The 'Dark Matter' in the Search for Sustainable Growth: Energy, Innovation and the Financially Paradoxical Role of Climate Confidence

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Abstract

Theories of economic growth have long recognised that innovation is a key but poorly understood force – the 'residual' of neoclassical growth models. These models have no representation of intermediate goods, or of the factors that generate and diffuse innovations, including learning-by-doing and scale economies; they are thus unable to picture how a suite of economic and institutional changes triggers waves of long-term economic progress, which in practice has been the long-term historical pattern. The absence of finance in these models is particularly problematic. The centrality of financial structures to understanding patterns of economic growth is acute concerning policies to shape efficiency, innovation and infrastructure in ways compatible with energy and climate security, since these require substantial upfront investment. However, uncertainty and a lack of confidence deter such investment. Environmental policy could reduce risk and thereby shape ultimately profitable investments. The paper outlines deep relationships between energy/carbon-related finance and wider debates about financial systems after the crisis. The paper finally proposes an agenda for future research towards alternatives to classical growth models, intended to address some of their limitations.

Keywords: technical change; economic growth theory; energy; climate finance

JEL Classification: B4, O30, O41, O44, Q01, Q43, Q50

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1 Introduction: back to the rhetorical jousting around energy, growth and the environment

Economic growth is typically expressed in terms of gross domestic product (GDP). Long-standing debates around GDP are about the fact that it is not a measure of welfare, nor is it a measure of economic prosperity. This justifies the rise of a large body of literature which pushes beyond GDP as a metric, capturing important but more subjective concepts such as happiness, freedom and the depletion of 'natural capital'. Less attention has been devoted to the confusion surrounding GDP itself. The 'man of the street' understands the word product as the sum of the market value of all goods – shoes, cars, houses, etc. produced and sold in a year. In fact, GDP is not the sum of total production but the sum of the 'value added' of all sectors in an economy at a particular time period, or the sum of wages, profits and a few taxes on production. The difference is the so-called 'intermediary products' necessary for total production[1]. What is a trivial point for a sophisticated economist has an implication on the very conception (vision) of the economy. Measuring GDP as an aggregate of all the value-added defines the growth engine as a 'value-creating machine'. This machine is fuelled by primary production factors (labour, capital, land, raw materials) and transforms intermediary inputs (amongst which energy) for producing final goods. But the GDP is not the total value of these final goods.

In this framework, any reduction in the availability of production factors, such as carbon constraints, will hinder economic growth. The logic is straightforward. Just as the Industrial Revolution was powered by coal, so too have fossil fuels more generally been a key driver of economic growth. Stabilising the atmosphere must inevitably constrain their use or otherwise drive up energy costs, thus hamper economic growth. A counter-argument is that environmental action may be associated with reducing the need for resource inputs, improving the physical efficiency of use, and stimulating innovation and the emergence of new industries which produce more value with fewer inputs. At the micro (firm) level, this argument was put forward as the Porter hypothesis – the idea that imposing environmental standards on industry might stimulate companies to be more efficient and innovative, and might also trigger learning-by-doing and economies of scale. Translated to the macro level, the equivalent hypothesis would be that

[1] Here lies the ambiguity of the notion of de-growth: sober development patterns might imply technical and structural changes with less inputs and more labour (for example, in the agriculture and food production or in maintenance works to lower the obsolescence of goods) which means a higher value added and a higher GDP.

carbon constraints may lead to the growth of whole industries through stimulating cost-effective improvements in energy efficiency and the development of alternative energies. The underlying economic processes involved relate to the 'First and Third Domains' of economic behaviour, respectively, in the terminology of (Grubb et al., 2014).

These are not inherently optimising processes, but relate rather to the 'Solow residual' – the portion of observed economic growth not readily accounted for in neoclassical growth models. This underlies the potential for economically beneficial interventions. This paper focuses mainly on the macroeconomic dimension of the 'third domain', related to innovation (and associated infrastructure investments). Specifically, this paper offers a slightly more formalised analysis of the ideas in Grubb et al. (2014, Chapter 11), and extends the arguments to outline and explore the central role of finance. The essential counter-counter-argument to the idea of stimulating growth through environmentally-related innovation is that if companies and economies can become more efficient and innovative, they will do this irrespective of a carbon constraint. There is no doubt that environmental regulation can stimulate innovation. The question is whether innovation itself is a finite resource, dependent on a limited pool of research talent: that accelerating innovation in energy, for example, can only come at the expense of slowing down innovation in other areas (for example, medicine, food production, high-speed transport). This phenomenon is known as 'crowding out'. The counter-counter-counter arguments are that innovation is not an optimising process in that societies underinvest in innovation for multiple reasons, and that innovation in one sector may spill over into other sectors with net benefits. Prominent examples include the development of nuclear power and gas turbines for power generation, both of which drew heavily on the foundations laid for military purposes. A recent example is the way in which the improved design of electric batteries – triggered by the explosion of pocket calculators, microcomputers and cell phones – are now being applied to electric cars. The central role of publicly-led innovation has been articulated, for example, by Mazzucato (2013). The difficulty in reaching any consensus on such issues is not accidental. It is at the heart of the debates in modern theories of economic growth and the difficulties in matching these theories to questions related to technical change (and how to direct technical change to tackle environmental and energy issues). One has to recall that, in the 1950s, modern growth theory aimed to support economic planning and policies, with an important focus on the choice between current consumption and current investment, and therefore between current consumption and future consumption. Thus, the 'long term' in growth models typically refers to a period of between 10 and 15 years, whereas the 'long term' of energy development trajectories encompasses 20–50 years – and for climate change even longer.

This temporal mismatch is one major obstacle to understanding the relationship between energy and the economy, epitomised by the enduring disconnection between 'top-down' models of whole economies and 'bottom-up' models which emphasise technological and sectoral details. The former approach favours very compact models in which energy is simply an aggregate factor of production of a Solow type growth engine. This was justified by the metaphor of the Elephant and Rabbit stew of Hogan and Manne (1977): if the stew 'contains just one rabbit (the energy sector) and one elephant (the rest of the economy), won't it still taste very much like elephant stew?' (p. B-2). In other words, since the energy sector represents only 2–5 per cent of the value-added, one does not need to significantly amend the established models of macroeconomic growth in order to take account of energy, or other natural resources. The question is whether this metaphor is relevant when: (a) very large changes in relative prices and external trade are to be envisaged; (b) partial equilibrium analysis shows 'negative costs' options and/or asymptotes on technical change which are not captured by the production functions of general equilibrium models; or (c) the focus of the analysis is placed on the short term conditions of the transition towards sustainable pathways, instead of the long-term steady states with no shock created by a sudden rise in energy prices (Ghersi and Hourcade, 2006) – and when these issues apply to a factor which is an input to much economic and consumption activity. The motivation of this paper is that this repetitive rhetorical jousting about the relations between energy, environment and growth will never be resolved unless one first clarifies what mainstream economics can really say about these links, and understands the intrinsic limits of its canonical Solowian growth model.

2 The dark matter of economic growth

2.1 Solow's residual – the discovery of dark matter

Robert Solow's first model of economic growth (Solow, 1956) focused primarily on the choice between present consumption and investment, and the way in which, thanks to changes in its labour and capital intensity, an economy impacted by an external shock can return to a stable growth pathway. To understand this focus, it helps to recall pre and post-Second World War discussions about how to maximise economic surplus through a mix of production factors and trade-offs between consumption and investments, which minimise the production cost of goods and services at each point in time. This result is supposed to be achieved automatically in a frictionless market economy with perfect markets for labour, capital, intermediary factors, and final products and services for consumers. In such an economy, market prices should indicate scarcity. A polar model for achieving the same result involves a benevolent Central Planner fixing the optimum production objectives of each sector, or more realistically decentralising its public objectives through appropriate pricing structures (Lange, 1936). Reality is somewhere between these two polar ideal types, and modern growth theory aimed at providing 'a framework within which one can seriously discuss macroeconomic policies that not only achieve and maintain full employment but also make a deliberate choice between current consumption and current investment, and therefore between current consumption and future consumption' (Solow, 1988, pp. 309–10). One consequence was the development of very compact models without considering the sectoral content of economic growth and the intersectoral linkages between the energy sector and the rest of the economy. After Solow's theory, the economic growth engine draws on labour (L) and productive capital (K) to produce overall economic 'product', GDP. This is the production function: GDP = f(K,L). Production can be either consumed (C), or invested (I) to increase income levels in the future: thus GDP = C + I. The stock of productive capital that can be used is determined by the level of equipment accumulated over years, built by saving part of the economic surplus instead of consuming it. It is common practice to accept this equation, taught in any first year course in economics, as obvious. Yet there is something implicit in it which should not be taken for granted and which is of importance in our discussion. Indeed, this specification puts aside the role of intermediary consumptions (IC) necessary to the production process. The original economic equilibrium is Y + IC = IC + C + I. Obviously, with a single composite good, this equation can be simplified into Y = C + I which is impossible in a multisectoral model where IC is a matrix. The consequence of this trivial mathematics is that intermediary consumption (amongst which energy) has no impact on growth dynamics and matters only from a purely national accounting perspective. Solow's approach actually comes to picture economic growth as the increase of production of a homogenous product like a 'jelly', as Samuelson (1962) put it, from a factory using two primary production factors (the machine capital K and labour L) in an optimal way to minimise the production cost of Y. This factory buys no intermediary product and its production increases through a higher endowment in each of the production factors and/or of the productivity of these factors. Labour L is governed by exogenous demographic trends whereas the availability of productive capital K depends on the number of 'machines' purchased thanks to the savings of every past year (minus their obsolescence). This number depends on past trade-offs between consumption and savings: the more people save, the more productive equipment can be built, and the faster the economic growth. In this model, economic growth per capita falls to zero when an incremental investment increases production only just enough to compensate for this depreciation. As the level of equipment of a society increases – associated with its cumulative capital investment, so does the share of its product devoted to refurbish or renew equipment. This leads to a condition known as zero-growth steady state. The only way out of this pessimistic conclusion is an exogenous technical change high enough to compensate for this mechanism through an increase of the overall factor productivity A(t) which operates like 'manna from heaven'. Two important points are worth noting about this productivity factor. First, in the absence of aggregate productivity gains captured by the exogenous growth of productivity A(t), the Solow model is compatible with a zero growth steady state, and this without any consideration of environmental and resources constraints imposing 'limits to growth' (first popularised by the Club of Rome) since energy and resources play no role in the growth engine. Secondly, A(t) does not give any direction to the growth engine, but rather acts as a fuel in the growth engine. To extend the metaphor, A(t) measures the quantity of gasoline and hence the number of kilometres that can be covered by a car, but only the orientation of the wheel decides the direction. This direction corresponds to the choice of techniques made at each point in time depending on the evolution of wages and capital costs. Solow (1957) first tested his growth model against real data for US economic growth, capital accumulation and labour in 1957; the results suggested that labour productivity had doubled between 1909 and 1949, with '87.5% of the increase attributable to technical change and the remaining 12.5% to increased use of capital' (p. 320). The attribution to 'technical change', which is neither labour nor capital availability, represented 40 per cent of economic growth over 1929–57 in the USA. Similar studies in France suggest that this factor accounted for more than 50 per cent of French economic growth in the decades immediately after the Second World War. In 'growth accounting', this factor A(t) became known as 'Solow's residual'. In this sense it represents the 'dark matter' of economic growth: unaccounted increases in the productivity of both labour and capital which enable more wealth to be generated from each input. The striking result is that a significant part of economic growth – around half by many measurements – appears like an economic 'manna from heaven' of productivity growth. In many ways this is a weakness of the underlying model, but it also contains some intuitive wisdom. It shows that economic growth per capita depends not only on the neoclassical mechanisms of economic theory – notably the optimal use of resources and capital accumulation driven by relative prices and competitive markets – but also on many other factors broadly equated to 'innovation' which, in practice, encompass a wide range of parameters, including institutional factors, such as the quality of the education system, the quality of macroeconomic policies, social cohesion, and the credibility of the political systems. This is after all what can be learnt from the economic historians (North, 1991) [2]. The framing effect of this model for discussing links between energy, environment and growth comes from Solow's response to the Club of Rome that put forward the limits to growth imposed by natural resources (Meadows et al., 1974; Solow, 1974, 1986). Solow, after first recognising the interest of the approach by Ayres and Kneese (1969) in the American Economic Review (which was a matrix approach in nature to track the physical interactions between the environment and the economy) added energy (E) as another primary production factor: Y = A(t). F(K,L,E). In this model, limited resources are not synonymous with zero growth if there are possibilities to substitute energy with more capital and labour. This model was criticised for proposing a form of sustainability which relies on technological optimism[3]. The mechanisms of growth in this model are as follows. Increasing the price of E relative to K and L allows for lowering the energy content of production and the selection of low energy intensive techniques leaves the rate of technical change unchanged. But this does not mean that the growth rate in the steady state is unchanged. This growth rate is governed by the ratio between savings (s) and the capital–output ratio (v): g = s/v. Without entering in mathematical demonstrations, the rationale is straightforward: for a given amount of savings, the higher the investment costs, the lower the capacity to purchase productive capital (machines, infrastructures) and to enhance economic growth. To extend the previous metaphor, any constraints on energy thus forces us to travel on roads of lower quality and/or to lower the speed of the car. This does not dash the hope of reconciling growth and climate policies. There is indeed some evidence that, through learning-by-doing and innovation, carbon-saving equipment will ultimately cost no more than the other techniques for producing energy. In this case, the bifurcation towards low-carbon pathways will entail transition costs (when low-carbon techniques cost more) but

[2]Pomeranz (2009) shows how the 'Great Divergence' between China and Europe before the modern time is rooted in the structure of the links between the central power of the Emperor and the structure of the peasant society; Aglietta and Bai (2012) show the recent rise of China after centuries of stagnation is typically due to the capacity of the communist regime after Ten Tsiao Ping to transform the destruction of the Chinese traditional peasant society in the Maoist period into a virtuous cycle where a regulated rural drift fuels the productivity increases of both agriculture and industry.

[3]The discussion between the so-called weak (Solow) and strong sustainability ultimately relates to a judgment about the possibility of finding technical man-made substitutes for irreplaceable assets (Common and Perrings, 1992; Hartwick, 1978; Pearce and Atkinson, 1995; Toman et al., 1995); and/or to overcome the entropy (Daly, 1997; Ayres et al., 1998).

will not affect the long-term growth rate of the economy. But here lies the start of rhetorical jousts. The problem is whether a non-neutral, redirected, low-carbon technical change results ultimately into a lower economic growth rate. Actually, this depends on where is the wheel to redirect technical change. The response lies within two extremes. One comes to assert that A(t) cannot be influenced by purely economic decisions and is entirely 'manna from heaven', so that the only viable aspiration for economic policy is markets that would make optimal use of resources and being grateful for the mysterious 'residual' (be it carbon saving or not) in addition to productivity gains. The polar opposite is not only to assert that productivity growth A(t) is itself driven by economic decisions but that it is intrinsically optimising – a view facilitated by the intellectual attraction in economics of optimising growth theories pioneered by Ramsey (1928). Part of this attraction comes from its mathematical elegance and consistency; but this is done at the cost of assuming optimal behaviour and perfect foresight, and neglecting fluctuations and shocks. Attempts to reconcile this with the observed data have proved fruitless. This discussion has multiple implications for energy and climate change policy because it frames particular ways of thinking. If the pace and direction of innovation is somehow 'optimal' (or beyond reach), it implies that trying to change direction comes at a cost. Conversely, if innovation is neither inherently optimising, nor beyond the reach of other influences, the switch from carbon-intensive to carbon-saving technical change is not necessarily costly, nor will it rely only on prices. It involves changing what is behind the mysterious 'residual'.

2.2 If dark matter is the fuel, where is the wheel?

The limits of considering technical change as a fuel with no impact on the direction of the 'engine' were noted early on. This direction can logically take three forms: technical change does not change the ratio between labour and capital (Hicks Neutral); it augments the labour content of growth (Harrod Neutral); or it augments its capital content (Solow Neutral). The discussion has some policy implications. Indeed, if technical change is spontaneously capital-saving, the required saving ratio to sustain a given per capita growth rate will tend to decrease: if fewer additional machines are necessary for a 10 per cent increase of total output, then one can devote a higher share of income to immediate consumption. The core question for policies to orient technical change in a desired way is about the causes of the bias. Is it price induced, which is the theory initially supported by John Hicks (1963). On this interpretation, a change in the relative prices of the factors of production is itself a spur to invention and to inventions of a particular kind – directed at economising the use of a factor which has become relatively expensive. Or, is it caused by factors which cannot be reduced to pure economic mechanisms (institutions, human capital, cultures, or researchers' routines)? This latter case would not necessarily mean that they are a 'free lunch' since they cannot be captured in absence of economic incentives, like the impact of new relative prices on innovation and capital costs. Ahmad (1966) gave a nice theoretical representation integrating both visions of the drivers of technical change. It first admits a 'historic innovation possibility curve' which is the total of new techniques that could be developed, some years ahead, with a given R&D budget and human capacity. This frontier translates, in economic theory, a 'bestpractice frontier' in the selection and use of techniques. Secondly, it makes the distinction between this innovation possibility curve and the set of techniques (the production function) actually available at a given time horizon, which results from the decisions made at each point in time given the sequence of relative prices prevailing in the economy. By doing so, it introduces a 'path dependency' which was later popularised by Arthur (1989), as the sequence of relative prices over time determines the amount of learning-by-doing accumulated in a given direction. This model is heuristically useful. However, the question remains: what share of this path dependency is due to the succession of relative prices, to R&D expenditures or to non-economic parameters? This is typically the question behind the controversy between the 'demand-pull' and the 'supply-push' theories. According to the former, innovation is spurred by demand, which itself is directed by relative prices; a classic demonstration is given by Griliches (1957) for hybrid maize. According to the latter, cumulated knowledge and the internal dynamics of technological research have a primary role even though the display of innovations is still governed by economic mechanisms. The controversy is far from being settled, even though the articles by Mowery and Rosenberg (1979) or the econometric study by Scherer (1982) tend to support the 'supply-push' theory. Nakicenovic and Nordhaus (2011) argue in favour of the role of prices as the ultimate driver of technical change: 'the major requirement to ensure cost effective innovation in climate-friendly technologies is that carbon prices be sufficiently high so that investments in low carbon technologies have a tangible and secure financial payoff'. But it can be responded that, if the innovation chain is broken, as it seems to be for energy, then pricing will not fix it (Grubb et al., 2014, chapter 9).

2.3 Growth models with endogenous technical change: attractive but unconclusive essays

Since Solow, there have been numerous efforts to endogenise drivers of innovation and technological change in growth models. Many of them sought to explain the divergence in growth rates between countries. These models were mostly developed between the 1960s and 1990s with varying degrees of success and accuracy. However, they suggest that there may be many possible endogenous drivers of productivity gains:

- **Learning-by-doing:** Arrow (1962) developed an economic model which included 'learning-by-doing'. He captured this concept by making knowledge and productivity dependent on cumulative investment in growth models. In this model, knowledge and productivity increase along with increases in total production and investment, not as a function of a specific investment. The content of investment matters for redirecting technical change. But this redirection is costless, at least in the long run, since only the total investment matter for the pace of overall productivity increase.

- **Improving labour productivity:** A few years later, Hirofumi Uzawa (1965) showed several ways in which the quality of the labour stock could also be influenced by investments and accumulated 'human capital'. The original Solow model indeed could not explain why capital in the USA appeared to be almost 60 times more productive than in India, leading to the paradox that capital should flow massively from India to the US. The solution was attributed to different levels of human capital arising from higher US investments in education and training.

- **Product quality and product variety:** Other models explored the role of product variety (Romer, 1990) and product quality (Aghion and Howitt, 1992) as major drivers of technical change. If consumers are willing to pay more for new or better goods and services, then there is an incentive for companies to invest more in R&D and profit by being the first with a new product. Similarly, consumers may be willing to pay more for increased variety in food or clothes, for example. This might explain why the energy sector (particularly utilities) has an unusually low level of R&D, which is attributed in part to the fact that energy is a homogenous good: for most consumers, there is no such thing as a 'better electron'.

These so-called endogenous growth models were mainly used to examine differences of productivity and income between countries, and to examine whether and how poor countries could grow faster thanks to a 'catch-up' of productivity levels. However, overall, growth theories proved inconclusive – ultimately because of the inherent difficulty involved in measuring some of the key processes (Sala-i-Martin, 1996). Finally, we know that the 'dark matter' of economic growth comprises numerous forces, often but loosely termed 'innovation', which in fact encompass factors as diverse as efficient regulation, institutional and technical change, education and infrastructure – as well as potentially more nebulous factors still, associated with culture, for example. Endogenous growth models thus made an important contribution to growth theory by pointing out the theoretical reasons for acting on policy parameters other than prices to direct technical change and enhance overall factor productivity. But they have failed so far to provide robust empirical evidence of the orders of magnitude at stake, at an aggregate level, in the interplay between growth, technical change, and innovation. We refer to the warnings of Solow (2001) about the 'false hopes' of endogenous growth models which come to replace the 'manna from heaven' with a 'manna from researchers' or with something else: I have found that even these deeper and more circumstantial models of endogenous growth all rest at some key point on an essentially arbitrary linearity assumption, on the claim that the rate of growth of this is a function of the level of that, where "that" is some fairly simple and accessible variable that can be maneuvered by policy[4]. In other words, at this level of aggregation, one can always find a miraculous parameter which can be adjusted. The danger though is that 'good news' from such abstract models can be easily disqualified and work against the thesis they aim to support[5].

2.4 The hopeless aggregation of microeconomic evidences

One hypothesis to explain why the attempts of capturing the links between technical change and growth remain an unachieved conversation is that mechanisms proven to be drivers of technical

[4]4. This quote is in the 2001 addendum of Solow's Nobel Prize speech as it appears on the Nobel Prize committee website : http://www.nobelprize.org/ nobel_prizes/economic-sciences/laureates/1987/solow-lecture.html.

[5]For example, in a recent essay (Acemoglu et al., 2012) explain that subsidising R&D on clean technologies would allow for ambitious climate policies with moderate carbon taxes, no impact on long-term growth, and small transitory GDP losses. However, in their very abstract model, productivity trickles from the brains of researchers directly down to the production of composite goods, without the intermediary of 'machines' and cumulated capital stock. It is very easy, given the difficulty of controlling the calibration of such an abstract model, to reverse its 'good news' into 'bad news'; the 'good news' suppose a totally unrealistic substitution elasticity between the 'clean' and the 'dirty' technique over a five year time period, which comes to say that a 1 per cent increase of fossil energy suffices to decrease its share by 10 per cent (Hourcade et al., 2012).

change at the sector level like learning-by-doing or economies of scale do not have the same meaning at the aggregate level. Most macroeconomic models continue to assume no economies of scale (doubling the level of production doubles the inputs in all production factors) whereas economies of scale are obvious in most industries: a steel industry was competitively producing 3MT/year in the 1950s against 20 MT/year currently; the same figures are 50 000 t/year and 750 000 t/year for naphtha (a key intermediary product of the petrochemical industry). The contradiction between the micro and the macro levels is not difficult to explain: the deployment of economies of scale in intermediary sectors (steel, nonferrous, petrochemicals) and manufacturing (automobile, semi-durable goods) allows for increasing final consumption but at a level not high enough to absorb the available workforce. This workforce is then redirected to other sectors (services, health, teaching, security, administration) which are more labour intensive and benefit less from economies of scale and learning-by-doing. The disappearance of economies of scale at the aggregate level of analysis was historically assumed in part for technical reasons[6], but behind common practice it contains a deep economic meaning. The second source of difficulty is that models describing the growth engine as a 'putty producing' machine (that is, an homogenous product) assume that technical change, be it autonomous or endogenous, encompasses both the choice of techniques (to produce each of the many products incorporated in the composite good with new sets of inputs) and structural changes (the modification of the set of products in the composite good). This process in turn is triggered by the evolution of lifestyles and localisation patterns, which are due to changes in tastes and institutions (and not only to relative prices) and which are part of Solow's 'residual' and behind the bias of technical change. To put it another way, technical change in aggregate models is far from being only a matter of choices of techniques and of productivity of these techniques. It is also a matter of the content of consumption patterns. Finally, aggregate models fail structurally to capture the interplay between changes in producing techniques, consumption patterns, and structural change. There is no doubt that innovation is key, but demand is necessary to fuel the trial-and-error process supporting the learningby- doing mechanisms, and to be able to benefit from economies of scale. One typical example is the almost one-hundred-year process of incremental innovations in the automobile industry initiated by the 'five dollar workday' introduced by Henry Ford in 1914, we will come back to this. The only attempt to give a comprehensive representation of the dynam-

[6]With unbounded economies of scale the production tends to the infinite and there is no possible convergence towards a stabilised growth pathway. Moreover, economies of scale are sources of rent and there is no law as simple as the remuneration of production factors at their marginal level of productivity can be easily established about the distribution of this rent.

ics of technical choice at the micro level can be found in Nelson and Winter (1982) and Nelson et al. (1976) who produced a model capturing firms' behaviour under 'satisficing' objectives (instead of a maximising function), and search and selection mechanisms. However, despite its influence in many quarters, their 'evolutionary theory' was never accepted as an alternative to Solow's model by the core of economic profession.

3 Technical change and growth through the lens of energy-economy models

Most economists after the Second World War did not consider energy issues as an important topic for understanding economic growth. Solow's (1974, 1986) response to the Club of Rome and Nordhaus‘ study on the optimal strategy to combat global warming remain very compact, stick to the exogenous technical change assumption, and do not really go into depth with regards to the link between redirecting innovation and growth. Historically there has been a relative disconnection between works in growth theory and works on the link between growth and energy, be they in multi-sectoral models including energy as one of the sectors of the economy or in engineering-based (bottom-up) models. Two strands of literature have in common the polarisation between: (i) views of technical change as due to 'exogenous' and time-related determinants; and (ii) attempts to treat technical change as endogenous to economic mechanisms. Only a few of them, building de facto on pragmatic adaptations of the canonical growth model, attempted to endogenise the feedbacks between energy, carbon constraints, and economic growth.

3.1 The AEEI: the dark matter of the energy/economy interface

Because of the difficulty of econometric models in explaining the dynamics of energy demand through variations of income and energy prices only, most of the empirical models introduce a non-energy price-related coefficient to decouple energy and growth, labelled as the AEEI (Autonomous Energy Efficiency Improvement Coefficient) (Manne and Richels, 1992). Resorting to the AEEI indicates that the decoupling between energy and growth cannot be explained solely in terms of prices. This observation presents a similar situation to Solow's model and his residual A(t) as the 'dark matter' of economic growth. Obviously, the remaining question is whether this AEEI, which was estimated at around 1 per cent per year for OECD countries in many modelling exercises, is a stable law of nature, whether it changes over time or can be increased by policies and behavioural changes. But we face again an aggregation problem. The higher the level of aggregation, the more the AEEI encompasses not only the technical improvement of production processes, but, like the autonomous productivity trend in the Solow model, also all structural changes which modify the energy content of growth. It should more accurately be labelled the Autonomous Energy Intensity Variation (AEIV): This coefficient, which has been negative in developed countries over the past decades, is positive in developing countries in their catch-up trends. Observed trends since the nineteenth century show that the energy/ GDP coefficient follows an inverted-U shape that correlates with industrialisation phases: the income/GDP elasticity increases in the industrialisation phase (with income elasticity higher than one) and then decreases to be well below one in developed countries. The steepness of this trend is lower and lower for new entrants in modern development, as though they had dug a tunnel to reach a direct access to modern technologies without passing through the high energy/GDP level experienced by the United Kingdom and the US in the nineteenth century (Figure 1). The higher the AEEI, the lower the energy prices required to accelerate this decoupling for reaching a given energy or carbon target, and the lower the costs of meeting this target. The problem is the AEEI appears as a 'manna from heaven', so that policies that increase the AEEI appear to be costless in the model. This is not the case in the real world, as such policies cannot be isolated from institutional mechanisms, and can entail high transaction costs, though as we note elsewhere (Grubb et al., 2014, chapter 12), many of these costs may be transitional in nature.

3.2 Price-induced energy intensity

This is why, in parallel with the efforts of the endogenous growth theory, a strand of the literature has attempted to identify the drivers of structural trends in energy efficiency – to resolve the 'exogeneity' problem by endogenising energy intensity in empirical energy/economic models. Not surprisingly, economists' first instinct was been to explore the relation between price and long run trends in energy intensity.

One early and influential approach in the 1980s and 1990s to endogenise technical change in energy/economy models was a sectoral productivity growth model (1981) which underpinned the 30-sector Dynamic General Equilibrium Model (DGEM: Jorgenson and Wilcoxen (1993)) for the US economy. This model uses for each sector a F(K,L,E,M,t) function with K, L, E, M standing for capital, labour, energy, and other inputs respectively, and t standing for

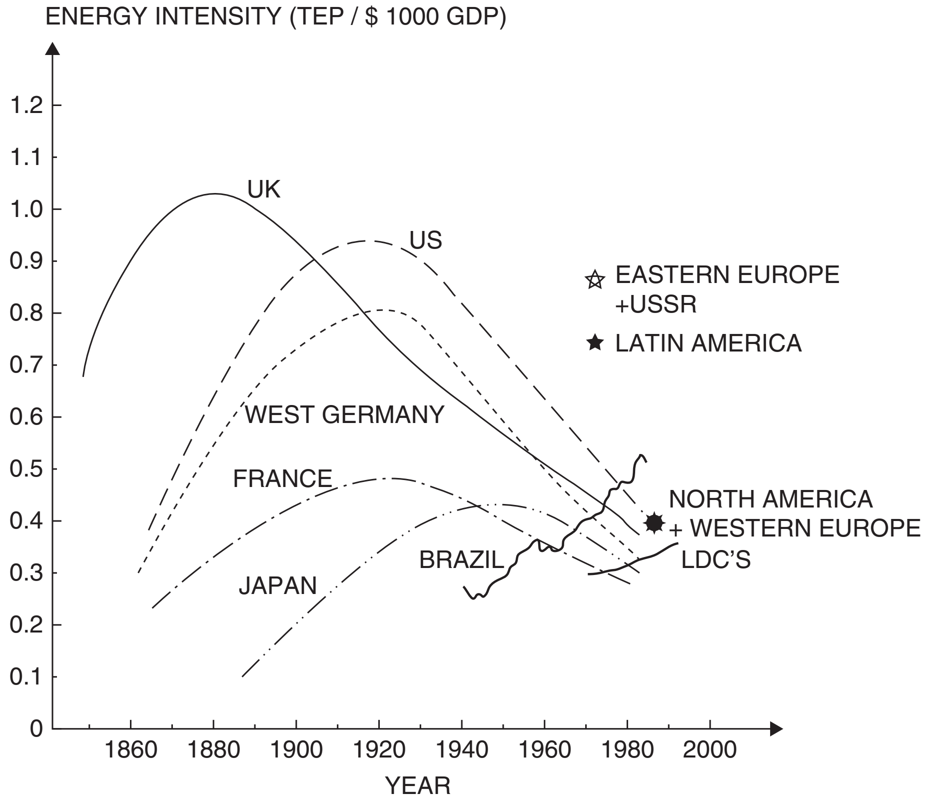

Figure 1: Evolution of energy intensity for different countries. Source: Adapted from Martin (1988) by Goldemberg (1992).

a time trend. The energy content of each sector (and of the overall economy) thus depends conventionally on the prices of energy relative to the price of other inputs, but it also depends on the time trend specific to this sector. In sectors where this time trend is positive, technical change is energy using. Jorgenson estimated these such sectors to represent a dominant share of the economy, which means, in plain language, that technical change is biased in an energy intensive way. Although they recognise that, in aggregate, this 'positive bias' is small, Hogan and Jorgenson (1991) conclude that 'any increase in relative energy prices will lead to a slower growth in total factor productivity' (p. 78). Thus redirecting technical change to save energy is possible in this model but depends totally on energy prices, and is costly because energy prices have to increase steadily to offset the energy intensive trends in technical progress; the observed decoupling between energy and growth results simply from changes in relative prices. But this result cannot be extrapolated into the future for two main reasons. First, it is not robust to the choice of the production function (Berndt, 1983). This is an intrinsic limit of F(K,L,E) or F(K,L,E,M) functions, which rely on a 'wrinkle' that consists in using data on the share of energy in the production costs of each sector to derive their implicit 'technical functions'. This methodology is justified by mathematical theorems (the 'envelope theorem') which are valid only if the used techniques are optimal for the prevailing relative prices. The meta-analysis conducted by Frondel and Schmidt (2002) over more than a thousand studies shows this technique to be a deadlock because the results on the substitution between energy and other production factors depend on the number of such factors that are accounted for in the production function, and on the time periods considered. Second, correlation is not causality, especially when econometric correlations do not pass stability tests (that is, calibrating over 1960–2000 instead of 1955–1995 changes the results substantially; see Berndt and Wood (1984)). The period studied included intense economic growth with cheap energy followed by the huge and sudden shock of the 1970s oil shock, with large international diversions of finance, followed by twenty years of economic instability. The last fifty years cannot be disconnected from the running out of the Glorious Thirty's growth engine (see below) and the end of the Bretton Woods system (1971). Both the post-Second World War economic cycles and the variations in energy prices are underpinned by such complex factors that it is difficult to find in structurally higher energy prices the cause of economic structural downturns. It is true that unexpected increases in energy prices have a negative short-term impact on production costs, purchasing power and growth (Hamilton, 2008). But to extrapolate an econometric exercise in the Jorgenson's style based on the past few decades would come to attribute the current economic world slowdown to the energy price increases between 2002 and 2008 and not to the impact of the burst of the real estate bubble on the banking system. The observation that shocks due to tensions between energy supply and demand have a negative impact on growth has little bearing on any underlying relationships between energy, productivity and overall growth potentials.

3.3 Innovation and 'crowding out': a matter of judgment about spillovers

The other main area of debate was the extent to which energy-related innovation is triggered by R&D spending and/or learning-by-doing mechanisms, and whether strengthening energy innovation by either route would lead to a 'crowding out' of other innovation, or conversely to a 'spilling over' of R&D into other sectors – with opposite macroeconomic implications. The argument goes as follows: The opportunity cost of a dollar of energy R&D is that one less dollar is available for any of three possible activities: consumption, physical investment, or investment in other R&D (. . .) ignoring the costs of R&D necessary to develop new technologies, such as those relying solely on learning-by-doing, overstate the gains from policy-induced technological change. (Popp, 2006, p. 14) Goulder and Schneider (1999) highlighted that the net effect depends on cumulated R&D investments and learning experience in 'clean' energy compared with fossil energy and non-energy production. Specifically, they identified that it depends on whether: (i) the potential for cutting down production costs is high or low in low-carbon technical options; (ii) past R&D investments and learning-by-doing have unleashed a significant share of this potential; and (iii) there are spillover effects of innovation from any sector to other sectors. The last factor can potentially counterbalance the crowding out effect. In this case, knowledge spillover and overall productivity depend on total accumulated investments in R&D and knowledge accrued from this, irrespective of whether investments are directed to low- or high-carbon technologies. We face a challenge to interpret these results, again due to the level of aggregation. Although these offer insights into economy-wide productivity, such insights are qualitative and cannot be applied at a smaller scale. Perhaps the large investments in military research provide an ab absurdo demonstration of the point. If there were no spill-over from military R&D into other sectors then countries like the US, the UK and France would have achieved a remarkable feat by maintaining rapid economic growth despite very high 'unproductive' R&D expenditures. The truth is that they have reaped spill-overs from military research to productive sectors of the economy. The crowding out versus spillover debate again seems inconclusive and diverts attention from a more important generic issue, which is the deficit of societal investment in knowledge, be it in the form of R&D or learning-by-doing incorporated in new industries. This was the basic warning of Romer (1986) whose work highlighted the gap between the social and private returns on investments. Private investments may benefit society as a whole, but private decision-makers may not be rewarded for the positive knowledge spillover of their investments. This can be thought of as a positive 'externality': the true value of R&D is undervalued in the market, so there is insufficient investment in knowledge. This gap between private and social value of investment is not only due to spillovers. It may be amplified by the regulatory regimes in energy sectors, investment risks related to the business cycles and risk aversion related to uncertainties in final demand and the performance of new technologies. The systematic underinvestment in innovation may also be worsened by the overall transformation of the business context in the past twenty years, from a managerial regime that allowed firms to focus on maximising their long-term value to one dominated by the maximisation of shareholder value at each point in time. The question of investment risk and finance is thus embedded in the fundamental evolution of the governance of industrial systems. Here again this evolution cannot but be one component of the ‘dark matter’ of growth in the compact growth model.

4 Innovation waves and growth cycles: when the ‘Golden Age growth’ is a historical exception

There is thus a need for a ‘new conversation’ and this need in part explains the appeal of ‘Green Growth’ concepts, which are increasingly called for, not least by many international economic organisations, but build on a much wider and deeper heritage.

4.1 Waves and cycles: a growth engine changing with technical paradigms and institutions

To dig deeper, it is useful to start by looking further back, to the time when economics was not always tantalised by the idea of stabilised, optimal growth. Prior to the 1960s, much of the interest was to explain the evident cycles and periodic crises in economic history. Economists like Ricardo, Marx or Schumpeter differed in their interpretations and political ideologies but explained this history through the interplays between institutions and technical change. Schumpeter launched the notion of creative destruction to explain the dynamics of capitalism through the role of entrepreneurs whose innovations disrupt the existing order. A stylised vision of the links between technical paradigms and growth cycles in history is sketched in Figure 2. After the first phase of mechanisation in the late eighteenth century, the Industrial Revolution was based upon the mastery of steam power and the deployment of railways; these two factors opened new economic frontiers with access to cheap coal and iron mines and a first phase of globalisation in manufactured (textiles) and agricultural goods. Most importantly, these goods could all then be transported over long distances. The mastery of electricity in the late nineteenth century launched a new wave of growth thanks to unprecedented access to power for heavy industry and better access to education thanks in part to electric lighting: on this was based the ‘Belle Epoque’, before its brutal end with the First World War. The core economic engine of the twentieth century, which became the dominant economic force after the First World War up to the middle of the 1970s, drew on mass production with economies of scale, typically in the automobile industry and electric appliances, with oil as the rising energy resource. After being inhibited by the world wars, this powered an unprecedented wave of growth, the ‘Thirty Glorious Years’, leading up to the oil shocks of the 1970s. It is probably no accident that the mathematical theories of stabilised economic growth took hold during this period: with steady growth and the gradual extension of the underlying economic model beyond the rich countries of the OECD, they were products of their time. The fact that the fundamental model seemed to survive the oil shocks and reassert itself during the 1980s only reinforced this belief. The collapse of the Soviet Union, whose economic paradigm was still to a greater extent based on the earlier industrial model of electrification and heavy engineering (which still dominated at the time of the Russian Revolution in 1919), further amplified confidence in the economic model of fossil-fuel based mass production led by consumer markets. The model was also aided for the following 20 years by the additional wave of growth spurred by developments in information technologies and telecoms, though the overall economic contribution of the IT revolution as a fuel for growth seems already to be waning. Yet as noted, the dominant growth theory itself contained the observation that around half of economic growth could only be explained with reference to 'innovation', and in and of itself carried no structural analysis of what drives such innovation. But this abbreviated economic history emphasises the importance of the co-evolution of technical and institutional changes which together involve large-scale transformations in industries, lifestyles and the spatial distribution of activities. The economic frontier in the US would not have moved so quickly to the West without the railway revolution; education levels would not have risen at the same pace without access to light and the radio; urban sprawl or mass tourism would not have taken the same form without the generalised use of motor cars.

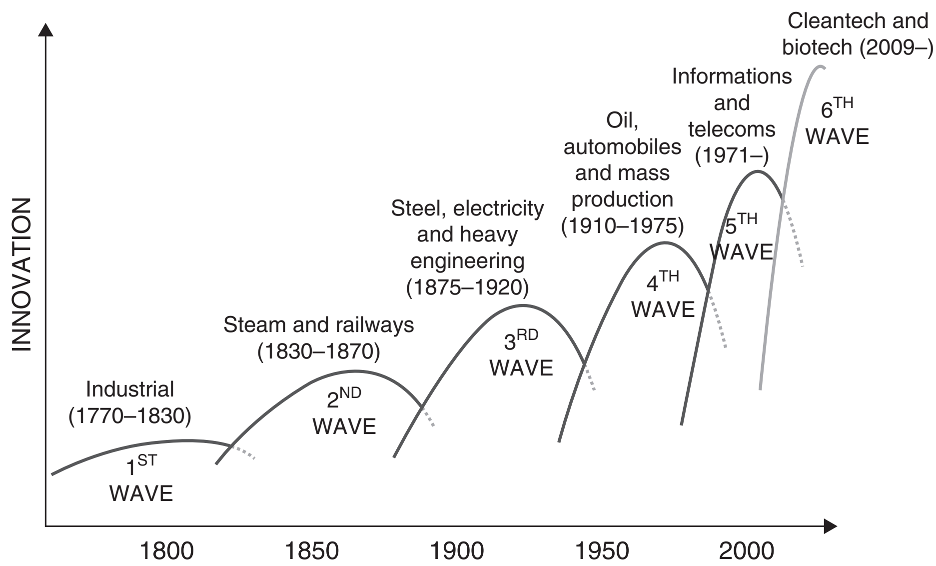

Figure 2: Waves of innovation. Source: Adapted by the authors from Stern (2012) and Perez (2002).

It follows from this view that enduring recessions in part are the 'manifestation of a 'mismatch' between the socio-institutional frameworks and the technico-economic sphere' (Perez, 1985). New technical paradigms cannot be deployed without appropriate institutions (property rights, political structures, social and business networks) and infrastructure. This is one of the key reasons why China missed the same Industrial Revolution launched in Europe in the eighteenth century, although both regions had comparable technical capabilities and income levels in the seventeenth century. It is also the reason behind China's impressive economic rise after Deng Xiaoping's reforms in the 1980s. This raises an obvious question: whether, in addition to the financial origins of the debt crisis itself, the enduring recession – and apparent global spread of the current economic malaise – may itself be a symptom of the exhaustion of the prevailing paradigm and a resulting mismatch, at the world scale, between the emerging technico-economic potentials and the existing institutions of economic governance. To do more than speculate, we thus first need to correctly understand the nature of the economic engine that drove the productivity gains of the age.

4.2 Lessons from the end of the Thirty (plus twenty) Glorious Years

The wave of technological transformation dominated by oil, automobiles and mass production reached its zenith in the 'Thirty Glorious Years' following the end of the Second World War. Centralised and more automated production techniques enabled huge economies of scale, both in intermediary industries and in the mass production of final goods. Particularly after the war, access to the vast pools of cheap Middle East oil also cut transportation costs and enabled industrialising economies to reach distant raw materials (energy, steel, non-ferrous goods) elsewhere. Institutional changes accompanied these advances to create virtuous economic cycles. They were deployed in different forms and at different speeds but shared these common attributes. The iconic example of such institutional changes is Henry Ford's $5 a day wage, introduced in his factories in 1914. Raising the minimum daily pay from $2.34 to $5 added to production costs but also fuelled the demand for cars. This allowed the industry to expand production, reap huge economies of scale and thus reduce production costs so that the elite's toy at the beginning of the century started to become a massappeal product. This is why the growth regime is sometimes labelled Fordism. It provided the technical basis for the economic triumph of Roosevelt's New Deal in the 1930s, which dug the US – and subsequently the world – out of the massive depression that followed the 1929 financial crash. The New Deal included a huge public investment in infrastructures, creating both the physical and financial basis for the expansion of automobile, domestic appliance and material industries, drawing on strong US coal and oil production. The economic model came to command a social and political consensus, albeit in different forms in different countries, typically involving negotiation between trade unions and employers with a focus on the maximisation of consumption. This era saw the reign of Keynesian economics. The implicit deal was that wages increased along with overall productivity in a virtuous economic cycle, and that public spending could boost expenditure to compensate for economic downturns. Instead, however, the globalisation of markets progressively undermined this virtuous cycle, imposing competitiveness constraints on wages and also on social security expenditures. In the late 1960s, there was the first alert about the exhaustion of cheap oil in the US and growing dependence on the Middle East. The 1970s oil shocks then revealed energy as the Achilles heel of this growth regime. Economic globalisation was simultaneously the product of Fordism, an amplifier, and its other major threat. The technological pattern was based on economies of scale which, increasingly, could only be realised when planning for international markets. For instance, medium-sized countries are large enough for the steel industry to invest in plants of 1–3 Mt per year, but a steel plant of 15–20 Mt per year makes sense only in the context of international markets. It also became more efficient to standardise the components of a car in order to use them in many models while adapting the end product to the country-specific consumers' preferences. An increasing share of industrial sectors became exposed to international competition and these sectors responded by outsourcing parts of their production or creating global companies (for example, Renault-Nissan or EADS-Airbus) to dilute investment risks across several markets. The policies that had supported the 'Thirty Glorious Years' thus increasingly bumped into an invisible wall, because part of the increase of final demand generated by higher wages, public spending or monetary easing went into higher imports instead of higher domestic production. Globally, after the impact of the oil shocks abated, growth resumed apace through two main channels: adoption of the model by the emerging economies playing catch-up in terms of industrial production and drawing initially upon the returns sought by Western investors, and the quest of Western consumers for cheap goods. But the famous aphorism, 'what is good for General Motors is good for the US', no longer held true. In the 1990s it was explained that the difficulties associated with globalisation were without consequence and that, indeed, further liberalisation and relaxation of banking regulation was necessary to free a new growth cycle within the OECD based on information technologies (IT) in a context of trade liberalisation. Along with globalisation, the IT revolution thus contributed to this extension of the Fordist era but has not fundamentally changed the dynamics. Indeed, as observed and displayed in Figure 2, its economic impact appears to have been quite short-lived. Instead, the rise of debt in the West fuelled an illusion of continued real growth. Many accounts of the enduring economic malaise since 2008 have focused on such distributional effects, along with the misplaced financial wizardry which for two more decades enabled the West to continue the fantasy of ever-rising consumption divorced from material content. The increase of real estate values, which occurred first and foremost in the USA and was subsequently imitated in several European countries, owed nothing to chance; it was allowed for, if not encouraged, by explicit policies to fuel consumption by an illusion of continued wealth. The real estate bubble and the laxity of Greenspan's policy were timely in masking the stagnation and even decline of the purchasing power of wages of the low and middle classes in the USA in the 1990s, and this solution expanded to other OECD countries and in an impressive manner in countries such as Spain or Ireland. The explosion of this bubble led to the current context of debt and recession, but it is important in understanding the more fundamental reason for economic stagnation, which is the fact that the socio-technical basis behind the virtuous cycle of Fordism itself began to run out of steam. This is for three main reasons:

- **Saturating economies of scale:** The easiest economies of scale in intermediary industries like steel, in 'semi-durable' products (cars, electric appliances) and in the food industry have been exhausted. Remaining economies of scale are increasingly offset by the management costs of ever more complex systems and the investment risks due to the increasing time lag between investment and its payback. Moreover the middle classes, once equipped with cars and semi-durable goods by mass production, redirected much of their demand to high-quality and diversified products and services less likely to bring economies of scale, like food and tourism. Productivity built on economies of scale cannot continue in perpetuity.

- **Delayed human and environmental consequences of consumption patterns:** The unintended environmental and social externalities of Fordist growth patterns had already started to become apparent in the 1960s. Environmental improvement was essential and beneficial but was not free, particularly where it involved 'end-of-pipe' solutions like desulphurisation. Mass food production is a typical example whereby, after the dramatic improvements of the 'Green revolution', the cumulative impact of pesticides, chemical fertilisers and energy use have had an increasingly counterproductive impact on agricultural productivity, and now generate instead a demand for higher food quality and security.

- **Energy vulnerability:** The most obvious examples of this are the two oil shocks in the 1970s and the resulting economic crises. During the 'Thirty Glorious Years', economies became increasingly dependent on oil due to urban sprawl and just-in-time production processes which increased transportation needs. In the US, low- and medium-income households spent on average 26–29 per cent of their budget on transportation and an equivalent amount on housing, and overall more than half of their income was spent on 'basic needs', which reduced their purchasing power for other products and hence further weakened the Fordist cycle.

The fact that in the neoclassical theories of economic growth, both environment and energy (along with other natural resources) are 'intermediate products' that cancel out in the growth equations has helped to blind economics to their central role. The complexity surrounding the nature and causes of productivity growth, with its attribution to the dark matter of 'innovation' as a proxy, also may have helped to obscure the central role of the ultimately limited engine of Fordist economies of scale, completing the disjuncture between the theories and impending realities. The expectation of unlimited economic growth is meeting the physical realities not just of a finite environment and resources, but of one of the basic 'fuels' that has sustained the last half-century – the waning economies of scale in the dominant fossil-fuel-based industries of the twentieth century.

5 The missing link: finance

The challenge ahead for economists is that they have no model able to picture, even in a stylised way, how a suite of economic and institutional changes may trigger waves of long-term economic progress, and what provokes their exhaustion. As revealed by the rise and fall of the Glorious Thirty Years, these institutions include the wage regime and labour legislation, the trade regimes which govern the links between economies with heterogeneous technical capacities and social systems, the capacity to internalise long-term consequences of everyday decisions and the link between the financial systems and the business regime. The major gap with empirical evidence is the absence of finance in the post-Solow growth models. This absence is not a detail which can be easily corrected because the Solow model presupposes the identity between the capital stock valued according the contribution of a unit of additional capital to the discounted flows of benefits, the capital stock valued by stock markets, and the cash needed to pay the levelised investment costs[7]. With this identity, there is no place for finance: it assumes implicitly that a confident lender advances the cash to cover the upfront costs of technologies based purely on rates of return, without any attention to either capital intensity, uncertainties or perceived risks. It would take a brave person to argue that the global economy is in a state of perfection – that it is operating at the 'best practice frontier', or indeed that innovation is an inherently optimising process. There are also enduring controversies about 'negative costs options' and 'no-regret policies'. Financial decisions – whether after conscious consideration, or by default – ultimately are at the heart of these debates. The debates can never be resolved without scrutinising the realities of a turbulent age in which decision-makers have imperfect foresight, savers refraining from investing, and recessions and unemployment result from adjustment failures.

5.1 Buridan's donkey syndrome

We live in an age in which unprecedented debt levels coexist with very high rates of savings (45 per cent of GDP in China, pension and insurance funds in the 'advanced' economies and sovereign wealth funds mainly in major oil exporters). In reality of course these are related: government debt is owed to financiers who hold huge pools of capital. The savings glut results in part from the fact that, during the last twenty years, the business environment led more and more investors to prioritise short-term shareholder value over the longer term value of the firm (Zenghelis, 2011). The difference between the managerial regime in the 1970s described by Galbraith (1973) and the new shareholder regime is emphasised by Jensen (1986). Some implications for growth dynamics are demonstrated in Hallegatte et al. (2008). Another factor may have been that the major growth sectors of recent years, such as IT, are intrinsically less capital-intensive than the investments of earlier phases of industrial development. The declining demand for investment in turn started to lead to increased institutional savings and depressed interest rates. These combined forces led the financial system to indulge in practices which had the attractive property – to the markets – of undervaluing risks in ways which were opaque to all (leveraged buyouts, utilising borrowing facilities at the same time as innovative market finance instruments, often generated these characteristics). The result is that capital markets, seeking risk-adjusted returns as high as 10 to 15 per cent, stopped investing in industry and used savings

[7] The levelised investment costs are the discounted sum of a constant flow of cash needed, over the duration of the investment, to cover the reimbursement of the 'loan' covering the upfront investment costs and the payment of the associated interest rate. This might be a real loan or, if the investment is self-financed, the opportunity cost of the capital for the firm.

to pursue capital gains, for example through real-estate bubbles. With the bubbles burst and financial controls necessarily tightening, the capital is unsure where to go. The situation in the aftermath of the financial crisis has thus been akin to the legend of Buridan's donkey which died hesitating between oats on one side and the pail of water on the other. This was a deliberate caricature of a theologian (Jean Buridan) who argued that decisions should be delayed until all the facts are known and weighed. Savers do not know where to really invest in industry. Here lies the operational link between debt policy, growth policy and climate policy: the need to awaken Buridan's donkey out of its hypnosis. To the extent that reducing investment risk associated with low-carbon projects would attract investment, it could contribute to clearing the savings glut and address one structural cause of the financial crisis. These are, of course, 'easier' options, notably to ease both monetary and environmental policy. The easy short-term path is to ease further the flow of capital into the traditional fossil fuel-related businesses to extend the fossil fuel frontier. This would essentially favour a revival of a Keynesian compact bankrolled by the hope of a new era of energy abundance based on shale gas and oil. This amounts to trying again to revive and extend the old paradigm of a growth model based on unsustainable consumption, fuelled by financial and natural debt, with numerous other potential problems to accumulate over time. But this is a zero-sum game: competition to attract heavy industry with low energy prices, and competition between the short-run interests of present structures against the long-run global interest in a low-carbon economy and stable climate. The shale gas revolution in this context is a double-edged sword: in the right context and properly governed, it can help to displace coal and bring down national emissions and energy prices, but its own emissions and geological characteristics set limits on this contribution and suggest it to be partly a palliative or transitional option. There is no guarantee that this will secure a stable, enduring economic recovery. It is already apparent that shale does not mean the end of instability (or of high prices) in global fossil fuel markets, nor does it provide an enduring solution to Buridan's syndrome. Ultimately, governments cannot plausibly protect fossil fuel investments (and investors) against the risks implied by climate change. A more enduring way out would thus be to 'awake' the donkey out of its hypnosis by consciously building a business environment in which the financial sector knows 'where to invest' for long-term gains which are less vulnerable to planetary risks. Herein lays the link between the low carbon transition and the reform of the financial and monetary systems.

5.2 The role of institutional finance

The key to achieving economic goals in ways compatible with environmental needs lies in attracting the huge pools of institutional capital – such as pension and insurance funds and sovereign wealth funds – to low-carbon investment. The volumes are huge – tens of trillions of dollars. At present, much institutional finance is earning paltry rates of return, typically 2 per cent or less. This indicates the difficulty of finding safe investments with high returns. The amount of additional investment required to decarbonise the development of energy systems globally (c.€0.5–1 trillion/year) is a lot of money, yet represents just a small fraction of available savings and between 1 and 2 percent of GDP around 2030 (Hourcade et al. 2012). At a time of such unprecedentedly low interest rates, infrastructure investment can be an extremely attractive proposition. The low-carbon 260 Finance, Macroeconomics and Environmental Policies transition heavily involves such infrastructure, much of it in the form of capital-intensive investments that yield a long-term stream of value – as with enduring reduced energy consumption from highly insulated buildings, high-speed railways or very low operating cost energy from renewable sources. The net cost of renewables at low interest rates can be highly attractive. The deterrent is risk – partly technological, but much of it also political. Conceptually, the fundamental point is that a constraint can reduce uncertainty – and hence reduce risk and enhance value. The 2008 financial crisis revealed the failure of the Basel process to set prudential rules apt to control the innovative capacity of the finance industry and avoid 'banking in a shadow'. As a matter of the utmost urgency, the US and EU governments have socialised 'bad debts' since 2008, and the international community is searching for tools to stabilise the international financial system. To understand how monetary flexibility targeted at low-carbon projects may be one item of the toolbox, the essential point is recognition that that modern monetary and banking systems rely on the commerce of promises (Giraud, 2001). There is a significant disconnection between the scale of the promises of funded economic initiatives and the existence of pre-existing counterparts. We are far removed from the time when gold and silver of the Lombards' strongbox backed the first letters of credit. The art of managers of the modern system consists in finding the right balance between a risky laxity, releasing speculative bubbles with significant social costs when they burst, and an extreme rigour that inhibits economic activity. Such an art plays on conventional indicators such as the ratio between loans, liquid reserves and authorised capital, or the payment into the deposit insurance system. The only 'strongbox' behind this commerce of promises is essentially the working capacities of nations, which guarantees that something of value is eventually created when the money is spent. But the crashes in Iceland, Dubai, Greece and Ireland and the difficulties experienced by Portugal, Spain and Italy demonstrate that the content of this strongbox is not unlimited when the creation of actual wealth falls short of the promises circulating on financial markets, including in the form of speculative bubbles. We will not go back to the times of the Lombard bankers or of the 'gold exchange standard'. However, debate is open as to what should be considered as a reserve asset. The dominant reserve currency in the modern world is the US dollar, backed by the promises of the US Federal Reserve. The declining dominance of the US economy in the world has led inevitably to speculation about whether a greater role may be played in the future by the Renminbi or the Euro, whether by design or default. Ultimately, of course, all of these also rely on the promises and credibility of the central banks. Another approach has focused on suggesting to use the Special Drawing Rights as a reserve currency. All of these are ultimately, of course, purely social constructs. Climate change has potential to inject a wholly new dimension into these discussions. The atmosphere – and, specifically, its capacity to absorb carbon without unacceptable climate or oceanic damage – is a global, finite asset. There is a real physical value to investments which improve energy efficiency or develop low-carbon supplies, and this will rise until such a time as the atmosphere is stabilised. A political agreement which forms a basis to monetise this value would still be a 'promise', but it would be one grounded in scientific realities. It could even be indexed to observable metrics of long-run climate change, like the global sea level – a structure which would also, in effect, invite climate sceptics to 'put their money where their mouth is'. Thus for example, if a sufficiently large group of countries agrees on a common minimum 'social cost of carbon', set to rise over time until emissions decline sufficiently, this value could be used for the creation of carbon-related assets by central banks. These could be posited in the asset value of these banks, like gold and foreign currencies. Development and commercial banks could thus get additional credits from central banks and issue carbon-related certificates for the project they fund. After due verification by a supervising authority these carbon certificates could be accepted as repayment by central banks. Technically, this would correspond to a carbon-based money issuance which has the theoretical advantage of being backed neither by pre-existing wealth nor by undetermined promises, but rather by the guarantee that something of recognised value will eventually be created (insulated houses, renewable energies, low-carbon transport infrastructure, targeted R&D). This would have a direct value, but the effectiveness of low-carbon value for the purposes of attracting investment could be enhanced through various other mechanisms, like carbon taxes or a floor price in emission trading systems. It is beyond the scope of this paper to discuss in more detail the technical options, which span from 'green investment banks' to projectspecific low-carbon investment bonds and many other related proposals. Our aim here is rather to suggest that the link between climate policies and a sustainable way out of the current systemic crisis has been 262 Finance, Macroeconomics and Environmental Policies underworked in the economic analysis of climate policies because of the absence of consideration of finance in existing growth models. To understand the importance of this link, imagine the following sequence: (1) banks and institutional funds could in parallel issue 'carbon' financial products, aimed at attracting domestic savers and institutional investors, with guaranteed return on investment slightly above that of usual safe deposits; (2) carbon assets could participate to the drawing rights from central banks of the IMF; and (3) the drawing rights could be transformed into carbon certificates for helping development and investment banks to provide low-risk loans. If backed by a sufficient weight of countries, the practical implication of this is that a new reserve currency could gradually emerge based on the long-term d for long-term, sustainable investments – rather than the converse, as appears to be too frequently the tendency emerging from the present dominant financial systems. Illustrations of possible mechanisms are given in Hourcade et al. (2012) and Neuhoff et al. (2010).

6 A new research agenda: towards an alternative to Solow

Solow (1988) himself calls for a new growth model, with two remarks. The first is a recommendation to devote more attention to the demandside of growth dynamics, and not to consider 'the markets for goods and labor [. . .] as frictionless mechanisms for converting the consumption and leisure desires of households into production and employment' (Solow, 1988, p. 311). The second is a call for a hybrid model that is relevant at different time scales: At short term scales, I think something sort of 'Keynesian' is a good approximation, and surely better than anything straight 'neoclassical'. At very long time scales, the interesting questions are best studied in a neoclassical framework and attention to the Keynesian side of things would be a minor distraction. At a five to ten year time scale, we have to piece things together as best as we can, and look for a hybrid model that will do the job. (Solow, 2000, p. 158) As noted, the 'long term' in a Solow-type model is still relatively short in terms of energy, climate change, or the processes involved in evolutionary economics. There have been some attempts in the field of growth theory to design an alternative growth model. (Johansen, 1959) built a model where the production function neither resorts to Leontief specifications with fixed coefficient technology, nor to well-behaved neoclassical production functions. His crucial contribution is to provide a model with no unique relationship between the output and the demand for production factors, and with a path dependency between the production function at a given point in time and the previous states of the world (production levels, relative prices). Another attempt relates to Kaleckian dynamics in capitalist economies, which describe investment decisions as driven by profit maximisation under imperfect expectations in nonfully competitive markets. Stiglitz (1990) argues that incorporating costs of adjustments in neoclassical growth model has ‘some semblance to those of the model that (Kaldor, 1957; 1961) and (Kalecki, 1939) attempted to construct [which] may be closer to the mark than the allegedly ‘theoretically correct’ neoclassical theory’ (pp. 57–8). These issues were ignored by mainstream economic theory for some decades. The consequence is, for example, that almost all Integrated Models are hung on a Solowian growth engine and neglect the Kaldorian/Kaleckian alternatives. Recently, some attempts were made to hybridise the modelling framework (Hourcade et al., 2006) by describing the general equilibrium both in values and quantities that can be controlled by specific expertise. In the 1990s, this was typically the long-term programme around the IMACLIM modelling architecture, which was meant to pursue three intertwined objectives: (i) secure that projected economies are supported by physical contents (for example, resources, technologies) consistent with engineering-based information; (ii) endogenise the economic feedbacks of policy signals necessary to induce large transformations of technological systems; and (iii) authorise disequilibria so as to capture transition costs of a policy or an exogenous shock. However, all attempts suffered from a lack of theoretical foundation for an alternative ‘growth engine’. This is why we will conclude here by highlighting some areas for future work.

6.1 Production functions and the interplay between growth and its physical content

Production functions, and the neoclassical parables hence derived, raised harsh polemics during the ‘two Cambridges’ controversy (Harcourt, 1969), before benefitting from a consensus that may mask misinterpretations. Solow himself (1957) qualifies the production function as a ‘wrinkle’, which is acceptable only at an aggregate level, for specific purposes, and implies the need to be cautious about the interpretation of the macroeconomic production functions as referring to a specific technical content. A key characteristic is that there is no practical distinction between (i) the equipment stock, which is, in physical terms, the productive capacity of machines and infrastructures available at each point in time; and (ii) the capital stock, which is the value of this equipment stock, incremented annually by the difference between investments and the depreciation of its value. These assumptions are appropriate as long as the equipment stock is used at its full capacity in a model aimed at studying long-run steadystate equilibria, and assuming no impact of the vagaries of the transition pathway on this equilibrium. Using production functions, the current state of the art implicitly captures the links between economic growth and demand for energy, material and environmental resources through income and price elasticities. Like in Manne's 'Elephant and Rabbit' metaphor, this approach is only valid as long as the growth engine itself is not significantly affected by the evolution of the 'physical sphere' that underpins economic growth. The physical sphere here refers to the combination of consumption patterns, technological styles and locational decisions which characterise development patterns. For instance, the economic globalisation dynamics in the 1950s and 1960s had something to do with the decrease in transportation costs and economies of dimension and scale in sectors like steel, non-ferrous metals or petrochemicals. They also had to do with the access to automobiles and other semi-durable goods by the ever-growing middle class. In the future, a rise in transportation costs (for instance, due to more costly energy and physical limits to economies of scale) might revert these dynamics. The same questions arise for instance about the direction of productivity growth in agriculture. It is the very aim of 'hybridisation' to hang economic growth to these physical realities, by combining economic and physical flows in a consistent framework, which can be used as a tool of dialogue with engineers.

6.2 Imperfect expectations and routine behaviours in an uncertain context

In a perfect foresight setting, physical constraints (such as a finite stock of resource, or an environmental externality) do not pose many problems: if well anticipated, such constraints induce appropriate changes in the production sector. All sustainability issues in fact derive from the fact that such constraints cannot be perfectly anticipated in reality. The differing characteristic times of the technical, environmental and economic systems may cause hysteresis effects, which may lead to bifurcations towards different long-term equilibria. Therefore, resorting to the Bayesian learning assumption is 'ad hoc' and not necessarily appropriate here. Instead, an alternative model should explicitly model 'beliefs' (on risks, technological responses or economic parameters) to demonstrate the role of public policy instruments in the 'coordination of beliefs'.

6.3 Firm's decision-making: 'shareholder value business' vs. 'managerial' regime

Most of today's models use levelised costs of investment to transform upfront investment costs into yearly costs paid over the lifetime of a project. This modelling is consistent with many of the industrial structures that existed in the 1970s, including in energy, when large integrated utilities could internalise the overall cost of projects, had long time horizons and sufficient financial capacity. The major risks could be estimated, and levelised costs could easily incorporate a risk premium. But this structure changed completely with the financial revolution of the 1980s and 1990s, and changes in key industry market structures, including the privatisation/liberalisation of many energy industries. An improved growth model should account for the fact that the equivalence between levelised and upfront costs is no longer guaranteed under uncertainty, with utility companies behaving as to maximise shareholders value, and not according to long term planning. If indeed the expected return of a technology A is higher than this of a technology B, the former might not be selected if its upfront costs during several years (highly indivisible investments) are so high that any unexpected additional cost could be perceived as undermining the profitability of the firm and downgrade its shareholder value.

6.4 The links between growth dynamics and income distribution

The separability between equity and efficiency issues, which derives from the second theorem of welfare economics, is often misinterpreted as meaning that income distribution has a no impact on economic growth and on the direction of technical change. This is incorrect, for two main reasons. First, part of the savings by the wealthy is not invested in production capacity. Instead these savings are often directed towards more speculative assets, or in economies which large rents are used domestically to conserve the existing social and power structure. Note that investment in speculative assets can be considered as having no impact over the long run equilibrium as they will be ultimately transformed into productive equipment. However, they are a 'detour', a form of 'preference for liquidity', which may have a strong impact on short and medium term dynamics. Secondly, styles of consumption differ by social class, which ultimately impacts not only the environmental footprint of consumption, but the direction of technical change. Another important and related issue is the perpetual reformation of the frontiers and links between the non-marketed economy (the family production of goods and services, the local public activities), the informal economy (with commercial but not registered exchanges) and the formal market economy. These issues are important to assess the implications of a ‘growth by equality’ versus ‘growth by inequality’ perspective on the rate and direction of technical change. This includes the trickling down of wealth, technical progress and consumption styles on lower classes – which determines the environmental footprint of growth patterns. The research agenda outlined here is needed for many reasons. Above all, it is needed to reconnect long term environmental issues with the concerns of policy makers about economic and social tensions caused by the current crisis of the globalisation process. Exiting the aftermath of the financial crisis in a sustainable direction is perhaps the most important challenge the world faces.

7 Summary and conclusions

This paper aimed at clarifying what mainstream economics can really say about the links between energy, growth and the environment. Theories of economic growth have long recognised that innovation is a key but poorly understood force – the ‘residual’ identified in neoclassical growth models. We showed that these models may be unable to picture how a suite of economic and institutional changes triggers waves of long-term economic progress and what may provoke their exhaustion. In particular, the absence of finance in post-Solow growth models is problematic. The centrality of financial structures to understanding patterns (both the pace and direction) of economic growth is particularly acute concerning policies to shape efficiency, innovation and infrastructure in ways compatible with energy and climate security, since these typically require great upfront investment. The wealth held in institutional investment funds could be particularly relevant for long-term secure investments, and energy infrastructure is a leading candidate. However, uncertainty and a lack of confidence deter such investment. To the extent that environmental policy can reduce uncertainty, it has potential to reduce risk and thereby shape and accelerate ultimately profitable investments. There could be in fact deep relationships between energy/carbon-related finance and wider debates about financial systems after the crisis. The agenda proposed for future research on alternatives to classical growth models could address some of the increasingly acknowledged limitations. This research agenda is needed for many reasons. Above all, it is needed to reconnect long-term environmental issues with the concerns of policy makers about economic and social tensions caused by the current crisis of the globalisation process. Existing Integrated Assessment models may provide useful insights on the adaptation of economies to low-carbon energy systems over the long run and the models. But they do not provide insights on how to trigger and conduct a transition in turbulent times. This paper has sketched some basic methodological components that would be needed to build models in which a large part of growth is no longer generated by a ‘dark matter’, but rather by the interplay between growth, technical change and institutions under resources and environmental constraints.

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