Energy embodied in traded goods for the United Kingdom, 1870-1935: Discussion of Methods and Sources

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This is a draft working paper that provides discussion of methods and results of calculating energy inputs to British traded goods in the late nineteenth and early twentieth centuries. This work has been conducted as part of the 'Who did the dirty work?' project in collaboration with Astrid Kander at Lund University, and is funded by the Swedish Research Council.

This paper aims to provide detailed discussion of methodology and sources that provides useful context for a range of publications. It currently covers the period 1870 to 1935, but will be extended to cover (1948) and subsequent benchmark years. Thus eventually the project will provide an overview of energy efficiency in British manufacturing over the century 1870-1970, also allowing calculation of embodied energy flows in trade that can be linked to post-1970 datasets.

It should be stressed however that this remains a work in progress. While the research presented below is at an advanced enough stage that any (unavoidable) error is likely to be small, new sources of information are always being actively sought and come to light. It is thus likely that updated versions of the paper will contain differences to previously published material (this paper was first put on-line in November 2016).

The current paper only contains details of energy inputs into traded goods of relevance for calculating the magnitude of the overall balance of embodied energy in British trade at the benchmark dates. A considerably larger set of data has been collected and will be the subject of analysis in the future, across all of the manufacturing sector.

This paper presents material from an ongoing research project. We are very happy for other researchers to utilise the methodological discussion, details of sources, and results of estimates of energy inputs into individual products. However, as this is being gathered for (among other things) an analysis of changes in technical and energy efficiency in the British economy over time, we ask that this data is not used for any such analysis without first seeking the permission of the author.

Overview of Sources

Estimates of energy embodied in trade have been established for four main benchmark points that correspond with the five most significant sources. These are the Report of the Royal Commission on Coal that was published in 1871, which included in its Appendix E either estimates or collected data on the level of coal consumption in particular industries; and Censuses of Production taken in 1907, 1924, 1935. Work on the census of 1948 is ongoing. Further censuses were also taken in 1912 (but never fully published because of the war; some of the results were including in the 1924 census), 1930, and 1937 (which suffered a similar fate to that of 1912 but that was partially reported in 1948).

The quality of data was lowest in 1871, and indeed for many products, there was no major direct information on fuel consumption collected by the commission; rather, estimates were provided to the commission of the amount of fuel per unit of output, and estimated levels of output were employed to compute likely fuel consumption. Generally, the procedure here has been to work the other way round; data on total fuel consumption is collected, and then divided by output data to produce a coefficient of the fuel input per unit of output. However, in the 1907 and 1924 census of production, the fuel returns represent less than 100% of all firms who gave returns. While some firms represent almost the entirety of the branch's output, in others, this is as a little as half; the average tends to the 70% mark. As the percentage of sectoral net value (gross revenue minus raw material costs) of these firms providing fuel returns is recorded, it is assumed that the other firms have similar levels of consumption relative to net output and consumption is scaled up accordingly. This assumes that those firms that are not returned were not in some way markedly unrepresentative of the branch as a whole, but there appears nothing to suggest that this might be the case on a reading of the censuses and accompanying notes. Very small firms, that might be expected to have a lower use of power technology, and that were under-represented in the surveys, generally only took up a very small proportion of output. This is especially true in those sectors that matter for the energy embodied in trade, which itself, as we shall see, is highly concentrated in a handful of sectors: metals, mining, textiles, and chemicals. From 1935 the fuel data is complete.

In the census of 1907 fuel consumption data refers only to coal. However, as the available horsepower of engines and turbines (steam, water, oil and gas, and electrical) is recorded, these can be used to give imputed values for fuel consumption. It was assumed in all censuses, for example, that a 1 hp engine was the equivalent of a 746 Kw motor, and on the basis of assumptions about the length of the working day and capacity utilisation, this can be turned into an estimate of electricity use (in later censuses there is more direct reporting of electricity use). These contain inevitable errors, especially as the utilization of electrical motors varied considerably across branches of industry. However, in 1907 electricity use was generally only a very small share of total energy consumption. All Internal Combustion Engines were assumed to run on oil (although some will have used gas derived from coal), while values for water power were imputed to the force of water hitting the wheel or turbine.[1] In the case of steam engines and turbines their primary fuel input, coal, was already included in the census.

For censuses after 1907 all fuel inputs for power use were directly recorded. Electricity generated on-site also has its fuel inputs recorded in the census, but that purchased from elsewhere was assumed to have the same balance of primary inputs as the whole electricity generating sector, even though this was not a truly integrated system until after WWII. Coal was overwhelmingly the dominant fuel for electricity generation for all years. In 1870, only data on coal use in the industrial sector is available, although water remained present as a significant input of *power*, albeit rapidly shrinking in relative terms as is revealed by the Factory Returns of that same year. However, when calculated in primary energy inputs – in part because of water's much more efficient utilisation of that primary input – water takes up a very small share relative to coal in any branch of industry. The figures presented for 1870 therefore only relate to coal.

[1] The method for this calculation is described in Warde (2006)

In the earlier censuses, as will be discussed, there are frequently difficulties in calculating the overall weight of output as well as fuel inputs. These difficulties are considerably reduced with improved reporting after WWI, and fairly complete detailing of inputs and outputs into all branches of industry by 1935 (which is not the same, of course, as inputs into individual products). Nevertheless, whilst this allows a very detailed input-output accounting for the manufacturing sector, the information is often not presented in an aggregated form. Very considerable labour still has to go into collecting and aggregating the data in the censuses.

Because British goods were in part manufactured from raw materials and intermediary products from overseas, the Royal Commission and Censuses of Production cannot be the only sources of data. In the case of imports, it would be desirable to have coefficients of embodied energy from every trading partner, but the current availability of data would not allow this exhaustive procedure. This means that generally such coefficients have been calculated for 'representative' countries on the assumption (applied with caution, as discussed below) that technology levels and inputs were similar across suppliers. Coefficients for crops generally come from the United States; forestry products from Sweden, and so on. Important inputs are discussed in each particular case below.

The basic method of calculating energy embodied in goods

'Process analysis', the method by which embodied energy is calculated, requires a version of input-output analysis that relates all of the material inputs to a final product, including those that are consumed in the manufacture and are not physically present in the final product itself (whether combusted or discarded as residual waste). It is important to be clear about the various steps in the production process as obviously errors could have serious implications for the results.

However, we have not attempted to reconstruct the embodied energy for *all* traded products. This is because with the great majority of products traded, the amount of embodied energy would make no significant difference to the final results, making up in many cases only a fraction of 1% of the total embodied energy traded. We have focused only upon those goods that would make any difference to our final aggregate totals. This means in practice that we calculate product-level estimates of embodied energy across the whole production chain for goods that account, in aggregate, for over 90% of the energy embodied in trade. The residual goods are treated more simply.

Many input-output analyses conducted today work at a relatively high level of sectoral aggregation and the linkages in the production chain are made according to *monetary value*. For example, the energy per $ of production of a raw material is calculated. Then the value of raw material that is required to produce a $ value of the final product is calculated. If $ 0.20 of raw material is required per $ of final output, then the embodied energy in the final product from that raw material is reckoned to be the energy input per $ of raw material production * 0.2. However at higher levels of aggregation, this method can introduce considerable errors. If one made this calculation for the raw material sector as a whole, for example, one would include products that required very small energy inputs per $, while others were very high. The accuracy of a particular calculation would depend on whether the raw material used for a particular good was close to the average of the sector as a whole. Often this is not the case.

To avoid these kinds of problems, and also in part due to data availability, we have traced the input-output relationships in *physical terms,* and calculated embodied energy inputs per ton of good. Nevertheless, a degree of aggregation is inevitable given the quality of the data. Generally we have attempted to get as close to the disaggregated production of goods as is possible, and in a way that allows the matching of data on embodied energy in goods with the data on traded goods. Fortunately, in the British case the categories used in the censuses of production were designed with the very purpose in mind of comparability with trade data.[2]

The ideal source is a census of production that provides all of the inputs that go into the production of particular goods, at a highly disaggregated level. This is the case, for example, for the British census of production of 1935. This allows us to trace the energy inputs throughout the productive system (aside from inputs that are imported from abroad). In earlier cases, however, the information is not as rich. We have made extensive use of censuses of production, but we have also deployed other primary and secondary sources when necessary.

In tracing the inputs into a final good, we have not sought to trace every single one, which would be an impossible task (think of all the components that go into even an early motor vehicle). However, most of these inputs have very little influence on the final figure of embodied energy. In the case of a motor vehicle, the timber that went into a wooden dashboard, or the leather for the upholstery of the seats, had a negligible influence on the total of embodied energy, which was completely dominated by the energy used in the smelting and forging of the metal used for the chassis and engine. Again, we have operated on the principle of only calculating what is significant for the results. Exactitude is never possible in such an analysis; but neither is it necessary.

Calculations for individual products

This section provides a more detailed description of how embodied energy per ton has been made for the products included in the analysis, to provide a better understanding of both methods and how sources must be interpreted and used.

The first step in this kind of process analysis is to determine the inputs required to produce a target product. Typically these inputs will include energy use (direct) and goods from other industries. The energy input into the final stage of production represents the *direct energy requirement*. Each non-energy input is then further examined to identify energy and non-energy inputs required for its production. This process continues to the point where the inputs are believed to add a negligible amount to the total energy use. The sum of energy inputs to all the stages of extraction, processing and production prior to the final stage of production the final good are known as the *indirect energy requirements*. Adding the direct and indirect energy requirements yields the *total energy requirements* for the production of one unit (ton, kg, etc) of a target product.

It is also very important to note that at each step in any production process, as well as including the additional *direct* inputs of energy, we must also remember to include the *indirect* embodied energy that went into producing that *energy supply*. For example, each 100 hundred tons of coal required around 6 tons of coal to be burned at mines for its extraction. This means that every ton of coal introduced at any point in the production process must be multiplied by 1.06 to provide the full tonnage actually required to produce a good. Energy also has ‘embodied energy’, just as any raw material or intermediary input. Also, the aim in

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all cases to discover the *primary energy inputs* into the production of any good. Electricity and coke are *secondary energy carriers,* being transformations of energy from *primary energy carriers*. Electricity may be generated from a range of different primary carriers but in the period in question came almost entirely from coal-fired power stations. The primary energy value of electricity is thus the coal that went into generation (including the embodied coal used at the mines to extract that coal).

1870 calculations include coal only. 1907 includes direct data on coal and coke consumption and estimates of the use of oil, water power and indirect coal consumption from purchased electricity derived from data on installed power equipment. In 1924 and 1935 data includes coal, coke and breeze; heavy oil; light oil; gas purchased; and electricity purchased, with appropriate inclusion of indirect energy used to produce the fuels in each case.

In these discussions we will refer to the *multiplier,* the number by which a unit of production of a final good (here we always use one ton) is multiplied by to give the *total energy requirements* that it embodies (here always expressed in Gigajoules, GJ). We use the term *technical coefficient* to indicate the relationship between the final weight of product produced (which is always reduced to one ton in constructing our estimates) and the weight of any given input. If a ton of the final good, for example, requires half a ton of a particular input, then the multiplier of embodied energy of the input has a technical coefficient 0.5 applied to it in calculating the embodied energy from that input going into a ton of the final good.

We call each part of the production process going in to the making of a final good a *step*.

The list below only includes those sectors or categories of product that have been calculated because of their significance in embodied energy flows in trade. Thus the data coverage is uneven between benchmark years, partly for reasons of the structure of inputs (whether they were sourced from home or abroad), partly for reasons of relevance to the issued of energy embodied in trade, and partly because of data availability. Thus the list below represents only a sub-set of the branches of production for which energy consumption can be calculated in each of the benchmark years. The large set not fully detailed in this document comprises, for 1907, 137 branches in total; for 1924, 78 branches; and for 1935, 105 branches.

All tons are metric tons unless stated otherwise.

Coal

All years: Coal consumed in mines can simply be related to total coal production to produce a coefficient. In later years the consumption of coke and breeze, heavy oils, light oils and electricity (converted into primary energy inputs into generation) is included.

The coefficients obtained are:
1870: 1.91 GJ/ton
1907: 2 GJ/ton
1924: 2.6 GJ/ton
1935: 1.74 GJ/ton

Iron Mines

1870: Direct data on coal inputs into iron ore mining are not available. For later periods (see below) the total energy requirements for iron ore mining have been calculated as being 0.2-0.6 GJ/ton in Britain and 0.2 GJ/ton in Sweden. I have used the multiplier calculated for British ironstone mines in 1907, i.e. the top of this range.

1907: Within this sector some 6.802 million tons or iron ore and ironstone were raised (although a larger amount of 8 million tons was also recorded under the coalmining sector, a very small share of the total output of this sector). This used 137 580 tons of coal, producing a multiplier of 0.61 GJ/ton.

1924: Data on complete inputs of iron ore, limestone, and other raw materials is provided in HMSO 1924 p.32. The resulting multiplier is 0.2 GJ/ton

1935: Data on output from the non-metalliferous metal and quarrying sector and all energy inputs gives a multiplier of 0.56 GJ/ton.

Pig Iron and ferrous alloys

1870: Step 1: In principle the first step take the energy requirements for iron ore mining and calculate the ratio of iron ore inputs in relation to final pig iron output. The energy requirements estimated are reported above, and statistics collected by the British Iron and Steel Federation indicate that the ratio of ore inputs to pig iron output in 1873 was 2.57.[3]
Step 2: Fuel consumed by blast furnaces in the production of pig iron was estimated by the Royal Commission on Coal (report published in 1871), and direct data was collected from 1873 and is reported by the British Iron and Steel Federation. The working estimate of 1871 was 3 tons of coal consumed per ton of pig iron but the direct reports of 1873 give a rather lower figure of 2.56 tons. The latter, directly reported figure has been preferred.[4] The total energy requirement for pig iron is thus **80.9 GJ/ton**

1907: Step 1: In principle the first step take the multiplier for iron ore mining and calculate the coefficient of iron ore in relation to final pig iron output. However the quality and source of ore varied quite widely, and around half of the ore must have been imported. In this year we thus take an average of the domestic (0.6 GJ/ton) and the Swedish energy requirements, representing imports (0.2 GJ/ton)[5], giving a figure of 0.4 GJ/ton. There was a coefficient of 2.4 tons of ore inputs per ton of iron produced, drawn from the statistics of the Iron and Steel Federation. This gives an input of 0.5 GJ/ton of pig iron.
Step 2: As noted above, fuel consumed by blast furnaces can be calculated annually from 1873 using separate sets of statistics on coal consumption and iron and steel production. In 1907 the figures for both pig iron production and fuel consumption were also noted in the Census of Production, although blast furnace fuel consumption was not actually part of the census returns itself. The direct energy requirement of pig iron smelting was 65.05 GJ/ton
Result: **66 GJ/ton**

1924: Step 1**:** The first input is iron ore. See above. The ratio of these ore and mineral inputs to final output is 2.88, giving a multiplier of 0.6 GJ/ton for pig iron output.

[3] British Iron & Steel Federation, 'A simple guide to basic processes in the iron and steel industry' (London, 1949), 24.
[4] Ibid.
[5]

Step 2: The output of the sector is recorded in HMSO 1924 p.32. This is related to total fuel inputs, resulting in the 64.9 GJ/ton

Result: **65.5 GJ/ton**

1935: Step 1: An estimated coefficient for iron and + limestone inputs (HMSO 1935, p.21) using Swedish estimate for iron ore: 0.2 GJ/ton. 2.58 tons of ore were used per ton of pig iron output.
Step 2: Blast furnace fuel data from HMSO including embodied coal in coal and coke: 51 GJ/ton

Result: **51.5 GJ/ton**

Iron and steel goods

This is a diverse and problematic sector. ‘Iron and steel goods’ predominately relate to the production of intermediate products of various qualities and sizes that are assembled by other branches into final goods, or used for rails, construction, shipbuilding etc. Average value/ton of these goods in 1907 had a very considerable range, from £5.4/ton to £98/ton, although most products are under £10/ton.

1870: Steps 1 and 2 Iron ore mining and pig iron smelting (see above).
Step 3 The Royal Commission on Coal of 1871 provides an estimate of coal used in the iron and steel industry (aside from blast furnaces). A ton of ‘malleable iron’ output was reckoned to require one ton of pig iron inputs, and 3.35 tons of coal.[6] This figure must be taken as indicative of the level and was based on consultation with industry rather than direct reporting. This gives a direct energy requirement in further refining and forging of 98.1 GJ/ton.

The total result for Iron & Steel goods is thus **177.5 GJ/ton**.

1907: Step 1: Iron ore mining (see above).
Step 2: Pig iron smelting (see above). One ton of pig iron is reckoned to correspond to one ton of output of iron & steel goods. See also the discussion in Step 3.
Step 3: The census of production does not give a single figure for the output of iron and steel goods, although it gives data on fuel consumption for this branch as a whole. It provides returns for ‘semi-manufactured products’ which are sold on out of the iron and steel trades for further manufacturing (schedule ‘b’); and finished iron and steel products made by the sector itself (schedule ‘c’). ‘Schedule b’ includes most of the production of steel, although we note below that there is also a much lesser amount of steel that is recorded as being sold by blast furnaces rather than as a semi-manufactured product, and thus is recorded beside pig iron in ‘schedule a’ of the census. This steel is probably an input into other goods described under ‘schedules b and c’.

We treat the sum of the weight of ‘schedules b’ and ‘schedule c’ as the final output of iron and steel goods and for which an energy requirement is calculated. The sum of these categories is however larger than the pig iron inputs (8.795 million tons against 8.17 million tons). Scrap is reused in the iron and steel trades, especially in the making of open hearth

[6] RC (1871), Appendix E, 178

steel (according to McCloskey this amounted to £5.19 million of inputs into open hearth processes, with £9.65 million coming from pig iron).[7] However, if the return for 'schedule a' steel is added to retained (i.e. not exported) 'schedule a' pig iron, the figure left for inputs to the goods produced under schedules 'b' and 'c' is 8.8 million tons, which matches output very closely indeed. However, there is no independent data in the census on the fuel consumption for 'schedule a' steel (which may, in fact, be included in the fuel figure for blast furnaces). And it should also be noted that the census returns state that 9.9 million tons of iron and steel goods were completed in total, but around 0.8 million tons of these were produced *outside* of the iron and steel sector. It is possible however that this represents some double-counting of intermediary goods produced within the sector that were then finished elsewhere. Because our task is to calculate energy requirements per ton of iron & steel output, we are not interested in the total iron & steel output, but only that which can be related to data on fuel consumption – i.e., that included in schedules 'b' and 'c', and that clearly includes the greater share of the total.

The uncertainties discussed above do mean however that there is a possible error of, at an absolute maximum, up to 10% in our calculated requirements (0.2 tons of coal per ton of final iron and steel goods, or 6 GJ/ton) in that part of the calculation that relates the amount of pig iron inputs to schedule b and c outputs. The census also records that there is likely a small amount of duplication between schedules b and c that may inflate their sum but by no more than 3% at most.

As stated above, the requirements for the fuel consumption of the iron and steel trade sector (which does not include blast furnaces) is then calculated on the basis of fuel returns in the census related to the sum output of schedule b and c. We should note however that the proportion of firms providing returns is very low, being from firms producing only 42% of the net value of the sector (the response to the Census of Production was generally much higher than this). If we assume that the rest of the sector consumed fuel at the same rate as those firms which provided returns, then iron and steel (excluding blast furnaces) accounted for a tenth of all coal consumption recorded in the census. Obviously there is some potential for error in our final total is these firms turn out to be unrepresentative. However the results appear to be consistent with results calculated for other countries, and also the results one would expect in allocating total domestic coal consumption.

The result calculated is that producing 1 ton of forged and refined iron and steel goods requires 33.9 GJ/ton, and the total embodied energy requirements for products from this branch are **99 GJ/ton**.

1924: In this year the census of production allow the reconstruction of three main steps in the production of basic iron and steel goods (which are themselves then further worked on to produce final engineered and refined products at home and abroad). The first step is the production of raw material inputs, iron ore, limestone, and other mined materials. By this stage coke had become much more significant as a fuel and chemical agent, and calculations of primary energy inputs must account for the coal inputs to coking. we have data on the conversion of coal into coke at cokeworks. The return from coke on coal inputs as feedstock was 67.2%. In addition, a small amount of coal was used within the works for firing the furnaces, providing light and transportation etc. This gives an embodied coefficient of 18.4

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[7] D. McCloskey, 'Economic maturity and entrepreneurial decline', Harvard economic Studies vol. 142, (Cambridge MA: Harvard Uni Press, 1973), p.142.

GJ/ton for coke (which also, we should remember, includes the energy embodied in coal from mining operations, as well as small inputs of other fuels such as oils and coal gas and electricity, the latter two of which are calculated on the basis of coal used in producing them, also with an appropriate adjustment for the energy embodied in coal). The second step is the smelting of pig iron using these in a blast furnace. The census then records steelmaking and further forging and refining as one sector; in some other sectors, these are done as two separate steps, depending on the techniques adopted.

<u>Step 1:</u> See above.

<u>Step 2:</u> See above. It is assumed that all retained pig iron and ferrous alloys (i.e. that are not exported) go into the iron and steel goods branch. However, this metal only accounts for 77% of branch output (scrap produced at this point has been excluded from branch output as it is assumed that it is recycled to produce open hearth steel). The shortfall must be made up by scrap that is introduced from outside the immediate process of smelting and refining, a major efficiency improvement on what had gone before in steel production by the 1920s. As the energy inputs to make this scrap occurred in an earlier cycle of production they are not added here as an *input*. This results in a ratio of pig iron input to output in the iron & steel goods sector of 0.77, so indirect energy requirements of a ton of iron & steel goods from pig iron are 64.4 * 0.77 = 49.6 GJ/ton.

<u>Step 3:</u> The total size of branch output is not easy to calculate, because the initial production of steel ingots, blooms etc. is largely recycled within the production process to make further bars, plates, girders, hoops etc. However secondary evidence and an Input-Output table produced for the census of 1935 suggests that the great majority of ingots and blooms were used as intermediary products within the sector, and only a small amount, some 143 000 tons out of many millions produced, were exported. It is thus assumed that for 1924 all ingots, blooms, billets and steel plates are consumed within the sector and should not enter final output, although this probably produces a small understatement of production. Total fuel consumed within the iron and steel sector can then be related to that final output, producing a coefficient of 39.9 GJ/ton. Final output sums the production of all output of rolling mills, castings, vehicle and locomotive bodies, galvanized plates, and also scrap when that is an *output* of the process and becomes a raw material for the next cycle of production.

Result: **89.7 GJ/ton.**

Iron and steel goods (smelting and rolling)

1935: <u>Step 1:</u> Inputs from mining and quarrying, as in Pig iron: 0.2 GJ/ton with 2.58 tons per ton of pig iron.
<u>Step 2:</u> Inputs of pig iron + inputs of scrap (from I-O table for iron & steel sector in HMSO 1935) come to only 82% of the total output of the branch. There are additional inputs come from semi-finished steel goods, which are themselves outputs of the branch; it is clear that in this branch a significant proportion of outputs are also ‘recycled’ as inputs (for examples steel bars and blooms are then made into plates, girders, hoops etc.) It is impossible to tell from the data how much production draws on previous years’ inventories and how much is recycled within one year of production. Total inputs to smelting and rolling are recorded as 12 296 000 tons for a final output of 11 097 000 tons. In the current coefficient I have assumed that as metal cannot be made out of nothing, the ratio between final output of the branch and pig iron + scrap inputs must be 1:1, even if it is unclear when the metal was originally smelted in a

blast furnace. In fact the sum of retained production of pig iron + scrap used in smelting and rolling is very close to the final output figure, at 10 920 000 tons. However as the scrap has been previously smelted, it is not an embodied energy input for the year 1935, and so I have assumed a 1:1 ratio between pig iron and output, but then deducted the total of scrap inputs (40% of the total) from this number. 51 GJ/ton but input only 60% of output.
Step 3: Smelting, rolling and forging fuel related to final output of branch. This does not include foundries which are treated separately. 19.8 GJ/ton.

Result: **50.7 GJ/ton**

Tinplate
1907: Step 1 Inputs for tinplate come from the iron and steel sector. With the lack of other information a 1:1 relationship between inputs and outputs is assumed, although this will likely lead to some underestimation of the metal inputs relative to output. 99 GJ/ton.
Step 2: Output related to fuel inputs into the sector: 41.7 GJ/ton.
Result: **141.2 GJ/ton**
1924: Step 1: Iron and steel goods as calculated above. It is assumed that the ratio of input to output is the same as in 1935, which is 1.11:1. 89.7*1.11= 99.6 GJ/ton.
Step 2: The tinplating process, relating fuel consumed to final output. 34.9 GJ/ton
Result: **134.4 GJ/ton**
1935: Step 1: Includes all steps as above for iron and steel goods: 50.7 GJ/ton. From the I-O table (HMSO 1935 p.79.) we have steel bar and rod inputs into the tinplate industry at a ratio of 1.11:1 of final output. I have ignored very small inputs of lead and tin.
Step 2: Final output is reckoned to be the final output of blackplates, tinplates and terned sheets. Most blackplates were then tinned, but some were sold out of the sector. This will leave a coefficient slightly lower than the real one for finished tinplates, but fuel is recorded for the whole branch, not each step of the process (HMSO 1935, p.76): 28.8 GJ/ton
Result: 85.1 GJ/ton

Foundry castings
1935: Step 1: Iron ore and pig iron inputs as above: 50.7 GJ/ton. As recorded in the I-O table they are only 96% of the final foundry output, but that figure is used here. However as with iron and steel goods the proportion of scrap is deducted, which amounts to 31% of inputs.
Step 2: Foundry output related to fuel consumption: 17.3 GJ/ton
Result: **53.1 GJ/ton**

Light castings
1924: Step 1: Iron and steel goods as calculated above. It is assumed that the ratio of input to output is 1:1. 89.7 GJ/ton.
Step 2: Fuel consumed in final manufacture and assembly related to total output. As the weight of gas and water appliances is not recorded, the weight of these is estimated on the assumption of £50/ton.
Result: **126 GJ/ton**

Tubes
1924: Step 1: Iron and steel goods as calculated above. The ratio of input to output is recorded as 1.22:1. 89.7 GJ/ton. Note that this sector also produces 77 000 tons of scrap that can be used elsewhere accounting for most of the 'wastage'. 89.7*1.22 = 109.4 GJ/ton.
Step 2: Fuel consumed in final manufacture and assembly, related to total output. 44.7 GJ/ton
Result: **153.8 GJ/ton**

1935: Step 1: All of the steps to produce iron and steel goods as above: 50.7 GJ/ton
Step 2: Branch fuel consumption is related to branch output, although a small amount of the branch output is only recorded as values, which is ignored. In this instance too the final output is larger than the input recorded on the I-O table by around 80 000 tons so I have used a 1:1 ratio of input metal and output. This may mean that the multiplier employed is slightly high.16.2 GJ/ton
Result: **66.9 GJ/ton**

Wire
1924: Step 1**:** Iron and steel goods as calculated above. The ratio of input to output is recorded as 1.22:1. 89.7 GJ/ton
Step 2: Fuel consumed in final manufacture and assembly, related to total output. Copper cannot be included as it is in 1935, because of the absence of data, but the addition would be marginal.
Result: **132.2 GJ/ton**
1935: Step 1: All of the steps to produce iron and steel goods as above: 50.7 GJ/ton
Step 2: Branch fuel consumption related to branch output, although a small amount of the branch output is only recorded as values, which is ignored. Note that our calculation relates to the *total* output of the wire trade, which covers a variety of metals: not just iron and steel: 14.8 GJ/ton. Again, we find that the sum of all metals inputs into production is slightly less than total recorded output, although output itself come in various forms and the input of iron & steel does seem to be somewhat larger than iron & steel wire output. This may mean that using the assumption of a 1:1 ratio we may be slightly understating the amount of iron and steel being used.
Step 3: We must also account for the inputs of copper and brass into wire making. The total input in tonnage is 8.6% of total output (HMSO 1935 p.154). As the energy used in copper and brass-making is 26.2 GJ/ton the amount per final output of wire is 26.2 * 0.086 = 2.3 GJ/ton
Result: **67.5 GJ/ton.**

Anchors, bolts, nails etc.
1924: Step 1: Iron and steel goods as calculated above. The ratio of input to output is recorded as 1.11:1 (this is exactly the same as in 1935). 89.7 GJ/ton. 89.7 *1.11 = 99.6 GJ/ton.
Step 2**:** Note there is no figure for the input of wire. This accounted for 15% of the coefficient in 1935. The small amount of 6 670 tons of copper are also not accounted for. Fuel consumed in final manufacture and assembly, related to total output. 44.5 GJ/ton, although this will be an undersestimate.
Result: **127 GJ/ton**
1935: Step 1: All of the steps to produce iron and steel goods as above: 50.7 GJ/ton. Direct inputs of these amount to 110% of output (bars + other in I-O table), so the multiplier must be increased by 1.1 in its relation to final output..
Step 2: Additional inputs of wire amount to 21.7% of output (see above)
Step 3: Fuel used in final manufacturing related to final output: 27.5 GJ/ton
Step 4: Small amounts of copper and brass (14 500 tons, HMSO 1935 p.125) are used: 26.2 GJ/ton at input weight being 2.7% of final output.
Result: **99.1 GJ/ton**

Hardware and hollowware

1924: Step 1: The inputs come from the tinplate sector, and are estimated on the basis of producers of only 42% of output giving returns. It is assumed that the ratio between input and output is 1:1. 134.4 GJ/ton
Step 2: Fuel consumed in final manufacture and assembly, related to total output. 958 tons of aluminium is not included. 56.1 GJ/ton.
Result: **190.5 GJ/ton**
1935: Step 1: All of the steps to produce iron and steel goods as above: 50.7 GJ/ton.
Step 2: As output is not recorded by weight but frequently by value, with ratios between value and weight (where available) very variable, I have considered output to be equal to input, ie with the assumption of no losses. This gives a final result very close to wire and tubes. It is also assumed that all are tinplated. 28.8 GJ/ton
Step 3: Fuel used in manufacturing to final output gives: 17.2 GJ/ton
Result: **96.7 GJ/ton**

Engineering

Engineering uses the output of the iron & steel sector as its main inputs. This is described above. The details below thus relate to Step 4 of the production of engineering goods that are reported under varying categories in different years.

1907: The main problem in calculating coefficients for the products of the engineering sector in this year is that fuel consumption is given for the sector as a whole, but the *weight* of output is only given for sub-sets of particular products. It is clear that the value/weight ratio is not constant across the sector, and in the products for which we have information varies from £24/ton to £57/ton. This means the correct weighting of the output of the sector is essential for an accurate calculation of the energy requirements per ton of output. Fuel consumption returns cover only 65% of output.

There are two ways to proceed.

METHOD A) assumes that the products of the engineering sector all have the same ratio of coal consumption/value output. This can then be applied to produce a coefficient per weight for products where the census reports such data. For simplicity and to match the original sources fuel is reported here as tons of coal (tce).

The steps taken with the available information for steam engines are:
1. Coefficient for 1 ton pig iron = 2.22 tce
2. Coefficient for processing 1 ton iron and steel = 1.16 tce
3. For engineering sector:
   a) Value of steam engines where weight recorded is £9.992 million for 228 000 tons, or £43.8/ton. The trade figures (valued at f.o.b) give a very similar result of £43.5/ton.
   b) 33 tons of coal are consumed for each £1000 output
   c) So ((43.8/1000)*33)*1.06) tons of coal/ton output = 1.53 tce

4. TOTAL per ton of steam engine = 4.91 tce

The steps taken with the available information for machinery are:
1. Coefficient for 1 ton pig iron = 2.22 tce
2. Coefficient for processing 1 ton iron and steel = 1.16 tce

3. For engineering sector:
   d) Value of machinery where weight recorded is £5.207 million for 153 000 tons, or £31.8/ton. The trade figures in this case give a very different result of £43.7/ton. This is partly because ‘other’ machines such as cranes, lifts, hydraulic machinery etc. are under-represented in the census returns giving weights but are a substantial part of exports. However, it also seems that like-for-like machinery is valued more highly in the exports (eg. agricultural machinery is £26/ton in the census but £36/ton in the trade figures).
   e) 33 tons of coal are consumed for each £1000
   f) So ((31.8/1000)*33)*1.06 tons of coal/ton output = 1.11 tce

4. TOTAL per ton machinery = 4.49 tce

If we assumed all *exports* from the engineering sector were homogeneous goods where fuel was used at the average consumption rate of 33 tons/£1000, we would get the following result:

1. Total value of sector exported is £30.8 million
2. Total tonnage of sector exported is 703 432 tons
3. Average value per £43.8/ton
4. Coal consumption per ton ((43.8/1000)*33)*1.06) = 1.53 tce

i.e. identical to the coefficient for steam engines.

This would imply a total embodied coal consumption of 4.91*703 432 = 3.454 million tons If however the same rate of coal consumption is assumed but value per ton is as that for machinery as calculated in the census, the total coal consumed would be 4.49*703 432 = 3.158 million tons. The difference between these figures is 296 000 tons of coal. This is 0.03% of the total amount of coal recorded as being consumed by industry in the census, and only a little over thousandth of British coal output at this date. It should be stressed that these figures do not represent a ‘range’ because we do not know the distribution of fuel consumption among the different product groups within engineering. They are just indicative of the kind of errors that are potentially introduced.

METHOD B) is to make an estimate of the total tonnage of metal processed in the engineering sector to create a direct estimate of coal consumed per ton of metal. This method makes the assumption that energy consumption is more likely to be related to material throughput than the value added in the sector.

It is not a simple matter to make this estimate. In the case of steam engines and machinery, the task is comparatively simple as the reporting in the census gives reasonable coverage of weight produced: 79% and 65% of the value of output respectively. If scaled to the total output by value of the sector, these accounted for 1.96 million tons of metal, more than the total of pig iron exports and almost one-fifth of iron production. An additional 0.31 million tons of machine and engine parts are recorded. However, the engineering sector also contains a large number of other categories that are only recorded as values and whose weight must be estimated. We proceed as follows:

1) In the case of vehicles without steam engines made within the engineering sectors (carriages, trams, cycles, motor cars etc.) we can use the value/coal consumption ratio from the separately reported vehicle assembly sector directly, and remove the calculated categories from engineering sector coal consumption when a coal/ton ratio is calculated for the residual of the engineering sector.
2) In the case of other machine parts where weight is not recorded: tools and implements; tanks and cisterns; and ordnance and ammunition, it is assumed that the value/ton ratio is the same as the average ratio in machinery production, c.£30/ton. On this basis these manufactures used 289 000 tons of metal.
3) The amount of copper utilised for electrical cabling and wiring is recorded for 72% of the output by value, and this is used to produce a total copper consumption estimate of 20 694 tons. Note that iron cabling in telegraphing etc. is recorded separately in a 'Wire trade' sector, not in engineering.
4) A value/weight ratio for electrical machinery can be obtained from the trade statistics, which as we might expect is very much higher than for most other engineered goods, at £75/ton. It is assumed that other electrical apparatus use metal in the same proportion as those exported, although the ratio may well be higher. Altogether this electrical engineering sector used 116 000 tons.

In sum, electrical engineering, 'other' iron manufactures and spare parts, and wiring and cabling used a total of 426 000 tons of metal, against 1.96 million tons for engines and iron and steel machinery, i.e. engines and non-electrical machines make up 87% of the total. Only a very significant error in estimate 2) could alter this figure substantially.

Our total estimate of metal consumed in engineering is thus 2.27 million tons, for which 3.51 million tons of coal were burned (not including adjustments for the coal required to mine coal). This gives us a sectoral coal/ton ratio of 1.55 tce. Rather coincidentally, this is very close to the ratio of 1.53 tce/ton calculated using the sectoral coal/value ratio, but rather higher than that estimated using the same technique for machinery, which lies somewhat below the sectoral average of value/ton. It appears from the trade statistics that there is a slight compositional effect by which the machinery exported is more valuable on average than that produced, hence the calculation using weight is more likely to be more accurate given the large share that machinery takes up in engineering exports.

Using METHOD B, we come to the following coefficients for one ton of steam engine or machinery:

Pig iron	= 2.22 tce
Iron and steel processing	= 1.16 tce
Engineering	= 1.65 tce (adjusting coal data to account for embodied coal)

Translated into GJ, the estimated energy requirements within engineering (including all machinery) are 48.2 GJ/ton.

The multiplier for embodied energy as a whole is **147.8 GJ/ton.**

1924: Step 1 Unlike in 1935, where input-output data is available, producers of only 45% of net output reported metal inputs in 1924. This gives 47% pig iron and 53% wrought iron and steel. In 1935, only 16% of inputs were pig iron. Given the very varied nature of engineering products and value/ton it thus seems unsafe to inflate the input figures from less than half of the sector that is so heterogeneous in its inputs and outputs. However, there are returns on weights and values of output of goods for 58% of the sector, largely machinery, boiler- and engine-making. Of these branches, some 59% of output provides precise weights, which can be used, given the weights and values are broken down by product, to estimate a total weight for these branches (the one branch with a low rate of reporting is 'other machinery' but this has an average weight/value ratio that is very close to the average for all these branches). If we assume that the average of this sample (covering 0.58*0.59 of total output, or 34%), it would give a total weight of 2.13 million tons, which may be compared with 2.3 million tons in 1935. 1924-35 is a period of slight price deflation, and gross output at the two dates was £156 million and £163 million respectively, which would imply a slightly higher output in 1935. If we assume a 1:1 ratio between inputs and output, as in 1935, then the 2.13 million tons of iron and steel input seems a reasonable estimate for 1924.

The issue remains of separating out inputs of pig iron and those from iron and steel goods, as the latter already have higher energy inputs. The census reports the use of at least 485 000 tons of pig iron in 1924 (form partial returns) as opposed to 370 000 tons in 1935. But it does not seem likely that the 1924 total could have been much higher, unless the structure of the industry had radically changed; and this goes against the fact that the great majority of pig iron must have been an input from the iron and steel goods sector. Here thus assume that 0.5 million tons of pig iron is used in mechanical engineering, and the rest of the metal input comes from iron and steel goods. Pig iron (as above): 64.4 GJ/ton
<u>Step 2:</u> Inputs from iron and steel goods is reckoned to be 77% of total output as described in Step 1. 89.7 GJ/ton.
<u>Step 3:</u> Fuel consumed in final manufacture and assembly, related to total output. 75.4 GJ/ton.

Result: **159.7 GJ/ton**

Mechanical Engineering

1935: <u>Step 1:</u> Because there is no clear declaration of total output weight, this has been assumed as equivalent to input weight, but this is certainly an overstatement and thus produces a multiplier which has an error and is too low. To compensate for this I have not included the weight of non-ferrous metals in final output, although this is an arbitrary correction. Direct inputs of pig iron and ferrous alloys: 51.5 GJ/ton and 16% of output (from I-O table)
<u>Step 2:</u> Iron and steel goods (from I-O table) at 50.7 GJ/ton and 66% of output (from I-O table)
<u>Step 3:</u> Fuel input into final manufacturing related to sum of all iron and steel inputs: 22.8 GJ/ton
<u>Step 4:</u> Castings (from I-O table) at 53 GJ/ton and 15.6 % of output.
<u>Step 5:</u> Inputs of Tubes (from I-O table) at 66.9 GJ/ton and 2.4% of output
<u>Step 6:</u> Inputs of copper and non-ferrous alloys (HMSO 1935 p.253) 26.2 GJ/ton and 2.6% of output
<u>Step 7:</u> Inputs of tin and aluminium (HMSO 1935 p.253) at 66.5 GJ/ton and 0.2% output.

Result: **75.2 GJ/ton**

Shipbuilding

As with engineering, shipbuilders are using the output of the iron & steel sector and thus here we effectively deal with Step 4 of the production process.

1907: Private yards produced 1 677 000 tons (note tonnage is a measure of volume, not weight, in the case of shipping) of ships in 1907. If the relationship between inputs of metal and registered tonnage is the same as the Danish case, the energy embodied in material inputs would be 114.7 GJ/registered ton. British shipbuilders then used an additional 1.025 million tons of coal, that is, 0.61 tce/ton, or 18.19 GJ. This would give a final coefficient of 132 GJ/ registered tons (4.43 tce/ton) for shipbuilding. 550 000 tons of this were exported, almost exactly one-third. This amounts to a substantial 2.463 million tons of coal.

1924: Step 1: The main task is to determine the amount of metal consumed in a year. In 1924 and 1935 the census records only shipping by *volume* (gross tonnage), and more importantly, only the amount of shipping wholly produced within that year. It is clear in both years that this represents only a small share of production, which also included a large amount of repair work. However, in 1935 it is possible to relate the value of output to the tonnage of metal (largely from iron and steel goods) consumed. On the assumption of relatively stable prices, this allows the calculation of the inputs of metal given the gross value of output, using a ratio of £91/ton (also plausibly within the range of the output/value ratios of mechanical engineering). This suggests a figure of 596 000 tons of metal were used in 1924, given that prices only changed marginally between these dates. From iron and steel production we apply the multiplier of 89.7 GJ/ton.
Step 2: Fuel consumed in final manufacture and assembly, related to total output. 29.5 GJ/ton
Result: **120.6 GJ/ton**

Note: this is not comparable with the 1907 figure which is an estimate applied to registered tons (volume)

1935: Step 1: In 1935, the full provision of input data allows calculation of the weight of output, so shipping tons can be calculated in terms of weight rather than registered tonnage, and are not comparable to multipliers calculated for registered tonnage above. Iron and steel inputs represented around 96% of the total weight of final output: 50.7 GJ/ton.
Step 2: Shipping also utilised inputs of light castings (2.8% of weight) and tubes (1.6% of weight).
Step 3: Energy inputs related to weight of final ship output, 16.8 GJ/ton
Result: **67.5 GJ/ton.**

Vehicles

1924: Step 1: The first challenge is to work out the amount of metal inputs into the sector. Despite good information from the I-O table for 1935 it is clear that values are a poor guide over time; although gross output (£) from the branch was similar in 1924 and 1935, more than twice as many vehicles were produced at the latter date (although the sector includes vehicle parts, bicycles, and motorcycles). However, the 1924 census does provide average weights for touring cars and commercial vehicles and their chassis, and the weight of engines can be drawn from the mechanical engineering sector. Assuming that other vehicle parts have the same value/weight ratio as touring cars (£275/ton), as one would expect this to me high given the nature of smaller components, the aggregate estimated metal input would be approximately 311 000 tons from iron and steel goods. This seems reasonable given that the larger production of vehicles consumed around 500 000 tons of metal in 1935. It remains, of

course, an approximation. From the iron and steel goods sector we apply the multiplier of 89.7 GJ/ton
Step 2: Fuel consumed in final manufacture and assembly, related to total output. 92.1 GJ/ton.
Result: **184.2 GJ/ton.**

1935: *(motor and cycles)* Step 1: Inputs into vehicle manufacture consisted of 68% iron and steel goods, 27.8% castings, and 4.2% tubes. Appropriate multipliers are used.
Step 2: Output of the sector by weight is related to energy inputs. The weight of the sector is presumed to relate to inputs on a 1:1 basis, a calculation that approximates closely to the level of output when putative weights are attributed to different kinds of vehicles (private, commercial, cycles, motors, and parts). 45.2 GJ/ton.
Result: **94.4 GJ/ton.**

Cotton Goods

There were four main steps in the production of dyed cotton cloth. Firstly, raw cotton was grown, ginned and bailed in the country of production. This cotton was then turned into yarn using steam-driven mechanized spinning machines. The third step was the weaving of this yarn into cloth. Finally, this cloth was subject to varied dyeing and finishing processes (although it was also possible that yarn was dyed before being woven into cloth).

For the benchmark of 1935 these steps are clearly differentiated in the British census of production and the coefficient and multipliers comparatively simple to calculate, even though this requires adding up a considerable amount of information on production of different types of yarn and cloth in the census. In 1907, as we will see, estimation requires a different approach with some margin for error.

1870: Step 1 We do not have direct data on the energy inputs into raw cotton in 1870 and so the same assumption is applied as for 1907, given the lack of major change in agricultural practice over this period. On average a bale of cotton imported to Britain in 1869 weighed 354 lbs, and 2 347 450 bales were retained for domestic consumption, making a total of 831.7 million lbs. Total output was 817 million lbs. This would suggest an extremely low wastage rate of 1.8%, rather less than that obtained in later years, and it is assumed that some manufacture in fact used inventoried cotton bales from 1868 when imports were rather larger. Thus a wastage rate of 8% in inputs relative to final cotton outputs, derived from later date (see below) has been applied.[8]
Step 2 The commissioners of 1871 reckoned that the amount of coal used in the raising of steam power in British cotton factories (spinning and weaving) was 2 456 138 tons in 1868, the last year for which data was estimated (to which must be added the coal used in mining that coal). Widespread evidence suggests that very little coal was used for any purposes aside from the raising of steam power. In that year, 876 000 million lbs of final cotton goods were produced (a higher total than in 1869), or 391 071 tons. This equates to 195.5 GJ/ton as a direct energy requirement for cotton manufacturing (including the energy embodied in coalmining). The total embodied energy requirement is thus **245.7 GJ/ton**.

1907: The quality of data in 1907 made calculations much more complex than did the far more detailed information in the later censuses of 1924 and 1935. The later census data,

[8] RC (1871), Appendix E, p.190.

where most of the ratios used below are directly available, is, however, entirely consistent with the processes of estimation presented here.

Unfortunately, in calculating a coefficient for cotton production in 1907 (but not at later dates) we must treat cotton goods as a whole, because fuel inputs recorded in the census of production are not differentiated between spinning and weaving. Preferably one would differentiate between the two different steps of spinning and weaving. There are thus only two steps in calculating embodied energy inputs.

<u>Step 1:</u> The production of raw cotton, which is drawn from estimates of the use of draught animal power in American agriculture. Here we calculated the input of draught power per hectare, and then calculating the average yield of cotton per hectare to assign a value per unit of output.[9] Cotton was also ginned, a process dominated by steam-driven gins in the early 1900s. Although we have not yet found direct data for fuel consumption for this process, data on electrical ginneries suggests a power requirement of around 81 Kwh per ton of raw cotton. If we assumed an equivalent power requirement for steam-powered gins, and assumed fuel consumption rates typical for engines of this period, energy use in ginning would be less than 3 GJ/ton in this period.[10] Lack of data means we have not adjusted our basic estimate from animal power employed in cultivation, but it seems that the additional energy inputs from ginning must be small and would not materially affect our final multiplier. We estimate that this required 46.5 GJ/ton of raw cotton. The coefficient for producing a ton of raw cotton must then be subject to a multiplier to reflect losses in the production process; around 6-9% was lost during spinning in 1907 (a figure that declined over time), and we have used a multiplier of 1.08. This means that the embodied energy from raw cotton production in each ton of output of cotton goods was 50.2 GJ/ton.
<u>Step 2:</u> The energy consumed in manufacturing is then related to the total weight of final cotton outputs. The rate of reporting of fuel consumption in the cotton industry was relatively good: firms producing over 81% of net production were accounted for in the returns, and it is assumed these are representative of the sector as a whole. By far the greater share of this final output was finished cloth (often called 'pieces') of some kind, but some was exported yarn and waste cotton products (which were recycled for yarn but also used as packing and insulation). As yarn and waste were subject to one less step than woven cloth, this means the average coefficient for cotton goods as a whole calculated is somewhat lower than the true coefficient for finished cloth, but obviously higher than that for yarn by itself.

However, and fortunately for us, there is a reasonably close correspondence between the production of different types of cotton, and the types exported. As 13.4 % of yarn was exported, and 83% of that retained was used for production of woven cotton pieces, this means the share of yarn production used in woven cloth was (100-13.4)*0.83 = 71.9%. 89% of woven cotton pieces were then exported. That means that of the total weight of cottons exported was 13.4 + (71.9/0.89) of total production, or 77.4%. Of this, 17.3% was yarn and 82.7% woven pieces. Thus domestically, woven cloth made up 71.9% of production, but in exports, 82.7%. As our coefficient is based on the final output of all cotton goods, this difference in composition means that it will be too low in respect to exports, which contained a larger share of woven cotton which embodied more energy.

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[9] Data was taken from Carter, S. B., A.L. Olmstead, R., Sutch, G. Wright, S.S. Gartner and M. R. Hains (2006), *The Historical Statistics of the United States, vol.4, Part D: Economic Sectors,* Millennial Edition, New York: Cambridge University Press.
[10] Freeman, P.J., *Ginning and baling cotton in the United States,* Mechanical Engineering Thesis, University of Illinois, 1916.

How serious is this compositional error? In 1935, spinning used 62% of the fuel and weaving 38% in making one ton of woven cotton cloth. This ratio may not, of course, have remained stable over time, but if we treat it as roughly indicative, then it would suggest that the ratio between the average coefficient of domestic production, and average coefficient of exports, would have been (28.1*0.62)+(71.9*1)/(17.3*0.62)+(82.7*1) = 89.3/93.4 = 95.6, or estimate of energy requirements would be roughly 95.6% of the true energy requirements. Hence the error, for our purposes, is small.

The total tonnage of cotton output was 803 571 tons (the sum of yarn exported plus that turned into woven or other cotton goods). The direct energy requirements in manufacturing were 169.2 GJ/ton, and thus the multiplier for calculating total embodied energy was **219.4 GJ/ton.**

1924: Step 1: Raw cotton inputs. A little surprisingly – and unlike 1935 – the weight of raw cotton inputs into yarn (estimated at 638 393 tons) is actually smaller than the quantity of yarn produced (recorded as 716 071 tons). (HMSO 1924, pp.38-9.) It is possible that this gap was made up by inventories, and more importantly, waste, which accounted for 10% of inputs in 1935. We continue to use the estimate that 46.5 GJ/ton went into raw cotton from animal power, in lieu of greater refinement of this multiplier in the light of much lower figures for 1935. Also see above for consideration of the possible impact of cotton ginning. Because of the lower rate of raw cotton input per ton of final product, 46.5 is multiplied by 0.89.
Step 2: Total cotton output, as in step 1, is recorded as 716 071 tons. 180.4 GJ/ton
Result: **221.8 GJ/ton**

1935: Step 1 Raw cotton imports were around 5% higher than production of various types of cotton. By this date the allocation of animal power to cotton yields a multiplier of only 11 GJ/ton, a considerable fall from earlier dates, although the use of animal power in cotton appears to be close to the average in American agriculture. Further work my refine these figures. Again, we have not added in any fuel used for ginning, although this is certainly less than 3 GJ/ton. Given the much lower overall multiplier for raw cotton, this makes the proportional potential error for raw cotton much larger, but affects the overall estimate of energy inputs into cotton goods little.
Step 2: In this year, spinning operations can be separated from weaving, giving a coefficient relative to the output of yarn. 98.8 GJ/ton.
Step 3: The most time-consuming operation is to calculate the weight of output of woven cloth, but the census fortunately provides all the necessary data for this to be calculated (such as precise conversions of yardage to weight of cloth). Output is 380 140 tons. Realted to energy inputs we get 60.1 GJ/ton.
Result: **170.3 GJ/ton.**

Finished cotton cloth

Much of the cotton exported had been finished in some way. A fourth step in calculating the multiplier for finished cotton goods is thus relating output of these cottons to the fuel consumption in the finishing industry, which was reported separately from spinning and weaving. The returns of the bleaching, dyeing, finishing and printing industry do not separate out these individual processes, but they do record the amount of cottons subject to these processes without duplication, as cottons subject to multiple processes were recorded only under the heading that predominated in their treatment.

All these estimates of embodied energy requirements are likely to understate the true total because we have not allocated production of dyestuffs and bleaches in the chemical sector to finished cloth, whether cotton or woollens. In total – that is, the total amount of dyestuffs, rather than the share that might have been embodied in exports – may have consumed as much as a million tons of coal. This is equivalent to a third of the total of the whole finishing sector, but well over a third of these was exported and thus were not embodied in any other domestically-produced goods. Nevertheless, any errors arising from the estimations employed below are much smaller than this potential absence. The production of dyestuffs is discussed under the chemicals sector.

1907: In calculating the energy input to dyed/bleached/printed (henceforth 'finished' cottons) we have to first determine the amount of cotton subject to these processes from the census of production.

1) Although some raw cotton and cotton waste was dyed, the amount was trivial at just over 1% of finishing costs, and will be ignored.
2) The amount of cotton yarn processed by the finishing industry in 1907 was 190.2 million lbs. While there is no direct information on what happened with this yarn, we know that none of it was used for machine belting or uncoloured 'grey' cotton cloths, and it is likely that this coloured yarn was woven into coloured cotton pieces. Secondary sources and later censuses of production suggest that this was done at a ratio of 1lb of yarn to approximately each 5.5 yards of cloth, and thus would have made up 1.04 billion yards of cloth, or 14.7% of woven cotton production, which totalled 7.076 billion yards.[11]
3) It is estimated that 4.83 billion yards of cotton cloth were bleached, dyed, printed or finished. This is an estimate because in 1907 no direct data on the extent of cloth solely finished is available, but only the total *cost* of finishing, and thus it has been assumed that the cost per lb of finishing was equivalent to printing (this produces an estimate that cloth that is only finished amounted to 30 million yards, only 0.6% of the total, so the total of this component was small compared to that dyed or printed). The costs imply that 68.3% of woven cloth was further processed after weaving, and 14.7% of woven cloth was made from coloured yarn, and the remainder, 19.5% sold as grey (untreated) cloth. Although these figures sum to 102.5% of known production, given that the length of cloth from made from the coloured yarn must be estimated, the level of error in this calculation is relatively small.
4) A low estimate (if we assume the potential error noted above must have marginally exaggerated either the production of finished cottons and not untreated grey cloth) is that 80% of cotton pieces were bleached, dyed or finished in some way. This amounts to 5.66 billion yards out of a total of 7.076 billion yards of cloth produced. This would have used 1.03 billion lbs of yarn, or 66.4% of yarn retained within the UK (the rest was used for machine belting, woven into grey cloths, or was waste often used as packing).

Having established an estimate for the total weight of dyed cottons, we now need an estimate of the energy inputs into these processes. As the use of coal in the finishing sector is neither

[11] TBC

differentiated by process not industry, it is assumed that the share of coal in the sector used by cottons (excluding raw and waste cotton) is the same as the share of the value of work in the sector done on cottons, which is 77.5%. It is clear that the value of processing per lb of cloth varies greatly by process: much higher in bleaching than in dyeing, for example. However this seems a reasonable procedure and is consistent with the findings from later censuses that give more direct information. The production of the dyes themselves would also have used energy (see the discussion of the chemicals sector). This is not calculated.
It is a simple matter to sum up the input-output coefficients per ton.

1) Raw cotton = 46.5 GJ (*1.08 to account for waste)
2) Cotton manufacture = 169.2 GJ
3) Finishing processes = 157.4 GJ
   TOTAL = **377.3 GJ/ton**

This estimate of energy requirements must however be considered a minimum, because stage 2) is based on the coefficient for *all* cotton goods, including yarn exported or used in machine belting that is not subsequently woven into cotton pieces. In 1907, cotton goods accounted for 25.7% of energy embodied in exports. The potential error introduced by using an average for cotton goods rather than having separate coefficients for yarn and cloth would shift this figure by less than 1%.

Another potential for error lies in the possibility that using the 'cost' method of allocating fuel consumption to cottons in the finishing sector is wrong. If it is, however, this error would predominately be reallocated to the woollens sector, thus raising the coefficient there (see blow). As woollens were less likely to be exported than cottons, this would then lead to an overstatement of the embodied energy in trade. To be clear as to any problems that arise, our estimates require the allocation of the total of 3 million tons of coal used in the textile finishing trades, of which we have estimated that 93% were used for cottons or woollens/worsteds. Of the cottons, we have seen that around 80% were exported, while approximately 60% of the woollens went abroad, with 77.5% of the coal in this sector being used on cottons and 15.5% on woollens. As a test of the potential error we can imagine that the proposed allocation was a gross error – say that only 57.5% should have been allocated to cottons, and 35.5% to woollens. In this case the error would be the difference between the two estimates embodied coal in exports resulting from the differential export of cotton and wool, in other words:
(0.8*77.5+0.6*15.5)-(0.8*57.5-0.6*35.5) = 71.3-67.3 = 4% of 3 million tons of coal,
or 120 000 tons out of a total domestic consumption of around 203 million tons of coal. In other words, the error is negligible for our purposes.

1924: <u>Step 1:</u> Manufacture of cotton goods. 221.8 GJ/ton
<u>Step 2:</u> The weight of goods that was finished depends on a conversion between square or linear yards (as cotton pieces were reported) and weight. The 1935 census reported that in 1924 for production as a whole, this ratio was 4.33 sq.yds/lb, although over 5 sq.yds/lb for exports. My own direct calculations from 1924 data give a figure of 5.23 sq.yds/lb. I have used the figure calculated directly from the 1924 census to produce a weight for cloth finished (which is reported in a mixture of weight and lengths), in part because this is closer to the figure reported in 1935 for exports. This yields an estimate of 412 594 tons of cotton (raw, yarn, but predominately pieces) being finished. In calculating a coefficient, it is assumed that the amount of energy used for cottons in the finishing sector is proportional to

the share of value in the sector taken by cottons: 72.4%. This gives a coefficient of: 151.2 GJ/ton
Result: **373 GJ/ton**

1935: <u>Step 1:</u> Manufacture of cotton goods. 170.3 GJ/ton.
<u>Step 2:</u> As in previous years, it is assumed that fuel inputs into finishing cotton reflect the distribution of costs in the finishing sector. The tonnage of cloth finished is reported directly or may be calculated directly from the census. 127 GJ/ton
Result: **295.2 GJ/ton**

Woollen Goods

The methodological issues here are essentially identical to those for cotton in 1907; the inability to distinguish between energy inputs into yarn only, and into weaving or other processes. An additional difficulty with wool is that a substantial amount of the material input comes from recycled rags. In addition, at each stage of wool production, substantial amounts of material are exported.

We have not attempted to estimate the energy that goes into the production of the raw wool clip, although it is possible to separate imports (much from Australia and South Africa) from the domestic wool clip production. However embodied energy from sheep farming is likely to be very low, given that wool production is much less labour intensive than cotton, and requires very little use of draught animals.

1907: An input-output table has been calculated for wool and worsted production in 1907 from the census of production. The object is to produce an estimate of total output of woollens to which the fuel data can be related, as the latter encompasses the sector as a whole. The points below list the major relevant observations for our purposes.

1) There is substantial rag recycling which involves sorting in factories, carbonization of pulverization of rags, and the making of 'pulled wool' products such as shoddy and mungo (rags and waste wool compressed together into a kind of felted material). Some of this is exported but by far the greater share is used as an input into further woollen yarn manufacture, and thus will be part of our final figures of output. However, 6% of the shoddy is exported. Because this is such a small amount of total production it is treated as if it had zero energy inputs. Most of the pulled wool (totalling 207 million lbs) goes into yarn production.
2) There are very substantial weight losses incurred during the washing of the wool 'clip' by the processing industry. Some raw wool is also exported, and a small amount retained as stock. This phase of processing is treated as if no fuel is consumed. We may note that the ratio of coal to installed hp suggests that the great majority of coal used in the woollen industries is used to drive steam engines, and not for other purposes such as heating water, space etc.
3) Retained raw wool (amounting to 347 million lbs) is then processed into 'tops', and 'noils'. 'Tops' are combed wool ready for making worsted yarns. 'Noils' are essentially a waste product from combing that can be used in making woollen yarns. A significant amount (35 million lbs) of tops are exported, and so enter our calculations as part of final output.
4) The next stage of production is yarn. This process differs for woollens and worsteds. Following the census, a c.15% loss is estimated in the spinning and carding process

for each product. Worsted yarns are made from 'tops'. 186 million lbs in total were spun, and over 80 million lbs exported. Woollen yarns are made from the recycled 'pulled wool' (see point 1 above), noils, and flocks, and the remaining washed raw wool. I have estimated that 241 million lbs of woollen yarn were spun, which is at the lower end of a range estimated in the census, but that matches best the figures provided when put into the input-output matrix. Very little woollen yarn was exported, only around 1% of production.

5) The yarn that is not exported is used to weave finished goods (woollen tissues, worsted tissues, and much smaller quantities of flannel, damasks, carpets, blankets etc.). Figures on the production of these goods, added to the exports of previously mentioned intermediary goods, allow us to calculate the total amount of final woollen goods. They are the sum of all yarn that goes into domestic production + exported yarn + exported tops + exported noils. This comes to 478 million lbs of wool.
6) This figure is used to calculate our per ton energy requirement, comparing it with all coal consumed in the woollen and worsted industry (including of course electricity converted into coal used for generation).

The resulting energy requirement is **262.3 GJ/ton**.

In terms of individual woollen goods, this coefficient could be significantly in error. Tops, for example, have only been subject to mechanized combing, not spinning or weaving, while yarn has not been woven. Woollen tissues (largely made from recycled shoddy but mixed with some uncombed pure wool and some noils as a by-product of combing) differ in their production processes from worsted (made with combed tops). If the composition of exports was the same as domestic production this would not matter. However, while 72% of the weight of wool in finished goods went into products that had gone through a full range of processing, this is only true of 57.8% of exports (the weight of exports had to be estimated by using lb/yard ratios calculated from the census; and in the case of some products such blankets and hosiery where no weight is recorded, assuming this were alike to carpets and woollen tissues, respectively. Shoddy and raw wool is excluded). 12.7% of export weight is accounted for by 'tops' although they accounted for only 7.5% of final woollen products using coal in their production. For exports the coefficient is thus a little too high, but to an unknown degree. Does this matter? Woollens and worsteds in total are estimated to have accounted for 3.3% of embodied energy in British exports in 1907, less than 0.5% of domestic coal consumption. Thus the potential for error is almost certainly rather less than 0.1% of domestic coal consumption at the very most.

1924 <u>Step 1:</u> Fuel inputs to raw wool are assumed to have been negligible.
<u>Step 2:</u> The total weight of all wool output (including yarns, noils and tops not further processed into pieces and tissues) has been calculated. Fortunately data within the census allows values recorded according to length to be converted into weights for most products. This total figure (221 700 tons) can then be related to total fuel inputs. 288.8 GJ/ton

Result: **288.8 GJ/ton**

1935: <u>Step 1:</u> Fuel inputs to raw wool are assumed to have been negligible.
<u>Step 2:</u> The total weight of all wool output has been calculated from data on 25 different products. This is related to energy inputs.
Result: **227.8 GJ/ton.**

Finished woollen goods.

Methodological issues are essentially the same as those for cotton.

However, the first thing to note is that woollens and worsteds account for only 15.3% of the value of the finishing sector, and hence the numbers involved are much smaller. Hence it is a simpler matter to disregard categories that will not be significant in our final calculations.

1) Proportionately more raw wool is bleached or dyed than raw cotton, about 5% of the value of the sector. However, if we take value as a rough guide to energy consumption, this would absorb only 0.05*15 = 0.75% of the sector's coal, ony around 23 000 tons. 15 million lbs was dyed, which we add in at point 4 below.
2) Some 49 million lbs of yarn were finished. This is 11.5% of the wool and worsted yarn produced.
3) 237 million yards of wool and worsted manufactures were stoved, dyed and printed, which is 60% of the 397 million yards produced. This is equivalent, based on the input-output model, to 169.3 million lbs of wool.
4) There are two further categories to account for: woollen manufactures that were finished only, accounting for 10% of the value of cloth treated in this sector assigned to woollen and worsteds; and hosiery, which accounts for 13% of the value treated in this sector. We may assume that processing a given weight of hosiery costs the same as processing the same amount of wool manufactures. This would imply that some 40.6 million lbs of hosiery were stoved, dyed and finished, plus an unknown amount of wool manufactures that were solely finished. This leaves a total of 208.2 + 40.6 + ? = approximately 260 million lbs: admittedly a slightly arbitrary estimate. We may remember that around 15 million lbs of raw wool was also dyed. The total weight processed may have been around 275 million lbs, or 80% of wool turned into manufactures of some kind. Although we do not know the amount solely finished, clearly the total amount of wool processed in this sector cannot have been very much larger; if it was 25% bigger it would account for the whole sector.
5) Energy use is assigned by the share of woollens in the value of activity in the sector, as with cotton. We attain a direct energy requirement of 116.3 GJ/ton, although we must acknowledge the considerable uncertainty and processes of estimation that must go onto this figure. Nevertheless, this concerns the allocation of less than half a million tons of coal in total. It seems unlikely that the error can be greater than a few tens of thousands of tons.

It is again a simple matter to sum energy requirements to reach a total embodied energy in woollens that have been finished in some way of **376.8 GJ/ton**. They turn out to be one of the most energy intense products.

For calculating energy embodied in trade, we assume that the ratio of the weight of manufactured products finished to that unfinished was the same as in production: 80%. Clearly, a large majority of the sector was finished. It is further assumed that all dyed wool and yarn is used in manufacturing within the UK. This could be in error if a significant proportion of the dyed worsted yarn was directly exported, but would in fact not affect our calculations regarding embodied energy in trade: the same embodied coal would simply be reallocated to another category.

1924: <u>Step 1:</u> From total woollen goods, calculate the weight that was finished. Fortunately, this can be aggregated directly from the data reported in the census. 288.8 GJ/ton
<u>Step 2:</u> The same procedure is followed as with finished cotton cloth: the share of fuel in the finishing branches is allocated according to the share of value added in the sector taken up by woollens (14.2%). This yields a coefficient of 125 GJ/ton.

Result: **413.8 GJ/ton.**

1935: <u>Step 1:</u> From total woollen goods, calculate the weight that was finished. Fortunately, this can be aggregated directly from the data reported in the census. 227.9 GJ/ton
<u>Step 2:</u> The same procedure is followed as with finished cotton cloth: the share of fuel in the finishing branches is allocated according to the share of value added in the sector taken up by woollens (14.6%). This yields a coefficient of 109.7 GJ/ton.
Result: **337.5 GJ/ton.**

Chemicals

1870: The really significant traded output of the British chemical industry was alkalis (soda ash, bleaching powder etc.) that were exported in large amounts 19th century, predominately to America. The main inputs to alkali production were limestone, salt, pyrites, and saltpetre. Of these, only salt is likely to have had any significant influence on indirect energy requirements. Use of coal in saltworks is reported in the 1871 Royal Commission report and it was estimated that salt required about half a ton of coal per ton of salt, that is, or 14-15 GJ/tons in energetic terms. We take the energy requirements to be 14.9 GJ/ton including embodied energy in the coal from mining.

Evidence from firms' costs suggests that salt inputs to alkali production were around 1.25 tons per ton of soda ash produced, representing an indirect energy requirement of 18.6 GJ/ton. The report of the Royal Commission allows us to assess the amount of fuel used per ton of salt input; the ratio is 3-3.2. If 3.1 tons of coal were used per ton of salt, this implies 3.1*1.25 tons of coal was used per ton of alkali output, or 3.9 tons (imperial), and a direct energy requirement of 123.3 GJ/ton (including embodied energy in the coal). This consistent with the range of direct reports of firms' coal use per ton of soda ash reported in Warren (1980).[12] Combined, these give us a total energy requirement of **141.9 GJ/ton**.

1907: The chemical industry is extremely complicated, and the census itself states that because of 'the varied and complicated nature of the industry', where many products are inputs into others, 'it has not been possible to frame any close estimate of the value of the products of this industry taken as a whole and after allowing for the elimination of all duplication.' Large amounts of chemicals produced were used as intermediary products within the industry; for example, only about a third of sulphuric acid, the most substantial product, was retailed by chemical companies. But this does not mean that the retailed share can be considered final output, because this may have been bought as an intermediary product by other chemical firms. Equally, some chemical products were made as by-products outside of the chemical sector itself; oil refineries, coke ovens and gasworks produced tens of thousands of tons of ammonium sulphate.[13] There were also imports, although predominately

[12] Warren, K., *Chemical foundations. The alkali industry in Britain to 1926* (Oxford: Clarendon, 1980).
[13] See the 1907 census as reported in in the 1924 census: *Final report on the third census of production of the United Kingdom (1924). Vol. IV. The Chemical and allied trades, the leather, rubber and canvas goods trades,*

of coal tar dyes whose weight was small (around 16 000 tons).[14] However, what concerns us is establishing a rough estimate of the make of the chemical sector itself which can be related to energy inputs recorded for that sector. Once we have estimated an energy requirement per ton of output, the question becomes whether the composition of that output of product corresponds with the structure of exports. The precise flow of intermediary goods within the sector is not important.

1) The total make of chemicals included in schedule of the sector itself that is attributed a weight (or volume from which weight can be calculated) comes to 2 510 185 tons (imperial). If this is a correct figure for the final product of the sector, it implies a coefficient of 45.7 GJ/ (metric) ton consumed within the sector itself. This energy requirement must be considered a minimum, however, as some of the recorded output would in fact have been an intermediary input within the sector. The output tonnage is a minimum, and as the reported energy use is invariant with respect to our estimate of output, it can only the ratio of energy use to output can only increase.

2) Salt was certainly a major input into any kind of soda compound, which accounted an output of 682 000 tons within the sector. In total the census reckoned that 774 000 tons of salt were used by alkali and chemical manufacturers. Calculating a coefficient for salt itself is problematic because a considerable quantity was piped directly into alkali works and not recorded in the sum total for the salt industry (although it is recorded in the mineral statistics). Thus 1.979 million tons were mined in total, but only 1.452 million tons returned to the census. It is not clear if the fuel consumption of the salt industry includes the coal consumed in vertically-integrated alkali producing firms, or relates only to that production returned for the saltworks schedule in the census, but the latter seems most likely. As the salt sector consumed 645 623 tons of coal, this leaves a coefficient lying somewhere between 9.8 GJ/ton and 12.9 GJ/ton. The higher figure is the likelier. This means that somewhere between 250 000 and 340 000 tons of coal were embodied in alkali production as energy indirect requirements via salt, which should also of course be raised by an additional 6% to account for the coal consumed in mining: but this is already a sum much smaller than the potential margin of error in these calculations.

3) If the coefficient for salt is estimated on the basis of fuel returns and production produced solely within the salt sector (ignoring that salt production within the alkali sector which is not directly assigned a fuel input in the census, but adding in coal used to mine the coal produced), we add a figure of 13.8 GJ/ton to the figure for the chemical industry. If this is equally distributed over the whole of chemical output (certainly an error!) the input of salt per ton of final chemical output was 774 000 / 2 510 185 = 0.308 so the input of embodied fuel from salt production per ton of chemical would be 13.8*0.308 = 4.25 GJ added to 45.7 GJ/ton to get 50 GJ/ton. Again, this should be considered a minimum.

4) Aside from salt the coefficient does not take into account other important inputs, such as limestone, or (imported) pyrites. However given an energy requirement in quarrying of 0.6 GJ/ton in Britain the influence on final results is marginal.

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the paper, printing & allied trades, and miscellaneous papers (London: His Majesty's Stationery Office, 1931), p.35.

[14] Ibid., p.26.

5) How do these estimates relate to the structure of exports? The reported weight of retailed output from firms in the sector was dominated by four products groups: soda compounds (27.2%); acids (27%); pitch (21.4%); and bleaching powder (5%). Exports were however almost completely dominated by soda compounds (79.6%) and bleaching powder (15%). This means we must examine the specific structure of alkali production to see to what degree it might diverge from the energy requirements outlined above.

6) Inputs into soda compounds were pyrites, saltpetre, salt, limestone, and coal (see above). Our time period represents an awkward (for us) zone of transition, as the more efficient Solvay method was replacing the LeBlanc process rapidly after 1900. 1907 probably represents a rather mixed picture, with the innovators, the firm of Brunner Mond, having about half the market. But by 1913, their Solvay, ammonia—soda method was completely in the ascendancy.[15] The limestone input in the Solvay process was about two tons per ton of output, which given the energy requirements for quarrying, represents around 1.2 GJ/ton of final output. Salt inputs to alkali production were recorded in the census as around 500 000 tons, whilst output was recorded as 807 000 tons (soda compounds + bleaching powders). This ratio seems to small compared to direct estimates of manufacturers' inputs available from the 1870s-1890s, which imply that we should assign *all* of the inputs to the chemical sector to alkalis, or 774 000 tons. This produces a coefficient of inputs to output rather closer to 1 ton per ton, and thus the indirect energy requirement would be 13.8 GJ/ton. The energy costs of pyrite and saltpetre inputs were very low. Hence indirect energy requirements for soda compounds were probably around 15 GJ/ton in the early 20th century for the Leblanc, Solvay, and indeed other processes. [16]

7) Fuel requirements are difficult to calculate because it is not always clear whether data relates to all of the steps within a chemical production process, or only particular ones. The typical soda production process first saw sulphuric acid produced using brimstone or pyrites. Sulphuric acid used much less energy than out calculation of requirements for a generic ton of chemicals: Drössler seems to have reckoned about 7.33 GJ/ton for sulphuric acid in Germany, and Partington a little less for the main but incomplete part of the process.[17]In 1924, sulphuric acid inputs into soda compounds were only around 0.11 tons per ton of output, so it is likely that any error in regard to the stage of acid production is marginal in any case. The acid was applied to common salt to produce the salt-cake, from which hydrochloric acid was a by-product which then was absorbed by lime to make bleaching powder. Meanwhile the salt cake was calcined with limestone to produce soda ash.[18] However, there was still a range of different processes to achieve this, so data on the energy requirements of one of these in no way resolves the question of the average. Best-practice was the Solvay process that according to Ayres and Warr had achieved 25 GJ/ton by 1913;[19] Partington gives

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[15] Reader, W.J., *Imperial Chemical Industries. A History. Volume I. The forerunners 1870-1926* (Oxford: Claarendon, 1970), p.217; Haber, L. F., *The Chemical Industry 1900-1930. International growth and technological change* (Oxford: Clarendon, 1971), pp..135-141; Musson, A.E., *The Growth of British Industry* (London: Batsford, 1978), pp.216-221.

[16] Estimates from firms of inputs to soda ash production can be found in L.F. Haber, *The chemical industry during the nineteenth century. A study of the economic aspect of applied chemistry in Europe and North America* (Oxford: Clarendon, 1958), pp.100-2.

[17] Kreps (1938), pp.23-4; Partington, J.R., *The Alkali Industry* (London, 1918).

[18] Kreps, Theodore J. *The Economics of the sulphuric acid industry* (Stanford, 1938), pp.23-4.

[19] R. Ayres & B. Warr, 'Energy, power and work in the U. economy, 1900-1998', p.31.

a figure of 17.8 GJ/ton in the 1910s; and put the making of bleaching powder at around bleaching powder 9-15 GJ/ton.[20] Earlier commercial data suggests the Leblanc process by the 1890s still using as a direct energy requirement around 82 GJ/ton from coal, while the Solvay process used 70 GJ/ton at its inception in the 1870s and 62 GJ/ton in the 1890s.[21] These figures suggest that Ayres and Warr's estimate of 50 GJ/ton for the early use of the Solvay process in the USA is either too low or inappropriate for European comparisons. Even if fuel use had fallen by the rate they suggest, c.50% by 1910, we would still expect very best practice in the industry to have a direct energy requirement of 35 GJ/ton, and a total energy requirement of **50 GJ/ton.**

Given these uncertainties we have retained the generic estimate of 50 GJ/ton for our calculations, understanding that it may produce an error in either direction. Further research would be required to reach a more confident estimate.

1924: As in previous years, chemicals are a difficult case, in part because the output of the sector is so diverse, and partly because much of the output is recycled as input within the sector, without the details of these flows being recorded. The census officials noted that avoiding duplication 'with any degree if precision is impossible.' (HMSO 1924, p.41). Hence the coefficient is calculated simply on the basis of the aggregate weight of all products. This will give a coefficient for the net output sold out of the industry that is too low because of transfers within the sector. It should also be remembered that significant amount of chemicals are in fact produced outside of the sector (for example, coal tar as a by-product of coke production, or sulphate of ammonia which is produced in gasworks, coke-works, and oil refineries) and in these calculations are produced 'for free' in energetic terms.

Result: **30.5 GJ/ton**

1935: Chemicals represented only a small share of British trade in 1935, and thus the multiplier calculated here has not undergone the full elaboration that would be desirable; work is ongoing. The multiplier has been calculated as a generic figure on the basis of the weight of the leading 26 products of any significant weight. Soda compounds and sulphuric acid are by far the largest of these, accounting for a little under half of the total. However, as some of these are undoubtedly intermediate products into other goods produced within the sector, the multiplier calculated is very probably an underestimate with the weight of final output being set too high. Nevertheless results from previous years, and ongoing efficiency improvements within the sector, suggest this error cannot be too great, and certainly not enough to affect estimates of embodied energy in trade.

Result: **25 GJ/ton.**

Salt

1870: The Royal Commission on coal estimated that about half a ton of slack (coal) was required per ton of salt produced.
Result: **14.7 GJ/ton.**

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[20] Partington p.30, p.123.
[21] Haber (1958), pp.100-2.

1907: See above in the discussion of chemicals.
Result: **13.6 GJ/ton**

1924: This is fuel reported used in salt mines and saltworks divided by recorded output.
Result: **8.79 GJ/ton**

1935: 4.9 GJ/ton

Cement

1907: Some 2.877 million tons of cement were made. 26.5% of this was exported (764 000 tons).

There is no direct information on how much material went into cement-making, but on the assumption that it was at last as much as the final weight of cement (although this would include water?), 2.877 million tons would come from the quarrying sector. However some was quarried directly by cement-makers themselves, and they obtained both chalk and limestone that is recorded separately in the census returns. It is not known from the census in what proportions such material was used (it may be present in the returns on Quarries and Mines produced by the Home Office). The value of the quarrying sector in returns of that sector was £3.638 million for 17.288 million tons quarried (although 3 small categories give no tonnage). This is substantially short of the total amount of quarried earths at over 33 million tons, the difference largely accounted for by brick-makers. If cement inputs made up 16.6% of quarry fuel and labour (2.877/17.288) they would consume 61212 tons of coal.

Even if these admittedly very speculative calculations are badly out they make very little difference to the fuel inputs directly into the cement sector.

1924: Simply fuel consumed divided by aggregate output (cement + gypsum). It was reported that the cement sector largely quarried its own raw material and hence does not need an input from quarrying

Result: **17.2 GJ/ton**

1935: 11 GJ/ton

Jute, hemp and linen

1907: Jute was largely made into bags and sacks, and used imported vegetable fibres. The total make of jute yarn was around 485 million lbs, of which 67.519 million lbs were exported, leaving 417.481 million lbs retained for domestic finishing. Unfortunately, final jute production is recorded in a variety of ways: yards of cloth, square yards of cloth, and hundredweight of cloth. There is no obvious way to aggregate these figures, and equally, as the finished goods are recorded in a non-standard way, they cannot be related directly to create a yard/yarn weight ratio.

By value, 47% of finished jute products were exported. I make the assumption that 47% of the retained weight of yarn was thus exported in this form, although in practice exported cloth was disproportionately in fabric recorded as yardage rather than be weight and may have been of higher quality than average, overstated energy content; although energy content itself is simply an average across a range of products, both yarn and finished goods. This would mean jute exports were composed of 197 million lbs of yarn.

155 million lbs of linen were produced, of which 16.442 million lbs was exported, leaving 138.558 million lbs retained for domestic production. This was made into 363.198 million yards of material, ranging from fine linens to sailcloth. Around 185 million yards of this, or over half, was exported. The data equates to a ratio of 2.62 yards per lb, assuming there was not a major drawdown of stocks.

65 million lbs of hemp were made; there is no record of exports taking place in the census.

In total, some 705 million lbs of yarns of jute, linen and hemp were made, the greater share of which was made into finished goods domestically. This equals 314 712 tons. This used 676 546 tons of coal.
141.178 million lbs of linen yarn was bleached or otherwise treated, along with 114.092 million yards of cloth; or the equivalent of 43.547 million lbs of cloth. This sums up to 184.724 million lbs of cloth being treated, a sum obviously larger than the entirety of linen production. Thus all linen has a higher coefficient for bleaching and other treatments, for which we add an average coefficient, although some linen was obviously treated at least twice. The total value of these treatments was £776 000, or 4.3% of the value of the work done in the bleaching/dyeing/finishing sector. Thus the amount of coal attributed to linen is

Fertilizer

1924: <u>Step 1:</u> It is assumed that inputs are the same as in 1935, having no better information for 1924 at this stage. However, it is obvious that this would depend on the nature of output, which should be compared, which may vary over time. Inputs from mining are estimated to be 1 GJ/ton.
<u>Step 2:</u> Inputs from generic chemicals: 30 GJ/ton
<u>Step 3:</u> Fuel consumed in final manufacture and assembly, related to total output. 8.3 GJ/ton.

Result: **10.4 GJ/ton.**

1935: <u>Step 1:</u> Generic chemical and pyrite inputs into fertilizer are provided. These made up 6% and 26% of the inputs into fertilizer respectively, with multipliers of 25 GJ/ton and c. 1 GJ/ton.
<u>Step 2:</u> Energy used within the sector is related to the total output by weight (divided into six major categories). 3.8 GJ/ton.
Result: **5.5 GJ/ton**

Sugar

1870 and 1907 There is no estimate of coal consumed in sugar refining for 1870, but we know that energy inputs into this process varied little over time or between countries. The sum total of products of the sugar industry in 1907 (including sugar, molasses, caramel, and glucose) was 807 950 tons. In comparison with total energy inputs this yields a direct energy requirement of 17.8 GJ/ton. The industry used a comparatively small amount of coal, around 455 000 tons. In fact Britain imported much more refined sugar than it produced. We do not know whether the inputs in 1907 came from sugar cane or beet, or in what proportion; it seems unlikely that more than 2-3 GJ/ton could be added at the most to the figure from this input (based on inputs to beet and cane that become available from the 1920s). We have retained an energy requirement of **17.8 GJ/ton** for the purposes of our calculations.

1924: Step 1: It is assumed that beet sugar is used – certainly introducing an error, as molasses are an output, only produced from cane sugar. The coefficient for beet production is taken from Germany. Today, the ratio of sugar beet input to refined beet sugar output in the UK is 7.14. I have used an estimated ratio of 8, but should be further checked. 0.31 GJ/ton
Step 2: Fuel in sugar refining related to total output. This will include some glucose and molasses and certainly a proportion of cane sugar, so result in a slight error.

Result: **13.3 GJ/ton.**

1935: Step 1: Inputs from agriculture are assumed to be from sugar beet. The multiplier applied is 0.31 GJ/ton with a coefficient per ton of sugar output of 2.48.
Step 2: The full weight of outputs of the sugar and glucose sector has been summed and related to energy consumed in that sector. 13.3 GJ/ton
Result: **15.5 GJ/ton.**

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