to be produced also explain why these types of innovations are so rare. If a leap in scale goes beyond a certain threshold new properties emerge and the whole social system reorganises itself around new norms and new institutions.

By being a cyclical model, therefore, Georgescu-Roegen's approach belongs to the same line of thought as the system dynamics developed by Forrester and Forrester (1971) and the Club of Rome (Meadows et al., 1972), or to Kondratieff waves used by Arrighi (1994). They all share the idea that biological and economic organisations are better described by "cyclical models" rather than those based on "unlimited growth" or "steady state" assumptions. However, Georgescu-Roegen's approach differs from the others in one significant way. Like other approaches within the complex system theory, he considered the economic process to be characterised by discontinuous and generally irreversible breakthroughs.[7] And (as we shall see) this is true in both the expansion and decline phases.

When Georgescu-Roegen developed his bioeconomic theory in the 70s, the EROI (Energy Returns on Investment) index (Cleveland et al., 1984)[8] had not yet become widely used, but it is possible to link this indicator to the classification of technological innovations proposed by Georgescu-Roegen (2011, p. 168–9). Not all *feasible recipes* (i.e. transformation processes that can be technically carried out) are of interest in bio-economic terms, only those with an EROI >1, which he defined as *viable technologies*, that is to say, those "capable of sustaining themselves as a living creature does" (Georgescu-Roegen, 2011, p. 169). Of the latter, only very few can actually be identified as "Promethean," that is those with an EROI far greater than 1 (I would say > 10).

For instance, cold nuclear fusion can be considered a feasible recipe (the reaction is indeed technically feasible) but it has never produced more energy than that employed in the process itself (Bardi, 2014). Not even renewables (wind, photovoltaic, geothermic) respect the above-described Promethean characteristics, or at least not completely (Cleveland, 2003). However much they are based on a new way of converting energy, and although their EROI - particularly that of photovoltaic cells has greatly increased since Georgescu-Roegen's time and is today between 6 and 12 (Hall et al., 2014) – these values (together with the diluted, diffused and discontinuous characteristics) do not seem capable of permitting a new leap in scale in social complexity.[9]

As we shall see, the U.S. economy would reach the peak in productivity in the 1930s, the same period in which the EROI of fossil fuels reached an extraordinary value of about 100. However, even when the 'Promethean Leap' took place, as in the early decades of the Industrial Revolution – bioeconomic theory suggests that the subsequent expansion phase will sooner or later come to an end (Georgescu-Roegen, 2011). But above all, the extraordinary leap in social complexity necessarily involves, as the Promethean myth suggests, a series of negative consequences that need to be analysed.

3. The "involuntary degrowth" of complex societies: the principle of diminishing returns

In order to complete the presentation of the theoretical foundations on which this analysis is based, it must be pointed out that a phase of decline or collapse in any particular society is not solely the outcome of the entropy law and/or the exhaustion of the material resources on which it feeds: it may originate in processes of a predominantly social nature.

This idea could already be found in classical works, such as those of Osvald Spengler (1926) and Arnold Toynbee (1947), although they were still replete with subjective, vague opinions. They frequently had recourse to terms such as the loss of 'worth', 'strength' or 'vigour' in order to evaluate civilisations' "decline". Despite the extraordinary effort applied to gathering historical evidence, even Toynbee's monumental comparative history of civilisations leaves itself open to similar criticism since it is unable to explain civilisations' decline in consistent, comparable, empirical terms.

In his seminal work, *The Collapse of Complex Societies* (1988), Joseph Tainter, an anthropologist and expert on complexity, reacts to these traditional approaches which he defines as "metaphysical", by basing his analysis of the rise and fall of a civilisation on sounder grounds. First of all, he concentrates on a clear relationship that exists, the one between the level of complexity of a social organisation and the returns that it is able to provide. In general, greater complexity means greater differentiation and specialisation of social roles, population growth, greater scale and hierarchy, increased technical abilities and an increasing flow of information.

The anthropological hypothesis behind this approach is that social organisations behave as *problem solving organisations*. They react to any new problem by increasing differentiation and specialisation, and they evolve by moving spontaneously towards greater levels of complexity. This anthropological hypothesis may not be fully adequate to describe hunter-gatherer societies (Sahlins, 1972), but it does seem to describe well the behaviour of modern industrial societies and, in certain conditions, even agricultural societies (Tainter, 1988; Gowdy and Krall, 2014). Innovation can be interpreted in this framework as a response of a society to new problems, in particular under competitive conditions at a societal level (Gowdy and Krall, 2014).

In differentiating and specialising, socio-technical organisations generally show an increase in complexity and hence also

[6] Recently Johan Goudsblom (2012), following Norbert Elias's analysis of civilisations, has proposed a periodisation based on three "socio-ecological regimes" (fire, agriculture and industrialisation), which identifies the same tipping points pointed out in the analysis proposed here. Even some paleoclimatologists have proposed a periodisation based on the same three stages, termed early, middle and late anthropocene (Glikson, 2013).

[7] In this sense the steam engine, for example, represents a sort of *hopeful monster* something completely new which cannot be reduced to earlier forms of transport that relied on the strength of animals. This idea was developed even in the biological domain by Goldschmidt (1933) and later by Gould and Eldredge, 1977 as the theory of punctuated equilibria. See also (Gould, 1986).

[8] The EROI, as we know, measures the relationships between the energy rendered by a particular source throughout its entire lifespan and the energy required to construct, maintain and dismantle its material structure.

[9] The greatest problems concern the setting up of the necessary infrastructures at a time when there is a reduction in the availability of total energy produced from fossils. In an important recent study, Sgouridis et al. show that the energy transition would "require installation of renewable energy plants to accelerate from 0.2 Tw/year in 2013 to peak between 6 and 10.2 Tw/year for an early or late fossil fuel phase-out respectively, in order for emissions to stay within the Intergovernmental Panel on Climate Change CO_2 budget recommendation". This clearly implies an acceleration in renewable installations from 30 to 50 times compared to the present rate. (Sgouridis et al., 2016).

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experience increasing costs associated with the management of this greater complexity. At the same time, once a certain threshold of complexity has been reached, any further increase in complexity engenders declining marginal benefits. Think, for example, of the introduction of a new medicine. The discovery of penicillin, a medicine which could be easily reproduced and whose benefits were innumerable, did not cost more than $20,000. Today, the introduction of a new antibiotic, besides involving far higher costs, presents fairly modest improvements in its therapeutic effects by comparison (Tainter, 2006). Needless to say, both processes (an increase in costs and a loss of marginal benefits) move in the same direction, feeding what Tainter (1988) defines as the principle of declining marginal returns (DMR).

What has been said thus far should be sufficient to clarify two fundamental points:

1) The principle of declining marginal returns cannot be reduced to economists' marginal productivity principle (although the latter may be considered a particular case of the former). The DMR principle generally operates on a wider temporal scale than that of the principle of marginal productivity and is multidimensional in nature. Behind expressions such as increasing "costs" or diminishing "benefits" there lies far more than what can be expressed in economic terms. The DMR principle undoubtedly includes not only all kinds of environmental and socio-psychological externalities (e.g. pollution, inequality, dissolution of social ties, etc.) but also a wide variety of negative effects, which cannot be expressed in monetary terms. Generally speaking, the introduction and maintenance of any innovation involves costs of adaptation, whether at a social level (for example, when new norms are introduced into public administrations) or at a technological one (Schumpeter's "creative destruction").
2) The principle of DMR describes a specific dynamic of social organisations (under biophysical/energetic constraints). This is its specific contribution: it is indeed capable of telling us something about the evolutionary dynamics of social systems which are facing increasing complexification. It is true that, theoretically, if we had infinite energy social organisations might well become more complex while avoiding, or compensating for, diminishing returns. However, besides the fact that in the present situation (in terms of population and pollution) infinite availability of energy is unlikely to be the solution to all our problems[10] (Kerschner, 2010), scenarios of unlimited (or even growing) availability of energy seem today to be highly improbable (Kerschner et al., 2013). In this framework, the DMR principle can thus provide a specific contribution in all those cases when the "fall" is not caused primarily by entropic degradation within an isolated system (as in G-R's approach) or by a reduction in the resources external to the system, as in Jared Diamond (2005) analysis of collapse. It can rather provide a contribution when negative effects are the consequences of a typical behaviour of social organisations which is one of increasing growth and complexification (where matter/energy inputs are constant or declining).
3) A process of "involuntary degrowth" (as a consequence of DMR processes) is not just a synonym for negative growth. Even though the two processes may be confounded in an initial phase, in actual fact there are some important differences. I would apply the term involuntary degrowth only if the system as a whole had passed the "first threshold of mutation" (T_0) (See Fig. 1). It is a multidimensional process that is measured on a different temporal scale from recession (decades, rather than years). Moreover, the most significant difference is that DMR processes generally lead to irreversible transformations. While a phase of recession is normally followed by one of recovery, a prolonged DMR phase usually leads to the system's collapse or to its reorganisation according to new rules. In this sense, Georgescu-Roegen's approach, like Tainter's, differs not only from standard economic models but also from cyclical models (such as Kondratieff[11] waves or Arrighi's model[12]), which do not foresee emergences or irreversible structural transformations.

4. The "great wave" hypothesis

At this point we can attempt to draw some generalisations and formulate some hypotheses. The arrival of a Promethean Technique usually gives rise to a phase of expansion. This phase is the one in which the benefits of investments grow proportionally more than costs (increasing returns) (up to point C_1 in Fig. 1). Once this first threshold of change has been passed, marginal benefits fall and costs rise, thus marking the organisation's entry into a phase of declining marginal returns. Therefore, every cycle of innovation can be described using a S-shaped curve, which is generally followed, once the second threshold has been passed (C_2), by a phase of decline in absolute terms.

In the case in which - by integrating the succession of various cycles as in Fig. 1 – a "Great Wave[13]" is obtained, it may be possible to draw some interesting conclusions. The first is that, in this case, the benefits that a certain society obtains from its own investments in complexity do not increase indefinitely. Once a certain threshold has been reached (T_0), the social organisation as a whole will enter a phase of declining marginal returns, that is to say, a critical phase, which, if ignored, may lead to the collapse of the whole system. In an earlier work, (using different data), I put forward the hypothesis that Europe, Japan and the United States passed this threshold at different times but most probably before the early 1970s (Bonaiuti, 2014).

Needless to say, neoclassical economists do not agree with this conclusion. They assume that technological progress (exogenous growth theory, Solow, 1956) or spill-over effects of a knowledge-based economy (endogenous growth, Romer, 1986) are generally capable of compensating for the declining returns of innovation (Sala-i-Martín, 2014). In his latest book Jeremy Rifkin, despite coming from a different background,[14] reaches similar conclusions. His position is interesting here because he completely overturns

[10] On the complex debate concerning energetic dogma, the Fourth Law of thermodynamics, etc., which saw the different positions of Georgescu-Roegen, Daly and Ayres, see the interesting paper by Kerschner (2010) and also Bonaiuti. (2011, p. 37–48).

[11] On the empirical evidence on long-term Kondratieff waves, see Korotayev and Tsirel (2010).

[12] According to Arrighi (1994) and Wallerstein (2004) the modern world system has been characterised by long hegemonic cycles of accumulation that started with the Italian cities of Genoa and Venice in the fifteenth century and terminated with the U.S. cycle of the twentieth century. Although it is a highly interesting alternative to standard theory, Arrighi's approach never took the bio-physical limitations of the economic process into due consideration. This major difference explains why his long-term cycles may continue indefinitely, without forming any "Great Wave".

[13] Robert Gordon (2000b), examining data on TFP, had already advanced the hypothesis of a "big wave" relative to U.S. technological innovation. Gordon's papers offer an important contribution to reconsidering the role of technological progress and an essential source for the empirical analysis of the U.S. slowdown. However, his approach operates within the standard macroeconomic analysis.

[14] Curiously enough, while in his first book *Entropy: A New World View* (1980) Rifkin enthusiastically embraced Georgescu-Roegen's approach, in later years he gradually modified his standpoint (Rifkin, 2000, 2014) until he reached diametrically-opposed conclusions.

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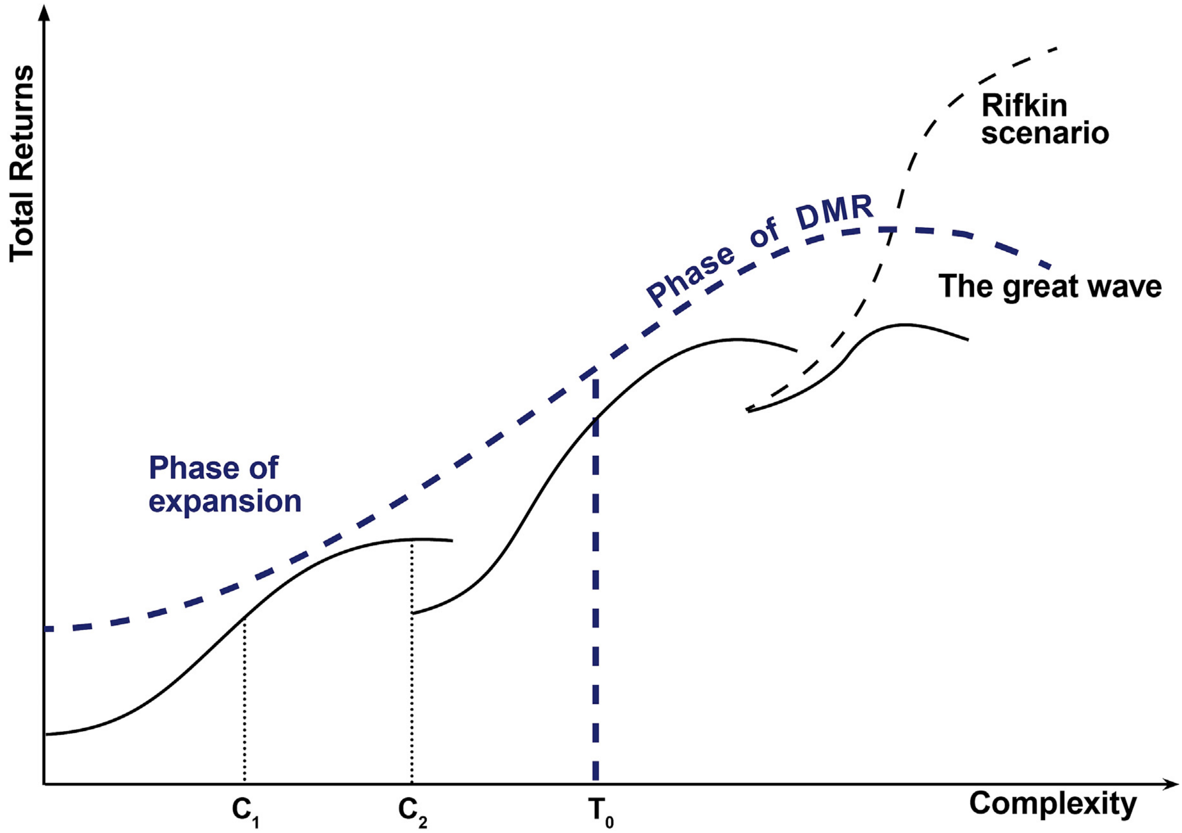

Fig. 1. The Cycles of Innovation following the Industrial Revolution: The Rifkin Scenario and the "Great Wave" Hypothesis.

the great wave hypothesis, speaking explicitly of the advent of a "near to zero marginal cost society". The Rifkin scenario is presented in Fig. 1. Clearly, in this scenario the system as a whole avoids declining returns since the boosts provided by the last cycle compensate for the slowdown resulting from the exhaustion of the preceding phase. Before discussing what the most plausible scenarios might be, it would be good to consider a few premises common to the different approaches:

Since in both kinds of scenario several S-shaped cycles can be observed, it becomes essential to individuate a starting point. This is precisely where Promethean innovations come into play. As we have seen, they can be merited with generating a discontinuity (an "entropic watershed", Rifkin, 1980) opening the door to a new "phase of expansion" (Fig. 1). Even standard economics recognises that the industrial revolution was a breakthrough. In our case, therefore, the starting point coincides with the widespread use of fossil fuels for powering machinery from around 1750.

Techno-scientific innovation and its benefits on the economy are generally considered to be the core drivers of the current socio-economic system. So, what evidence do we have concerning the returns on innovation[15]? There are not many studies able to provide meaningful answers to this question, particularly in the very long run.

The only research that shares the interpretative framework proposed here is probably the work carried out by Strumsky et al. (2010). They used the patents issued by the United States Patents and Trademarks Office to construct an index of the level of innovation and used the number of researchers involved in each patent as a proxy for the costs involved. The results reveal declining returns on an innovation over the whole period: the average size of research teams grew inexorably (48%), while the returns (measured in patents/inventor) correspondingly decreased (by 22% overall) (Strumsky et al., 2010, p.499). As Max Planck (1949) had already clearly stated, in scientific research the effort required to obtain further progress increases implacably. Strumsky, Lobo and Tainter's paper of 2010 was an important contribution to research into declining returns on innovation. Its limitation, however, is that the data therein only relate to the period after 1975, which is too brief to reveal the trend in the returns on innovation after the last Promethean revolution.

Despite considerable limitations,[16] it was decided to adopt Total Factor Productivity (TFP) (% of growth) as an indicator of (marginal)

[15] It must be clarified that even standard economics acknowledges how every single innovation (or even a sector of innovations) engenders declining returns. What is essential, therefore, is to analyse whether the process of innovation, taken as a whole, presents declining returns or not, a field of research that has hitherto been the subject of scanty enquiry.

[16] The use of TFP as an index of technological progress in a complexity framework presents considerable limitations. Some of these, concerning the measure and role of capital, were pointed out as early as at the time of the Cambridge Controversy by Piero Sraffa and Joan Robinson (Burmeister, 2000), demonstrating how the neoclassical theory of production presents problems of circularity and aggregability (scale). Besides these limitations that were already pointed out by the Austrian school, the greatest one, from a bio-economic point of view, is that TFP is calculated starting from data on GDP, hence not taking into consideration the different types of negative social and ecological externalities. At present, there are various kinds of indicators of well-being (e.g. ISEW or GPI) that present a better approximation of what we have defined as the "costs" (and benefits) of complexity (Bonaiuti, 2014, pp. 61–65). Unfortunately, we do not have historical series of these indicators from before the 1950s. It was, therefore, decided to use TFP series, despite the limitations, with the aim of attempting an initial estimation of a general trend, bearing in mind that many "costs" (but also some benefits) will probably be underestimated.

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returns on innovation. TFP is generally considered a measure of disembodied technological change, which should be taken broadly. The indicator shows growth in output not attributable to growth in conventionally measured (capital and labour) inputs (Field, 2009).

5. The three cycles of the industrial revolution and the great wave

Systematic measurements of TFP have been available, at least for Great Britain and the U.S.A., since the second half of the 1940s. For earlier periods I relied on Field (2009), who picked up and adjusted Kendrick's work (1961) concerning the USA. As far as the period following the Industrial Revolution is concerned (1750–1860), I used the data published by A'Hearn et al. (2014) concerning Great Britain.[17] The trend in the percentage variations in TFP growth obtained by assembling these indices (and calculating average values in order to compensate for short-term oscillations), is shown in Fig. 2:

The graph shows the presence of three cycles, which describe the first, second and third Industrial Revolutions (IR1, IR2, IR3)[18] respectively.

IR1 began in England in about 1750 thanks above all to the much-celebrated development of the coal-powered steam engine (Watt, 1769), and then its application to the railway system, the cotton industry (Hargreaves' Jenny, 1764) and to transportation on waterways. The construction of the railway network combined with the transcontinental telegraph network (completed in 1861), were probably the most important organisational innovations of the nineteenth century. The effects of these innovations on TFP growth would not be seen clearly until after 1830. This delay is explained by the time required for the adaptation and application of general purpose technology (like the steam engine) for specific uses, as well as by the minor role that the industries involved in the technological revolution initially played compared to the economy as a whole. Data (relative to Britain) show values increasing from 0.34 for 1800–1830, to 0.76 for the period 1830–1860.

The American economy felt the effects of the industrial revolution later, after the end of the Civil War (from 1870). Field (2009, p. 181) estimated that there was a strong average annual growth rate for private non-farm TFP of 1.95% from 1869 to 1892, moderating thereafter (from 1892 to 1919) to 1.1%. To summarise, the data pertaining to the variations in TFP (in the UK and U.S.) for the first industrial revolution (IR1) seem to conform to an S-Shape Cycle of the type shown in Fig. 1.

The second industrial revolution (IR2) commenced with the invention of the electric engine, electric light and internal combustion engine in about 1870. Interpreting data concerning the TFP of this period is complicated by the inevitable superimposition of the exhaustion of the effects of IR1. Productivity shows a faster growth between 1929 and 1941: it increased from an average 2.2% in 1919–1929 to a peak of 2.78% in 1929–1941 (Field, 2009). About 80% of the growth in TFP during the 1920s was due to increases in manufacturing productivity. Field, 2006 paper reveals how in the 1930s the increases in productivity span various sectors, not only manufacturing but also transportation and public utilities. In any case, the increases in TFP in the period 1929–41 were the highest of the whole of the twentieth century. It may seem strange that the greatest acceleration in productivity occurred at a time of an economic contraction, the 1930s. However, one must bear in mind that times of crisis are frequently periods of a sweeping transformation and productive reorganisation. It is not merely by chance that total employment in Research and Development in US manufacturing rose from 6274 in 1927 to 27,777 in 1940 (Field, 2006, p. 214). In particular, it is precisely in those very years that what is defined as Modern Business Enterprise reached maturity in the US, which availed itself of new, more efficient methods of the organisation of labour besides the widespread electrification of factories, with its extraordinarily beneficial effects on productivity.

In addition to the remarkable pervasiveness of this type of innovation throughout the whole productive system, its consequences on consumption and quality of life were equally relevant. According to Robert Gordon (2012), two innovations merit particular attention: first, the ability to pump water through a system of pipes (indoor plumbing) and, second, the advent of domestic electricity and lighting, which radically transformed urban life, with long-lasting effects on expenses in several sectors.

Once the peak of IR2 had been reached in the late 30s, the TFP of the American economy declined to about 2% in the years 1948–73. This relatively high value was upheld mainly by increases in the transport sector: the U.S. built its first interstate highway system in the 1930s, and the road network was largely completed from 1956 to 1973, leading to a five-fold increase in the quantity of goods transported by interstate trucking. Although average values remained high, the trend from 1948 to 1973 declined, following the decline in manufacturing. This negative trend then continued in the years 1973–1989 to reach a scanty 0.34% per annum, a datum that clearly shows that the long wave linked to the second industrial revolution was coming to an end.

However, before coming to any firm conclusions about the *Great Wave* hypothesis, it is necessary to consider the debate on the third industrial revolution and its capacity to compensate for the downswing we have seen.

6. The rise and fall of the ICT revolution

As we have seen, in his latest book, Rifkin (2014) supports the argument that we are moving toward a *near-to-zero marginal costs society*. Moving towards near-to-zero marginal costs implies, in actual fact, increasing returns. To Rifkin's mind, this new phase of expansion is assumed to pivot on a "single operating system" formed from two innovations: the ICT revolution and the new "smart energy grid" based on renewable energies.

First of all, it should be clarified that when Rifkin foresees a scenario characterised by a "near-to-zero marginal cost", he is not denying the decline in productivity linked to the exhaustion of the second industrial revolution. But he believes in the advent of a new, stronger and more pervasive revolution, which will make it possible to re-launch the productivity of the whole system.

By the term 'ICT revolution', we generally mean the body of innovation related to the diffusion of the Internet in the mid-1990s. However, if we look at it more closely, the elaboration of information by means of computers, with their capacity for replacing human labour, actually started much earlier. Mainframe computers were already being used to undertake routine, repetitive administrative work as early as the 1960s. Many electronic innovations, such as automatic telephone switchboards, punch cards, electronic storage systems, typewriters, etc., which were particularly useful in managing information in various sectors (banking, insurance, accounts and so on), were already widely employed before 1995.

Therefore, we also have in this case a long period when IR2's cycle of declining returns overlaps the emergent cycle of the third industrial revolution. Yet, if we examine the data pertaining to the

[17] I used data pertaining first to Great Britain and then to the U.S. because they represent the leading economies in the periods considered (GB for IR1 and the U.S. for IR2 and IR3 respectively); it is, therefore, reasonable to imagine that these were the first economies to enter a phase of declining returns.

[18] The anomaly concerning the reduction in the averages of TFP in the period 1941–48 can be interpreted as a consequence of the Second World War.

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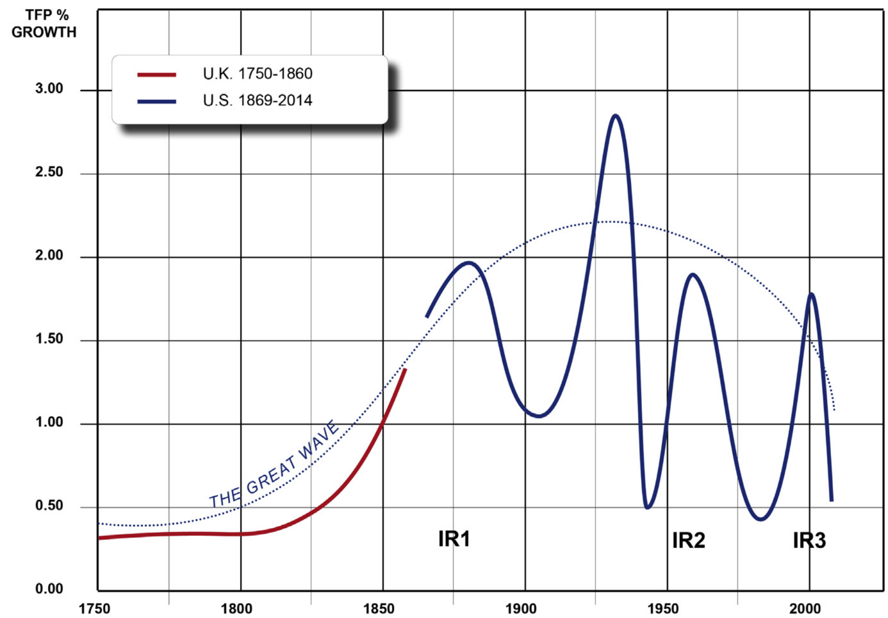

Fig. 2. TFP % – Private Non-Farm Business Sector (1750–2014).
Sources: From 1700 to 1860 Brian A'Hearn et al. (2014); from 1868 to 79 to 1948 Field (2009) Tab. 2 based on Kendrick (1961); from 1948 to 2014 U.S. Bureau of Labour Statistics (BLS). Private Non-Farm Business Sector. Data on the vertical axes are averages of TFP % change per year, calculated for the following periods: 1760–1800; 1800–30; 1830–60; 1869–92; 1892–1906; 1906–19; 1919–29; 1929–41; 1941–48; 1948–73; 1973–89; 1989–2000; 2000–05; 2005–14.

productivity of labour in the United States in that period, we can find no clear traces of any increase in productivity associated with the fledgling ICT revolution. This incongruence was noticed by Robert Solow who pointed out: "You can see the computer age everywhere but in the productivity statistics" (Solow, 1987). However, at that time, ICT applications were benefiting only a very small part of the overall American economy. The effects of the ICT revolution became, on the other hand, very marked after 1995. The increasing returns implicit in Moore's Law[19] made processors and their relative software more and more powerful and economically-inviting to an ever-expanding market. This was accompanied by the extraordinary development of Internet and e-commerce, a process largely completed in the U.S. by 2005. This expansion, and the huge investments that sustained it, raised the TFP of the U.S. economy to 1.52% (average from 2000 to 2005).

The 'New Economy' boom was welcomed enthusiastically by a whole army of commentators (Toffler, 1991; Negroponte, 1995; Rifkin, 2000) who already saw in this technological change a transformation that was more important than the one that had been brought about by the development of electricity or the internal combustion engine.

Ten years later, however, the picture seems to have changed radically: from 2005 to 2014, the rate of growth in TFP returned to pre-boom levels, to a mere 0.5%. Robert Gordon, who had already stated his reservations about the influence of the ICT revolution, concluded that "the productivity impact of IR3 evaporated after only eight years" (Gordon, 2012, 2015). This is indeed a very brief period if we compare it with over eighty years (1891–1972) when innovations made at the start of the second industrial revolution produced their effects, and consistently maintained productivity at over 2% per annum.

The detailed trend of TFP of IR3 is presented in Fig. 3. Here, too, data show the classic bell-shaped curve that we observed for IR1 and IR2, but the overall effect of IR3, both in peak values and even more in the total duration, is in no way comparable to that of IR2.

Source: U.S. Bureau of Labour Statistics (BLS). Private Non-Farm Business Sector. Data on the vertical axes are averages of TFP % change per year, calculated for the following periods: 1973–1989; 1989–2000; 2000–2005; 2005–2014.

There are also *theoretical* reasons for doubting IR3's ability to experience the effects of expansion of the size and duration comparable to those of IR2.

Unlike what happened in the First Industrial Revolution, the development of ICT has not seen an accompanying discovery of a new Promethean technology, i.e. a new qualitative transformation of energy (or a variation in the former one, as in the case of IR2). Moreover, the use of ICT is subject to (strict) limitations of *time*. There can be no doubt that the extraordinary variety of applications that is already available, and potentially will continue to be created, is in contrast to the fixed amount of time human beings can allocate to interacting with them. From the economic point of view this time limitation means that, in actual fact, every individual merely substitutes one application for another. Moreover, as far as ICT's ability to generate increases in demand is concerned, it is clear that many activities offered on the web, such as the chance to download information, books, music, videos, etc., are frequently *substitutes* for economic activities that were previously carried out in traditional ways. The same logic applies to e-commerce and to "business-to-business" activities. In the end, it all tends to be a zero-sum game (Gordon, 2000a).

There are also good reasons for thinking that the increases in productivity shown by IR2 were linked to the improvement in the average level of education which rose over a few decades from primary school level to secondary level, with the education system providing learning suited to the further development of the manufacturing system. It is difficult to imagine improvements as

[19] Moore's law (after Gordon E. Moore, the co-founder of Intel) is the observation that the number of transistors in an electronic integrated circuit doubles approximately every two years. Intel stated in 2015 that the pace of advancement has slowed since 2012.

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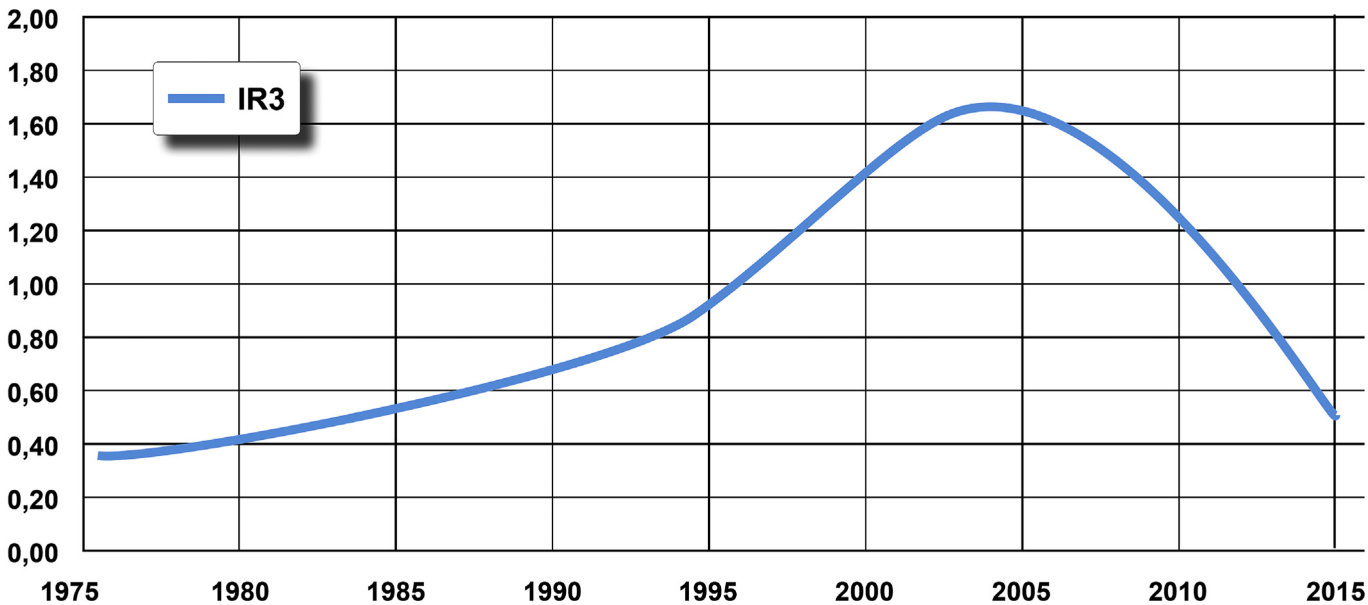

Fig. 3. TFP % – Private Non-Farm Business Sector (1975–2014).

significant today, in a context of rising debt and declining marginal returns in the educational system (Tainter, 2006; Cowen, 2011; Gordon, 2015).

The speed and capacity with which computers and smart phones have penetrated the market are undoubtedly extraordinary, but the author agrees with Robert Gordon, who states that they cannot withstand comparison with the arrival of electric light in homes, the automation of factories, the freedom to travel offered by the car or aeroplane, the use of plastic and, in general, of new chemically-produced materials, and last but not least, the huge improvement in quality of life achieved by urban sanitation and indoor plumbing (Gordon, 2000a, p.72).

In the last few years the economic slowdown has been noted even by standard economists who have started to speak openly of "secular stagnation"[20]. The basic idea is that, after the financial crisis, despite years of zero interest rate there are no signs of a satisfying recovery of the global economy. Recognising, as did Larry Summers (2014, 2015) and Paul Krugman (2014), that what we are experiencing is something quite different from an ordinary crisis, it is an important step that in some way legitimize the debate on *post-growth* society. However, the discussion on secular stagnation is rooted in standard macroeconomic theory. Even if from different perspectives, all these authors[21] advocate economic interventions aimed at stimulating a return to growth. Above all these analyses do not offer any indication of the length or magnitude of future cycles of innovation. As Georgescu-Roegen has already pointed out (Georgescu-Roegen, 1971, 2011) standard economics lacks an evolutionary theory and, consequently does not even take into consideration the possible irreversible changes in the system (as degrowth supporters do). From this perspective the bioeconomic approach seems more promising: it does not only ascertain the slowing down of innovation processes, but offers an explanation of it, making it part of a more general hypothesis on the evolutionary trend of the system (the Great Wave), open to various possible future scenarios.

7. Conclusions

The concept of Promethean Technologies is one of Georgescu-Roegen's fundamental contributions to bioeconomic theory. It reveals how the process of innovation is not only the outcome of small incremental variations but is also the result of discontinuous, epoch-making innovation. Since greater complexity requires more accessible energy, Promethean technologies are the only ones capable of producing a leap in the scale of complexity of human societies.

Tainter's principle of Diminishing Marginal Returns, on the other hand, offers a basic understanding of societal dynamics as a consequence of increasing complexity. Increasing complexity leads, in fact, to diminishing returns. By integrating G-R's bio-economic view with Tainter's principle of diminishing returns, the author has formulated the hypothesis that, after the Promethean/Industrial Revolution returns on investment in complexity follow a "Great Wave" trend.

The second part of the paper offers an initial enquiry into the Great Wave hypothesis, using Total Factor Productivity as an indicator of returns on innovation. The analysis of data shows that the period after the Industrial Revolution can be divided into three large cycles (IR1, IR2, IR3), and that each cycle presents a S-shaped trend, albeit of a different magnitude and duration.

In the US the application of coal/steam-engine/telegraph technology stimulated a rapid increase in productivity, reaching a peak between 1869 and 1892 (at almost 2%). Yet it was to be the great innovations of the second industrial revolution (the electric engine and the internal combustion engine) with their momentous potential both for manufacturing and domestic consumption (electric light, indoor plumbing) that took TFP values to their peak (2.78%) and, more than that, *kept* them high (at around 2%) for at least another 25 years, thanks in particular to innovations in the transport system. However, after the peak in the 1930s productivity

[20] The debate was started by Larry Summers in late 2013, on the occasion of an official meeting of the IMF, reviving a concept first proposed by Hansen in 1939. See the volume edited by Teulings and Baldwin (2014).

[21] Starting from a few shared facts (slow growth rates and the problem of 'zero bound interest rates'), several authors have mainly concentrated on the demand side and therefore on the new role played by fiscal and monetary policy (Summers, 2014, 2015; and Krugman, 2014), while others, like Gordon, 2014, 2015, have focused on the supply side and related 'headwinds' (population growth slowdown, education, etc.).

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decreased until it reached a modest 0.34% in the period 1973–95. Although the use of computers and ICT has led to a significant revival of productivity, both the empirical evidence and theoretical reasons lead one to conclude that the innovations introduced by IR3 are not powerful enough to compensate for the declining returns of IR2.

This of course does not exclude the possibility that a new expansive cycle may follow the decline of IR3. What the Great Wave hypothesis suggests, however, is that - without the intervention of a new Promethean technology - it is likely to be less influential, and briefer, than the previous one: a conclusion that it would be impossible to draw by applying the instruments of standard macroeconomic theory (Summers, 2014, 2015; Krugman, 2014; but also Gordon, 2015). This is the reason for emphasis having been placed here on a few bio-economic concepts and on complex system theory.

In short, an analysis of TFP data for the three cycles after the Industrial Revolution seems to be consistent with the hypothesis of a Great Wave. This means that the U.S. economy seems to have reached its first threshold of mutation - and hence entered a phase of diminishing returns on innovation -in the thirties. This conclusion, moreover, thus appears to be consistent with evidence from research in other fields, i.e. energy (Hall et al., 2008), mineral resources (Bardi, 2014), agriculture (Coelli and Prasada Rao, 2005), health, education and scientific research, (Tainter, 2006; Strumsky et al., 2010), demonstrating that advanced capitalist societies (the U.S., Europe and Japan) have entered a phase of declining marginal returns or *involuntary degrowth* in many key sectors (Bonaiuti, 2014), with possible major detrimental effects on the system's capacity to maintain its present institutional framework.

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