Futures 61 (2014) 13–22

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

Renewables, manufacturing and green growth: Energy strategies based on capturing increasing returns

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ARTICLE INFO

Article history:
Available online 5 May 2014

Keywords:
Increasing returns
Renewable energies
Manufacturing vs. extractive industries

ABSTRACT

Energy futures and the case for renewables and cleantech can be framed in terms of their contribution to mitigation of climate change, as well as cleanliness and absence of carbon emissions. By contrast, energy security is generally discussed in terms of access to fossil fuels. In this paper we make a different case for renewables: we contrast the *extraction* of energy (fuels), which – in spite of technological change – takes place under diminishing returns, with the *harvesting* of nature's renewable energy, which takes place in a process utilizing manufactured devices, where manufacturing generates increasing returns and costs decline along steep learning curves. This gives a fresh perspective on both renewables and energy security. We argue that energy choices can be framed as choices in favour of increasing returns (based on manufacturing), vs. choices in favour of diminishing returns activities, which usually involve extraction of fossil fuels. Such a framing does not entail assumptions as to whether the entire energy system can be converted to renewables, but simply as choices made at the margin – whose effects will cumulate over time. Energy security through renewables manufacturing therefore promises to be a fruitful area of futures studies.

1. Introduction

Energy policy and the discussion of energy futures has moved to the centre-stage of political and policy debate – driven by concerns over global warming and the impact of the continued burning of fossil fuels. The case for renewables and cleantech is usually given in terms of contribution to mitigation of climate change, as well as cleanliness and absence of carbon emissions. Energy security too is widely discussed, and usually in the context of securing access to fossil fuels, either of the traditional kind (oil, gas, coal) or the new non-traditional fuels (coal seam gas, shale oil).

In this paper we link the two and thereby make a quite different case for renewables, couched in terms of their contribution to energy security. Renewable energy systems embody technological change, manufacturing, learning curve effects, and the capture of increasing returns. Because they are produced by manufacturing activities, which can be conducted virtually anywhere, they offer prospects of long-term energy security for the countries that adopt them. Renewables may be viewed as a developmental strategic choice – and the effects on climate change mitigation, energy security and environmental cleanliness are useful and desirable adjuncts.

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http://dx.doi.org/10.1016/j.futures.2014.04.011
0016-3287/

We argue that the choices in favour of manufacturing and the capture of increasing returns do not entail assumptions as to the operation of the entire energy system. Much of the debate over renewables turns on questions as to whether they can support baseload power for an entire industrial economy, or supply power at peak load times given their fluctuating character. We are not entering such arguments in this contribution, because we frame the choices as taking place at the margin, where a new energy investment project is being considered. Each new investment can be evaluated in terms of whether it contributes to energy security, through being based on manufacturing, or whether it contributes to long-term insecurity, through being based on fuels whose supply and geographic location are beyond most countries' control.

These matters actually have a long history. We make the case in this article that there is a continuation between arguments mounted over past centuries in favour of manufacturing and increasing returns (going back to the treatise by Antonio Serra, composed in Naples in 1613 (Serra, 1613/2011)) and today's arguments over energy choices. There have of course been many contributions to the debates over optimal economic choices for countries (e.g. see recent contributions such as Acemoglu & Robinson, 2013 or Reinert, 2007). Our point is that these ultimately turn on the issue as to whether domestic manufacturing is to be encouraged or not. Now the same issues can be seen to emerge in debates over energy issues. In particular we make the case that choices made by countries in favour of 'green growth' (e.g. by China or Korea) are part of a long developmental tradition that is now about to be given a new lease of life by the renewable energies question.

Our argument clarifies why growth in incomes is compatible with ecological security, if achieved through the application of manufacturing technologies which generate increasing returns – like renewables. What results is 'green growth' that is entirely compatible with planetary ecological limits that need to be respected by any economy. This is an attractive alternative to the case for 'zero growth' (that dooms poor countries today to perpetual poverty) which is Malthusian in inspiration. So our argument is that green growth is based on foundations of renewables and the capture of increasing returns, and represents an optimal way forward for China, India and other large industrial countries today. Our argument supports the point that renewables constitute the carriers of a new sixth technoeconomic paradigm (Mathews, 2013). As the emergent dominant technology they promise to embody continuous learning effects and declining costs (increasing returns) thereby becoming the next general purpose technology.

Our argument concerning increasing returns as applied to energy questions has a different emphasis from that employed by economists who have recently 'rediscovered' increasing returns. Much interesting work has been done on questions to do with geographic clustering, technological change and path dependence, utilizing increasing returns arguments. But we are going back to the core, which is to contrast industries that generate increasing returns with those that are boxed in by diminishing returns. This is where it all started – with Serra's original insight – and that will prove to be the most significant feature of today's energy choices.

Antonio Serra, we argue, would not be surprised by these conclusions; he would wonder simply why it took so long to realize their significance.

2. Renewable energies: technological change, learning curves, declining costs and increasing returns

Measurable productivity increase may be a product of several factors, most of them resulting from technological change in one form or another. New sources of energy, e.g. solar panels, are *product innovations*. But within the same technological process, in theory two different types of productivity increases may occur. We may observe (a) *process innovations* which shift the whole cost curve downwards, or (b) *increasing returns* where costs diminish as the result of the same technology being applied in a larger volume of production. The difference here is that the former lies in representing a shift in the cost curve, while the latter may be viewed as a movement along the same curve. As recognized by Schumpeter (1954, pp. 262–263) when we observe productivity increases over time, these two phenomena (a shift in the cost curve vs. movement along the same curve) are generally impossible to separate in real life.

Schumpeter therefore suggests using the term 'historical increasing returns' to describe a combination of both phenomena.[1] Plotting real production costs over time enables us to create learning curves, depicting how costs of production decrease over time as a result of all factors mentioned above. Agriculture and extractive industries also have technological change and experience curves, but as opposed to manufacturing, agriculture and extractive industries are facing one factor of production which is determined by nature (land, ore, oil) and will therefore always, sooner or later, run into diminishing returns. In such activities, the observed cost and productivity data will be a net effect of the positive effect from adding new capital and technology, improving productivity, and the negative effect of diminishing returns from moving into more marginal land (agriculture), or deposits of ore and oil that are inferior or more costly to access.

In mining and extractive industries a drop in production will lead to marginal mines (and, if possible, oil wells) being closed down. In such cases of falling production, the level of productivity will therefore go up, whereas in manufacturing a similar fall in volume of production would make unit costs go up. A sudden drop in production will reveal to what extent an industry is operating under conditions of diminishing returns. For example, when tin production in Bolivia fell by 61 per cent

[1] We may also use the term 'generalized increasing returns' as introduced by Buchanan and Yoon (1999) in their exposition as to why neoclassical economics abandoned the notion of increasing returns. Their argument is that the concept was dispensed with for purely technical reasons to do with closing the general equilibrium system; the equations would not balance without the assumption of constant returns (or diminishing returns). See also Reinert (1980, 1996). Needless to say that this was an assumption not backed by empirical evidence.

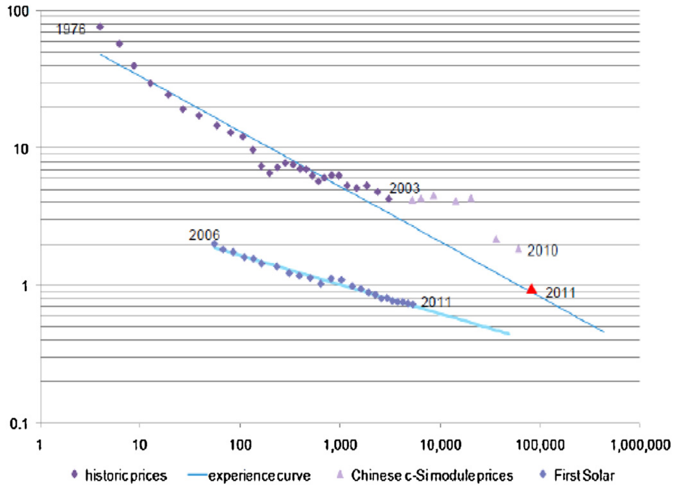

Fig. 1. Cost reductions for solar photovoltaic power, 1976–2011.
Source: Bazilian et al. (2013).

during the Great Depression (1929–1932), this decline in production was accompanied by an *increase* in labour productivity of 26 per cent (Reinert, 1980, chap. 8). If oil prices should fall, we will of course experience a similar phenomenon: the average cost of extracting oil will come down because in the long run the most costly – and also environmentally hazardous – production areas would be closed and the cheapest ones would continue operating.

It is worth pointing out that such a law of diminishing returns also applies to renewable energy sources such as wind farms, where the first choice of location will be made to harvest wind energy of highest quality, and subsequent choices will have to be made to capture less energetic wind locations. This is an inescapable feature of any activity that depends on choice of land, where one choice precludes subsequent choices. But this argument most emphatically does not apply to the manufacture of wind turbines, nor manufacture of solar photovoltaic cells, nor of lenses and mirrors utilized in concentrated solar power production: all of these renewable power devices can be manufactured subject to declining costs and increasing returns.

The point we are trying to emphasize is that very different economic laws apply to activities that are subject to increasing rather than to diminishing returns. Renewable power – relying on renewable supplies of solar, wind or geothermal energy – can for all practical purposes be generated by devices that are manufactured, and which thereby enjoy increasing returns. We argue that this opens up a new perspective on global sustainability. Consider Fig. 1, which shows the declining costs of generating solar PV electric power as experience accumulates. All manufactured products are subject to learning curves – namely reductions in costs of production as experience accumulates. Renewable energies are no exception to this generalization. The learning curves associated with renewables are well recognized (Bazilian et al., 2013; Reinert, 1980).

The trends in 2012 are dramatic, with crystalline-silicon costs declining by 20% and now getting below the costs for next-generation thin-film solar cells. Meanwhile the learning curve for wind is also strong in terms of cost reductions – if less dramatic than the case of solar PV.

Consider the significance of such experience curves. The cost decline of 20% per year for solar PV means that a factory can generate the same power (utilizing solar PV systems) for 20% lower cost. Year by year, these lower costs mean that more can be produced with the same level of investment, generating a greater return. These are the effects of 'increasing returns' – a concept that was once central to practical economic reasoning but has tended to disappear from neo-classical economics because increasing returns are not compatible with equilibrium (see footnote 1). Likewise with the case of wind, the same level of investment in power generation can produce more, or 'increasing returns' – but in this case, at a rate of 7% rather than the 20% achievable with solar PV. Wind power too in its early years was able to generate striking increasing returns.[2] Of course the various renewables follow different learning curves and have different cost reduction characteristics – but our point is that as a group they exhibit patterns of cost reduction rather than cost increases. In this we concur with studies of future scenarios for renewable energy such as that by Sadorsky (2011).

Intel chairman Andy Grove emphasized the lack of predictability when a prototype technology is scaled up: 'Never judge a technology after seeing the first prototype'. What will be the combined effects of scaling up and cumulative learning as both scale and experience increase?

[2] For a strong defence of renewables and their future industrial impact, see Scheer (2011). On the emerging transformation this implies for the global business system, see Mathews (2011).

These facts are the most significant features of wind and solar power – and they stem from the fact that these power systems are the product of manufacturing, of systems that harvest nature's continuous flow of energy rather than mining and extracting past energy stores in fossilized form. The firms, regions and countries that specialize in the manufacture of renewables can count on being able to enjoy rising levels of power generation, from a given base, without regard to the geographical and physical constraints that apply to fossil fuels and other commodities that are extracted from the earth. Moreover the countries that specialize in power production from manufactured renewable power systems can expect to enjoy strong developmental effects, as one industrial value chain interacts with another value chain and the two generate further interactive effects, or synergies. These are the source of systemic increasing returns, and the more a country produces them, the more benefits the country will enjoy.

The learning (or experience) curve also drives the industrial dynamics of the renewables sector in ways quite unanticipated by standard economic theory. The dramatic fall in costs means that solar PV power is becoming competitive with power generated by conventional thermal (coal-burning) power stations. This phenomenon, termed 'grid parity' has been widely anticipated, but expected sometime after 2020. Now it is imminent, or has already arrived in some well-insulated regions, according to authoritative sources such as McKinseys. This means that the traditional business model of large, centralized power stations serving large grids with baseload power is being overthrown, in favour of diffuse and decentralized generation by independent power producers. The solar PV learning curve is thus on the crest of creating a large wave of creative destruction in the power industry, exactly as explained in Joseph Schumpeter's view of how technological change takes place.

Leading consulting firms like McKinsey, Deutsche Bank, Citibank and Allianz in their reports to investors are now calling attention to the imminent cross-over in costs between those incurred by solar generation and thermal (coal-fired) generation. Grid parity has been widely predicted, but organizations like Deutsche Bank are now describing it as having arrived in key markets.[3]

We should also keep in mind that increased energy efficiency, e.g. coming from installing better insulated window panes, is also subject to 'historical increasing returns' – the combination of technological change and increasing returns – taking place in the production of insulated glass and other manufactured products.

By contrast, the extraction of raw materials (e.g. oil or gas) is always subject to diminishing returns. This is because they are exhaustible, placed where they are 'by God', i.e. independently of human choice, and as one seam is extracted, so a more difficult seam has to be tackled. Even when accompanied by technological innovation (such as hydraulic fracturing), this limit of increasing difficulty translates into rising costs (the opposite of the situation in manufactured renewable systems) and so the returns decline – or 'diminishing returns'. The arguments over 'peak oil' are necessarily of this kind. The real argument is not whether the oil or gas is going to run out, but over the rising costs as the peak is passed. In the US today, the celebration of newfound 'energy independence' masks the fact that coal seam gas and shale oil are far more expensive (as well as dirtier and more energy hungry) to produce than their conventional counterparts. Extracting oil from tar sands or gas from coal seams is what Klare (2012) calls 'extreme resources' – in the sense that they are extremely difficult to extract, extremely dangerous and extremely dirty. Here we find diminishing returns writ large – without the counteracting effect of increasing returns coming from repetitive manufacturing as in the case of wind turbines manufacturing. Let us emphasize that we are not arguing that extractive industries are not unprofitable – indeed huge profits are being made right now in the coal seam gas and shale oil industries in the United States. What we are arguing is that such industries eventually come up against diminishing returns.

The world of energy is only now discovering the key differences between manufacturing as a source of wealth (utilizing manufactured renewables) and resource extraction, which is subject to diminishing returns. The importance of diminishing returns was clearly recognized by English 19th century, pre-industrial economists, including Malthus, Ricardo and Mill and extending to Marshall. Indeed diminishing returns were central to Malthus' (1798) arguments made at the close of the 18th century that agricultural (and extractive) productivity could not keep pace with population growth.[4] Diminishing returns were central to Ricardo's doctrine of rent, whereby he argued that landlords were a parasitic class helping themselves to the surplus created by farmers as they extracted returns from soils of ever declining levels of fertility, subject to perfect competition. The same argument carried over to miners and resource extraction, and could today be applied to the superior profits in the oilfields operating under lowest cost.

As the culmination to this line of argument, in his classical 1848 textbook John Stuart Mill explains as follows:

> 'I apprehend (the elimination of Diminishing Returns) to be not only an error, but the most serious one, to be found in the whole field of political economy. The question is more important and fundamental than any other; it involves the whole subject of the causes of poverty;...and unless this matter be thoroughly understood, it is to no purpose proceeding any further in our inquiry' (Mill, 1848: 176).

This was followed up by Alfred Marshall, the founder of neo-classical economics. In the first edition of in *Principles of Economics*, in 1890, Marshall (1890) – quoting the Bible's *Genesis* – not only reminds his readers that diminishing returns was

[3] See the reference to this Deutsche bank report at RenewEconomy, here: http://reneweconomy.com.au/2014/deutsche-bank-predicts-second-solar-gold-rush-40084.

[4] These arguments are still alive today, in 'neo-Malthusian' form; for a defence, see Randers (2008).

the cause of Abraham's parting from Lot and of most of the migrations of which history tells, but he also suggests taxing activities subject to diminishing returns in order to give bounties to activities produced under increasing returns.[5] This was a sound judgement which could see a new lease of life in arguments today over environmental taxation.

We have been arguing, individually as well as together, that there is another tradition of economic reasoning that better reflects the reality of countries' development. As opposed to the barter and commercial vision embodied in Adam Smith and Ricardo, this 'Other Canon' tradition focuses on the real drivers of growth in productive forces and in production itself, focusing on the generation of increasing returns.

Our argument is that converting the world supply of energy from the areas of diminishing returns – where technological change continuously batters against a 'flexible wall' of diminishing returns – to one of harvesting energy under increasing returns with learning curve effects applying in the manufacture of the devices utilized, will represent a qualitative change in the global quest for sustainability. Let us probe more deeply, then, into the sources of increasing returns and how they are generated by manufacturing industries.

3. Manufacturing and increasing returns

The world's leading information technology industries have been expanding rapidly over the past two decades, driven by year-on-year cost reductions and improvements in efficiency. In the case of semiconductors, this has been captured as Moore's law – while similar relations between cost reduction and efficiency improvement apply to other IT products such as flat panel displays, PCs, tablets etc. etc. These phenomena are captured by the broad notion of "increasing returns". Thus we would emphasize that increasing returns characterize the world's leading high-tech manufacturing industries, and have done so for the past 20 years.

In fact recognition of this phenomenon goes back not just 20 years but several hundred years. Four hundred years ago – in 1613 – from his prison cell in Naples Antonio Serra wrote a book which established for the first time why some cities or regions grow rich while others stay poor. Joseph Schumpeter credited Serra with being "the first to compose a scientific treatise... on Economic Principles and Policy" Schumpeter (1954, p. 195). Antonio Serra's book, *A Brief Treatise on the Causes which can make Gold and Silver Plentiful in Kingdoms where there are no Mines* (Serra, 1613/2011), developed the novel argument that countries did not need gold or silver mines to be rich; they grew rich by their own efforts in building industries which generated increasing returns – by which he meant manufacturing industries. Thus Naples, groaning under the control of the Spanish empire, was impoverished, while Venice, Genoa, and Florence were growing wealthy based on their export of manufactured goods.

Serra established two basic dichotomies that have proved to be of crucial importance in economics. First of all, he made a sharp distinction between the financial and monetary sphere of the economy and the real economy, and argued that the key to wealth was found in the latter: "if the economic process as a whole functions properly, the monetary element will take care of itself and not require any specific therapy" as Schumpeter restated Serra (ibid).

Serra's second dichotomy – and this was a true innovation – was to distinguish between economic activities subject to increasing returns (where unit costs fall as the volume of production increases) and those subject to diminishing returns (like agriculture and extractive industries where one factor of production is limited by nature). Serra saw the wealthy countries/ regions basing their economies on selected large number of different manufacturing activities, with their capacity to capture synergies and increasing returns, while the poorer countries remained dependent on agriculture and extractive industries, which were always subject to diminishing returns. This was the reason why some nations (or regions) grow rich while others stay poor.

The case can be made that this same distinction has characterized every successful development practice – from Britain's support of the woollen manufacturing, starting with Henry VII in 1485 through its industrial revolution, to Germany and the US in the 19th century, to Japan and East Asian countries in the 20th century, and now to China (and to some extent India) in the 21st century. We also find this subject returning frequently in economic theory. Serra's key point underpinned 19th century industrial policy of all nations industrializing following England – Friedrich List (1841, chap. 29) quotes him – and Serra's main point was made succinctly clear in an influential article (Graham, 1923). This article in turn was used by Paul Krugman and others in the Strategic Trade Policy debate that started in the 1980s. However, these newer debates were concerned with geographic clustering and trade, and did not employ the basic dichotomy between increasing (manufacturing) vs. diminishing returns (agriculture and extractive industries) which had been used over the three centuries from Serra to Graham.

3.1. How renewables manufacturing generates increasing returns

At the core of manufacturing lies its capacity to generate increasing returns, where for every unit of input added there is a greater than proportional increase in output. Such a state of affairs is – after a certain point – impossible in agriculture or in extractive industries (or even in wind farms), where by contrast diminishing returns prevail. But in manufacturing, whether

[5] For a discussion of the diminishing role of increasing and diminishing returns – because of their incompatibility with equilibrium – over the different editions of Marshall's *Principles* see Reinert (1999).

carried out in a single establishment (Adam Smith's famous pin factory) or more significantly across a cluster of associated activities, systemic interactions can occur (termed synergies) that make the whole output greater than the sum of its individual parts. Systemic interactions lie at the core of increasing returns – which are found in manufacturing industries but not in extractive and agricultural activities. This is why the cities that grew to prominence in the early Modern era were all based on manufacturing, and why manufacturing remained the option of choice for all countries that industrialized and grew wealthy.

Firms earning increasing returns are attracted to each other, forming value chains of manufacturing activities where the whole chain earns returns greater than those available to individual members of the chain. This again is a systemic effect – and is captured in phrases such as synergies, linkages (Albert Hirschman), 'external economies' (Alfred Marshall), cumulative causations (Gunnar Myrdal), or positive feedback effects, or manufacturing multipliers. The reduction in costs sometimes takes place as major technological breakthroughs, but more often is the result of thousands of small increments and innovations introduced by firms at different points along the value chain, each one building on those that came before and paving the way for subsequent improvements. The costs reduction is a systemic end-result – a measure of the dynamism of the economic system, in much the same way that temperature is a physical measure of the molecular movement of a gas or liquid.

When mass production is added to this economic process, it brings in as well the role of the market. As the market expands (through declining costs and increasing returns) so it generates opportunities for specialization – for an increased division of labour – which improves productivity – generating further increasing returns – and enabling the market to expand still further, generating another round of increasing returns.[6]

It was the American economist Allyn Young who explained this process well, in a remarkable paper read to the British Association in 1928 (Young, 1928). Young dispensed with the usual abstractions utilized by economists – marginal revenues, equilibrium and so on – and instead focused on the principal issue, which is how through specialization and division of labour markets are expanded and wealth is accumulated. Young emphasized that in the real economy, large investment decisions are needed before firms enter markets, in order to produce in quantities anticipated by market growth rather than at the current (possibly very small) market size. Thus he argued that the theory to do with marginal pricing is irrelevant to real decision-making in mass production industries – as amply verified in the near-century of industrial experience since Young was writing.

Scholars grapple with phrases or metaphors to describe this reality – as in phrases like 'virtuous circles' or 'circular and cumulative causation' – all of which are based on increasing returns or manufacturing multipliers. In our view, the best and most graphic phrase is that coined by Kaldor – increasing returns propagate through manufacturing value chains like a 'chain reaction', where each addition of an increasing return (multiplier) is based on earlier such multipliers.[7] The greater the intensity of linkages secured, the greater the multiplier effect. This is the secret of the effectiveness of manufacturing clusters, or industrial districts – or, in the case of green production, of eco-industrial clusters or parks.

China is taking advantage of all these positive effects with its focus on building green industries such as renewable energy industries and eco-industrial parks. These are usually viewed through climate change mitigation lenses or energy security lenses – but they can also be viewed, we argue, as green developmental strategies where increasing returns underpin the whole process.

Mainstream economics obscures this process with its relentless focus on equilibrium, perfect competition, constant returns to scale, and the representative firm. All these concepts make sense only in a world of free trade abstracted from any resemblance to real business processes – which is why all the successful and wealthy countries today pursued strategies based on developmentalism and industry policy rather than purist free trade based on equilibrium reasoning. Renewable energies could well prove to be the 'tipping point' in the current process of transformation. They may be said to be leading the world into its new Anthropocene era – when human activities shape the earth and biological world.[8]

4. Green growth vs. zero growth

In response to concerns over the future of the planet, many are calling for an end to economic growth – in the name of respecting ecological limits and finite planetary resources.[9] The problem is that this concern is based on a misunderstanding of the character of economic growth. If it is extensive growth, i.e. based on increasing resource throughput, then it is clear

[6] The most important theorem in economics is Adam Smith's proposition that the division of labour is limited by the extent of the market – meaning that market size sets a limit on specialization, and as specialization is increased, so market size can expand. Serra already gives us the basis for this insight in 1613, when he describes how the multiplicity of manufacturing activities in Venice and the increasing number of customers attracted by this multiplicity are factors which mutually reinforce each other: "each of which lend force to the other" he says, in describing what we would today call a virtuous circle (Serra, 1613/2011, p. 127). See Young (1928) for an insightful elaboration on Smith's point.

[7] The notion of 'circular and cumulative causation' was introduced into economic reasoning by Myrdal, and was taken up by Kaldor (1970) – as explained in detail by Toner (2000). Related concepts in the setting of development economics are the 'big push' (Rosenstein-Rodan) and balanced vs. unbalanced growth (Nurkse, Hirschman). We argue that all these concepts acquire a fresh significance as they are transposed from development concerns to strategies for green growth.

[8] The Anthropocene was a term coined by Nobel Prize winning chemist-geologist Paul Crutzen (2002); see Steffen et al. (2011) for a useful elaboration.

[9] See for example Jackson (2009).

that it must one day come to a halt and be succeeded by a stationary state – if humans and life in general are to survive. But it is perfectly possible to have intensive growth, i.e. growth in incomes without a corresponding growth in resource throughput. This is what is meant, in fact, by increasing returns – getting more out of what is put in. So capturing increasing returns means, essentially, embarking on a process of intensive growth – which if based on renewable energies (always available) and resource recirculation, can be called accurately 'green growth'.

It is to be expected that new 'green' sectors like renewable energies and circular economy linkages (industrial symbiosis) will grow and propagate based on their capacity to generate synergies and increasing returns, in exactly the same way that Kaldor (1970) foresaw that regions based on manufacturing activities would flourish at the expense of regions locked into diminishing returns activities. The manufacturing activities involved in renewables production span numerous value-chains and the creation of clusters (such as the China windpower cluster at Tianjin and the electric vehicle cluster at Wuxi) where firms interact and generate combined increasing returns – just as automotive firms have clustered and captured increasing returns in the Detroit region in the US or around Wolfsburg in Germany.

Our argument is that similar concerns play out in national energy choices. China's opting for green growth is likely eventually to trump its black growth (fossil-fuelled, resource-extensive) model, for the distinctive reason that green growth promises to propagate through increasing returns, synergies and multipliers, in a process best described as a chain reaction. By contrast its current black development model is subject to diminishing returns and fails to capture economies of scale or synergistic linkages. While its scale is currently expanding, it is destined to shrink in relative terms while the green growth sector of the economy expands. This is an optimistic perspective – one that is grounded in reality. The contrast with the pessimism of conventional economics – known for good reasons as the 'dismal science' – is stark indeed.

5. Renewables, path dependence and technoeconomic paradigm shifts

The history of industrialization, for the 400 years since Serra wrote his treatise in Naples, is one of poor countries becoming rich by focusing policy on building and protecting a manufacturing base. This was the policy of the Italian city states; and of European nation states from England starting in 1485 through the post-WW II Marshall Plan which had as its main purpose to resurrect the European manufacturing (i.e. increasing returns) sector.

The key is to reap the advantages of market expansion, specialization and increasing returns that unfold in the processes of circular and cumulative causation – or the 'chain reaction' that expands wealth. This has been the key in previous dominant and general purpose technologies – steam engines, railroads, power stations, automobiles, electrical goods and most recently electronics and IT. As argued in this journal by Mathews (2012), each of these could be viewed as carriers of new waves of technoeconomic development, driving a new surge of investment and propagating its effects through competitive emulation and productivity enhancement across the entire economy.

The central idea in the depiction of these successive waves of industrial transformation (creative destruction) is that they are driven by a new 'lead' technology that is widely available and applicable across all sectors; that is subject to dramatically falling costs; and is cheaper than its competitors. It can be argued that these three conditions are all satisfied (or in the case of the third, on the point of being satisfied) by renewables (Klare, 2012). This carries the implication that renewables are on the cusp of a vast investment surge, one that will carry within it some speculative activity but where (according to the framework introduced by Perez (2002, 2010) real investment in new infrastructure will rapidly take over.

China already demonstrates these characteristics of a 'sixth TEP' vanguard country, where investment in renewable energy systems vastly outranks that of any other country – even of industrial giants like the US and Germany.[10] China's energy investments are channelled towards clean energy in terms laid down by the 12th Five Year Plan, covering the years 2011–2015. This envisages a total of $760 billion being invested over 10 years in seven strategic industries, dominated by clean energy and clean technology. It is these strong investments that promise to underwrite the global success of China's renewable energy industries and exports, not low labour costs; if anything, it is low capital costs, with low-interest loans from state-owned banks and local administrations that are driving China's energy trajectories.[11]

We may take the case of Germany as an illustration of the current trends. When the Merkel government reversed nuclear policy and closed down nuclear plants in Germany, following the Fukushima nuclear disaster in Japan, this action spurred a great acceleration in the uptake of renewables. New coal-fired plants that had already been commissioned came on stream, but no new coal-fired plants have been commissioned since the German turnaround. Investments have been made in

[10] Chinese investment in new renewables installations each year is far ahead of industrial rivals. In 2010 China invested $54.4 billion in clean energy systems, of which $47 billion was invested in hard asset installations like wind farms and solar arrays. By contrast the US private investment in clean energy totaled $34 billion, of which only $21 billion went into hard assets. In 2011 China's investments in renewable energy systems maintained their level (against global trends) at $54.2 billion, and rose again in 2012 to $65.1 billion – while that of the US and Germany declined. Of the leading powers, only Japan also raised its investment levels to $16.3 billion, a 75% increase. See the Keynote presentation by Michael Liebreich, Bloomberg New Energy Finance, at the BNEF Summit in New York, 2013, available at: http://about.bnef.com/presentations/bnef-summit-2013-keynote-presentation-michael-liebreich-bnef-chief-executive/.

[11] Of course China's renewable energy industries have been buffeted by competitive forces, and some firms, like Suntech in solar PV and Huarui in wind power have crashed. While these collapses have attracted widespread adverse comment, we see them on the contrary as a healthy sign, meaning that the renewable energy sector really is competitive – meaning that inefficient firms or over-leveraged firms are being subjected to market discipline. On China's choice of green industries, see Mathews (2012) and successive works by the economist Hu Angang (Hu, 2006a, 2006b, 2011).

improvements in the German grid, enabling it to receive higher levels of fluctuating electric energy. At the same time, new renewable sources such as concentrated solar power with molten salts heat transfer technology are able to generate power at night as well as during the day.

The emphasis in authors who have recently 'rediscovered' increasing returns – such as Arthur (1996) in the context of technological change and path dependence, or Krugman (1991) in the context of geographical clustering and inter-regional trade, is that increasing returns are generated by positive feedback loops that magnify small initial conditions and generate thereby path dependence – whether of a technology or a geographical location.[12] We do not deny the importance of these arguments – but we wish to point out that they do not depend fundamentally on the distinction between industries generating increasing returns from those condemned to diminishing returns. It is this distinction that (we argue) is the more fundamental – and which will play an important role now in energy debates. But path dependence will of course play its role here too, as a new energy-based technoeconomic paradigm gets under way based on renewables.

6. Policy implications of viewing renewables as the next manufacturing driver

Now it can be argued that it is the turn of energy, with renewables in the vanguard, to yield insights based on these arguments. The key policy goal is the expansion of the market, which in turn leads to greater scale of production and reduced costs, captured as increasing returns. This is a goal that is much clearer and better supported by evidence than generic calls for 'more innovation' or for taxes on carbon-intensive activities. We are doubtful that railroads were successful because of taxes imposed on canals, or that word processors triumphed because of taxes on typewriters.

It was widely understood in the past that a period of protection was needed to get these new industries, with their new technological carriers, off the ground. This was 'infant industry protection' – understood and recognized even by Adam Smith. But in the case of renewables, any subsidization of power production to expand the market for renewables is ridiculed and obstructed – by vested interests,[13] to be sure – but even more forcefully by 'neutral' economists who insist that markets be allowed to function 'free of interference'. Yet some kind of support and protection is needed if the new shoots (in Chinese, *hsinchu*, or *xinzhu*) are to be allowed to flourish and such support has until now been crucial also to key innovations.[14]

In fact the situation is fast approaching where solar PV systems promise to generate power for lower costs than conventional thermal power where firms have to bear the cost of purchasing the raw material inputs. This is called 'grid parity' and it marks the point where electric power produced using renewables becomes cost-competitive with conventional power production – without subsidies. This situation is now widely expected. But a more general perspective based on manufacturing means that this situation has always occurred where one dominant technology is being replaced by another.

What are the policy implications of the approach outlined here? Our Schumpeterian/Youngian analysis leads us to view the acceleration of market expansion as the key consideration – because this will drive down costs through the learning curve. As costs decline, so the market expands – and as the market expands, so more specialized activities can be developed, which enhances productivity and leads to further market expansion, which further drives down costs, and leads to further specialization – and so on, round and round. This 'circular and cumulative causation' remains fundamentally the capitalist growth engine. The insight that these mechanisms of cumulative causation lie at the core of successful capitalism was Antonio Serra's great contribution to economics.

Thus policies that are focused clearly on market expansion are the preferred option for driving the uptake of renewables – rather than subsidies or tax credits, which are favoured in many jurisdictions. The German innovation of feed-in tariffs, which encourage independent power producers by setting a floor under the price at which they can sell power to the grid, and require grid operators to accept such power at the given price, has proven to be extremely effective at growing the market – and are now being taken up around the world and in China as well. If combined with direct promotion of productive activities, such as through tax credits and requirements to build local supply chains, the renewables energy industry can be expected to expand rapidly and overtake its fossil-fuelled rival. New forms of path dependency can then be expected to develop – based not on fossil fuels but on renewables systems.

Against these policies have to be set the continuing very high levels of subsidies paid to fossil fuel industries, through tax breaks for oil well drilling, opening new pipelines and subsidies paid to keep costs of fuel low to consumers. Clearly the most significant policy to drive uptake of renewables is one targeted at dismantling subsidies paid to fossil fuels.

But the mention of subsidies paid to fossil fuels draws attention to the wider "carbon lock-in" found in advanced economies, that holds back growth in renewables sectors. The newly-industrializing countries like China, India and Brazil might be expected to be less constrained by such lock-in, which is another reason for anticipating their strong performance in building renewables industries.

We see the strength of feed-in tariff systems as encouraging wider uptake of renewables options, because of guaranteed payments, and encouraging innovation, because of tariff degression. In this sense such feed-in tariffs are superior to conventional policy tools such as subsidies, tax breaks and redeemable certificates, in that they do not engage directly with the tax system at all.

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[12] For a useful overview of increasing returns arguments, with applications to many strands of social scientific thought, see Pierson (2000).

[13] For a discussion of Veblenian vested interests and 'industrial sabotage' in the energy sector, see Reinert (2012) particularly at pp. 32–38.

[14] On state support for and guidance of innovation, see studies by Bresnitz (2007), Block and Keller (2011) and by Weiss (2014).

7. Concluding comments

Recent scholarship on global history (e.g. Pomeranz, 2000; Wong, 1997) points to China having been the world economic and technological leader for over a millennium, ceding the lead to Europe only during the 1600s. As Europe took over world leadership, its energy system was still largely organic – powered by wind and water (the total number of wind-powered mills is estimated to have been 200,000 and the number of waterwheels some 500,000 in Europe at the dawn of the Industrial Revolution) as well as muscle power. With the Industrial Revolution, which enabled first Britain and then other Western countries to tap into the prodigious resources of fossil fuels, there has been produced an amazing array of human inventions, lifting millions and now billions of people out of poverty. But – up to this point – the process of industrialization is based on extraction and combustion of fossil fuels. This model of development is now understood to have clear limits. If harnessed to extractive activities and fossil fuels, with their finite limits, the capitalist growth engine will eventually have to run down, through diminishing returns. But whether that end-point comes in time to save the planet – or ourselves – is a matter of debate.

Seen from the perspective of Antonio Serra, the path to sustainability lies in avoiding diminishing returns. If this is so, the key to our industrial civilization's avoiding its decline lies in escape from the diminishing returns and pollution generated by combustion of fossil fuels, putting in its place a system of harvesting energy under increasing returns. We see the obstacles to bringing about such a transformation in the West to be formidable ('carbon lock-in'). It is entirely plausible that China will assume leadership of a post-fossil fuels era through its capacity to harness a renewable energy system based on increasing returns reaped through manufacturing.

Once harnessed to renewable sources and resource recirculation, energy systems based on renewables will expand incomes through increasing returns, and lead to greater prosperity as well as a cleaner planet. The idea that energy may be harvested in this way rather than extracted is not a new one, but in modern times it has not been achieved at any important scale outside the production of hydroelectric power.[15] Now is surely the time to extend a clean harvesting system under increasing returns at the expense of polluting extraction under diminishing returns.

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[15] As US economist Erasmus Peshine Smith (1814–1882) wrote to Henry Carey, a fellow economist: "The entire universe then *is* motion, and the only point is how much of the universal and ceaseless motion we shall utilize, and how much we shall permit to be working against us" (quoted in Hudson, 1968: p. 104).

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