ENERGY, EROI, AND ECONOMIC GROWTH IN A LONG-TERM PERSPECTIVE

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EXTENDED SUMMARY

MOTIVATION

In the early twenty-first century, perhaps more than ever before, people are inquisitive about how wealth is created in a given society, what causes it to rise and fall, and how it is distributed among people. Set against the scale of human history as a whole, these questions are in fact quite recent. For centuries, theologians and political philosophers were attracted rather by reflections about whether social harmony and individual freedom could be compatible. It is only in the last two hundred years or so that *economics* has come to be identified as a distinctive scientific field, the purpose of which is to study how the natural propensity of people to truck, barter, and exchange (Smith 1776) manifests itself at the aggregate level.

What people truck, barter and exchange are goods and services that ultimately come from the transformation of raw materials from nature. By convention, value added is positively accounted for during the successive processing of intermediate materials into final goods and services, and the aggregation of all value added represents the total output of the economy. ***Economic growth*** formally represents the annual rate of growth of the macroeconomic output (generally the gross domestic product, or GDP) and the question of its origin and evolution remains the deepest mystery of economics.

Many people, consciously or not, seem to consider that economists alone can legitimately try to answer these two fundamental questions: Where does economic growth comes from? Why are some countries much richer than others? This attitude toward partitioning complex problems is really recurrent in modern societies. Because questions become increasingly specific and require more detailed knowledge than ever, science has been divided into multiple disconnected areas that all try to carry out precise investigations. But multipolar approaches are needed in order to respond intelligently to such complex societal questions. The aim of this thesis is to give more space to the diverse interactions that innately exist between history, economics, natural sciences, mathematics, and physics, in order to address the essential question of the origin of economic growth.

The basic representation of human society that economists have gradually conceptualized is highly surprising: it is a productive system creating goods and services using people's labor and the past accumulation of physical and human capital, without the clear necessity to use raw materials. For most mainstream economists, the possibility of increasing economic output is primarily defined by the combination of available factors of production (labor, physical and human capital) with *technological change.*[1] Economists have difficulties in precisely defining what technological change is and explaining where it comes from, but it is surely an essential component of the economic process. Furthermore, since technological change has always been increasing in the past, mainstream economists generally assert that there is no reason to think that it will not continue to do so.[2]

But even mainstream economists recognize that technological progress and the accumulation of production factors are only *proximate causes* of growth (if not partial consequences). These factors direct the economic growth process in the short run, but they cannot explain why approximately two hundred years ago some privileged regions (Western Europe and North America) underwent an Industrial Revolution that launched them on a path of relatively sustained high growth rates compared to the previous millennia during which all regions of the world were trapped in a state of Malthusian near-stagnation. One of the most important questions, if not *the* most important question in economics is to understand why these precise regions of the world escaped from Malthusian stagnation at an early date through industrialization, whereas others have had a delayed take-off and seems to be catching up more or less rapidly (respectively Eastern Asia, South and Central America on the one hand, Africa and South Asia on the other). To explain this phenomenon of *Great Divergence*, economists and historians think that some, so-called *ultimate*, but more properly *deep-rooted*, *causes* of a biogeographical, cultural, institutional, or accidental nature must be considered if we are to understand the process of long-term economic growth. Of course, scholars do not agree on the relative importance of these factors in explaining why some countries are so rich and others so poor. Endless debates have preoccupied economists/historians on this subject for the last two hundred years, and there have been attempts for some years now to finally build a *Unified Growth Theory* (UGT). As shown in this thesis, a really important aspect of the economic growth process has been forgotten, and that until acknowledged, every UGT will be flawed.

In really simple terms, a real human society is a productive system transforming natural resources into goods and services that people require to satisfy a given standard of living. And among all these natural resources that are mostly forgotten in mainstream economic theories, one in particular seems obviously primordial if the human productive system is to function: ***energy***. The first part of this thesis will show that the only possible ultimate or fundamental cause of growth is energy consumption, or more precisely ***useful exergy consumption***, which is the quantity of primary energy extracted from the environment, transformed into usable forms and dissipated by the economic process. The role of energy (more accurately exergy) must be properly understood to form the basis of a coherent UGT. Building such a comprehensive UGT

[1] Throughout this thesis the terms *technological change* and *technological progress* are used interchangeably. I see no apparent formal differences between the two but I usually prefer technological change. The reason is simply that for me technological *progress* contains a normative dimension in the sense that every technological modification would necessarily be better for the economic system and, *a fortiori*, for people's welfare, which I think is absolutely not true.

[2] The leading economic growth expert Philippe Aghion supports this idea in his numerous peer-reviewed articles and in this short French video: http://www.francetvinfo.fr/economie/croissance/video-est-ce-la-fin-de-la-croissance_809791.html.

is a long-term research goal and the present thesis should be understood as the first step along that path. For now, it is important to detail the research question investigated in this thesis and what it tries to accomplish.

RESEARCH QUESTION

If the role of energy consumption as the fundamental cause of economic growth is not well recognized among scholars, the addiction of modern economies to fossil energy resources has been clear in the public sphere since the two oil crises of the 1970s. Considering that fossil energy resources exist as stocks and are therefore ultimately limited in amount, considerable emphasis is now placed on the increasing need to use renewable energy forms. But it must be highlighted that a renewable energy resource is also constrained, not in terms of total recoverable quantity, but in the quantity available for a given time and in particular for a year. This question of the magnitude of a nonrenewable stock or a renewable flow of energy can be understood as the *availability* of energy resources. The different questions regarding the availability of energy resources and the supply mix that a country should choose have monopolized almost all economists and policy makers' attention regarding the potential of energy as an economic constraint. But economists have largely ignored another major concept: ***net energy***. Net energy is basically calculated as the gross energy produced minus the energy invested to obtain that energy. A derived idea of net energy is the ***energy-return-on-investment***, abbreviated to ***EROI***, which characterizes, not the availability, but the *accessibility* of an energy resource. The EROI of an energy resource defines the amount of energy that must be invested to exploit a given energy resource. It represents the difficulty of extracting *primary energy* from the environment and delivering it to society. But primary energy (coal, oil, gas, solar radiant energy, etc.) is of little use for the economic process as it must be converted into *final energy* forms (refined liquids, gas, heat, electricity) that are ultimately dissipated to provide *useful energy* services (light, heat, and motion). Moreover, across this array of energy forms (primary, final, useful), the fundamental laws of thermodynamics stipulate that only a part of the energy, which is called ***exergy***, is productive in the physical sense and hence can be used up in the economic process.

These notions have been conceptualized by pioneering thinkers in ecology and physics and applied to many different systems, including the economy. Yet, mainstream economists have ignored the importance of these concepts in their theories. The questions that immediately come to mind are: How can theories that disregard the physical essence of the economic system explain past historical growth? Why does mainstream economics ignore the importance of natural resources, and more specifically energy, in the growth process? Are energy availability and accessibility really important control variables of the economic growth process? Is it possible to equate the aggregated technological progress of the economy with its primary-to-useful exergy conversion efficiency? To summarize, the fundamental research question of the present thesis is:

What is the importance of energy for economic growth?

This dissertation is composed of seven chapters over which two separate but related issues are explored. Chapters 1 to 3 form an original essay assessing whether net energy (exergy) has played a major role in the economic growth process so far, while Chapters 5 to 7 correspond to published papers investigating what the net energy (exergy) constraint could imply in a future where societies will ultimately have to make a complete transition towards renewable energy. With its central position, Chapter 4 provides some answers to both issues.

USEFUL EXERGY CONSUMPTION AS THE FUNDAMENTAL CAUSE OF GROWTH

The four main facts of long-term economic growth

Chapter 1 focuses on the description of the four main hard facts of long-term economic growth. The transition from stagnation to growth is visible in the growth rates of key variables such as per capita income, population density, fertility, and levels of industrialization and urbanization. The differential timing of the take-off from stagnation to growth among regions of the world and the associated variations in the timing of their demographic transitions led to the phenomenon called the Great Divergence. The initial take-off of England from the Malthusian Epoch was associated with the Industrial Revolution that started there in 1750–60, and then spread to Western Europe and the Western Offshoots (USA, Canada, Australia, and New-Zealand) during the first part of the nineteenth century. The economic take-off of Latin America and West Asia took place toward the beginning of the twentieth century, whereas East Asia and Africa’s economic take-offs were further delayed well into the twentieth century. Moreover, the human adventure seems (self-)organized in hierarchized-nested adaptive cycles that define both its structure and its dynamic functioning (Civilizational, Secular, Generational, Kondratieff, Kuznets, Juglar, and Kitchin cycles). Finally, it is clear that the improvement and diffusion of new technologies, such as general purpose technologies, are closely connected with energy consumption.

Deep-rooted and proximate causes of economic growth

This first chapter gives also a detailed description of the different so-called *ultimate* causes of growth that should preferably be termed *deep-rooted* causes. Several biogeographical factors undeniably had a deep-rooted influence on the timing of the Agricultural and Industrial Revolutions. Those biogeographical factors include favourable climatic conditions, size and orientation of major continental axes, length of the coastline with respect to the mainland size, and mostly the favourable location of primary exergy flows (biomass, then water and wind) and stocks (coal, then oil and gas). Cultural and institutional attributes are interlinked in an intractable endogeneity and seem to be the consequences more than the causes of economic growth and development. Finally, it is possible that some historical events (colonization, silver trade between the Americas and Europe and onward to China from 1500–1800) generated temporary constraints that might have prevented or delayed the economic take-off of several countries.

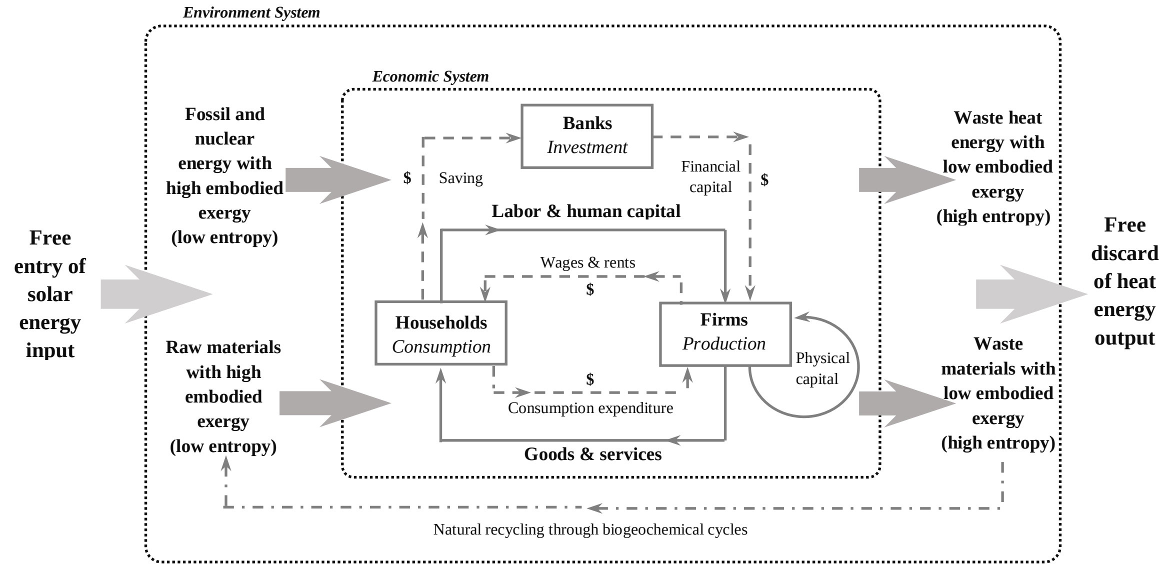
In order to have a more complete description of the economic growth process, Chapter 2 concentrates on the study of mainstream theories that focus on the state of sustained growth attained by industrialized countries. Despite a considerable literature, the proximate causes of economic growth of these theoretical economic models are always the same. They consist in the accumulation of physical and human capital, and the improvement in the efficiency of the economy to grow output from these inputs. This last variable is called technological change by mainstream economists and corresponds to a catch-all aggregation of many different features of the economic system that should in fact be regarded as consequences of economic growth, or at the very best, facilitating factors: the division and organization of labor, the broader organization and efficiency of markets, the improved skills of laborers, the contribution of information and communication technologies, but also the beneficial effects of inclusive institutions (which, for example, protect private property rights and consequently incentivize innovation and R&D). Without further clarification on this central concept, some researchers have recently tried to build a Unified Growth Theory (UGT) that was also analysed in this second chapter. This extensive review of all mainstream economic growth theories was indispensable to see that they fail to properly explain the growth process and that they are completely disconnected from any biophysical reality.

Exergy, entropy, and economic growth

Chapter 3 starts by analyzing the misguided reasons for overlooking natural resources, and in particular energy, in mainstream economics. Then, essential concepts such as exergy and entropy are described to explain that the first and second laws of thermodynamics always apply to the economic system and shape its functioning. Applying these fundamental laws to the economic system demonstrates that mainstream economists see the economy as a perpetual motion machine of the first kind, that is, a machine that performs work though endless cycles without any input of energy. Hence, the mainstream conception of the economic system is a conceptual artifact that can absolutely not exist in the real world. Energy makes up a small share of total production costs not because it is less important than capital or labor as a production factor, but rather because the biosphere and geosphere generate the physical free work that we use abundantly and free-of-charge.

As put by Atkins (2010, p.22), if the first law of thermodynamics was found to be false, “wealth–and untold benefits to humanity–would accrue to an untold extent”. The second law of thermodynamics is also essential to understanding that in reality the economic system is an open system (in the thermodynamic sense) that extracts and converts low entropy matter-energy into even lower entropy products and gives off high entropy wastes that are freely discarded in the environment (see Graphical synthesis 1). The unspontaneous decrease in entropy associated with the increasing order of matter from raw to refined materials in the forms of goods is only possible because an even higher amount of entropy production is associated with the degradation of exergy extracted from the environment. The biophysical approach shows that only useful exergy consumption can be considered as the fundamental cause of economic growth. The capacity to extract primary exergy from the environment and the ability to convert it with increasing efficiency into useful exergy services (in the form of light, heat, electricity, and mechanical power) is clearly the principal mechanism explaining economic growth.

Moreover, with such an approach, technological change can be precisely defined as gains in the aggregate efficiency of primary-to-useful exergy conversion. It is understandable, then, that structural limits of materials will define the ultimate limit of the aggregate technological level of the economy, and this ultimate limit might be closer than expected. In particular, the stagnation of the aggregate efficiency of primary-to-useful exergy conversion in industrialized countries since the 1970s seems to be an important cause of the slowdown in economic growth endured by those same countries for the last forty years. Moreover, a biophysical approach to the economic system shows that the so-called dematerialization of the economy, or decoupling of GDP, is a pure illusion that has no logical reality.



Graphical synthesis 1. The economic system as an exergy-degrading real machine.

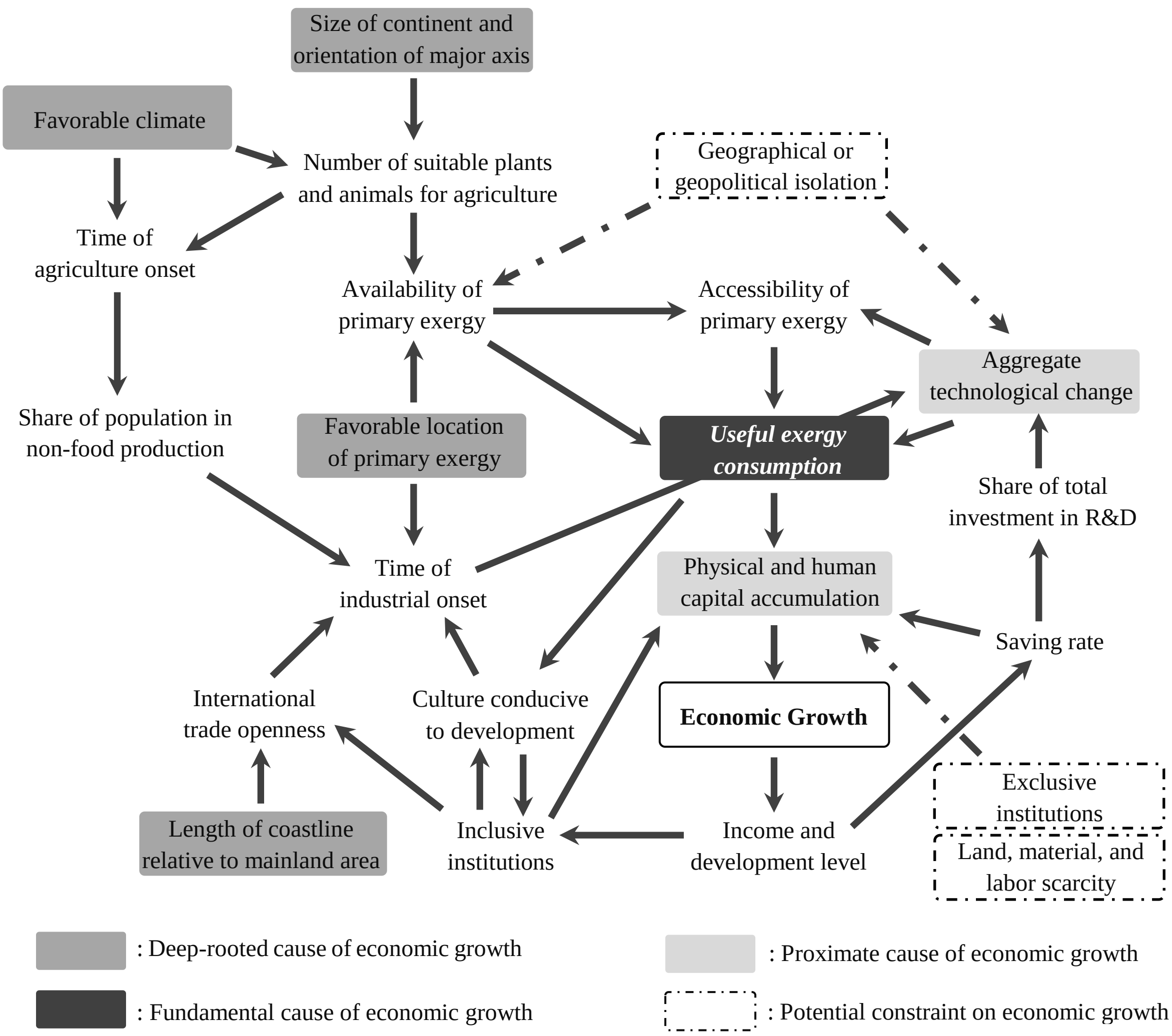
Useful exergy consumption and societal development

As Sieferle (1997) put it, "universal history can be subdivided into three parts. Each part is characterized by a certain energy system [foraging, farming, fossil fuels burning]. This energy system establishes the general framework, within which the structures of society, economy, and culture form. Thus, energy is not just one factor acting among many. Rather, it is possible, in principle, to determine the formal basic structures of a society from the pertaining energetic system conditions". Regarding the causal relation between systems of energy capture and value systems adopted by societies, it is important to stress that "it is not that individuals are caused to adopt values by their society's mode of energy capture. Rather, over the course of long stretches of history, and as a result of innumerable social experiments by inventive humans, the societies that are best organized to exploit available modes of energy capture–by their social structures, economic and political institutions, culture and values–will tend to prevail over and displace other societies that are less well organized. Social forms and the associated values that are ill adapted to human survival and comfort, given available technologies, will give way to more effective institutions and values" (Stephen Macedo in the introduction to Morris 2015, p.XIX).

In agrarian societies, economic growth depends on the capacity of people (that are often coerced as slaves or serfs) to extract increasing solar exergy in the form of food, fodder, motion (from water and wind exergy flows, which are derived from solar exergy), and woodfuel (here again indirect solar exergy), and on the ability to transform those primary exergy resources into useful exergy in the form of light, heat, and mechanical power. On the other hand, during the last two centuries, animal and human labor has been gradually replaced by fossil-exergy-activated machines which drove have driven down the cost of goods and services (in terms of the number of working hours required to buy such products) and have consequently increased demand and production. In current developed countries, this long-term substitution seems to have been the dominant driver of economic growth since the Industrial Revolution (Ayres & Warr 2009, p.168). More recently, transistors powered by electricity have started to further reduce biological limitations as they assist the human brain in processing and storing huge quantities of information. Hence, in modern industrialized societies, it is “exergy that drives the machines in mines and on drilling sites, in power stations, factories and office buildings, on rails, road and farms, in the air, and on the sea. In short, it activates the wealth-creating production process of industrial economies” (Kümmel 2011, p.37).

To sum up, the so-called *causes* of growth generally emphasized by standard economics, such as inclusive institutions (property rights protection, democratic expression), conducive cultural traits (scientific and hard-work spirits), Smithian features (market size, competition, variety of products, division of labor) and others (international trade openness), should more appropriately be regarded as facilitating factors and even consequences of growth. The fundamental cause of economic growth is useful exergy consumption, which is the combined capacity to extract primary exergy from the environment and the ability to transform it into useful services in the form of light, heat, electricity, and mechanical power. The differences between fundamental, deep-rooted, and proximate causes of growth and its consequences are summarized in the Graphical Synthesis 2.

The first part of this thesis (Chapters 1 to 3) highlights the adequacy of the biophysical/thermo economics approach for understanding the economic growth phenomenon. If conventional theories are unable to correctly explain the four long-term facts of economic growth (transition from stagnation to growth, Great Divergence, interdependence between technological change and energy consumption, and hierarchized-nested adaptive cycles dynamics), this thesis shows that, at least for the first three of them, the role played by energy in the economic system is primordial. Higher energy availability and accessibility are predominant in explaining that the onset of the Industrial Revolution occurred in Britain and not elsewhere. The local energy availability and accessibility, and the magnitude and time differences in the spread of technologies that enable an increase in the aggregate primary-to-useful exergy conversion efficiency have largely defined the direction of the Great Divergence. As a consequence, the future economic growth of countries will depend essentially on (i) the continued increase in the aggregate efficiency of primary-to-useful exergy conversion, and/or (ii) the continued increase in the extraction of available primary exergy resources. The former point has already been discussed but the later needs to be addressed in terms of net energy (exergy).



Graphical synthesis 2. Fundamental, deep-rooted, and proximate causes of economic growth.

NET EXERGY CONSTRAINT IN THE COMING CENTURY

Energy-return-on-investment as a measure of accessibility

The availability of an energy resource is given by its level of ultimately recoverable resource (URR) in the case of a non-renewable stock and its technical potential (TP) in the case of a renewable flow. However, the ease of extracting an energy resource, that is to say, its accessibility, is given by its energy-return-on-investment, or EROI. The EROI is a crucial indicator of development because all societies need energy resource that deliver more energy than is invested to use them. Furthermore, it seems logical to think that all different types of societies have a notional minimum EROI required to sustain their level of development. Chapter 4 presents in detail the static (meaning for a given year) calculation methodology of the EROI of a given energy system, the different controversies surrounding such a calculation, and hence the limits of this concept. Studies have shown that fossil energy resources to which modern economies have become accustomed and on which they are dependent do not generate as much net energy as before. Indeed, all studies estimating EROI time-series of fossil fuels have so far reached the same result: declining trends in recent decades with maximum EROI already passed. A price-based methodology developed in this same chapter put this issue in a new perspective. It showed that maximum EROI has indeed already been reached at global level for oil and gas production, but for coal, net energy gains are still to be expected thanks to forthcoming technological improvements. On the other hand, recent studies show that unconventional fossil fuels do not generate as much net energy as conventional fossil energy used to do. Most importantly, renewable technologies in which policy makers and many experts see humanity's future present EROIs that are (currently) lower than past and current fossil fuel EROIs, especially when the intermittent nature of these renewable energy resources is taken into account. Of course, there is great scope for improvement in these immature technologies, but for them too, the *First Best Principle* that consists in the use of the best resources first before turning towards lower quality resources applies. Hence, all economies will eventually head towards a future in which ever more energy is invested in the energy-extraction sub-system of the economy, making net energy delivered to society less readily available.

EROI and qualitative depletion of metals

Chapter 5 sheds some light on the close relationship between the energy and metal sectors from the EROI perspective. First, it supports the position of Rankin (2011) by estimating that 10% of global primary energy production is consumed by the metal sector. Then, it is shown that the energy consumption of the metal sector has increased faster than the rest of the economy since 1973. As shown by previous studies, this apparent increasing energy requirement of the metal extraction sector is mainly due to decreasing ore grade. The decline in quality of ores is a natural process that occurs across different scales (deposit, nation, and world) and implies that more energy is needed to extract a given quantity of metal. Because renewable technologies have higher metal intensities than conventional means of electricity production, the question of the sustainability of a transition consisting in a shift toward renewables is legitimate, especially because those energy systems have lower EROIs than fossil fuels. Logically, the goal of remainder of this chapter is to estimate how the energy requirement associated with metal extraction could impact the EROIs of different electricity producing technologies.

A first analysis consists in calculating the sensitivity of the EROIs of renewable and nuclear technologies assuming different levels of ore grade degradation for a specific metal. The kind of results that it is possible to obtain are explained through the example of three metals (copper, nickel, and chromium), although this kind of sensitivity calculation can be performed for any metal used in a given technology. Each technology displays a specific sensitivity to a particular metal that can be measured through the methodology developed in this fifth chapter. In a second step, this methodology is adapted in order to estimate the sensitivity of the EROIs of the same technologies to a similar depletion of all rare metals. This exercise is useful to see that energy requirements associated with metal extraction could have a significant impact on the capacity of these "green" technologies to deliver net energy to society. Of course, the question of the speed of degradation of the average ore grade of a given metal remains unanswered. This evolution will be different for each metal but will ultimately have a negative impact on the EROI of renewable technologies.

In the context of a transition toward renewables that are more metal-intensive than fossil energy systems, all other things being equal, the increasing energy requirement of the metal sector due to metal ore grade degradation will further increase the demand for renewable energy. Moreover, the intermittency of these technologies implies the need to expand and reinforce the transmission grid and storage capacities, which will generate an even greater demand for metals. As a consequence, in the perspective of a transition toward renewable technologies, a potential vicious circle could develop between the energy and metal sectors. It is currently impossible to say if such unpleasant situation would effectively arise but this chapter has started a quantitative exploration of this issue.

Energy expenditures, economic growth and the minimum EROI of society

Chapter 6 presents estimations of the level of energy expenditure, i.e. the amount of GDP diverted to obtain energy, from 1850 to 2012 for the US and the global economy, and from 1300 to 2008 for the UK. Results indicate that the level of energy expenditure in the economy, seems to play a limit-to-growth role since as long as it has remained above 6–8% of GDP, high economic growth rates have never occurred in the last several centuries for the US, the UK, and even the global economy. More precisely, periods of high or suddenly increasing energy expenditure levels are associated with low economic growth rates: for instance from 1850 to 1945 (very high energy expenditure levels), from 1975 to 1976 (surge), and from 1981 to 1983 (surge). On the contrary, periods of low and decreasing energy expenditure are associated with high and increasing economic growth rates: for instance from 1945 to 1973, and in the early 2000s.

Furthermore, we were able to show that in order to have a positive growth rate, from a statistical point of view, the US economy cannot afford to allocate more than 11% of its GDP to primary energy expenditure (in the absence of other major limits of a geographical, geopolitical or institutional nature). This means that considering its current energy intensity, the US economy needs to have at least a societal $EROI_{min}$ of approximately 11:1 (that conversely corresponds to a maximum tolerable average price of energy of twice the current level) in order to present positive rates of growth.

Finally, over the more restricted period 1960–2010 for which we have continuous year-to-year data for the US, we performed several Granger causality tests that consistently show a one way negative causality running from the level of energy expenditure (as a fraction of GDP) to economic growth.

Economic growth and energy transitions

Chapter 7 builds a bridge between the endogenous economic growth theory, the biophysical economics perspective, and the past and future transitions between renewable and nonrenewable energy forms that economies have had and will have to accomplish. The model supports the evidence that historical productions of renewable and nonrenewable energy have greatly influenced past economic growth. Indeed, from an initial almost-renewable-only supply regime, the model reproduces the increasing reliance on nonrenewable energy that has allowed the global economy to leave the state of economic near-stagnation that characterized the largest part of its history.

The model supports the idea that both the quantity of net exergy supplied by energy-producing sectors to the energy-dissipative economy and the ability of the economic system to use this exergy are key elements of economic growth. Unlike similar approaches, the theoretical model respects some of the many fundamental biophysical limits of the real world. These are formalized in the functional forms that we have established for the capital requirements of nonrenewable and renewable energy productions, and in the technological level of the economy formally defined as the aggregate efficiency of primary-to-useful exergy conversion.

The main result of the model presented in this seventh chapter is that for a global economy in which energy-producing and energy-consuming sectors are technologically consistent, and in the absence of any correction of the price system, the final efficiency of primary-to-useful exergy conversion of the economy must be high enough (above 0.35) to ensure a smooth future transition from nonrenewable to renewable energy that does not negatively impact economic growth. In our model, the global economy cannot avoid a temporary energy lock-in (unanticipated nonrenewable energy peak occurring at a low level of renewable energy production) when this requirement for a future technological level is not attained. In such circumstances the energy transition from nonrenewable to renewable energy induces an overshoot and then degrowth of the economic product. Such a lock-in behavior of the economic system can be (at least partially) avoided through the implementation of a carbon price, which also has the benefit of decreasing GHG emissions from fossil-fuels use and hence mitigates climate change.

The second part of this thesis (Chapters 4 to 7) suggests that maintaining a future high net energy supply is likely to become increasingly difficult given the past evolution of fossil fuel EROIs and considering the current low EROIs of renewable energy-producing technologies towards which industrial societies are supposed to make a transition. There are of course significant opportunities for maintaining a high societal EROI or adapting to decreasing EROIs. But from a systemic point of view, industrialized societies seem not to be designed to run with low-density energy resources that come with low EROIs. Until proven otherwise, high economic growth is only possible if high-density energy resources infuse the economic system and allow physical and human capital accumulation, the establishment of inclusive institutions, higher material standards of living, higher qualitative leisure, and in summary greater welfare for people.

RESEARCH PERSPECTIVES

It is essential to build a unified theory of economic growth for two reasons. First, the understanding of the contemporary growth process will always remain incomplete if growth theory cannot reflect within a single framework the various qualitative aspects of societal development. For so long as the economic take-off encountered by some privileged countries two hundred years ago remains a mystery, confidence in modern economic growth can only be fragile. Second, a comprehensive understanding of the obstacles faced by less-developed countries in reaching a state of sustained economic growth can only be achieved if the factors that prompted the transition of the currently developed economies to a state of sustained economic growth can be identified and their implications modified to allow for the differences in the growth structure of less-developed economies in an interdependent world.

The research begun in this thesis will require further work in order to develop a unified theory of economic growth that respects the biophysical constraints of the real world. As stated in the introduction, a multidisciplinary approach is needed to make a success of such a project. A truly unified theory of economic growth will only be achieved once the role of exergy consumption will be correctly taken into account and accurately linked with other determinants of the growth process, namely the deep-rooted and proximate causes of economic growth.

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