DOI: 10.1111/ehr.13194

THE ECONOMIC HISTORY REVIEW

ORIGINAL ARTICLE

Factor prices and induced technical change in the industrial revolution

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Abstract

Using historical data for the 1700–1914 period, this paper analyses the nature and direction of technical change in Britain. The evidence in this paper indicates that, over this long period, labour-saving technology adoption was a major response to changes in relative factor prices, thus supporting the hypothesis that 'induced innovation' was a major driver of technical change during the British industrial revolution. Labour saving was made possible and sustained by capital-augmenting and energy-augmenting technical change coupled with continuous capital accumulation and abundant energy supplies. This process placed the British economy on a higher capital–labour ratio equilibrium, and was the primary force driving sustained productivity growth, which further raised wages and living standards.

KEYWORDS
factor-saving technical change, induced innovation, industrial revolution

The British industrial revolution was a pivotal phase in the long-run transformation of the world economy, ushering in a new era in economic and technological development.[1] Despite its central role in the history of economic growth and development, its causes remain a source of open debate.

Applying the idea that factor price differences drove technological choices, Allen argues that Britain's high wages and abundant coal deposits played a pivotal role in inducing the development

[1] Mokyr, *Enlightened economy*; van Zanden, *Long road*; Fouquet and Broadberry, 'Seven centuries'.

of the technologies which underpinned the British industrial revolution.[2] This 'induced innovation' hypothesis is now seen as a major explanation for technological change during the British industrial revolution, although more rigorous empirical analysis is needed.[3]

Existing evidence on the role of factor prices in driving technological choice in the industrial revolution is limited to historiography, industry case studies, and cliometric research.[4] In particular, Allen provides detailed analysis of the productivity-enhancing technologies adopted in textiles, mining, and iron smelting to explain the role of relative factor prices in promoting labour-saving technical change in eighteenth-century Britain. The analysis, however, does not show whether labour saving responded to factor price changes and whether and when labour saving began contributing to productivity growth.

In this paper, we revisit this 'induced innovation' hypothesis and evaluate its consistency with historical evidence using novel long-run macroeconomic and price data. To advance the debate, we derive time paths of three distinctive factor-specific (i.e. labour-augmenting, capital-augmenting, and energy-augmenting) technology indexes. We analyse the indexes jointly with relative-factor prices (measured as the wage–rental ratio and wage–energy price ratio) and other aggregate data to provide evidence about the nature of the technical change and assess whether Allen's claim is consistent with historical evidence. To provide comparability of our findings with the existing research, we also conduct a growth decomposition exercise. Proceeding in two steps, we decompose output growth (i) using the conventional growth accounting framework whereby total factor productivity (TFP) is derived as a residual, and (ii) using the three technology indexes.

The results reveal that labour's contribution to output growth is dominant until around 1830; technical change leaves a sizeable macroeconomic footprint only afterwards, and the growth of technical change was mainly driven by labour-saving innovations. To be specific, technical change was labour saving but also capital deepening and energy using. Cheap coal coupled with the relatively low rental cost of capital overcame the burden of growing wages in the nineteenth century. The results also support the 'induced innovation' hypothesis: the technology indexes respond strongly to movements in relative factor prices. The divergence in factor prices made mechanisation more attractive and affected the employment of factor inputs in production through the substitution of labour with energy and capital. This put the economy on a new, higher capital–labour ratio equilibrium where labour, endowed with more capital, became more productive. Higher labour productivity meant higher wages, and the resulting increase in demand required a capacity expansion response that entailed further labour saving. Therefore, productivity growth was the consequence of the race between rising wages and capital accumulation.

The paper adds new insights to the literature in several ways. First, the paper goes beyond case studies and considers recently revised rich macroeconomic data. Second, the paper addresses and provides answers to open questions about the nature and role of technical change in the industrial revolution. Third, it is the first study to estimate and analyse three distinctive input-specific technology indexes. The existing research on technological progress during the industrial revolution concentrates on 'neutral' technological progress (or TFP) and treats it as a 'black box' that needs to be filled with economic content.[5] Using the factor-augmenting indexes, this paper conducts growth decomposition analysis to provide comparability with the existing research. Fourth,

[2] Allen, *British industrial revolution.*

[3] Crafts, 'Understanding productivity growth'.

[4] Allen, *British industrial revolution;* Broadberry and Gupta, 'Lancashire'; Wrigley, *Energy.*

[5] In particular, Crafts, 'Recent research'; 'Steam'; 'Productivity'; Crafts and Harley, 'Output'; Crafts and Woltjer, 'Growth accounting'.

the paper provides new and valuable evidence on shifts in energy technologies and their role in productivity growth.

The following section reviews the existing literature. Section II outlines a model of induced innovation directed by relative factor prices. Section III introduces the aggregate production technology and the procedure for estimating the factor-augmenting technology indexes. Section IV presents the data collected and used in the analysis, and Section V presents the results and the analysis of the derived technology indexes as well as the growth accounting exercise. Section VI reconciles the quantitative evidence with the historical accounts. The penultimate section provides sensitivity analyses, while the conclusion summarises our findings and identifies topics for future research.

I

Over the past 40 years, a number of new or, at least, distinctive explanations as to why Britain industrialised first have been advanced.[6] Research on this topic has a long lineage, going back to Jevons's original work, *The coal question*, in 1865.[7] More recently, a new line of research has been introduced by Allen, who starts by highlighting Britain's unique wage–price structure, whereby wages were relatively higher than the cost of energy in the eighteenth century. He goes on to argue that this wage–price divergence was a precursor to the industrialisation of Britain in that it affected the demand for technology by giving British businesses rare incentives to develop labour-saving but energy-using technologies that set in motion sustained capital deepening.[8]

Hicks was the first to argue that factor price changes determine the direction of technical change: 'A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economizing the use of a factor which has become relatively expensive . . . '.[9] Habakkuk invoked Hicks' induced innovation hypothesis to explain the labour-saving bias in agricultural technology induced by the scarcity of labour and abundance of land in the United States in the nineteenth century.[10] Allen applies this idea to the British industrial revolution, arguing that relative factor prices induced labour-saving innovations. He points out that technical change reduced all production costs, but it reduced labour costs more than other costs, especially in the cotton textile and iron smelting industries. Allen analyses industry-level case studies, and hence, the claim that the industrial revolution was, at the core, a set of labour-saving, capital-deepening, and coal-using technical changes could well be put in question.

Attempts to link the industrialisation of Britain to factor price developments on the basis of case study evidence have been criticised.[11] Notably, Kelly et al. advance a 'unit labour cost' argument in which what matters for businesses is not the nominal or real wage rates but rather wages adjusted for labour productivity.[12] They agree that Britain had a high-wage economy, but when adjusted for

[6] Crafts, *British economic growth*; North and Weingast, 'Constitutions and commitment'; McCloskey, 'Industrial revolution'; McCloskey, *Bourgeois dignity*; Crafts and Harley, 'Output growth'; Temin, 'Two views'; Pomeranz, *Great divergence*; Galor and Weil, 'Population'; Lucas, 'Industrial revolution'; Voigtländer and Voth, 'Why England?'; Mokyr, *Enlightened economy;* Allen, *British industrial revolution;* Wrigley, *Energy*.

[7] Jevons, *Coal question*.

[8] Allen, *British industrial revolution.*

[9] Hicks, *Theory of wages*, p. 124.

[10] Habakkuk, *American and British technology*.

[11] Mokyr, *Enlightened economy*; McCloskey, *Bourgeois dignity*; Kelly et al., 'Precocious Albion'; Jacob, *Knowledge economy.*

[12] Kelly et al., 'Precocious Albion'.

high labour productivity (due to better nutrition), British labour was not expensive. Drawing on Salter's research on the induced-innovations hypothesis, other critics argue that businesses would be interested in economising overall costs, regardless of factor prices.[13]

Mokyr claims that Allen's model could be applied to only a few industries but not to the British industrial revolution as a whole.[14] Mokyr cites the evidence from patents compiled by Macleod that labour saving was a stated goal in only 4.2 per cent of all patents taken out in the 1660–1800 period.[15] Mokyr, nevertheless, agrees that relative factor prices may determine the direction of technical change.[16] In a recent study, Nuvolari et al. found that 38 per cent of patents filed in the eighteenth century were for inventions that saved labour.[17] However, the authors did not show that high wages induced these inventions. Crafts compares competing claims between Mokyr and Allen and finds viewing the industrial revolution through the lens of induced innovation appealing.[18] However, he concludes that the link between factor prices and innovations is not fully persuasive and requires more rigorous empirical analysis.

It has been argued that large sectors of the British economy did not benefit from technical change until after 1830. Von Tunzelmann, for example, found evidence in support of labour-saving bias in technical change only after 1830.[19] Mokyr argued that technological progress was not significant enough to affect the whole economy before 1830.[20] Kander et al. suggested that the takeoff in labour saving occurred between 1820 and 1830.[21]

Allen argues that price-induced labour-saving efforts were particularly intense in industries which jointly accounted for most of the productivity growth (i.e. textiles, metals, and mining) as early as the eighteenth century.[22] The latest estimates of industrial output weights by Broadberry et al. for 1700 show that iron, coal and textiles accounted for 50 per cent of the industrial output, and the industry's share in gross domestic product (GDP) was 41 per cent in England.[23] Thus, one could expect the labour-saving bias in technical change to leave a macroeconomic footprint by the eighteenth century.

II

In this section, we outline a model of induced innovation which will be the basis for our interpretation of the empirical findings. The model shown in figure 1 incorporates the characteristics of factor substitution and complementarity associated with technical change.

[13] Mokyr, *Enlightened economy*, and Jacob, *Knowledge economy*, invoke Salter's criticism (in *Productivity*) of Hicks' induced innovations hypothesis to challenge Allen's characterisation of the British industrial revolution.

[14] Mokyr, *Enlightened economy.*

[15] Macleod, *Inventing the industrial revolution*.

[16] Mokyr, *Enlightened economy*, p. 272.

[17] Nuvolari et al., 'Patterns of innovation'.

[18] Crafts, 'Understanding productivity growth'.

[19] von Tunzelmann, 'Technology'.

[20] Mokyr, 'Technological change'.

[21] Kander et al., *Power to the people*.

[22] Allen, *British industrial revolution.*

[23] Broadberry et al., *British economic growth*.

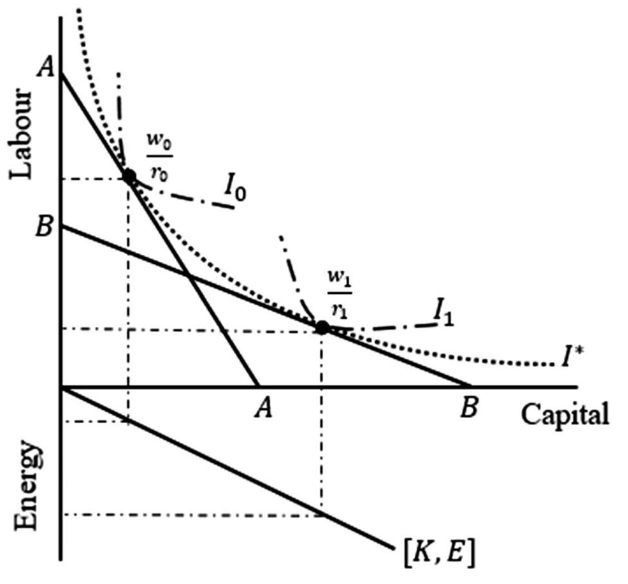

FIGURE 1 A model of induced innovation: relative factor prices and induced technical change. *Source:* Adapted from Hayami and Ruttan, *Agricultural development*.

The process of technical change can be described in terms of movements along the innovation possibilities curve (IPC), I^*; each point along the IPC corresponds to technologies that use different combinations of factor inputs (i.e., labour (L) and capital (K)). IPC is the envelope of less elastic isoquants, such as I_0 and I_1, corresponding to different types of technology. The $(K,\ E)$ line represents the complementary combination of energy and capital stock for a given level of labour required to operate the capital stock.

We hypothesise that technical change responds to (exogenous) factor prices. Assume that at time 0 the wage rate (w_0) is low relative to the cost of capital (r_0). A minimum-cost equilibrium point is at w_0/r_0, with an optimal combination of labour, capital stock, and energy. At the prevailing price ratio w_0/r_0, a new technology represented by I_0 (e.g., a new power technology that requires a certain combination of labour, capital, and energy to be operational) is invented. Now, assume that, at time period 1, labour becomes more expensive relative to capital and energy, say, owing to a shortage of labour and/or abundance of energy. The higher price ratio, w_0/r_0, prevailing for some time encourages the invention of a new class of power technologies represented by I_1 that save relatively expensive labour and use a cheap combination of capital stock and energy. The new minimum-cost equilibrium point thereby shifts to w_1/r_1 and radically changes the factor proportions settling at a higher capital–labour ratio.

The new technology represented by I_1 increases output per worker and, given the complementary relationship between capital and energy represented by the (K, E) line, corresponds to a higher intensity of energy per worker. In this simplified presentation, innovation is considered as the substitution of a combination of capital and energy (K, E) for labour (L) in response to a change in the wage rate relative to capital stock and energy prices.

In historical context, James Watt's separate condenser steam engine adapted to drive the power looms in textile mills enabled the labour-intensive textile production to move from cottages to factories. This resulted in the use of less labour relative to the combination of capital and energy. Increasing labour productivity meant higher wages, which encouraged further labour saving, and thereby further tinkering with (steam) technology.

The model succinctly captures the characterisation of Britain's industrialisation as a self-sustaining dynamic factor substitution process, whereby positive feedback between relative factor costs and capital accumulation sustains long-run economic growth. It offers an explanation for the shift to the modern growth regime as a function of relative factor costs, resource endowment, and the technological frontier.

III

In our analysis, we derive implicit factor-augmenting technology indexes, using a nested three-factor constant elasticity of substitution (CES) production function. We attempt to determine the extent to which the variations in technology indexes track factor–price ratios. If changes in price ratios consistently explain the variations in the derived technology indexes, we interpret the empirical findings as supporting the model of induced innovation.

As outlined in the model of induced innovation in the preceding section, we hypothesise that capital stock and energy are complementary factors of production, as a minimum of energy is required to operate machines. We assume that there were substantial substitution possibilities between labour and the capital/energy bundle. However, in our empirical model, we do not impose any restriction on the relationship between the factors of production. We let the data speak for itself by specifying a general two-level nested CES model of output as follows:

$$Y_t = \left\{ \left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho} \right]^{\frac{\gamma}{\rho}} + \left(A_{l,t}L_t\right)^{\gamma} \right\}^{\frac{1}{\gamma}} \tag{1}$$

where Y_t is the output, L_t is the labour, K_t is the capital stock, and E_t is the energy. $A_{i,t}(i = \{l, k, e\})$ is a technology index augmenting factor inputs. $\rho = \frac{\sigma_{k,e}-1}{\sigma_{k,e}}$ and $= \frac{\sigma_{ke,l}-1}{\sigma_{ke,l}}$, where σ_i is the elasticity of substitution between input factors.

Under competitive market conditions, factors are paid marginal productivities $p_i = \frac{\partial Y}{\partial X_i}, i = \{l, k, e\}$, and the cost share of each factor in output evolves according to the following three equations:

$$\frac{p_{e,t}E_t}{Y_t} = S_{e,t} = \frac{\left(A_{e,t}E\right)^{\rho}\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}-1}}{\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}} + \left(A_{l,t}L_t\right)^{\gamma}} = \frac{\left(A_{e,t}E\right)^{\rho}\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}-1}}{Y^{\gamma}} \tag{2}$$

$$\frac{p_{k,t}K_t}{Y_t} = S_{k,t} = \frac{\left(A_{k,t}K\right)^{\rho}\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}-1}}{\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}} + \left(A_{l,t}L_t\right)^{\gamma}} = \frac{\left(A_{k,t}K\right)^{\rho}\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}-1}}{Y^{\gamma}} \tag{3}$$

$$\frac{p_{l,t}L_t}{Y_t} = S_{l,t} = \frac{\left(A_{l,t}L\right)^{\gamma}}{\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}} + \left(A_{l,t}L_t\right)^{\gamma}} = \left(\frac{A_{l,t}L}{Y}\right)^{\gamma} \tag{4}$$

Rearranging Equation (4) and solving for $A_{l,t}$ gives

$$A_{l,t} = \frac{Y_t}{L_t} S_{l,t}^{\frac{1}{\gamma}} \tag{5}$$

Dividing Equation (2) by Equation (3) and solving for the capital-augmenting technological progress index gives

$$A_{k,t} = \frac{A_{e,t}E_t}{K_t} \left(\frac{S_{k,t}}{S_{e,t}}\right)^{\frac{1}{\rho}}. \tag{6}$$

Using Equations (5) and (6) in Equation (1) and then simplifying gives the equation for the labour-augmentation index:

$$A_{e,t} = \frac{Y_t}{E_t} S_{e,t}^{\frac{1}{\rho}} \left(1 - S_{l,t}\right)^{\frac{\rho-\gamma}{\gamma\,\rho}}. \tag{7}$$

Equations (5–7) can be used to compute the time paths of factor-augmenting technical change indexes. We lack the estimates of the elasticities of substitution $\sigma_{k,e}$ and $\sigma_{ke,l}$ and thus need to estimate them.

Since CES functions are non-linear in parameters, non-linear least-squares procedure can be used to estimate the parameters directly using Equation (1). However, direct estimation may poorly identify the parameter estimates.[24] There could be multiple solutions, and parameter estimates may be sensitive to starting values along with a lack of convergence towards the true parameters.[25] León-Ledesma et al. suggest using a multiple-equation estimation method which provides more information and enables imposing cross-equation restrictions. We thus estimate a system of three equations using Equation (1) and the ratio of cost-share equations. The three-equation system in logarithmic form is given below:

$$\ln Y_t = \frac{1}{\gamma} \ln\left(\left[\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right]^{\frac{\gamma}{\rho}} + \left(A_{l,t}L_t\right)^{\gamma}\right) + u_t \tag{8}$$

$$\ln\left(\frac{S_{k,t}}{S_{e,t}}\right) = \rho \ln\left(A_{k,t}K_t\right) - \rho \ln\left(A_{e,t}E_t\right) + u_t \tag{9}$$

$$\ln\left(\frac{S_{l,t}}{S_{e,t}}\right) = \gamma \ln\left(A_{l,t}L_t\right) - \rho \ln\left(A_{e,t}E_t\right) - \left(\frac{\gamma}{\rho} - 1\right) \ln\left(\left(A_{e,t}E_t\right)^{\rho} + \left(A_{k,t}K_t\right)^{\rho}\right) + u_t \tag{10}$$

where $u_{i,t}$ are random error terms. We estimated the system with an added assumption about the evolution of the factor-augmenting technology indexes. The technology indexes are assumed to evolve according to $A_{i,t} = A_0 e^{\lambda_i t}$, $i = \{l, k, e\}$. A_0 is the initial state of technology equal to unity; λ_i is a curvature parameter, and in the present context, it is the rate of factor-augmenting technical

[24] León-Ledesma et al., 'Identifying the elasticity'.

[25] Henningsen et al., 'Capital-labour-energy substitution'.

change; and t is a time trend.[26] λ_i is treated as an unknown parameter and estimated empirically. This approach lets the data provide information about the rate and direction of technical change. When $\lambda_k = \lambda_l = \lambda_e$, technical change is Hicks-neutral, and the marginal rate of substitution does not change when an innovation occurs (innovation does not affect the relative mix of factor inputs).

The factors of production are measured in different units (i.e., capital stock is measured in monetary units, labour in hours, and energy in heat units), and this may render the interpretation of the production function parameters difficult. To avoid this, we follow the literature on CES model estimation and normalise all variables and the factor augmentation trends to unity in 1700. Besides, normalising variables aids in finding the optimal parameter estimates ensuring convergence.[27] The system is estimated using the non-linear seemingly unrelated regression (SUR) method. SUR is a more efficient estimator in the presence of cross-equation residual correlation. We expect the residuals from the individual equations to correlate owing to the common macroeconomic shocks to the system.

Using energy as a factor of production is not a novel idea. Recent research in energy economics[28] and economic history[29] consider energy to play a crucial role in economic growth. Despite the growing interest in the role of energy in the industrialisation of Britain, economic historians have not used energy as a factor of production in cliometric and econometric analysis. Instead, land has frequently been used as the third factor of production to account for the contribution of agriculture to economic growth. In our model, land is represented as part of aggregate energy.

In the pre-industrial economy, energy was produced mostly by the agricultural and forestry sectors that used land as an input. Our measure of aggregate energy input includes data on woodfuels and animal muscle power, which were 'fuelled' by agricultural products (i.e. fodder). Recent evidence by Broadberry et al. suggests that the income share of agriculture in output shrank from 27 per cent in 1700 to 19 per cent in 1851.[30] Fouquet shows that the factor share of energy declined from 40 per cent to 19 per cent in the same period.[31] Since the income shares of land and energy moved in the same direction, we impose a simplifying assumption on the model that land input is broadly represented by aggregate energy.

IV

We collect original and revised historical data from numerous independent sources. Only a few series are available for the whole sample period, from 1700 to 1914. Therefore, where necessary, data are interpolated and spliced together to give continuous and geographically consistent series. Data transformations are made under plausible assumptions by drawing on relevant literature to preserve data quality. The problem of data quality is compounded by the changing geography of

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[26] In econometric estimations, the time trend, t, is set to equal 0 at the initial point so that $A_0 e^{\lambda_i t} = 1$ consistent with the normalisation procedure.

[27] León-Ledesma et al., 'Identifying the elasticity'; Henningsen et al., 'Capital-labour-energy substitution'.

[28] van der Werf, 'Production functions'; Fröling, 'Energy use'; Stern and Kander, 'Role of energy'; Kander et al., *Power to the people;* Kander and Stern, 'Economic growth'; Hassler et al., 'Directed technical change'; Stern et al., 'Directed technical change'.

[29] Wrigley, *Energy*; Allen, *British industrial revolution*; Malanima, 'Energy consumption'.

[30] Broadberry et al., 'When did Britain industrialise?'.

[31] Fouquet, *Heat.*

the British Isles over the two centuries under consideration. The territory considered in this paper is the whole of Great Britain, including Wales and Scotland. Not all series are fully available for Great Britain, and where possible, we spliced short series for Britain using data for England and the UK. Short-term cyclical fluctuations of all variables used in the econometric estimations and descriptive analyses are removed using the Hodrick–Prescott filter.

Econometric analyses require data on output, labour, physical capital stock, and energy. Estimates of nominal GDP based on the value-added approach and GDP deflator for the 1700–1870 period are from Broadberry et al.[32] Both the series are extended to 1914 by splicing them to Thomas and Dimsdale's estimates of nominal GDP and GDP deflator for Great Britain.[33]

Data on energy consumption are the sum of annual use of animal muscle power, wood, coal, crude oil, and town and natural gas in million tons of oil equivalent[34]. Data on labour are from Thomas and Dimsdale. The labour input is total annual average hours worked estimated by multiplying the labour force by annual average hours worked per person per year.[35]

Data on the real net stock of reproducible fixed assets for the period between 1760 and 1914 are from Feinstein.[36] The series is the weighted sum of the value of the stock of dwellings, industrial and commercial buildings, plant, machinery and equipment, rolling stock, vehicles, and ships. The series is on a decadal basis for 1761–70 to 1841–50 in 1851–60 prices, and on an annual basis for the 1850–1914 period in 1900 prices.[37] The decadal values are converted to annual frequency to create continuous annual series using geometric growth rates between the decadal values. The resulting annual series are then rebased to 1900 by splicing them with the data for the 1850–1914 period.

For the period before 1761, we extrapolated Feinstein's capital stock series backwards to 1700 using an index of producer goods from Hoffmann.[38] The index is the weighted average of the quantities of iron, non-ferrous metals, and other materials generally used in the production of physical capital stock.

Research on historical wage rates has produced numerous average wage series for England; yet, there is no national average wage for the period considered.[39] Wage series constructed for English building labourers and/or craftsmen have been used in the literature widely as they broadly represent the long-run trend of money wages in England.[40] There is also no continuous wage series for Great Britain covering the 1700–1914 period. Allen has constructed, perhaps, the longest series of wage rates of building labourers and craftsmen in England. The arithmetic average of Allen's wage rates is used as a measure of average British wages. Using other series does not alter the empirical results presented in the next section.

Similarly, there is no single market price for energy for Great Britain. Economic historians have relied on available information from the price records of energy carriers delivered to

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[32] Broadberry et al., *British economic growth.*

[33] Thomas and Dimsdale, 'Millennium'.

[34] Fouquet, 'Long-run demand'.

[35] Estimates of labour force data for Great Britain are not available for the full period. We used British workforce data for the 1760–1854 period and UK data for the 1855–1914 period to construct longer series (Thomas and Dimsdale, 'Millennium'), which were then extrapolated back to 1700 at the growth rate of population index from Broadberry et al.

[36] Feinstein, 'National statistics'.

[37] Capital stock data for the 1850–1914 period is for the UK.

[38] Feinstein, 'National statistics'; Hoffmann, *British industry*, tab. 54, pt. A, col. 4.

[39] Crafts and Mills, 'Trends in real wages'; Feinstein, 'Pessimism perpetuated'; Clark, 'Macroeconomic aggregates'; Allen, 'London'.

[40] Allen, *British industrial revolution*; Broadberry et al., *British economic growth*.

various institutions in England and the records of prices of coal at the pithead.[41] Perhaps the most definite energy price data is available from Fouquet, whose price series on coal, petroleum, firewood, provender, and natural and town gas are used to estimate an average energy price.[42] The aggregate energy price measure is the average of prices of individual fuels weighted by their share in total energy consumption mix.

The last of the price data required for the empirical analysis, the rental cost of capital, is estimated using data on bank rates and a consumer price index from Thomas and Dimsdale, the Schumpeter–Gilboy and the Rousseaux price indexes for producer goods from Mitchell, and the price index of capital goods and depreciation rates for physical capital stock estimated using data on gross fixed capital formation from Feinstein.[43] The rental price of capital is estimated using the Hall–Jorgensen formula:

$$r_k = \frac{P_k}{P} \, (i - \pi + \delta) \tag{11}$$

where P_k/P is the relative price of capital, i is interest rate, π is inflation rate, and δ is depreciation rate. The only available measure of relative price of capital goods is from Feinstein for the period between 1850 and 1914.[44] The index is spliced to the Schumpeter–Gilboy index for producer goods for the 1700–1801 period and the Rousseaux price index for principal industrial products for the 1802–50 period to yield a continuous relative price index for capital goods.

Humphries and Weisdorf provided data on labour cost share in output for the 1260–1850 period.[45] We merged their data with Mitchell's estimate of labour share in national income for our preferred continuous labour share series for the 1700–1914 period. The cost share of energy is available from Fouquet for the entire period.[46] Capital cost share is calculated as a residual using the data on the shares of labour and energy following Madsen et al.[47]

V

This section presents the results and the analysis of the derived technology residuals as well as the growth-accounting exercise. Below, we present the empirical estimates of the elasticity of substitution and drift parameters using the system of Equations (8–10).

Table 1 presents the estimated elasticities of substitution and rates of factor augmentation. All estimates are statistically significant. As expected, the elasticity of substitution between capital/energy composite and labour ($\sigma_{ke,l}$) is greater than unity, and between capital and energy ($\sigma_{k,e}$), it is smaller than unity. The estimated rates of factor-augmentation for labour, capital, and energy (λ_l, λ_k, and λ_e) are statistically significant and precisely estimated. The joint test of significance, $\lambda_k = \lambda_l = \lambda_e$, indicates that technical change was not Hicks-neutral.

[41] Fouquet, *Heat*; Allen, *British industrial revolution.*

[42] Fouquet, *Heat*; Fouquet, 'Long-run demand'.

[43] Thomas and Dimsdale, 'Millennium'; Mitchell, *British historical statistics;* Feinstein, 'National statistics'.

[44] Feinstein, 'National statistics'.

[45] Humphries and Weisdorf, 'Unreal wages?'.

[46] Fouquet, *Heat.*

[47] Ibid.; Madsen et al., 'Four centuries'.

TABLE 1 Estimated elasticities of substitution and rates of factor augmentation

	Parameter estimates (standard errors)
$\sigma_{k,e}$	0.397 (0.026)
$\sigma_{\mathrm{ke},l}$	3.863 (0.454)
λ_l	−0.005 (0.001)
λ_k	−0.003 (0.000)
λ_e	−0.006 (0.000)

Note: $\sigma_{k,e}$ = elasticity of substitution between capital and energy, $\sigma_{\mathrm{ke},l}$ = elasticity of substitution between the capital/energy composite and labour, λ_l = rate of factor-augmentation for labour, λ_k = rate of factor-augmentation for capital, and λ_e = rate of factor-augmentation for energy.

The small elasticity of substitution between capital stock and energy is evidence of a limited scope for factor substitutability between the two factors, at least in the short run. It reflects an important feature of the British industrial revolution. Britain had an energy economy. The share of energy expenditure exceeded 20 per cent in the eighteenth century[48] – the growing stock of capital required greater amounts of energy to be operational. Investment in plant, machinery, and equipment increased by more than 10 times its original value between 1760 and 1850, and a large proportion of aggregate investment was in buildings and works.[49] Under such circumstances, energy had to increase for growth to be sustained. Equally, an abundant supply of energy without sustained capital accumulation would have limited the scale of production possibilities. Likewise, capital deepening with limited energy supply would have pushed growth back to levels seen during the pre-industrial period.[50]

The technology drift coefficients, $\hat{\lambda}_i$, are estimates of implied growth rates of the factor-augmenting technology indexes. The estimated average annual rate of labour-augmentation is negative, which is counterintuitive, and contradicts the observed rise in A_L from the late eighteenth century shown in figure 2(a). We do not have a plausible interpretation for the negative labour-augmentation rate considering the historical context and consider it a spurious result.[51] Fortunately, this result does not affect any subsequent estimates or analysis. The estimates for the other factor-augmentation rates have the correct signs validating the historical narrative, which we discuss in the following sections.

Figure 2 shows the technology indexes derived using the estimated elasticities of factor substitution in Equations (5–7) alongside the average real wage and energy price for the 1700–1914 period. There is a positive association between the technology indexes and factor prices.

[48] Fouquet, *Heat*.

[49] Feinstein, 'National statistics'.

[50] Wrigley, *Energy*.

[51] The difficulties in identifying the elasticities of substitution and growth rates of factor-augmenting technical change using the CES production function have been well documented. The received wisdom in the literature suggests that their joint identification is challenging (León-Ledesma et al., 'Identifying the elasticity'; Henningsen et al., 'Capital-labour-energy substitution'). In our analysis, a potential cause of the poor estimation could be the choice of the method of normalisation. We thus normalised the production function using the average arithmetic value of each variable. This did not yield more plausible results. Therefore, we retained our original baseline estimates.

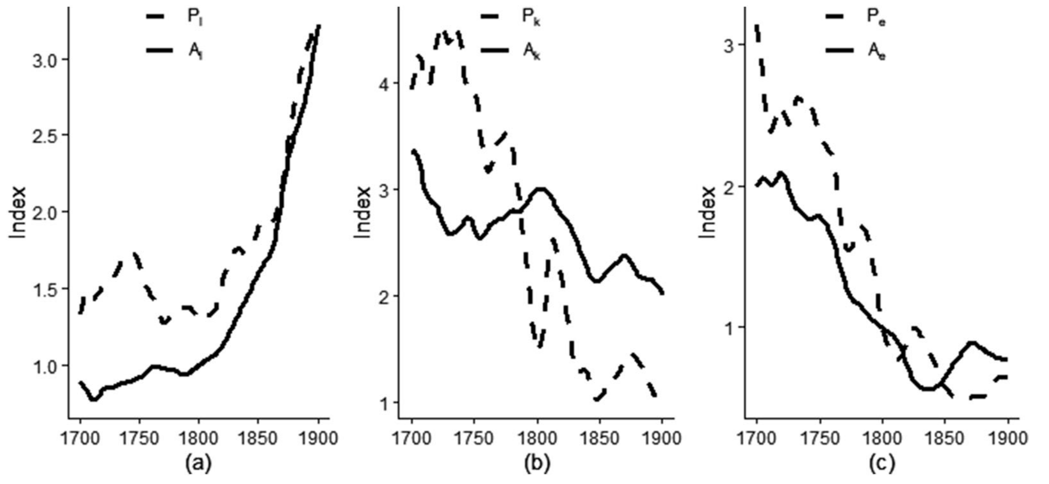

FIGURE 2 Time paths of factor-augmenting technology and factor price indices: (a) real wage (P_l) and labour-augmenting technology index (A_l), (b) real cost of capital (P_k) and capital-augmenting technology index (A_k), and (c) real energy price (P_e) and energy-augmenting technology index (A_e).

Source: See Section IV.

Technology indexes track factor prices closely and appear to respond to price changes. From a theoretical perspective, a downward-sloping technical change index does not make sense, and it appears to be inconsistent with the recent research on energy technologies. Fouquet, Allen, and Kander et al. report persistent increases in energy efficiency owing to the development of energy-specific technologies in both the industry and domestic sectors.[52] This will be examined in more detail in the next section in a broader context.

So, was technical change labour saving? As the preceding analysis reveals, the labour-augmenting technology index closely tracks the trend growth of real wages. However, a high or increasing cost of labour does not necessarily induce labour-saving innovations unless businesses experience rising wages relative to the cost of other input factors and expect the trend to continue in the future.[53] Thus, the answer depends on the movements in the ratios of average wage to rental cost of capital and to energy price.

We now examine the responsiveness of factor-specific innovations in a plot of relative factor rewards and the technology indexes. Figure 3 shows the time paths of factor–price ratios and factor-augmenting technology indexes. The wage–rental ratio rises until about 1760, reflecting an increasing cost of labour relative to the cost of capital. The labour-augmenting technology index increases until about the same time before stagnating and declining which appears to be in response to the declining wage–rental ratio after 1760. The technology index begins its persistent upward climb, closely tracking the wage–rental ratio after 1790. It appears to respond to movements in the factor–price ratios. In particular, both the rate and direction of technical change seem to be determined by the movements in wage–rental ratio. Therefore, we interpret the labour-augmenting technical change index as a labour-saving technology index.

There was modest labour saving well before the onset of the industrial revolution: between early 1710 and 1760. The index stagnates and gradually declines between 1760 and 1790. It takes off after

[52] Fouquet, *Heat*; Allen, *British industrial revolution*; Kander et al., *Power to the people*.

[53] Fellner, 'Comment'.

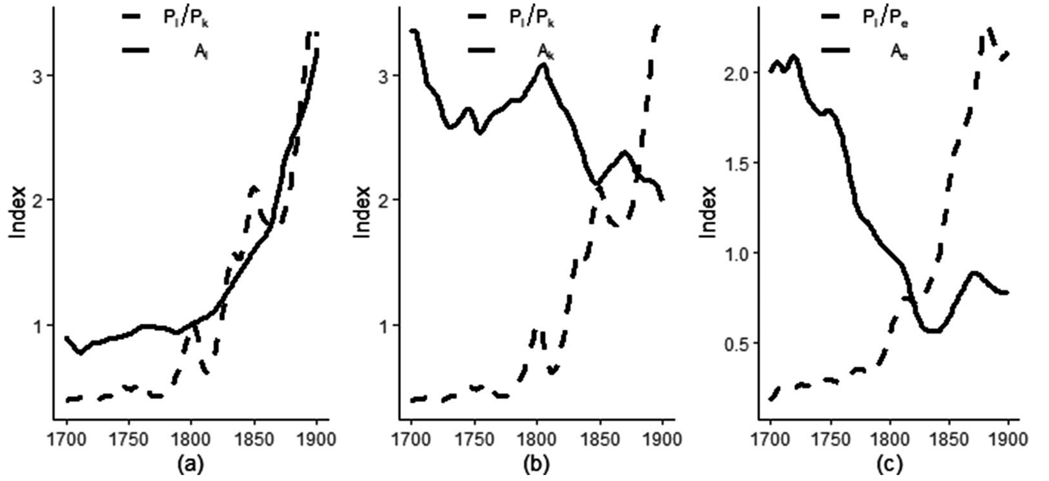

FIGURE 3 Factor–price ratios and technology index: (a) wage–rental ratio (P_l/P_k) and labour-augmenting technology index (A_l), (b) wage–rental ratio (P_l/P_k) and capital-augmenting technology index (A_k), and (c) wage–energy price ratio (P_l/P_e) and energy-augmenting technology index (A_e).

Source: See Section IV.

1790, and its growth rate notably increases after 1820, indicating intensified efforts to save labour. The average annual growth rate of the index in the 1700–1820 period is 0.2 per cent, and it is 1.3 per cent between 1820 and 1914. This evidence somewhat supports von Tunzelmann's narrative that technical change did not have a tendency towards saving labour until after 1830.[54]

In contrast, the capital-augmenting and energy-augmenting technology indexes respond negatively to increasing wage–rental and wage–energy price ratios. Over the eighteenth century, the capital-augmenting technology index declined in the first three decades and then increased until the turn of the century. Wage–rental ratio increased gradually during this period. Trends reversed at the turn of the next century indicating a strong response of innovative activity to increasing relative cost of capital. Equally strikingly suggestive is the association between the energy-augmenting technology index and relative energy price. There is a clear negative association between them. On balance, the direction of technical change appears to be labour saving but capital and energy using.

The time paths of the ratio of the labour-saving technology index to the energy-augmenting technology index (A_l/A_e) and to the capital-augmenting technology index (A_l/A_k), shown in figure 4, provide an interesting insight about the bias of technical change.

In the absence of biased technical change, we would expect the indexes to move in the same direction at a fairly similar rate of growth. Thus, we would expect the ratios of the indexes to have no tendency to drift up or down. However, persistent and exponential growth in the ratios indicates that the incentive to save labour appears to be greater than the efforts to save capital and energy. Throughout the eighteenth century, there is gradual divergence in the ratios. Efforts to save labour relative to other factors intensifies after 1810 and then accelerates after 1860. Allen's incentive-based explanation for the bias in the technical change finds support in this evidence.[55]

[54] von Tunzelmann, 'Technology'.

[55] Allen, *British industrial revolution.*

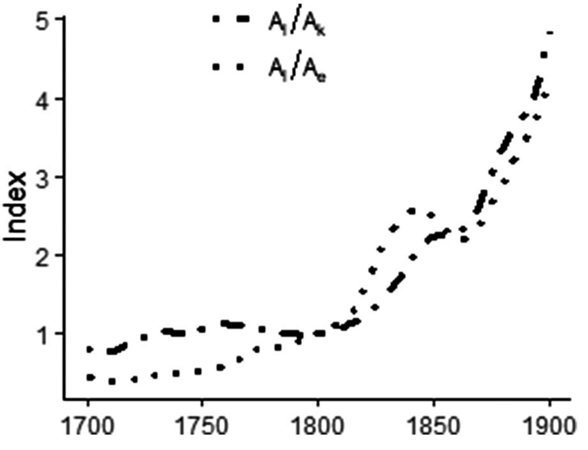

FIGURE 4 Ratio of factor-saving technology indexes (A_l/A_k, A_l/A_e).
Source: See text.

The graph also shows the possible time shifts in energy technologies as the transition to coal-based technologies accelerated during the second half of the eighteenth century.[56]

Next, to enable comparison with the prior research, we conduct growth-accounting decomposition in terms of contributions to average annual growth of GDP in percentage points. We begin the analysis assuming that the production technology is of Cobb–Douglas form and analyse the contribution of labour, capital stock, energy, and TFP to output growth. TFP is calculated as the residual following the conventional growth accounting framework widely used in the literature.[57]

Conventional growth accounting with the Cobb–Douglas specification does not allow us to analyse the contribution of factor-specific technical change to output growth. We address this restriction by relaxing the assumption of unitary elasticity between factor inputs and by allowing for potential bias in factor augmentation. This enables us to combine the growth rates of the implied technical change indexes, A_l, A_k, and A_e, with the growth rates of the three factors of production to assess the contribution of factor-specific technical change to output growth. We use average factor cost shares as weights for the growth rates of factor-augmenting technology indexes. It is not a complete conventional growth-accounting exercise because the factor share-weighted growth rates of input factors do not sum up to the actual output growth rate. The predicted GDP growth rate is the factor share-weighted sum of the rates of growth of inputs and the three factor augmentation indexes:

$$Predicted\ \frac{\Delta Y}{Y} = s_l\frac{\Delta L}{L} + s_k\frac{\Delta K}{K} + s_e\frac{\Delta E}{E} + \underbrace{s_l\frac{\Delta A_l}{A_l} + s_k\frac{\Delta A_k}{A_k} + s_e\frac{\Delta A_e}{A_e}}_{\frac{\Delta A}{A}} \tag{12}$$

Here, s_i is the constant cost share of input factor i in output. In what follows, we assume that factor cost shares for labour, capital stock, and energy equal the sample average values: 0.67, 0.17, and 0.16, respectively. Estimated factor cost shares vary over the 1700–1914 period. The average labour cost share increased from 0.62 to 0.73, that of capital stock decreased from 0.23 to 0.10, and the energy cost share was 0.19 in 1801–30 but declined to 0.11 in the 1900–14 period.

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[56] Stern et al., 'Directed technical change'.

[57] Crafts, 'Productivity growth in the industrial revolution'.

TABLE 2 Conventional growth-accounting decomposition

		Contribution from			
	$\Delta Y/Y$	$\Delta L/L$	$\Delta K/K$	$\Delta E/E$	$\Delta A/A$
1700–60	0.52%	0.23%	0.17%	0.15%	−0.02%
1761–1800	1.13%	0.84%	0.16%	0.26%	−0.14%
1801–30	1.64%	0.82%	0.29%	0.37%	0.16%
1831–60	2.29%	0.60%	0.41%	0.53%	0.75%
1861–99	2.03%	0.40%	0.35%	0.31%	0.97%
1900–14	1.68%	0.50%	0.28%	0.15%	0.76%

Source: See Section IV.

Conventional growth decomposition analysis presented in table 2 is based on the periodisation commonly used in growth accounting studies.[58] Labour contributed the most to output growth until 1830. The growth of capital stock and energy played equally important and growing, but relatively small, role in the same period.

The estimates of TFP growth ($\Delta A/A$) contribution to output growth are lower across periods, possibly owing to the inclusion of energy, but the general trend of growth is unchanged (i.e. gradual acceleration). TFP declines throughout the eighteenth century. Improvements in the efficiency with which the economy utilised the resources did not reach 0.3 per cent per year until after 1830, and they are lower than the estimates reported in recent research.[59] TFP left a sizeable footprint on output growth only after the 1830s, when steam and rail technologies began making marked headway, even beyond a handful of modernised industries.[60] The contribution of labour declined after 1830, and those of capital and technical change increased. If anything, this implies that the capital-deepening drive was in full swing and shaped the economy's growth experience in the nineteenth century.

Conventional growth decomposition does not permit us to attribute the variation in the growth of TFP to any specific factor or event. This results in guesswork based on historiography and limited data. Table 3 presents the growth decomposition of factor inputs and factor-specific indexes using Equation (13), which effectively decomposes TFP into three factor-specific technology indexes. The growth rates do not add up to output growth; however, the difference between the actual and predicted output growth is insignificant, which gives credence to our analysis. Our model predicts a gradual output growth consistent with the revisionist view.[61]

An important result is that there was little labour saving in the eighteenth century. Labour saving became the main driver of growth in the nineteenth century. This is not surprising because the important labour-saving innovations of the eighteenth century were slow to diffuse and had a long lagged effect on output.[62] For example, important innovations and improvements in steam

[58] Ibid.; Crafts, 'Sources'; Crafts and Woltjer, 'Growth accounting'.

[59] Crafts, 'Understanding productivity growth'; Crafts, 'Productivity growth in the industrial revolution'; Antràs and Voth, 'Factor prices'.

[60] Crafts, 'Steam'.

[61] Crafts, 'Understanding productivity growth'; Broadberry et al., *British economic growth*.

[62] Nuvolari and Tartari, 'Bennet Woodcroft'.

TABLE 3 Growth decomposition using factor-specific technology indexes

	Actual $\Delta Y/Y$	Predicted $\Delta Y/Y$	$\Delta L/L$	$\Delta K/K$	$\Delta E/E$	$\Delta A_L/A_L$	$\Delta A_K/A_K$	$\Delta A_E/A_E$
1700–60	0.52%	0.52%	0.23%	0.17%	0.15%	0.10%	−0.07%	−0.05%
1761–1800	1.13%	1.15%	0.84%	0.16%	0.26%	0.02%	0.05%	−0.19%
1801–30	1.64%	1.64%	0.82%	0.29%	0.37%	0.54%	−0.09%	−0.29%
1831–60	2.29%	2.29%	0.60%	0.41%	0.53%	0.64%	−0.06%	0.16%
1861–99	2.03%	2.03%	0.40%	0.35%	0.31%	1.03%	−0.05%	−0.01%
1900–14	1.68%	1.67%	0.50%	0.28%	0.15%	0.87%	−0.16%	0.04%

Note: Predicted growth rate of output is the sum of the share-weighted growth rates of factor inputs and the factor-augmenting indexes (see Equation 12).
Source: See Section IV.

technology happened over the long eighteenth century but their productivity footprint on output showed up only after the 1830s.[63]

There was hardly any capital- and energy-saving technical change. Instead, there was a drive towards capital deepening and energy expansion as evidenced by negative growth estimates for the capital- and energy-specific technology indexes. Besides, steam technology of the eighteenth century was power hungry and grossly inefficient.[64] The high cost of installing and operating steam engines held back their diffusion, and it was not until after the 1830s that steam technology became more efficient and adaptable.[65] This is reflected both in the low contribution of labour-saving technical change and negative capital- and energy-saving technical change in the eighteenth century.

Labour-saving technical change contributed the most to output growth in the nineteenth century. This required investment in capital stock in the form of steam technologies, and steam technologies became more efficient in the second half of the nineteenth century. Even then, the increased efficiency did not translate into energy savings owing to rebound effects, which is discussed in the next section in more detail. Most efficiency gains were due to technologies that saved labour. On balance, technical change was the main long-run driver of output growth, and it was strongly biased towards saving labour and using capital and energy.

These findings are in alignment with the prior research that TFP growth was modest and that technological progress played an important role in the nineteenth century.[66] Our results are, however, different in terms of magnitude and time of changes. There are a number of reasons for this: (i) we use the most recent estimates of output, capital stock, labour, and the factor share of labour; (ii) in our model, energy is a factor of production – adding energy affects the residual, TFP index, but does not have significant impact on its secular trend; and (iii) perhaps more importantly, we decompose and analyse the possible biases in technical change.

To put empirical findings in the context of the industrial revolution, there was, initially, a gradual movement towards the development of labour-saving, capital-intensive, and resource-using production technology. Efforts appear to have intensified investments in labour-saving technologies after 1830s, which brought about the acceleration in productivity growth documented by

[63] Kanefsky, 'Diffusion'; von Tunzelmann, 'Technology'; Crafts, 'Understanding productivity growth'.

[64] Allen, *British industrial revolution*.

[65] Crafts, 'Steam'; Fouquet, 'Heat'.

[66] Antràs and Voth, 'Factor prices'; Crafts, 'Productivity growth in the industrial revolution'; Crafts, 'Understanding productivity growth'.

revisionist historians.[67] As will be shown in the next section, energy-specific innovations induced greater consumption of energy that crowded out energy savings. Incremental energy-saving innovations (e.g., efficiency improvements in steam technology) made mechanisation more attractive, resulting in greater demand for energy. The ultimate effect was the sustained increase in productivity growth, especially in the nineteenth century. Thus, labour saving was the indirect outcome of the energy-saving efforts, which also led to the expansion of energy inputs.

VI

An important finding of this paper is that the technology indexes closely track the long-run trends in relative prices, suggesting the presence of induced technical change. Another important result is that, contrary to the perceived wisdom, energy-augmenting innovations declined during the industrial revolution. Recent research documents that energy efficiency increased manyfold in the 1700–1914 period.[68] Improvements in the utilisation of steam power in the industrial sector and increased efficiency of iron furnaces and forges, as well as the adoption of high-pressure steam engines in railroads, shipping, and passenger transport services, led to significant energy savings.[69] As such, one would expect the energy-augmenting technology index to have a positive trend.

Technical change could have had a double effect on energy use during the industrial revolution; it could have been energy saving and energy expanding.[70] Technical change was energy saving when innovations resulted in greater economic output per unit of energy input, and it was energy expanding when innovations led to new applications of coal-based industrial innovations, which expanded the space of production possibilities such as in textiles, mining, railways, and sea transportation. The interplay between the two forces resulted in energy efficiency rebound effects. By considering the existence of rebound effects, in what follows, we explain why the energy-augmenting technology index is downward sloping.

Kander et al. suggest that energy savings were persistent but generally modest during the industrial revolution.[71] Persistent energy efficiency improvement is likely to lead to energy savings; however, some of the energy savings might be lost owing to rebound effects. Direct rebound effects occur because energy efficiency improvements imply that the cost of generating energy services (e.g. heat, power, or transport) falls, which leads to a rise in the consumption of energy services. Demand for energy was highly elastic during the industrial revolution,[72] and coupled with energy-saving innovations, the low coal price encouraged greater consumption of coal, resulting in a higher energy consumption per unit of economic output. Thus, ‘pulled-up’ energy consumption may have offset energy-efficiency improvements.

Essentially, there were two countervailing forces in operation arising from technical change: one that saved energy and the other that expanded its use. Thus, on the one hand, the introduction

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[67] Griffin, *Short history,* outlines the revisionist perspective that productivity was not as drastic as the earlier research suggested.

[68] Fouquet, *Heat*; Allen, *British industrial revolution*; Kander et al., *Power to the people*.

[69] Fouquet, *Heat;* Allen, *British industrial revolution*.

[70] Kander et al., *Power to the people*.

[71] Ibid.

[72] Fouquet, ‘Long-run demand’.

of energy-efficient technologies provided energy and cost savings; on the other, their adoption enabled a faster accumulation of energy-using physical capital stock in various branches of the economy. As such, innovations in steam technology made steam engines a type of general-purpose technology by early nineteenth century.

Steam technology had a limited application in generating economic output in the early eighteenth century; however, innovations reduced the (house-sized) coal-hungry (Newcomen atmospheric) engine used to drain mines to the small and mobile yet powerful (Stephenson's) steam locomotive that pulled several tons of carriages. Early Newcomen engines consumed 45 pounds of coal per horsepower-hour, and this was cut to 15 pounds of coal per horsepower-hour by 1830s.[73] New steam engines were of different design, more powerful and more fuel efficient; their widespread adoption lead to the phenomenal growth of aggregate demand for coal.[74] Therefore, in the battle between the two countervailing forces that energy-augmenting technical change brought about, energy expansion won out and this explains why energy-augmenting technical change has a negative growth rate.

Fouquet documents a range of historical accounts of the rebound effect in the provision of various energy services.[75] Freight transport services became cheaper owing to the application of steam technology in sea and rail transport service provision in the nineteenth century. The desire for timely and safe delivery of goods over long distances at low cost increased the demand for freight transport services. Similarly, demand for passenger transport services increased as a result of falling passenger transport service prices.[76] Advances in lighting technology led to the reduction in the cost of lighting during the industrial revolution.[77] The net effect of these changes resulted in a spectacular rise in the demand for coal, and later for gas and kerosene (for lighting).

The dynamics of technological progress changed after 1840. By 1840, coal had become the main source of energy in Britain, and the technologies of this period were more efficient.[78] Fouquet finds that, for a number of energy services, rebound effects declined from the second half of the nineteenth century.[79] So, energy savings may have started to dampen the energy expansion effects of technical change.

The evidence reviewed so far lends credence to the conjecture that technical change was biased in a labour-saving and capital-deepening (accumulation) direction during the industrial revolution. Capital deepening did not occur in isolation; building capital equipment required cheap raw materials (i.e. bricks, metal, and energy). Once built, capital stock required even more energy input to become operational. Thus, the cost of energy was a major consideration in investing in physical capital in the industrial revolution, and capital deepening must have been coupled with energy expansion at every stage of capital accumulation.

It is worth considering the changing incentives in the diffusion of steam technology during the industrial revolution. A steam engine, especially in its primitive form, was not only made of cast iron but also of bricks and wood, as well as other materials. Fouquet documents that metal parts were around 60 per cent of the total cost, with the rest of the materials making up the remaining

[73] Allen, *British industrial revolution*.

[74] Kanefsky, 'Diffusion'; idem, 'Motive power'.

[75] Fouquet, *Heat*, pp. 276–9; Fouquet, 'Long-run demand'.

[76] Fouquet, 'Long-run demand'.

[77] Fouquet and Pearson, 'Long run demand for lighting'.

[78] Fouquet, *Heat*.

[79] Fouquet, 'Long-run demand'.

TABLE 4 Ratios of selected variables (index 1700 = 100)

	1700	1800	1850	1914
Capital–labour ratio	100	128	203	486
Energy–labour ratio	100	168	379	839
Labour productivity	100	106	159	378

Source: See Section IV.

cost.[80] As the transition to coal from biomass was well underway in the eighteenth century, all these raw materials became cheaper, especially iron. The reduction in the cost of acquiring physical capital and the further refinement of steam technology for efficiency gains reduced the effective cost of providing power. Fouquet estimates that the running cost of generating one kilowatt hour (kWh) of power was around 450 pence in 1760. The cost fell to 100 pence by 1800 and to 30 pence by 1870.[81]

This was key to the widespread diffusion of steam technology and, hence, the greater accumulation of coal-using physical capital in otherwise traditionally labour-intensive industries. Steam technology permitted the growth of textile mills with a centralised power source, new forms of organising production processes, and large-scale production.[82] A lack of energy expansion would have halted the capital-deepening direction of growth in Britain.

Table 4 illustrates the capital-deepening and labour-saving trend of the British economy. The bias appears to have been towards energy use and away from labour input. The growth of energy and capital input was much greater than that of labour. Businesses directed their efforts towards saving labour and using greater amounts of energy and physical capital.[83] Cheap energy coupled with energy-augmenting technical change enabled greater accumulation of capital stock. The growing scale of production required even more energy to sustain the productivity growth. In line with productivity growth, wages grew faster, and labour-saving efforts rapidly increased after 1800. Because of this positive feedback loop, British businesses did not run into diminishing marginal returns to inputs. Together with labour-saving innovations, energy-specific innovations in various branches of the economy ensured the sustained accumulation of capital.

The rate and direction of the energy-augmenting technology index changes after 1840 (see figures 2 and 3): the continued decline of the index in the previous periods comes to a halt as the average real energy price reversed its trend. This can be explained by considering the broader context. In the early stages of industrialisation, the adoption of coal-using technologies increased reliance on coal. The situation reversed in the later stages when greater efforts were directed towards developing coal-saving innovations. Over the long 1700–1914 period, the supply of coal was elastic owing to improvements in mining, land, and canal transportation services. This, in turn, instigated efforts to develop coal-using technologies. These innovations enabled businesses to achieve scale economies, which boosted the demand for coal in subsequent decades. The hunger for coal eventually made it the basis of the economy's fuel supply by 1850. Being a common fuel for industrial use, coal made up a sizeable fraction of production costs, and hence, a higher coal price would have rendered adopting coal-using technology less profitable. Innovative

[80] Fouquet, *Heat*.

[81] Ibid., p. 120.

[82] Berg, 'Factories'.

[83] Kander et al., *Power to the people*.

activities were thus directed at economising coal use.[84] On one hand, rising real wages induced intensified labour-saving efforts after 1850; on the other, technical change became increasingly energy saving in response to rising coal prices.

VII

In this section, we analyse and discuss the sensitivity of the baseline econometric results to: (i) alternative data and (ii) parameter constancy using rolling window regressions.

How sensitive are our results to alternative data? The estimates of energy consumption and energy's share in national income are the only complete series used in our econometric analysis. For the other series, we spliced short series and constructed continuous data on GDP, capital stock, labour, and labour's factor share. There was little scope for sensitivity analysis with alternative data. Nevertheless, we experimented with alternative data on GDP to test the robustness of our baseline results. Using the alternative series in the baseline model yielded theoretically implausible point estimates of the elasticities of substitution.[85] Thus, we do not report the results from the alternative series. Besides, the alternative GDP series have been criticised by economic historians.[86]

Is the elasticity of substitution constant over time? The CES function imposes the assumption that the elasticity of substitution is constant over more than two centuries. It is possible that the elasticity of substitution in the baseline model changed over time given that the British economy switched from a low growth to a modern growth regime in the nineteenth century. Therefore, the baseline model is estimated with rolling-window simulations to capture the variation of the elasticity of substitution over time. A key issue is to determine the window length. There is no rule of thumb – our decision on the size of the window is based on historical and economic context as well as the time series properties of the data. We set the window length to 80 years after experimenting with various window and increment lengths. The estimation window shifts in 1-year increments, dropping an observation and adding another as it rolls in time. Shorter windows produced theoretically and empirically implausible and non-stable estimates. Longer windows produced consistent estimates, but choosing a longer window confounds technological shifts that occurred in a short span of time in the nineteenth century.

Figure 5 shows the evolution of the elasticities of substitution, $\sigma_{k,e}$ and $\sigma_{\mathrm{ke},l}$. The dotted horizontal line marks the benchmark elasticity of substitution value of zero, and the dashed lines are 95 per cent confidence bands. Panel (a) shows the time-varying estimates of elasticity of substitution between capital stock and energy, $\sigma_{k,e}$, which are consistent with the theory. The confidence band narrows, indicating improved precision of the estimates as the window moves forward. All estimates are positive and less than unity, as in our baseline results. The results suggest a high degree of complementarity between capital stock and energy. However, the degree of complementarity declines, as the last ten estimates are approximately 0.96. Nevertheless, in the present context, the findings support our conjecture that the mechanisation of textiles and mills required

[84] von Tunzelmann, 'Technology'.

[85] We used GDP series from Clark, 'Macroeconomic aggregates'.

[86] Broadberry et al., *British economic growth*, pp. 247–57. Broadberry et al. criticised Clark's output data, constructed using an income-based approach. They took issue with the real wage rates Clark used to construct GDP per head. Clark's real wage series follow the broad pattern of daily real wage rates established by Phelps-Brown and Hopkins, 'Seven centuries', even though the authors warned against interpreting their series as a measure of living standards.

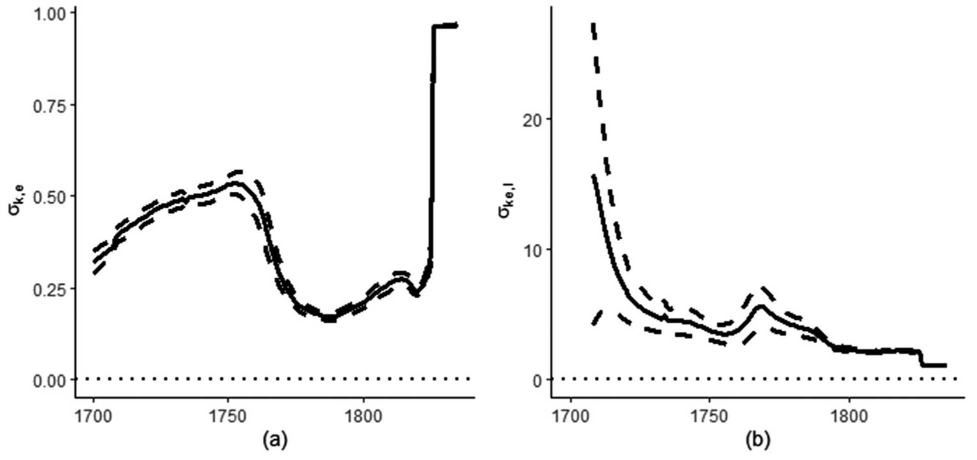

FIGURE 5 Time-varying elasticity of substitution between (a) capital stock and energy, $\sigma_{k,e}$, and (b) capital/energy composite and labour, $\sigma_{ke,l}$.

Note: Dashed lines are 95 per cent confidence bands, and solid lines are point estimates of the elasticities of substitution.
Source: See text.

minimum energy to operate, and there were few substitution opportunities between energy and other factor inputs.

In panel (b), we report the time-varying elasticities of substitution between capital/energy composite and labour, $\sigma_{\mathrm{ke},l}$. The first eight estimates have been excluded from the analysis as they were theoretically and empirically implausible, possibly affected by the quality of the underlying early data.[87] The remaining estimates are between 1.06 and 16, indicating a high degree of substitutability between labour and capital/energy composite. This evidence strongly supports our findings from full sample estimations that the elasticity of substitution between capital/energy composite and labour is greater than unity. Essentially, these baseline results are robust.

VIII

In this paper, we investigate the nature and the role of technical change before and during the industrial revolution. Using historical data from 1700 to 1914 in a three-factor CES production model, we derive labour-, capital-, and energy-augmenting technology indexes. Our analysis reveals that capital stock and energy are close complements, and capital/energy composite and labour are substitutes. The complementary relationship between energy and capital stock implies that sustained economic growth required continuous capital accumulation and abundant energy supplies.

The analysis of the time paths of the implied technology indexes shows that technical change responded to movements in relative factor prices. The labour-augmenting technology index closely tracks the average wage and wage–rental cost of capital ratio. The capital- and energy-augmenting technology indexes decline in lockstep with factor prices. The paper interprets

[87] Gechert et al., 'Death to the Cobb-Douglass production function?', survey the empirical literature on the elasticity substitution between capital and labour. They find that theoretically implausible negative elasticities are not uncommon in the literature.

these behavioural shifts as strong responses to changes in factor prices. In other words, British businesses responded to growing wages and declining energy (i.e. coal) prices by investing in labour-saving but energy-using technologies. Our findings render support for the induced innovation hypothesis.

How important was induced technical change to the industrialisation of Britain? It was important in many ways. First, energy-using technical change increased the demand for energy, thereby expanding the market for coal. Coal was abundant, and it was a cheap input into production, which meant that Britain faced lower obstacles on its industrialisation path than its continental counterparts did. Second, energy-using technologies reduced the relative cost of capital; cheap coal implied cheap metal (from the mid-eighteenth century)[88] and, hence, a low-cost physical stock of capital. Investment in machinery coupled with cheap energy shifted production from homes to factories, resulting in labour savings. Labour saving was sustained only because it was possible to increase capital accumulations and expand energy use. Ensuing productivity growth sustained higher wages, which improved the living standards of workers in the nineteenth century.

Our findings support Allen's characterisation of Britain's industrialisation as a self-sustaining dynamic factor substitution process, whereby positive feedback between relative wages and capital accumulation sustained long-run economic growth.[89] However, in line with the arguments put forward by von Tunzelman,[90] Mokyr[91], and Kander et al.,[92] we find that labour saving was modest until 1820. Nevertheless, the results enable us to explain the shift to a modern growth regime as a function of relative factor costs, resource endowment, and the technological frontier. In sum, Britain's industrialisation does appear to be (at least, in part) the result of responses to pressures arising from market conditions whereby labour was expensive and energy was cheap.

ACKNOWLEDGMENTS

The authors would like to thank Rachel Male, Peter Pearson, and Gregor Semieniuk, as well as three anonymous referees and the editor, Giovanni Federico, for their valuable comments and suggestions. We would also like to thank Steve Broadberry, Alexandra de Pleijt, Jane Humphries, and Jacob Weisdorf for sharing their data with us. The authors acknowledge support from the Grantham Research Institute on Climate Change and the Environment at the London School of Economics and the Economic and Social Research Council (ESRC) Centre for Climate Change Economics and Policy (CCCEP) (ref. ES/R009708/1).

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How to cite this article: Otojanov, R., Fouquet, R., and Granville, B., 'Factor prices and induced technical change in the industrial revolution', *The Economic History Review*, (2022), pp. 1–25. https://doi.org/10.1111/ehr.13194