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Technological Revolutions and Economic Growth: The "Age of Steam" Reconsidered *

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> "The steam engine, then, we may just look upon as the noblest machine invented by man – the pride of the machinist, the admiration of the philosopher...."
>
> M.A. Alderson, *An Essay on the Nature and Application of Steam,* 1834

1. Introduction

Not so long ago most economists, though recognising that technical progress was the key determinant of economic growth, preferred to consider it as essentially "exogenous", or, to say it better, as something that was not amenable of a fully satisfactory explanation using the conventional economist's toolkit. In the words of Joan Robinson, economists regarded technical change as something given to us "by God, scientists and engineers". With a touch of proper modesty, economists decided that understanding the reasons underlying God's behaviour was far outside their reach. Interestingly enough, such a view of technological progress regarded in the same way the behaviours of scientists and engineers. These, when considered from an economic point of view, were seen merely as "carriers" of the autonomous logic of technological progress.

Since then, a drastic shift of perspective seems to have taken place. The second part of the 1980s saw the emergence of the "new (neoclassical) growth theory". Technical progress was not only regarded as the driving force of economic growth, but it was claimed that its dynamics could be finally explained using conventional economic analysis. This body of literature rapidly established itself as the new orthodoxy with respect to the connection between technical change and economic growth.

There is another remarkable difference between the "old" and the "new" version of neoclassical growth theory. As was pointed out by Hahn and Matthews, the "old" neoclassical growth theory did not pretend to be a theory of economic history (Hahn and Matthews, 1964; see also Hahn, 1988). The more circumspect and less ambitious aim of the major part of the "old" neoclassical growth models was to illustrate the behaviour of a set of critical variables assuming that a number of very restrictive assumptions were satisfied. Of course, it was reasonable to hope, that, an improved understanding of the mechanics of growth in these imaginary situations - "golden ages" (using another expression coined by Joan Robinson) more likely to belong to some mythical lost world rather than to the actual course of history of mankind - could contribute to shed some light on the growth record of capitalist economies. However, at least among the most attentive contributors to the neoclassical approach as Hahn himself, claims laid in this direction were particularly modest. As Hahn and Matthews stated in their survey, it was rather clear that historical patterns of economic growth could not be adequately described by means of steady-state growth models (Hahn and Matthews, 1964).

This seems to have changed in the new growth theory. Not only there is the claim that the new models can finally provide an adequate picture of the endogenous process of technical change. A number of contributions have also contended that endogenous growth models may be applied in a rather straightforward way to the study of concrete episodes of economic growth. In particular, this claim seems to characterize a rather recent development of the endogenous growth theory, the so called general purpose technologies (GPT) growth models (see the essays collected in Helpman, 1998). It is worth noting that the concept of General Purpose Technology is essentially a 'domestication' in the ambit of endogeneous growth theory of a number of key-ideas that were originally expounded by authors (Freeman and Perez, 1988, Freeman and Louca, 2001) coming from a more heterodox (neo-Schumpeterian) tradition.[1]

In the original formulation proposed by Bresnahan and Trajtenberg (1995), GPT are defined as technologies endowed with three salient characteristics: a) they perform some general function, so they can be employed in a wide range of possible application sectors, b) they have a high technological dynamism, so that the efficiency with which they perform their function is susceptible of being continuously improved, c) they generate "innovation complementarities", that is to say that their adoption stimulates further rapid technical progress in the application sectors. Steam power, electricity and information and communication technologies are most frequently put forward as clear-cut examples of GPTs.

A particularly interesting aspect of this class of endogenous growth models is that they generate patterns of growth that are characterized by episodes of acceleration and deceleration determined by the implementation of successive GPTs, producing on a long time scale a wave-like profile. More specifically, these models assume that a new GPT requires a rather a long period of "acclimatization". Hence, the initial impact of GPT on productivity growth is typically rather "small". This phase of sluggish dynamic of productivity concludes when the GPT is finally fully "acclimatized" in the economy. Then, the rapid rate of technological change in the GPT and in the application sectors (due to the innovational complementarities of the GPT) produces an increase in the rate of overall productivity growth. Finally, as the scope for further improvements in the GPT is progressively exhausted, this phase of rapid productivity growth will gradually peter out.

Borrowing the expression from Harberger (1998), David and Wright (1999) have suggested that the progressive penetration of a GPT in the economic system triggers a dynamics of productivity growth that is 'yeast-like', in the sense that, spurred by the GPT, productivity tends to grow at the same, uniform and relatively rapid rate in a wide range of application sectors. Vice versa, before the phase of penetration, the dynamics of productivity is instead 'mushroom-like', this means that productivity growth rates tend to be highly idiosyncratic without much correlation across industries. In their paper, David and Wright analyse the development and diffusion of electricity in this perspective, linking the yeast-like behaviour of early twentieth century productivity of US manufacturing with the progressive penetration of the "dynamo" in the economy. In this historical interpretation (see also David (1990)) one may indeed recover deep analogies in the diffusion processes of steam power, electricity and ICT technologies and explain the relatively slow pace of diffusion common to the

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[1] For a critique of the neo-Schumpeterian view of economic history, see Bruland and Smith (1999).

emergence of any new GPT. In this view, the rise of what Freeman and Perez (1988) define a ‘new techno-economic paradigm’ is deeply affected by a number of ‘retardation factors’. The emergence of new GPTs brings together painstaking processes of co-evolution and co-adaptation of new technologies, new organizational forms, new institutions and new consumption patterns. Retardation factors do not concern technologies only, but also, and mostly, the interface between technology and society. Thus, it would turn out to be quite misleading to envisage the affirmation of new GPTs without taking into explicit account the inter-relations with other elements of the existing economic system, including of course other technologies.

The aim of this paper is to review the development of steam power technology in the light of the key ideas proposed in GPT growth models. It seems to us, that this is a particularly fruitful perspective for drawing a preliminary appraisal of the merits and limitations of this class of endogenous growth models.

2. The economic impact of the steam engine (A tale of two Nicks)

Writing in 1845 Friedrich Engels (and with him many other informed contemporaries) had few hesitations in identifying the driving forces of the epochal transformation he was witnessing: “The history of the proletariat in England begins with the second half of the last century, with the invention of the steam engine and of machinery for working cotton. These inventions gave rise, as is well known, to an industrial revolution, a revolution which altered the whole civil society; one, the historical importance of which is only now beginning to be recognized” (Engels, 1845, p. 15).

This view of the early phases of industrialization, ascribing a central role to the steam engine as driver not only of economic growth, but also of other dramatic changes such as the rise of the factory system, was (and still is) resumed in a major part of the historical studies on the British industrial revolution. Writing about one hundred years after Engels, T.S. Ashton (an author whose ideological standpoint was indeed poles apart from Engels’) regarded the steam engine as “the pivot on which industry swung into the modern age” (Ashton, 1948, p. 58). Perhaps the most terse version of this “traditional” account of the British industrial revolution is the one given by Landes (1969). Landes considers the industrial revolution as the outcome of a combination of three interrelated streams of technical advances:

1) “mechanization”, that is the substitution in a wide range of production process of machines (“rapid, regular, precise, tireless”) for human skills
2) adoption of new power sources, most importantly the steam engine which permitted the utilization an almost boundless energy supply
3) extensive use of new raw materials (in particular the substitution of minerals for animal and vegetable substances, most prominently the substitution of iron for wood).

These innovations revolutionized production processes in a wide array of industries determining a marked acceleration in the rate of productivity growth. Furthermore, they “compelled” the adoption of a new mode of production, the factory system.

In more than one sense, Landes' account can still be considered as broadly accurate. However, it is important to remark that more recent research has suggested that a number of substantial qualifications ought to be added to it. Unfortunately, we do not the have the space to discuss here the current historical debate on the British industrial revolution, however for the limited purposes of this paper it will be sufficient to refer to Landes' account.

The picture emerging from traditional accounts of early industrialization, such as the one provided by Landes, is one in which steam power seems to be one, but it is worth stressing *only one*, of the core driving forces of a wide process of economic transformation. Even when considering only the ambit of technology, Landes suggests that the steam engine was one component of *three* interlinked streams of technological advances.

In the context of this complex historical process in which an intricate set of mutually interacting forces were at work, the task of providing a quantitative evaluation of the economic significance of a "macro-innovation" such as the steam engine appears to be a remarkably arduous.

However, though formidable, these difficulties have not discouraged research efforts. More than twenty years ago, Nick von Tunzelmann (1978), adopting a social saving framework of analysis in combination with a more traditional appraisal of backward and forward linkages, provided a careful assessment of the economic effects of steam power technology. More recently, Nick Crafts (2003) has produced a new estimation of the economic impact of steam using a standard growth accounting framework. It is useful to discuss these two contributions by considering first Crafts' exercise.

In order to evaluate the contribution of steam power to productivity growth, Crafts adopts a modified version of the standard growth accounting framework. The rather straightforward extension consists simply in distinguishing between different types of capital (steam and other) and in decomposing TFP in two components, one associated with technical advances in the production of steam capital and the other related to "non steam" TFP growth.

As is well known, Nelson (1981) has compellingly argued against the overall interpretative relevance of this type of exercises. In a nutshell, the main issue is the neglect of the "interaction" between technical change and capital accumulation. This consideration casts non minor doubts on the general validity of TFP as a reliable measurement of the contribution of technical change to labour productivity growth.

Table 1: Annual Cost per Steam HP per year (current £)

Year	Annual Cost
1760	33.5
1800	20.4
1830	20.4
1850	13.4
1870	8
1910	4

Source: Crafts (2003), p. 19.

However, although Crafts' exercise is couched in the standard growth accounting framework, it employs a rather unorthodox method for estimating the impact of TFP on labour productivity growth. Instead of calculating the rate of technical change in steam power technical change as a TFP residual, Crafts gives a *direct* estimate of the impact of technical progress of labour productivity growth. Crafts calculates the contribution of steam TFP to aggregate productivity growth by estimating the aggregate social savings determined by the reductions in steam power costs presented in Table 1.[2] The data on the reduction in steam power costs collated by Crafts are reported in table 1 (data are in current pounds, Crafts uses the GDP deflator to convert them in real prices). The data refer to what Crafts considers to be a normal context of steam engine usage: a textile mill in Lancashire.

The social savings are simply calculated by multiplying the decrease in the real cost of a steam HP between two periods with the total steam HP in use in the final year. This, clearly, represents the costs that, *ceteris paribus*, the economy would have sustained assuming that steam technology had not improved with respect to the initial year. Estimates of the extent of steam usage in the years of table 1 are taken from Kanefsky (1979)'s study of the diffusion of steam power technology in British industry. Kanefsky's data consider total steam HP employed in manufacturing and in mining. It is important to note that these data (here presented in table 2) intend to cover power capacity installed rather than that actual power use. Although the picture of the diffusion of steam power emerging from table 2 is probably roughly correct, in our judgment, these figures still contain some overestimation of the extension of the use of steam *vis-à-vis* the two other sources of power, especially for the years 1760,1800, and 1830. This mainly because very small productive units (which typically employed wind and water) are likely to have gone unnoticed. Notwithstanding this consideration, the slow growth of steam power until the first quarter of the nineteenth century is still apparent.

Table 2: Sources of Power in Use in HP (mainly mining and manufacturing)

Year	Steam	(%)	Water	(%)	Wind	(%)
1760	5000	5.88	70000	82.35	10000	11.76
1800	35000	20.59	120000	70.59	15000	8.82
1830	160000	47.06	160000	47.06	20000	5.88
1870	2060000	89.57	230000	10.00	10000	0.43
1907	9659000	98.14	178000	1.81	5000	0.05

Source: Kanefsky (1979), p. 338.

Kanefsky's figures also allow to Crafts to calculate the contribution of capital deepening in steam power to labour productivity growth. This is done by multiplying the growth of capital intensity in steam for an estimate of the share of steam capital in total income. The results of Crafts' growth accounting exercise are given in table 3.

Crafts, employing a similar methodology, also calculates the contribution to labour productivity growth from steam power employing in railways. Here, data availability force Crafts to compute the contribution stemming from the *total* reduction in transport costs determined by the railways on labour productivity growth. In these calculations, Crafts uses

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[2] It can be shown that, when the standard assumptions are satisfied, the rate of TFP growth is equivalent to the real cost reduction (Harberger, 1998).

the social savings estimates of Hawke (1970) and Foreman Peck (1991). The total contributions of stationary steam engine plus railways as calculated by Crafts are given in table 4.

Table 3: Contributions to labour productvity growth from stationary steam power (% per year)

Years	1760-1800	1800-1830	1830-1850	1850-1870	1870-1910
Rates of growth:					
Steam HP per worker	4.3	3.90	4.2	5.20	3.9
TFP in steam technology	2.8	0.00	1.2	3.50	1.7
Contributions:					
Capital deepening (A)	0.004	0.02	0.02	0.06	0.09
TFP (B)	0.005	0.00	0.02	0.06	0.05
Total contribution (A+B):	**0.01**	**0.02**	**0.04**	**0.12**	**0.14**
Steam income share (%)	0.1	0.40	0.5	1.20	2.2
Social Savings (as % of GDP)	0.2	0.00	0.3	1.20	1.8

Source: Crafts (2003), p. 20.

Table 4: Total contribution to British labour productivity from steam engine technology (% per year)

Years	Stationary steam engines (A)	Railways (B)	Total (A+B)	Labour productivity growth
1760-1800	0.01	-	0.01	0.25 (1760-80); 0.9 (1780-1831)
1800-1830	0.02	-	0.02	0.9 (1780-1831)
1830-1850	0.04	0.16	0.2	1.65 (1831-1873)
1850-1870	0.12	0.26	0.38	1.65 (1831-1873)
1870-1910	0.14	0.07	0.21	1.55(1873-1899);0.85(1899-1913)

Source: Crafts (2003), p. 22; for total labour productivity growth Crafts (1995), p. 752.

Crafts estimates show that steam power technology, during his heyday (which should clearly be in the second half of the nineteenth century) gave a sizable contribution to overall productivity growth, although never a overwhelming one. In the period 1830-1870 the largest contribution from steam came through the "railroadization" of the British economy. The contribution from stationary steam engines was remarkably "small" until the 1850s. In the second half of the nineteenth century the contribution from stationary steam grew in size achieving its peak in the 1870-1910 sub-period. However, even in this phase, the contribution from stationary steam did not account for more than 17% of aggregate productivity growth.

As we have suggested before, growth accounting exercises are to be interpreted with more than particular caution (if not with outright scepticism). However, in this case, data limitations have forced Crafts to provide a direct estimation of the contributions of steam technology by reviving the social saving approach, rather than estimating the economic impact of technical change as a residual. We would like to contend that this can be considered as a rather sound "guesstimate" of the *direct* impact economic impact of steam power technology (in particular, the last row of table 3, where the social savings are expressed as percentage of GDP provides us with a rough estimate of the orders of magnitude in question). [3] Note that these estimates must be regarded as upper bounds, because they do not allow for readjustments from firms and other economic units in the counterfactual world without technical progress.

Let us now turn our attention to the contribution of capital deepening. Here, at least for those not converted to the neoclassical theory of production, the shortcomings troubling growth accounting exercises re-emerge. In particular, the partial elasticity of output with respect to (steam) capital is estimated using the income share of steam capital. In spite of this, table 3 still conveys an important message concerning the rate of accumulation of steam capital. As can been seen from the first row of the table, the rate of accumulation in stationary steam power, although sustained, was never spectacular.

Table 5: Share of "steam" capital in the total capital stock

Year	Steam capital (in millions of current £)	% of steam in the gross stock of capital (Mining and Manufacturing)	% of steam in the gross stock of capital (Plant, machinery and equipment)
1760	0.21	1.17	0.81
1800	1.96	3.44	2.61
1830	9.6	7.22	7.87
1870	51.5	9.77	11.03
1907	144.885	12.26	12.81

Note: Calculated using the data on steam capital cost per HP (replacement costs) from Crafts (2003, p. 19), the data on total HP installed from Kanefsky (1979, p.338, here in table 2), data on the gross capital stock from Feinstein (1988, pp. 437-440).

For sake of comparison, the annual rate of growth of railway capital per worker in the period 1830-1850 was equal to 22.8 % (Crafts, 2003, p.21).
In our view, this indicates that the (expected) rates of return in stationary steam did never greatly exceed those of other forms of investment. Accumulation of steam capital in industry was not driven by sharp investment booms. As a consequence, the substitution between water and steam as power for industrial applications was protracted and long delayed.

Table 5 gives estimates of the share of steam capital in the total capital stock. In particular, we have computed two figures, one for the share of steam in the total capital stock in mining and manufacturing and one by type of asset which considers the share of steam in the "plant, machinery and equipment" stock of the total economy. This can be taken as a rough indication of the relative "weight" of steam technology in the stock of capital. Rather consistently with what we have noticed so far, the share of steam seems to attain a sizable share in the stock of capital only in the late nineteenth century.

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[3] It is worth noting that the estimate of the social savings proposed by Crafts for the period 1760-1800 is consistent with the social savings calculated by von Tunzelmann (1978, p.149) with a more sophisticated approach (0.11 per cent of GDP).

Table 6: Steam power by industry, 1800-1907

	1800		**1870**		**1907**	
	Number of engines	**(%)**	**Steam HP (power in use)**	**(%)**	**Steam HP (power capacity)**	**(%)**
Mining	1064	48.56	360000	26.22	2415841	26.49
Textiles	469	21.41	513335	37.39	1873169	20.54
Metal manufactures	263	12.00	329683	24.01	2165243	23.74
Food and drink trades	112	5.11	22956	1.67	266299	2.92
Paper manufactures	13	0.59	27971	2.04	179762	1.97
Building trades	12	0.55	17220	1.25	347647	3.81
Chemicals	18	0.82	21400	1.56	182456	2.00
Public utility (waterworks, canals, etc.)	80	3.65	36000	2.62	1379376	15.13
Others	160	7.30	44375	3.23	309025	3.39
Total	2191	100	1372940	100	9118818	100

Sources: for 1800, Kanefsky and Robey (1980), for 1870 and 1907, Musson (1978) taking into account the adjustments suggested in Kanefsky (1979).

Table 6 collates the available quantitative evidence on the penetration of steam technology across industries in various years. As the table shows, the spread of steam technology in British industry was heavily *concentrated* in a handful of sectors. In all three years considered in table 6 mining, textiles and metal manufactures account for more than 50 % of steam industrial power. In this respect, traditional accounts of industrialization that have depicted an economy running exclusively on steam are clearly in need of some revision. In fact, the progress of steam powered mechanization was far from being uniform both across and within industries.[4] Even in sectors that employed steam intensively, a number of critical phases of the production process continued to be carried out using hand tools well up to the late nineteenth century (for a very good overview of the balance between steam power and hand technology in different industries, see Samuel, 1977).

It should be stressed that Crafts' estimates consider only the *direct* impact of steam power technology on labour productivity growth. In other words, they asses the impact of the first two properties of Bresnahan and Trajtenberg' s definition of GPT namely, the pervasiveness (which obviously corresponds to the capital deepening effect) and the technological dynamism (which corresponds to the rate of TFP). The "innovational complementarities" of steam power are completely left out of the picture. The neglect of "innovational complementarities" was originally remarked by Paul David (1975, chap. 6) in his critique of Fogel's social savings calculation of the "railroadization" of the US economy during the nineteenth century. Clearly, if the technology in question stimulates the generation of further technical or organizational innovations in the application sectors, its economic impact cannot be appropriately assessed by means of social saving calculations.

Accordingly, von Tunzelmann (1978) decided not to limit his appraisal to the social saving calculation, but he provided an evaluation of the forward linkages of the steam engine. The approach followed by von Tunzelmann (1978) was to examine in detail the technical and economic evolution of the textile industries, searching for possible links between

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[4] As Samuel (1977) as noted, in many production processes formidable technical difficulties frustrated the continuous attempts of developing 'self-acting' machines.

improvements in steam power technology and the introduction and/or diffusion of textile innovations. Von Tunzelmann (1978) analysis of the evolution of textile technologies reveals that spillovers from steam were, by and large, negligible during the first half of the nineteenth century. In the second half of the nineteenth century, the forward linkages between steam and the textile sectors became more consistent, and, in some specific cases, it is possible to relate the adoption of innovative vintages of "automatic" machinery to reductions in steam power costs.

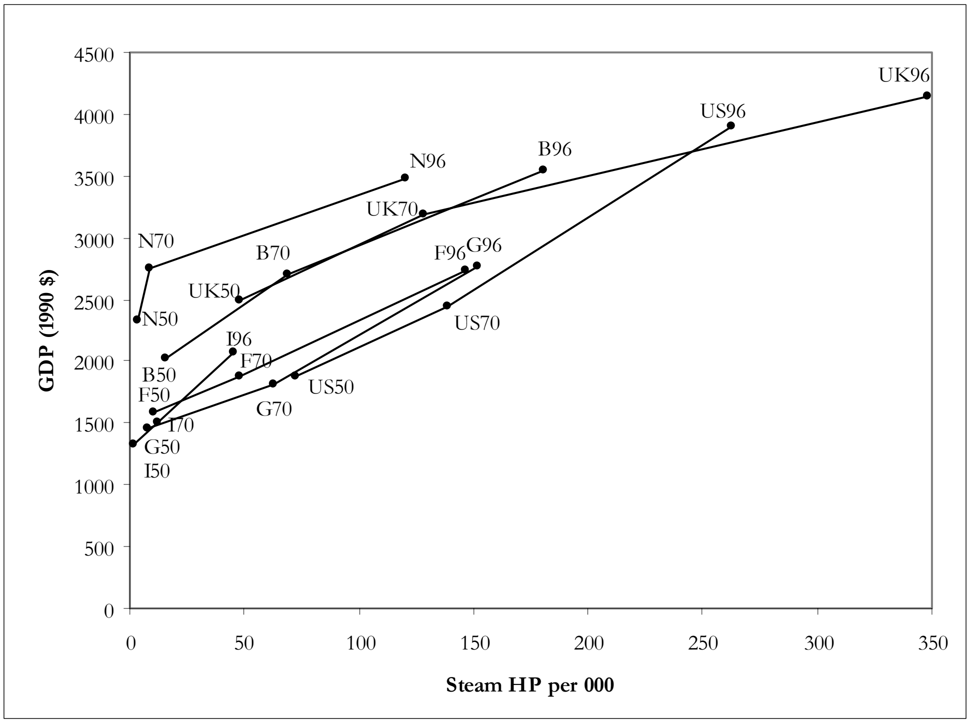
Another attempt to estimate the economic impact of steam technology has been recently carried out by Rosenberg and Trajtenberg (2001). In particular, Rosenberg and Trajtenberg argue that, in the United States, steam technology became an "engine of growth" only with the development of the Corliss' engine design. Corliss' design determined a reduction in steam power costs which moved the cost differential between water power and steam decidedly in favour of the latter. According to Rosenberg and Trajtenberg, this induced a major relocation of production activities towards urban centres permitting the exploitation of major agglomeration economies and, in this way, fostering economic growth. It is worth noting that Rosenberg and Trajtenberg empirical study merely assesses the existence of a correlation across space between the adoption of Corliss engine and population growth. Hence, most of the hypothesis proposed in their paper concerning the link between Corliss engine and economic growth ought still be considered conjectural. Interestingly enough, Rosenberg and Trajtenberg were unable to find direct evidence of "innovational complementarities". It is worth to quote their remarks at length:

> We also devoted significant efforts toward searching for evidence of innovational complementarities in the more straightforward sense of the Corliss engine 'prompting' improvements in specific user sectors. However we could not find compelling, first hand evidence to that effect. We did find repeated assertions that the improved regularity of motion delivered by the Corliss allowed textile manufactures to move up the quality ladder from low-grade coarse fabrics to finer grades of cotton yarns and other fibers such as wool. There is also some material suggesting that the performance advantages of the Corliss may have prompted the (re)design of more efficient textile mills. The problem is that we could not find the empirical equivalent of a 'smoking gun' in this respect ...(Rosenberg and Trajtenberg, 2001, p. 8).

This shows again that the assessment of the "innovational complementarities" involves a painstaking detailed historical investigation of the interdependencies between different technological trajectories.

Using the data on the comparative diffusion of steam power included in Landes (1969) and dating back to *Dictionary of Statistics* by Mulhall (1909), we may draw an admittedly naive picture of the relationship between the level of national income and the extent of steam power penetration in each country. Figure 1 would seem to powerfully prove that national economic performances of industrial countries during the 19th century may be fully explained by the comparative diffusion of the steam engine technology. Notably, one remarkable exception to this pattern is given by Netherlands. Still, most observations contribute to a picture which indeed appears 'too good to be true'. Indeed those aware of the limitations of the historical source used by Landes may actually conjecture that the estimates of steam horsepower installed was constructed in such a way to reflect the commonly perceived ranking of industrial countries in terms of economic power, e.g. UK being the leader with both the highest level of income and the highest degree of technological achievements. As a matter of fact, a few historical accounts (see Kanefsky, 1979 for the UK and Lintsen, 1995 for the Netherlands) have contested the overall reliability of these data on the diffusion of steam technology.

Figure 1: Steam power installed and real GDP levels, 1850-1896 (United Kingdom, United States, France, Germany, Italy, the Netherlands)



Source: for GDP levels and population data from Maddison (2001), data on steam HP installed from Landes (1969), p. 221.

At this juncture, it is probably useful to summarize our survey of the historical literature concerned with the economic impact of steam power technology. Some features of the economic history of the steam engine seems to be neatly captured by the GPT view of the economic growth, others appears, instead, more problematic.

Clearly, the protracted and long delayed diffusion process of steam technology is consistent with the prolonged "acclimatization" phase posited by Bresnahan and Trajtenberg.

Being a prime mover, the steam engine was almost *ex definitione* a technology endowed with a high degree of "pervasiveness". However our discussion has suggested that "pervasiveness" can be measured along many dimensions and that radical innovations such as steam, electricity and ICT are likely to be widely different in this respect. Perhaps a possible solution to this problem would be to elaborate a more rigorous definition of pervasiveness in terms of an input-output framework (Rosenberg and Frischtak, 1984; see Verspagen 2002, for an interesting attempt of identifying pervasive technologies using input-output data).

Steam power was also a technology endowed with a certain degree of technological dynamism, in the sense that its efficiency was progressively increased by means of a succession of refinements and improvements. This appears to be clearly consistent with the GPT definition. However, it is also worth noting that the rate of improvement (according to the data collected by Crafts) was for long periods of time far from being particularly remarkable. This contributes to account for the slow substitution between steam and water power.

Historians of the steam engine (see, for example, Hills, 1989) have also pointed to various examples of "innovational complementarities" from steam. As mentioned, von Tunzelmann (1978) has shown that these assumed sizable economic significance only from 1840 onwards. A precise quantification of the economic gains stemming from this form of spillovers has not been so far attempted. If we were asked to put forward a wild guess, we would contend that the, overall (that is to say direct plus spillover effect) the contribution of steam to economic growth in the second half of the nineteenth century was surely palpable, but it was far from obliterating other sources of economic growth, in particular, given the resilience of hand-technology pointed out by Samuel (1977), of transformations of the labour process.

3 The development of the high pressure expansive engine

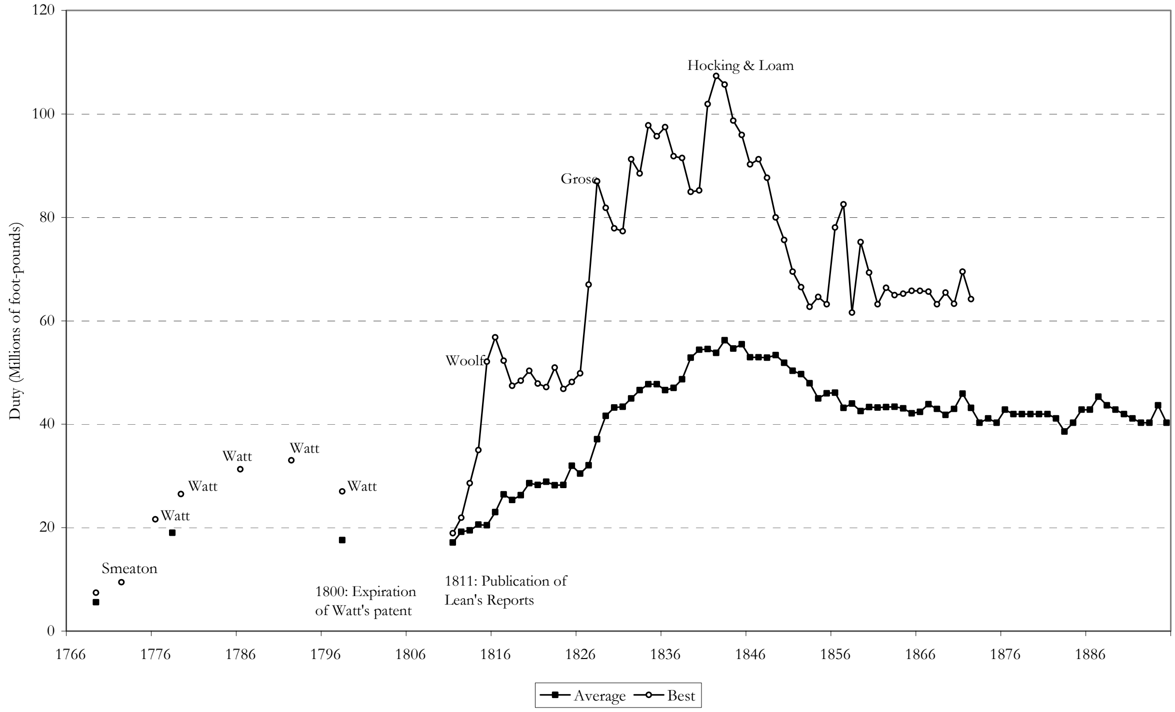
In this section we want to examine in detail the issue of the "technological dynamism" of the GPT. As we have seen, in his calculations of social savings, Crafts considers the reduction in the annual cost for one steam HP in what he deems to be a typical situation, a textile mill in Lancashire. The critical innovation underlying the major part of the reduction in steam power costs presented in table 1 was undoubtedly the development of the high pressure expansive engine (for a thorough overview of the evolution of steam engine technology, see Hills, 1989).

Interestingly enough, the high pressure expansive engine was introduced before the attainment of a consolidated theoretical understanding of the working principles of the steam engine. Cornish engineers took the lead in the exploration of this specific technological trajectory. The Cornish mining district was endowed with very rich lodes of tin and copper, whose exploitation, however, was severely hampered by flooding problems. The development of steam power technology (in this case in the form of steam pumping engines) provided an effective solution to mine drainage. In Cornwall, coal had to be imported from Wales by sea and, for this reason, was particularly expensive. As a consequence, Cornish mine entrepreneurs were eagerly interested in improvements in the efficiency of the steam engine that could curtail their dear fuel bill. Starting in 1811, they sponsored a monthly publication containing detailed reports on the performance (measured in 'lbs. of water raised one foot high per bushel of coal consumed' or, as it was termed by contemporary engineers, the 'duty' of the engine), technical details and operating procedures of the steam pumping engines at work in the county. Joel Lean, a highly respected mine engineer, was entrusted with the compilation of the reports and the publication was known as *Lean's Engine Reporter*.

The publication of *Lean's Reporter* marked the transition of the Cornish mining district to a peculiar form of innovation process which Robert Allen (1983) has labelled "collective invention". In collective invention settings, rival firms prefer to reciprocally share the new technological knowledge they discover, rather than protecting it using patents. When innovations are highly cumulative, regimes of collective invention are likely to yield higher rates of technical progress than those based on "closed" and proprietary knowledge. Interestingly enough, in the contemporary engineering literature, engines built on the basis of the Cornish design principles were not ascribed to this or that particular engineer, but simply known as "Cornish" engines, properly acknowledging the cooperative and cumulative character of this particular form of technological development. Nuvolari (2004) provides a detailed account of the institutional set-up supporting inventive activities in steam engineering in the Cornish mining district.

Walter Vincenti (1990, chap. 5) has argued that engineers typically make use of systematic data collection and analysis to *bypass* the absence of an adequate theoretical understanding of the operative principles of a technology. This was exactly the situation in early nineteenth century steam engine technology. At that time, the steam engine was still conceived as a vapour-pressure engine and not as a heat engine, so that there were no theoretical principles that could account for the impact on the efficiency of the engine of the use of high-pressure steam and of the principle of expansion. Systematic collection and analysis of performance data allowed to Cornish engineers to consistently individuate fruitful lines of technical advance, so that, between 1820 and 1840, the Cornish pumping engine represented the highest engineering achievement in steam power technology.

Figure 2: Duty of Cornish Engines, 1769- 1895



Sources: 1769,1772, 1776, 1778 (Lean, 1839);1779,1786, 1792 (Dickinson and Jenkins, 1927);1798 Gilbert (1830); 1811-1872 (Lean II, 1872); 1873-1895 Trestrail (1896).

As a matter of fact, immediately afterwards the publication of the engine reports, the thermodynamic efficiency of Cornish engines begun to improve steadily. Figure 2 displays the behaviour of the "duty" of Cornish pumping engines as portrayed in *Lean's Engine Reporter.*

The figure clearly shows the phase of relative "stagnation" of the late eighteenth century and the rapid growth phase from the 1810s. This phase of rapid growth of technological performance (characterized by three rather sharp bursts) appears to cover approximately the period 1811-1846. After that, in accordance to Wolf's law, Cornish technological practice seems to run into diminishing returns. This coupled, with deeper mining shafts and harder drainage conditions, determined a deterioration in the efficiency of the engines.

It is particularly interesting to compare figure 1 with table 1. According to table 1, the period 1800-1830 is phase of stagnation where steam engine does not make any progress with respect to Watt times. In figure 1, instead the period 1810-1830 is a phase of staggering improvement in engine performance.

It cannot be assumed that the Cornish experience passed by unnoticed. In fact, some of the most competent contemporary observers paid a great deal of attention to technological developments introduced in Cornwall. For example, John Farey, changing quite drastically his initial publication plan, devoted the major part of the (unfinished) second volume of his *opus magnum*, to the Cornish engine, making extensive use of the data contained in *Lean's Engine Reporter.* [5] The superior fuel efficiency of the engines of the Cornish type was also widely discussed in France by scientists and engineers interested in the functioning of the steam engines.[6] Sadi Carnot himself concluded his *Reflexions sur la puissance motrice de feu* mentioning the duty of 56 millions achieved by the engine erected by Arthur Woolf at the Wheal Abraham mine.

Thus, a large body of engineering literature on steam technology in the early nineteenth century was informed by the debate on the different technological practice characterizing the employment of steam power in Cornwall (where it was adopted the high pressure expansive engine) versus the rest of Britain, especially the manufacturing districts of the North, where the favourite option was the Watt low pressure engine.

The superior fuel efficiency of the Cornish practice led many contemporaries to describe this situation in terms of a "technology gap" between Cornwall and the rest of the country. Among others, N. P. Burgh, in *A Practical Treatise on the Condensation of Steam* published in 1871, described the general complacent attitude towards the adoption of technical novelties in steam engines prevailing in the textile manufacturing districts in the early nineteenth century in these terms:

> The matter before them was all-sufficient because it answered up to a certain point of working duty, and thus *mutual contentment* reigned where an equal desire for further knowledge ought to have been (cited in Hills, 1989, p. 113, italics added).

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[5] According to the original plan, the second volume should have comprised two parts: the first describing the developments in engine design occurred in the early nineteenth century, the second one outlining a scientific analysis of the working of the steam engine, see Woolrich (2002).

[6] In the 1810s the Cornish engine reports were reprinted regularly in *Annales de Chemie et de Physique* (see Cardwell 1971, p.157, also for other examples of early French inquiries on the performance of Cornish steam engines). In the same period, the *Philosophical Magazine* edited by Alexander Tilloch (one of the "patrons" of Arthur Woolf during his permanence in London) published summaries of *Lean's* report.

William Fairbairn,[7] a highly influential character of the Lancashire engineering community, was one of the leading advocates of the technical merits of the high pressure expansive engine. However his pleadings remained for a long period unfulfilled:

> For a great number of years a strong prejudice existed against the use of high pressure steam and it required more than ordinary care in effecting the changes which have been introduced: it had to be done cautiously, almost insidiously, before it could be introduced. The author of this paper believes he was amongst the first in the Manufacturing Districts who pointed out the advantages of high pressure steam when worked expansively, and for many years he had to contend with the fears and prejudices of the manufacturers... (Fairbairn, 1849, pp. 23-24)

Similarly, John Farey (1971, p. 307) denounced a widespread and culpable "state of apathy as to consumption of fuel" in the "great manufacturing districts of the North". [8]

Up to the late 1830s, other commentators remained instead rather sceptical of the fuel efficiency of Cornish engines, actually denying the existence of a Cornish technological lead in steam engineering. This was also partially due to the fact that the superior fuel efficiency stemming from the expansive use high pressure steam remained theoretically unaccounted for. As a consequence, the dramatic early rise of the duty of the (best-practice) Cornish expansive engines (in the 1810s up to more than 40 millions and by the late 1820s to more than 80 millions) was not easily accepted outside Cornwall. In 1836 there was a heated debate on the pages of *Mechanic's Magazine* on the general reliability of the "reported" duty figures of Cornish engines. Two years later, G. H. Palmer published an article in *Transactions of the Institutions of Civil Engineers*, in which he contended that the levels of fuel efficiency claimed for the Cornish engine were undoubtedly exaggerated (because in open contrast with the caloric theory of heat):[9]

> If the statements given to the public by the Cornish engineers, whose sincerity I cannot doubt are correct, I dare not trust to call nature to account for the undue favouritism she confers upon our Cornish friends by enabling them to perform results that the London, Manchester and Birmingham engineers cannot approach.......Upon what principle then, permit me to ask, can the Cornish engines perform so much more than all other engines. Strong, indeed, should be the evidence that ought to outweigh or cancel the....laws of nature, and induce this Institution to sanction statements of duty more than double of the best Watt engine, and still more, surpassing the limits Nature has assigned steam to perform. (Palmer, 1838, pp. 44-46)

The most strenuous defender of Lancashire technical practice was perhaps Robert Armstrong. In his *Essay on the Boilers of Steam Engines* published in 1839, he declared that the Cornish duty figures were undoubtedly "gross exaggerations", the real duty probably being equal to about 30 millions. He concluded that "there is nothing in the Cornish system of management that can be profitably imitated by…..[Lancashire engineers]" (cited in Pole, 1844, p. 59).

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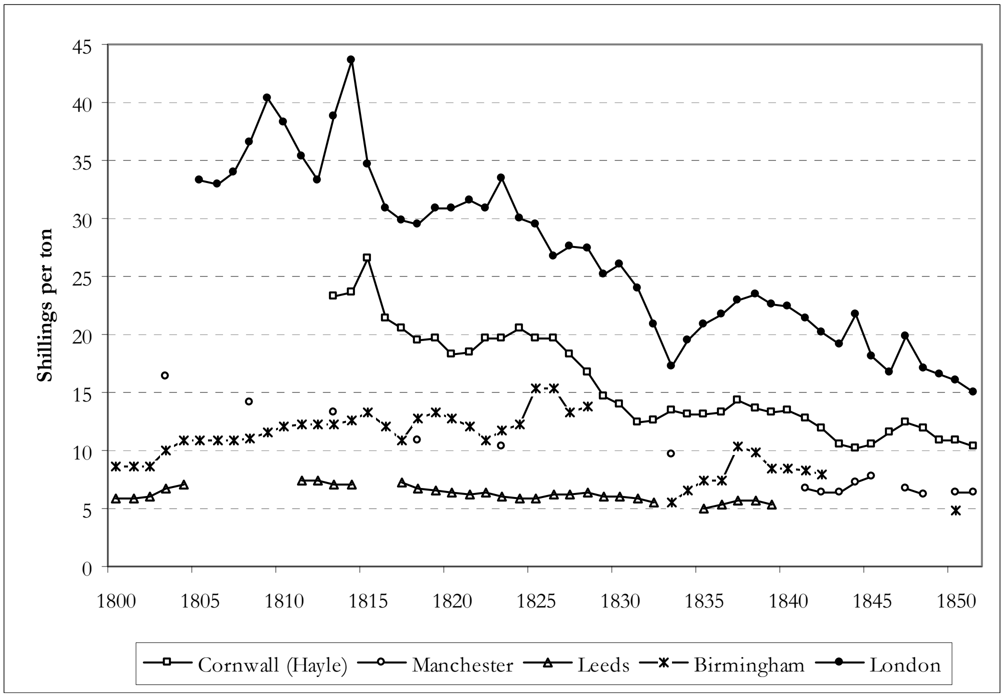
[7] For an appraisal of the life and activities on William Fairbairn , see Musson (1970).

[8] D.K. Clark described the English engines presented at the 1862 International Exhibition in London in these blunt terms: "[The engines of English builders] in general testified to a feeling of absolute indifference to economy of steam or fuel, and probably in some instances, to ignorance of the conditions on which economical working is to be established" (cited in Hunter, 1985, p. 600).

[9] In the same article Palmer, on the basis of the caloric theory of heat, fixed the maximum duty attainable by a steam engine to 44 millions (Palmer, 1838, p. 46)

Widespread incredulity in the virtues of high pressure steam surely hindered the diffusion of high pressure designs in the early nineteenth century, however it is important to recognize that other factors were affecting adoption decisions. As a matter of fact, the most simple explanation that can be put forward for the different technological practice between Cornwall and the other manufacturing areas of Britain (say Lancashire) is that this divide reflected the local circumstances of steam usage, in particular the differences in coal prices.

Figure 3: Coal prices in Britain, 1800-1850



Sources: for Manchester, Leeds, Birmingham and London: von Tunzelmann (1978, p. 97); for Hayle: von Tunzelmann (1974, pp. 199-200).

As suggested by the available data, coal prices were higher in Cornwall (the region could not rely on any local supply of coal and all the coal employed had to shipped from South Wales) than in Lancashire throughout the period in question.

Figure 3 displays the behaviour of coal prices in various location for the period 1800-1850. In this time span, price of coals in Cornwall appear to have been higher than those prevailing in Lancashire (Manchster), Yorkshire (Leeds) and in the Midlands (Birmingham). It could then be argued that the differential rates of technical progress in the different British regions naturally reflected the local availability of coal supplies. This clearly would amount to a simple "scarcity-push" explanation of the differential rates of technical progress. In this respect, note that the price of coal in London (a location whose technical practice was similar to Lancashire) instead, was higher than in Cornwall.

The contemporary engineering literature, rather than a "scarcity-push" explanation suggested the existence of highly uneven technological opportunities related to the different applications of the steam engine (for driving machinery in the North of England and for

pumping mines in Cornwall). The fuel efficiency attained by using high pressure steam expansively engine was lower for rotary engines than for pumping (reciprocating) ones (this because in reciprocating engines the early cut-off of steam in the cylinder could be exploited to a larger extent). Some of the available evidence however does not fit in this picture, pointing again instead to disbelief in Cornish achievements.
The first high pressure engine pumping engine erected in the London was installed at the London waterworks as late as 1838. The installation was preceded by a travel of Thomas Wicksteed (the engineer of the London waterworks) to Cornwall where he conducted a detailed research on the merits of the Cornish engine (Wicksteed, 1836, 1838, 1841). In one of his papers, Wicksteed listed a number of technical innovations which characterized the Cornish high pressure practice, which had no counterpart in London (Wicksteed, 1836, pp. 122-125). Although Wicksteed heartily encouraged the shift to the Cornish engine, the management of the waterworks was still rather reluctant and the engine was finally installed only under the condition that it would perform a duty of 90 millions over twelve consecutive months, otherwise a penalty had to be paid (Barton, 1965, p. 258).

The delayed adoption of high pressure expansive engines at the London waterworks (where engines could be employed rather straightforwardly according to the Cornish practice and where the cost incentive was higher than in Cornwall) clearly demonstrates the existence of a technology gap between Cornwall and the rest of England, at least as far as reciprocating engines are concerned. However even when entrenched disbeliefs in the fuel superiority of high pressure expansive engine had been dispelled, it was still doubtful whether Cornish practice could have been successfully transferred to mill operations, where the application of the steam engine to industrial processes generally required a smooth piston movement.

> It is a question, also, whether the extreme use of the Cornish system is suitable for those manufacturing engines, one great and essential quality of which is uniformity of motion. A steady velocity in the motive power, is of such consequence in cotton spinning, and several other of the arts, that any loss of it would be dearly by economic gain. The momentum of machinery, is but trifling: and an equivalent must be found for it, in order to obtain the whole value of the Cornish system (Parkes, 1842, p. 67).

Josiah Parkes wrote so in 1842. Some of the problems created by the irregular power cycle could be solved by expanding the steam in separate cylinders, reviving in this way, the Woolf compound design, which had not been crowned with much success in Cornwall.[10] This involved some loss of fuel efficiency. As William Pole noted:

> Th[e] principle...[of expansion] has hitherto been applied to the greatest advantage in engines with a single cylinder, used for pumping purposes, as in Cornwall. In these cases the peculiar nature of the motion admits of the steam being cut off after a small fraction of the stroke has been commenced, and allowed to expand during the remainder. When however the principle of expansion is applied in this mode to engines for producing rotary motion, some difficulties arise, which limit considerably the extent that the expansion may be carried to, and therefore reduce in a corresponding degree the economy of fuel. The Double Cylinder Engine offers a mode of applying the expansive principle to rotary motion, which removes or at least greatly mitigates the objections to the single cylinder...(Pole, 1862, p. 242).

A quantitative estimate of the profitability of the high pressure expansive engine for powering mill machinery has been provided by von Tunzelmann. More specifically, Von

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[10] Josiah Parkes suggested an alternative solution: the adoption of Cornish pumping engines as "water returning" engines for cotton mills (Parkes, 1842, pp. 67-68).

Tunzelmann (1978, p. 91) has calculated the "threshold" coal price at which, it would have been economically worthwhile in "rotary" applications to switch from a Watt low pressure engine to a high-pressure one, in about 1835 as 12 *s.* per ton. As it is evident from the behaviour of the coal price series of figure 2 in the North (Lancashire and Yorkshire) coal prices were, at least since the early 1820s below that level. Hence, notwithstanding its superior fuel efficiency, the high pressure engine did not represent the most economic option (given its higher capital costs) in locations where the price of coal was low.

This result, according to von Tunzelmann, goes some way in the direction of rehabilitating Lancashire entrepreneurs from the "damnation"[11] to which contemporaries, such as Farey had condemned them:

> The failure may have been one of the inventors rather than the businessmen: inventors were unable to come up with a satisfactory high-pressure rotative engine until about the mid 1830s (von Tunzelmann, 1978, p. 90).[12]

Table 7: Prices and Capital costs for the engines produced by Benjamin Hick, 1841

	Low pressure condensing 40 HP (£)	Woolf compound 40 HP (£)	Low pressure condensing 50 HP (£)	Woolf compound 50 HP (£)
Engine	960	1130	1170	1350
Boiler	240	320	280	400
Total	1200	1450	1450	1750
Cost p.a.	162	197.25	195.25	238.75
Cost per HP p.a.	4.05	4.931	3.905	4.775

Source: Hills (1989), p. 119. In calculating capital cost p.a., following von Tunzelmann (1978), p. 72, we have made the subsequent assumptions: depreciation rate set at 7.5% p.a. for the engine and at 12.5% p.a. for the boiler, interest rate set at 5%.

This situation seems to have changed rather drastically by the early 1840s. We can compute the threshold coal price between a low pressure condensing engine and a high pressure one for 1841 using a list of prices for the steam engines produced by Benjamin Hick. Hick was one of the pioneers of the introduction of compound high pressure engine on the Woolf plan in the textile industries and his engines are probably to be considered as best-practice for the time.[13]

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[11] "From damnation to redemption: judgments on the late Victorian entrepreneur" is the title of a famous paper by McCloskey and Sandberg (1971), in which the thesis of an entrepreneurial failure (i.e., technological conservatism) of late nineteenth century Britain put forward by historians such as Landes (1969) is rebutted.

[12] The Woolf rotative engine was imported quite successfully in France by his former partner Edwards in the late 1810s. In 1824, a witness before a Parliamentary Committee declared that, to that date, about 300 Woolf engines had been erected in France by Edwards (Jenkins, 1933, p. 61). Rotative engines on Woolf design (although in very small numbers) were also produced by some manufacturers in Britain during the 1820s.

[13] A glowing appraisal of Hick's compound engines is given in Farey (1971, p. 306) :"Mr Woolf's engines have never been tried, and are scarcely known in the great manufacturing districts in the North of England and in Scotland. It should be mentioned that Mr Hick of Bolton, in Lancashire, has of late taken up the making of Mr Woolf's compound engines, and has made two engines of a larger size than any previous engine of the kind. They are excellent specimens, and improved proportions of the parts, with every perfection of execution which has hitherto been attained in the construction of steam engines; and although both have been sent abroad, one

In Table 7 we report Hick's prices and our estimates of the annual capital costs for engines of 40 and 50 horsepower (these were probably the most typical sizes for mill engines at the time).[14]

In his price list, Hick also indicated figures for the fuel consumption of the engines: the low pressure engine consumed 14 lbs. of coal per HP-hour, whilst the Woolf compound, 5 lbs.[15] Note that 5 lbs. of coal per HP-hour correspond to a duty of approximately 37 millions (Pole, 1843, p. 171). The average duty of Cornish pumping engines (acccording to Lean's reports) in the same period (early 1840s) was above 50 millions (see figure 1). This difference can be taken as a (rough) indication of the loss in fuel efficiency determined by the use of the high pressure engine with a regular piston movement and not with the very irregular Cornish cycle.

With the level of fuel efficiencies stated by Hick, assuming that the engines worked on average 3800 hours a year,[16] the threshold coal price for the engines (of both sizes) in table 7 is equal to about 1 *s.* 1 *d* a ton.[17] This price is even lower than the cost of "slack" coal at the colliery pithead.[18] Our calculation, thus, suggests that in the early 1840s the high pressure technology had already become profitable for any (conceivable) level of coal prices. In fact, from the late 1830s, manufacturing areas begun *slowly* to install high pressure engines (see von Tunzelmann, 1978, p. 85).

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to France, and the other to Spain, they will probably lead to the introduction of such engines in the manufactories of Lancashire,"

[14] See, for example, Hills (1989), p. 116.

[15] Zachariah Allen estimated the average fuel consumption of the steam engines installed in Manchester in 1831 as 13 lbs. About ten years later in 1842, Fairbairn considered this to be about 10.5 lbs, see Hunter (1985), p. 600. In the same year Josiah Parkes considered 15 lbs to be more representative of the average coal consumption (Parkes, 1842, p. 67).

[16] This can be considered a reasonable estimate for the textile industries. In other industrial branches, engines normally worked slightly less, see von Tunzelmann (1978), p. 73.

[17] The formula used is $p_t \Delta CH = \Delta K$, where p_t is the threshold coal price, ΔC the fuel saving (per HP-hour) brought about by the adoption of the high pressure engine, H the numbers of hours worked in the year, ΔK the difference in capital cost per HP p.a.

[18] Von Tunzelmann (1974, p. 63) gives a price of 2s. 8d. for slack coal for a Staffordshire colliery in the period 1828-36. Note that our calculation suggests that threshold price computed by von Tunzelmann for 1835 is probably overrated. The source of this over-estimation is in the estimated increase in capital costs resulting from the adoption of the Cornish high pressure boiler, which von Tunzelmann assumes to increase in direct proportion with heating surface (this amounts to multiply the price of the "corresponding" low pressure boiler by 7.5). Thus, for a 30 HP engine, he puts total boiler cost at £1500. Casual evidence seems to suggest that this errs far too much on the high side. In 1838 *three* boilers for a 60" engine for the Fresnillo Mine in Mexico were sold for £ 963 (Barton, 1965, p. 280). In 1841, James Sims offered, in an advertisement published on the *West Briton*, a 80" pumping engine for £2600, *inclusive of boilers* (Barton, 1965, p. 52). These figures are broadly consistent with the prices of table 7.1. In this respect, one has to take into account, as von Tunzelmann (1978, pp. 83-84) himself acknowledges, that in low coal price regions, steam engine manufacturers like Hick, generally avoided to construct the full-size Cornish boiler, opting for a "shortened" and cheaper version. The upshot of these considerations is that probably since the late 1820s-early 1830s it would have been economic profitable to install (locally adapted) versions of the high pressure engine even in low coal prices regions, vindicating Farey's allegations of some "technological complacency" in the behaviour of Lancashire entrepreneurs.

These cases of early adoption did not amount to a slavish imitation of the Cornish practice. Lancashier engineers tried to "acclimatize" the engine to local circumstances and find a balance between gains in fuel efficiency and the higher capital costs involved in the use of high pressure (von Tunzelmann, p. 86). Accordingly, the shift to high pressures was coupled with the introduction of a number of adaptations/modifications, such as the "compounding" of existing engines with the addition of a high pressure cylinder (the so called 'McNaughting'), the employment of smaller versions of Cornish boilers, etc.

In our interpretation, the persistent technology gap between Cornwall and Lancashire in the first half of the nineteenth century is to be accounted for by the localized nature of technological knowledge. Put differently, different rates of technical progress in steam engineering ought to be related the *cognitive dimensions* of the inventive process.

A particular insightful way to probe into this ground is to adopt Giovanni Dosi's paradigm/trajectory approach (Dosi, 1982). Dosi defines a technological paradigm as "'model' and a 'pattern' of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies" (Dosi, 1982, p. 152, italics in the text). The term paradigm is borrowed from Thomas Kuhn's philosophy of science. In case of technologies, the concept of paradigm refers to a framework, jointly adhered by a significant group of innovators, guiding the search for technical advances in particular historical contexts,. In this way, a technological paradigm set the boundaries of the domain in which future technological developments will take place. Dosi suggests that it should be possible to "deconstruct" each technological paradigm into a set of "heuristics". These represents the prevailing accepted rules prescribing the procedures to be adopted in the search for innovations (i.e., "in order to develop a more efficient engine, try to increase the rate of expansion").

It is interesting to note that the notions of technological paradigms and heuristics are intended to be broader in their scope than mere sets of engineering prescriptions. In Dosi's view, technological heuristics are the product of the "amalgamation" of what might be termed the "autonomous drift" of a technology (i.e., the "compulsive sequences" of challenges and solutions individuated by Rosenberg (1976) which are insensitive to market signals) with "inducement factors" of a genuinely economic type (i.e., current and expected factor prices). This means that local circumstances can, to a certain extent, shape the pattern of technological development. In our case, both the early development of high pressure in Cornwall and the various attempts of upgrading the low pressure engine in Lancashire can be seen as a reflection of how the different economic needs of the various regions were incorporated in technical practices.

The heuristic search process practised by the inventors' community, by channelling inventive activities in specific and finalised directions, generates relatively ordered patterns of technical change, called "technological trajectories" , which, at least in principle, can be mapped in both the space of input of coefficients and that of product characteristics (Dosi, 1997, p. 1533).

The paradigm/trajectory view of technological evolution points to three essential features of the evolution of technologies:

i) the *local* nature of technical progress: inventive activities are paradigm-bounded and, for this reason, they are highly selective and focussed in rather precise directions.

ii) along a specific technological trajectory, technical advances are strongly *cumulative*, that is to say that they are strongly related to previous attainments.

iii) finally, technological development is likely to display strong *irreversibility* features. This means that techniques developed along particular trajectories are likely to become superior to "old" ones for every factor prices configuration (as shown by our calculation of the threshold coal price). This means that once the movement along a particular technological trajectory has gained momentum, it becomes relatively irresponsive to change in input prices. Note, for example, that the rapid improvement in fuel efficiency of the Cornish engines continued despite coal prices in Cornwall are clearly characterized by a *downward* trend (see figure 3).

To sum up, the basic argument put forward in this section is that the emergence of the two distinct technological practices in British early nineteenth century steam engineering requires to take into account not only the economic needs of the various regions and of the application sectors, but also the processes of accumulation of technological knowledge. As we have shown, this implies the adoption of an interpretive framework capable of explicitly taking into account the "specificities" of the technology in question

Our suggested interpretation is that steam engineering practice in Britain during the early nineteenth century was characterized by the existence of two rival technological paradigms, the Cornish paradigm advocating high pressure used expansively and the Lancashire one, favouring low pressures (sanctioned by the authority of James Watt). Technological development within the high pressure paradigm, proceeded following two (to a limited extent) overlapping sets of heuristics (which over time consolidated themselves in two distinct design traditions): the first set of heuristics prescribing procedures for innovation in single cylinder pumping engines adopting the irregular Cornish power cycle and the second one concerning the compound engine and its application to manufacturing purposes. Technological opportunities determined a more rapid progress along the technological trajectory generated by the single cylinder set of heuristics, than along the compound mill engine one. Furthermore, many inventions matured along the single cylinder trajectory could not be readily transferred to the compound trajectory.

All this leads us to consider the "entrepreneurial failure" of Lancashire entrepreneurs and their delay in shifting to high pressure steam in a rather different perspective. Clearly, the evidence presented above points to the technological conservatism of Lancashire industrialists. However, our interpretation stresses that the major stumbling block was represented by the lasting resilience of the low pressure paradigm in Lancashire. Hence, one could also note that influential contemporary advocates of the high pressure expansive engine such as John Farey and William Fairbairn were by and large ineffective in their efforts of instigating in the Lancashire engineering community the "revolutionary climate" needed for the successful and "timely" subversion of the low pressure paradigm and, precisely for this reason, indulge in the temptation of laying a non minor part of the responsibility at their doors.

As we have seen the adoption of the high pressure expansive engine in Lancashire mills required the introduction of a number of non trivial design modifications. In fact, "sectoral" circumstances dictated to engineers different goals (fuel efficiency in Cornwall, speed and smoothness of motion in the manufacturing districts of the North, increases in the power/weight ratio for steam engine of locomotives, etc.), prompting the search for innovations in different directions. Technological advances aimed at improving the effectiveness with which the steam engine could cater these specific sets of user requirements were indeed a leitmotiv of the development of steam power technology during the entire nineteenth century. The emergence of these application specific knowledge bases made difficult the transfer of innovations from one application to another. Due to the essentially idiosyncratic nature of these innovative activities, the evolution of the 'engineering knowledge bases' underpinning the various applications of the steam engine proceeded along rather differentiated trajectories. Accordingly, in each application domain, stable sets of engineering heuristics emerged from the combination of sector specific economic and technical circumstances with what might be called the more "general" internal logic of steam technology. This determined a highly uneven rate of technological advance among the various application domains. Using the David and Wright (1999) terminology, the dynamics of innovation rates across applications was not "yeast-like", but "mushroom-like".

In fact, when the economic history of the steam engine is examined carefully, one can find a number of examples showing innovations matured in a particular application niche that could not be (successfully) transferred to the other application sectors.

As already mentioned, according to Rosenberg and Trajtenberg (2001) the widespread adoption of steam power in manufacturing was made possible by the invention of the Corliss engine that permitted the delivery of a continuous and steady rotary motion, even when faced with changes in the load. The engine was developed in the US by George Corliss in the period 1850s. Besides improving the regularity of the motion, Corliss' inventions also greatly increased the efficiency of the steam engine, by making possible a better exploitation of the expansive power of steam. Interestingly enough, the Corliss valve gear, which was so successful in stationary practice, could not be applied to locomotives. In 1851 Corliss tried to successfully enter in the manufacture of locomotive building the *Advance* a locomotive whose motive power was delivered by a Corliss engine. The design was far to complicated and proved to be a complete failure.[19]

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[19] A contemporary witness recalled the experiment in these terms: "The locomotive was possessed of a certain inborn cussedness which could be hardly be the attribute of a mere machine – her spiritual nature was a sort of Mephistophelian cross with a Colorado mule - and as to her physical constitution and membership a cotton factory 'mule' was simple in comparison. The Old Jigger had, as nearly as I can remember, 365 valves, one to break down every day in the year. And as a valve motion, well, nobody ever counted the number of its pieces. They were as the sands of the sea-shore. Most of them used to jar-off, the first few trips of the week, after which all men in the shop could comparatively keep track of the rest of them. I will say for the Old Jigger that she made the best indicator-card I saw from a locomotive; clean cut-off, almost a theoretical expansion curve, and an exhaust as if she had knocked out a cylinder head. Well, once in a while, after she had been jackassing over the road about four hours behind time, and we had pinch-barred her into the road-house, we used to pull out these indicator-cards of hers, and talk them over right before her, and we would look at her and ask one another why in thunder an engine that could make a card like that would act as if the very old-chief engineer was in her. And next morning she would rouse up and pull the biggest rain that had ever been over the road - ahead of time" (Testimony of Alexander Holley, one of the machinists of the *Advance,* cited in White (1997), p. 202).

Similarly, the introduction of high pressure steam engine for ships involved the adoption of another "localized" design. In this field, fuel economy was obviously of paramount importance. However, technical difficulties and strong attachment to low-pressure design prevented adoption of high-pressure steam, expansion and compounding until 1850s (Hills, 1989, p.146). The application of these principles began only after the basic principles of thermodynamics had been laid down, and hence the advantages of high-pressure steam were also understood correctly from a scientific point of view.[20] In the case of steam ships, and quite contrary to the case of the Cornish engine, compounding became the norm, and soon the average engine would expand the steam in three steps using as many cylinders.

The opening up of compounding as a new trajectory for ship engines is to be ascribed to the engines designed by John Elder (who was a close associate of Rankine) in the early 1850s. Notably, Elder was probably one of the first to notice that compound engines were more efficient than single-cylinder engines at steam pressures exceeding those normally in vogue. Elder's compound design became soon the favourite one for marine use. In the late 1850s and early 1860s, fuel efficiency of marine engines improved rapidly following a dynamics of rapid incremental change analogous to the one of Cornish pumping engines (Cardwell and Hills, 1976). Thus, while the compounding design was 'locked out' in Cornwall, where it was used at pressures that did not allow its full thermodynamic advantages, it 'locked in' in the case of marine engine building, where it was further developed and refined.

Of course, these examples from the history of steam power are far from a complete overview of the developments in the field. However, we feel that they provide a good illustration of the differences in the rates of technical progress across application sectors. In this respect, one could imagine that, after the 1850s, with the rise of scientific thermodynamics, some optimal and general design principles could be elaborated. However this was not the case. As noted by Gustave Adolphe Hirn, one of the leading pioneers of scientific thermodynamics, the formulation of a full fledged scientific theory of the steam engine had been of little help in actual steam engineering developments, precisely because sector specific functional requirements were already dictating too many features of the engine design (Cardwell, 1994, p. 314). Curiously, although thermodynamics was developed as the "science of steam engine", it exerted a much more powerful influence on different technological fields. This facet of the modern history of science was aptly remarked by J.D. Bernal:

> [A]lthough the laws of thermodynamics arose from consideration of the genesis of mechanical work – animal, chemical, electrical, and most of all from heat – it cannot be claimed that their formulation led to any immediate change in the practice of power production. Steam engines continued to be developed along lines indicating engineering improvements rather than any logical thinking out of the application of new principles......The one significant attempt at a Carnot cycle engine, Sir W. Siemens' superheated steam regenerative engine of 1858, was not a success. Where such a financial and technical genius failed others were not likely to succeed. Even to this day there is only one heat engine, the Philips'air engine of 1942 that has been inspired by purely thermodynamic conceptions, and even that has not come into general use.
>
> The practical value of thermodynamics has been rather as a general guide to the design of the new internal combustion and turbine engines, whose basic mode of working was determined by mechanical possibilities. Where thermodynamics has been used most directly and successfully is in modern chemical engineering and in

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[20] Note, instead, that thermodynamics did not play any role in Corliss' improvements. This suggests that, to some extent , sector specific knowledge bases relied on different sources of innovation.

the reverse of the heat engine – refrigerating machinery and heat pumps – of which only the former came into use before the end of the century (Bernal, 1953, pp. 67-68).

4 Concluding remarks

Our reappraisal of the economic history of the steam engine was aimed at providing a critical evaluation of the interpretive power of GPT based growth models. As noted in the first section, the GPT view of economic growth is elaborated around three properties of technological revolutions namely, their technological dynamism, their pervasiveness and their capacity of inducing further innovations (technical and organizational) in the using sectors. Although intuitively appealing, our discussion has shown that these concepts ought to be more rigorously defined, especially in view of empirical applications of the models.

The case of the "age of steam" shows a technology that is surely pervasive, but it is characterized by uneven rates of technical advance across application sectors.
This was due to the fact that in each application domain technical progress was dependent on distinct sectoral procedures of engineering knowledge accumulation.

In an early speculative appraisal of the economic impact of information technologies, Keith Pavitt stressed the importance of taking properly into account "the differentiated and cumulative nature of technical change" (Pavitt, 1986, p. 45). In particular, he noted that improvements in information technologies were going to be clearly affected by the existing technological trajectories. Rather than "creative destruction" the penetration of information technologies across application sectors was going to determine processes of "creative accumulation" with information technologies being integrated into the existing "local" procedures of innovation.

Endogenous growth models incorporating general purpose technologies (GPT) do not seem particularly well-equipped for taking into account the "local" aspect of the accumulation of technological knowledge. In this respect, we would contend instead that an evolutionary approach to modelling may be much more promising. We propose that such evolutionary modelling exercises should indeed focus on the salient features of the process of technological knowledge accumulation, rather than "black-boxing" it into knowledge product functions or similar analytical constructs. Silverberg (2002) has recently proposed the use of percolation models, and these may be able to provide a useful formalization of Dosi's paradigm-trajectory approach, and are well suited to deal both with cases of very 'uneven' technical advances and with cases in which technologies progress uniformly on a broad front.

Our discussion has also revealed two other apparent shortcomings of GPT-growth models. First, these models are built around a simple deterministic scheme of invention and diffusion of a single technology with its ramifications. This does not appear to adequately capture some of the insights of the original neo-Schumpeterian perspective of radical technological breakthroughs and long waves. The original neo-Schumpeterian view emphasized the role of "constellations of major technical innovations" explicitly acknowledging the (mutual) interdependencies among major technological trajectories. Hence, this view is indeed very similar to the one sketched by Landes for the British industrial revolution. To a degree, each of these major trajectories is likely to be characterized by its own pace of advance. The amalgamation of this cluster of technological innovations with deep changes in the organization of production gives birth what might be called a new system of manufacturing (which is supposed to characterize a specific period of the economic history of capitalist economies). Again, it is important to emphasize that the diffusion of the new system of manufacturing across sectors will exhibit a rather uneven character.

The second limitation of the GPT-models concerns the microfoundations of the model. GPT-growth models retain the perfect-foresight equilibrium framework which is a common feature of all the neoclassical analysis of economic growth whose overall interpretive relevance has been criticized time and again (see Nelson, 1998 and Dosi and Fagiolo 1998 for recent "statements" of this critique) . Moreover, the assumption of perfectly rational and perfectly informed agents, justified by the concern of neo-classical models with equilibrium, 'steady state' outcomes only, implies a complete neglect of the 'out-of-equilibrium dynamics'. However, this representation of technological change and of its relation to economic growth forcefully hides some of the crucial 'dynamic' properties of a process which is in continuous evolution and far from smooth in its diffusion. In a steady-state framework the closest proxy for history may be seen in specific 'initial conditions' that determine which steady state growth will be attained. But this is a quite an unsatisfactory way of inserting historical accounts in economic growth models (see Castaldi and Dosi (2004) and Hodgson (2001) for two recent discussions of the historical nature of economic evolution). Our discussion of the development of the high pressure expansive engine in various application sectors has shown (once more!) that technical change takes typically place in environments characterized by highly imperfect information and "strong" uncertainty. As we have seen, entrepreneurial failures were sweeping and persistent features of the development to the high pressure engine in various application sectors. Accordingly, notwithstanding their ambition of providing an interpretation of the historical pattern of economic growth, it is extremely doubtful that models based on optimising behaviours can satisfactorily probe into this ground.

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