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Kander, Astrid; Schön, Lennart

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The energy-capital relation—Sweden 1870–2000

Astrid Kander a,*, Lennart Schön b

a Centre for Innovation Research and Competence in the Learning Economy, Lund University, Sweden
b School of Economics and Management, Department of Economic History, Lund University, Sweden

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Abstract

This paper explores short and long-run changes in the energy to capital relation. The $K/E$ ratio is calculated for Sweden 1870–2000, at the national, industrial and branch levels. A basic result is a substantial long-run increase in the $K/E$ ratio which is positively correlated with the relative price $pE/pK$. The price response is stronger in energy intensive industries than in labour intensive industries. By considering the useful work (energy services) provided by energy sources, estimated using an aggregate measure of thermodynamic efficiencies, we can conclude, however, that energy services and capital have developed fairly evenly over the 20th century and thus that the long run increase in the $K/E$ ratio depends on embodied biased technical change. From a natural resource and environmental perspective it is clear that the economy has managed to cope with relatively less energy over time, but with a stationary (near constant) capital to energy services ratio. From a growth perspective our results indicate high complementarity between energy services and capital.

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Keywords: Capital; Energy services; Complementarity; Substitution; Biased technical change

1. Introduction

A main issue concerning energy’s role in production is its interplay with capital in the long run. This paper uses long time series to disclose some stylised facts regarding the energy to capital relation in the short and long run. The $K/E$ ratio is calculated at the national, industrial and branch levels for Sweden 1870–2000 and the correlation with the relative price $pE/pK$ is investigated. Presumably, the incentives for biased technical change or substitution have worked differently in
energy intensive and labour intensive branches of industry. The response to the relative price of energy has been markedly different in these two sectors of industry. Two aggregates of energy intensive branches and labour intensive branches are used to illustrate this.

Theoretically, any long-run change in the $K/E$ ratio may either be an effect of substitution or of biased technical change. It is not the ambition of this paper to determine the relative effects of these two factors, because in practice they work together dynamically, albeit with different emphasis over the short and long run. We do, however, test both the short-run responses to price incentives, which can largely be expected to be caused by substitution, and introduce a new method for appreciating the long-term effects from embodied biased technical change. We use a historically and empirically grounded technical efficiency ratio for capital that expresses the average efficiency of converting ‘primary energy’ to ‘energy services’ (Ayres and Warr, 2003, 2005). This time series expresses the technical energy efficiency improvements of capital, i.e. the embodied technical change, and is used to establish capital/energy services ($K/E_{ser}$) ratios. These ratios show to what degree capital has made use of energy more or less effectively over time, because $E_{ser}$ incorporates the effects of technological progress.

We argue that it is relevant from a natural resource and environmental perspective to explore the basic $K/E$ ratio to see how much energy the economy has used relative to its capital. However, from a growth perspective and in an aggregate production function context, it is more interesting to explore the $K/E_{ser}$ ratio. This ratio gives a better picture of substitution versus complementarity aspects of energy and capital.

The outline of the paper is the following: Section 2 provides a theoretical introduction with a brief account of previous relevant studies. Section 3 describes our data and methods. Details on the data construction are found in the Appendix A, the data series are available from the authors on request. Section 4.1 explores the changes in the $K/E$ ratio and its correlation with prices. We test the hypothesis that the $K/E$ ratio is positively correlated with relative energy prices by comparing the $K/E$ ratio with energy prices relative to capital costs ($pE/pK$), both in the short and long runs. Section 4.2 examines the hypothesis that there is a stronger relative response of the $K/E$ ratio to prices in heavy industrial branches than in light ones. Section 4.3 analyses to what extent long run changes in the $K/E$ ratio are due to embodied biased technical change. Section 5 summarizes the results.

2. Theoretical framework

In an aggregate production function framework the relation between capital and energy may change as a consequence of both biased technical change (which is the same as factor augmenting technical change) and substitution.

If we think of the graphical representation of these concepts (see Fig. 1) we could give the following simple definitions:

(1) Biased technical change is the same as a change in the curvature of the production function, saving more on one factor of production than another. This means that the optimal ratios of the production factors used at any given price ratio change and, therefore, so do the cost shares. In the example of Fig. 1, a company moves from E1 to E2, thus saving energy, at the same time as the capital stock is unchanged ($C_1 = C_2$). Factor augmentation is basically a very similar idea to biased technical change. The factor augmentation assumption is that all technical change can be broken down into changes in the effective units of all the inputs. If the rate of change in the augmentation indices is unequal then biased technical change follows.
Fig. 1. Biased technical change vs. substitution.

(2) Substitution is movement along an isoquant of a production function, indicating changed proportions of the production factors as a consequence of changing relative prices. Techniques are selected from an existing set rather than developing new technologies.

Any observed change in the $K/E$ ratio over time may have been the result of substitution or biased technical change, or a combination of the two.

By focusing on the long-run relationship between capital and energy, our interest is closer to the body of studies dealing with biased technical change and factor augmentation than it is to the studies dealing with pure substitution. The elasticity of substitution between energy and capital concerns the direct responses to changing relative prices; movements along an existing and known production function isoquant. Empirical studies of substitution are hence not concerned with technical change, which is treated as exogenous. In a long-run relationship it is, however, realistic to expect that changing relative prices will stimulate biased technical change and not only lead to movements along an existing production function. There are, of course, different time perspectives involved in substitution and technical change. While substitution may be more immediate, technical change is a more time-consuming process. This article illuminates both the long run and the short run responses to relative price changes.

An intuitive realistic answer to whether energy and physical capital are substitutes or complements is that they are neither perfect substitutes nor completely non-substitutable (complements). Some energy will always be required to run machines, but there need not be a proportional relation, especially not over time and in different sectors of the economy. The actual relations have not yet been well sorted out by studies on substitution versus complementarity. Quite a large number of studies tried to estimate the relation between energy and capital after the oil price increases of the 1970s. In our opinion they have not produced any results to clearly resolve the important issue of how difficult it has been so far to substitute capital for energy, and what can be expected in the future. This may partly be due to an excessive elaboration of various measures of elasticity, which makes the studies difficult to compare. The original Hicks elasticity of substitution (Hicks and Allen, 1934a,b), expressing the curvature of the production function has been supplemented by many other measures, all looking at the behavioural side of the economy, but differing in what parameters are held constant and what price-quantity relations are focused on (Stern, 2004).
For a time there seemed to be consensus about a few stylized facts in the substitution-complementarity debate, namely that capital and energy act more as substitutes in the long run and as complements in the short run (Siddayao, 1986; Apostolakis, 1990). This was based on differences in outcome between cross section data and time series data. However, Frondel and Schmidt (2002) recently questioned this resolution of the issue. They claimed instead that the issue of substitutability is reduced to a question of cost shares, when the standard econometric approach of using a static translog model is employed. In their overview of several empirical studies they find that the cross-price elasticities (which are behavioural responses of input choices to changes in prices) and the cost shares of energy and capital are clearly correlated. Only when cost shares of both factors are small will energy and capital be classified as complements, but in all other circumstances they will be substitutes. Frondel and Schmidt find this a problematic feature of the estimates so far and advocate the search for a more dynamic model approach. An alternative and more credible interpretation of the correlation between the size of cost shares and substitutability is, however, to regard this as reasonable, and depending on differences in technology. For heavy industries, with large amounts of capital and energy, there will be larger incentives to substitute capital for energy when energy prices rise, than for labour intensive industries. This idea is empirically investigated in Section 4.3 of this paper.

The issue of biases in technical change was already raised by Hicks in his classical work, The Theory of Wages, where it is stated that “a change in the relative prices of factors of production is itself a spur to invention, and to invention of a particular kind-directed to economising the use of a factor which becomes relatively expensive” (Hicks, 1932, p. 124). This proposition stimulated a lot of critical debate (Salter, 1969; Samuelsson, 1965; Rosenberg, 1972; David, 1975; Olsson, 1982) that pointed to the difficulties of separating biased technical change from factor substitution.

Biases in energy use have been studied by among others Jorgenson (1984), Hesse and Tarkka (1986), Boyd and Karlson (1993), Ilmakunnas and Törmä (1994) and Lundmark and Söderholm (2004). The results of these studies differ in whether technical change is energy-saving or energy-using and, just like the substitution studies, do not bring any general clarification of the issue; no stylized facts.

Factor augmentation is conceptually close to biased technical change. The idea of factor-augmenting technical change is basically very simple. By factor-augmenting technical change with only two production factors is meant that the production function may be written \( Y = f(aL, bK) \), where \( Y \) is output, \( L(t) \) is labour, \( K(t) \) is capital, \( a(t) \) is an index of labour’s productivity and \( b(t) \) is an index of capital’s productivity. This can easily be extended to more factors of production, like energy and materials. There is thus no \( A(t) \) term, no technical change term, affecting all the production factors equally. The basic idea is that all technical change, both biased and neutral, can be attributed individually to increased productivity of the production factors. A specific case of factor augmentation technical change is called Harrod neutral technical change. This is when labour is augmented, through increases of \( C/L \) and \( Y/L \), while the \( C/Y \) ratio and the marginal product of \( C \) remain constant. (Hawke, 1980, p. 179).
A relevant question for the energy to capital relation is to what extent technical change is embodied in new vintages of machines that are more energy efficient than the old ones, and to what degree energy to capital savings can be accomplished without investing in new machinery, i.e. through disembodied technical change (new knowledge, learning by doing). The presumption that much of the technical change would be embodied in new machinery was, however, not confirmed empirically by Solow (1987), to his own surprise. Solow used an econometric approach, while Berndt et al. (1993) employed even more advanced econometric techniques, separating embodied from disembodied factor augmentation in the manufacturing sectors in the US, Canada and France in the 1970s and 1980s. They found the role of embodiment to be surprisingly small, something they speculated could depend on price deflators already accounting very well for input changes, or output measures failing to account adequately for quality change. We suggest that the method applied in this study, i.e. using a direct measure of technical efficiency increases in capital equipment, has the potential of giving an answer to the role of embodied technical change that is closer to intuitive expectations.

In conclusion, given the state of the art of capital-energy studies, we believe that there is scope for studies that take a different methodological approach to the advanced econometric modelling with a full production function approach where output and labour are also included. First, the results from previous econometric modelling are far from conclusive and sometimes even counter-intuitive. Second, the production function approach means including restrictive assumptions concerning the nature of the production process and the linkages between the production factors that are all the more unsuitable when taking into account the length of the time period encompassed in our study.

We suggest that our analysis of both the short-term responses to relative prices and longer term changes makes the relations between energy and capital more clearly visible. In addition, we think that using direct information on the innovations that have spurred the technical energy efficiency of capital offers an alternative method to estimate the effect of embodied technical change.

3. Methods, data and measures

3.1. Methods

Our research is in a quantitative and appreciative branch of economic history. Typically, it addresses questions that are regarded as crucial for contemporary society and aims at providing stylized facts in response to these questions by investigating and describing trends and periodical fluctuations. The long time perspective (over 100 years) is combined with medium long perspectives (decades or specific periods). The short-term, static perspective, is of minor importance, but not absent from our analyses. Here we use regression analyses to trace the strength of short-term responses to relative price changes.

3.2. Data

The data used is a set of energy quantities and energy prices that has been constructed by the two authors of this article (Schön, 1990, 1992; Kander, 2002) on basis of printed statistical sources. The sources and methods used are described in the Appendix A.

Capital stocks are constructed from investment series based upon the Historical National Accounts of Sweden, using the Perpetual Inventory Method (PIM) and assuming a straight
2% annual depreciation of building capital and 4% of machinery capital (Schön, 2004). The construction of capital stocks and the \( K/E \) ratios are further described in the Appendix A.

### 3.3. Measures

In a production function context it makes sense to adjust the production factors for capacity use, because only the part of the various stocks \((L, K)\) that actually enters production should be included in the production function. When it comes to energy, Ayres and Warr (2005) argue that we should count only the fraction of the available energy actually consumed in performing useful work (in transportation, space heating, industrial high and mid-temperature heat, electricity supply, light). This utilized energy is normally referred to as energy services.\(^2\) Energy services, \(U\), are given by the primary energy, \(E\), multiplied by the thermodynamic efficiency ratio, \(f\), which is the ratio between inserted energy and energy services provided by the machines. The thermodynamic efficiency ratio has improved substantially over time; for instance for electricity generation by a factor of 10 and for mechanical machines by a factor of 2–4 over the last 130 years, while heating stoves already had undergone dramatic increases in efficiency during the 19th century and only increased their performance by roughly 50% after 1870. These technical changes mean that the energy services actually employed by the economy have grown faster than the amount of energy. This may be regarded as higher capacity use of energy over time.

It is a time consuming job to carefully estimate the average thermodynamic efficiency ratio for an economy and this has so far only been attempted for the US economy 1900–2000 by Ayres and Warr (2003, 2005). It may be presumed that improvements in the thermal efficiency of machines diffuse among economies, so that for specific types of energy converters the efficiency will be more or less the same at a certain point in time. Here, we simply apply the thermodynamic efficiency figures calculated by Ayres and Warr for America to Sweden. This is because in this context it does not make sense to devote all the needed effort to estimating a Swedish-specific efficiency ratio.\(^3\) Differences in the Swedish and American average thermodynamic efficiency ratio will largely be an effect of the composition of thermal/mechanical/chemical energy, and these figures are not readily available for Sweden. We use our Swedish energy figures and multiply them with the average thermal efficiency for the US to get a reasonable indicator of the energy services employed in the Swedish economy.

### 4. Results

#### 4.1. K/E ratios and relative price of energy

The \( K/E \) ratio in Sweden increased in the period 1870–2000, both economy-wide and in industry, see Fig. 2. The long-term growth has been slightly different with an average annual increase of 1.7% in industry and 1.4% at the GDP level.

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\(^2\) Ayres and Warr use the concept exergy instead of energy. Exergy is the sum of the four components: kinetic, potential, physical and thermal. Typical reported energy content of fuels (heat of combustion) are very similar to the exergy content, electricity being the only energy source with an exergy conversion factor equal to 1, hence we have not concerted fuel contents into exergy units in this study.

\(^3\) Sensitivity analyses performed for the US using the REXS system dynamics model (Warr and Ayres, 2006) also suggest that the overall conclusions in this paper would not be seriously affected by inaccuracy in this measure caused by applying US efficiency estimates.
The observed increase of the $K/E$ ratio means that the capital stock persistently has grown at a higher rate than energy use, both at the GDP level and in industry, indicating an energy saving bias in capital accumulation, or that more quality has been added to the capital stock in relation to a given amount of the energy utilized by this capital.

Next we test the reasonable hypothesis that the relative price of energy has stimulated this increase in the $K/E$ ratio. We calculate the correlation between the $K/E$ ratios and the relative price of energy to machinery ($pE/pM$) and expect a positive correlation. For industry we have annual data for the period 1890–2000 on both the capital/energy-ratio and the relative price of energy to capital goods, shown in Fig. 3.

The result is that there is fairly strong correlation of both short-term movements in the series, with a time lag up to 3 years, and long-term changes in levels.
In the long term the price of energy has risen in relation to machinery—roughly two times since 1910 and three times since 1890. In the same periods the stock of total capital has increased four times and the stock of machinery eight times in relation to the quantity of energy. While the relative energy price has increased by 1.0% annually since 1890, the capital to energy ratio has risen by 1.7% and the machinery to energy ratio by 2.4% annually. Thus, this long-term form of price elasticity of the $K/E$ ratio is on average 2.4 for machine capital and 1.7 for total capital. This is a high elasticity and indicates that the possibility of substituting capital for energy in the long term has been considerable. Econometric tests generally give lower price elasticity. However, the price elasticity results here are not just substitution effects, as in the econometric tests, but the combined effect of substitution, biased technical change and structural changes.

There is also a periodic pattern in the changes of the relative price and the $K/E$ ratio. Thus, periods of marked increases in the $K/E$ relation (i.e. in the 1910s, the 1940s and the 1970s) have been preceded by pronounced relative price changes. The relative price changes do not originate only in supply shocks on energy markets but also in developments of machinery prices with a background in innovative activity. That was clearly the case in the decades around 1900, with the second industrial revolution, that brought a new generation of machinery to the market at decreasing relative prices before the price shocks of the First World War. Relative prices of machinery also fell decisively during the 1930s before the Second World War. Furthermore, in the early 1950s both machinery and energy prices fell in relation to general price indices, supporting the strong increase in both capital stock and energy volumes in the post-war growth era. At the end of the 1960s relative machinery prices fell once again preceding the oil price shocks. The general picture is thus that trend breaks in the price ratio ($p_E/p_M$) preceded changes in the volume relation ($K/E$), that in turn were reinforced by the subsequent crises on the energy market.

This lagged reaction of the $K/E$ ratio to relative price changes is clearly visible in a short term econometric model, which better depicts pure substitution effects. Thus, a model with a lagged structure of relative price changes of energy to machinery ($p_E/p_M$) gives a good fit to short term changes in the capital to energy ratio ($K/E$) in Swedish industry 1890–2000. The best fit was found for model 1, with three lags. Additional lags did not give significant values and were therefore omitted. The autoregressive term $AR(1)$ does not influence the result to a large degree; coefficients are significant even without it and only marginally larger, but it gives better Durbin Watson statistics and was therefore included in the results in Table 1.

Model 1:

$$D \ln(K/E) = C + b_1 \times d \ln(p_E/p_M(-1)) + b_2 \times d \ln(p_E/p_M(-2))$$
$$+ b_3 \times d \ln(p_E/p_M(-3)) + b_4 \times AR(1)$$

<table>
<thead>
<tr>
<th>$b$-coeff</th>
<th>$T$-stat</th>
<th>Prob.</th>
<th>Adj. $R^2$</th>
<th>DW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>0.009</td>
<td>1.36</td>
<td>0.175</td>
<td>0.29</td>
</tr>
<tr>
<td>$d \ln(p_E/p_M(-1))$</td>
<td>0.377</td>
<td>6.27</td>
<td>0.000</td>
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</tr>
<tr>
<td>$d \ln(p_E/p_M(-2))$</td>
<td>0.157</td>
<td>2.55</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>$d \ln(p_E/p_M(-3))$</td>
<td>0.154</td>
<td>2.56</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>$AR(1)$</td>
<td>0.077</td>
<td>0.77</td>
<td>0.441</td>
<td></td>
</tr>
</tbody>
</table>
Table 2
Annual percentage change in the relative price of energy to machinery and in the capital/energy ratio in heavy and light industries in Sweden 1925–2000

<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Relative price</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy/machinery</td>
<td>+1.1</td>
<td>+2.5</td>
<td>−2.3</td>
<td>+3.9</td>
<td>−1.3</td>
</tr>
<tr>
<td>Heavy industries K/E</td>
<td>2.0</td>
<td>1.5</td>
<td>1.5</td>
<td>4.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Light industries K/E</td>
<td>1.5</td>
<td>0.3</td>
<td>1.8</td>
<td>3.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Heavy industries: metal works, pulp and paper, earth and clay industries. Light industries: engineering, wood industries, food industries, textiles and clothing industries. Source: Schön (1990), Statistics Sweden. Note: The reason for the missing years 1988–1991 is that the original study is up to 1987 and that downloadable series at Statistics Sweden are only available from 1992 onwards.

The T-statistics show that the lagged short term changes in the relative price are all statistically significant and the coefficients show that they have a clear impact upon the capital to energy ratio (Table 2). Thus, the combined short term elasticity in the capital to energy ratio to relative price changes during the preceding 3 years is close to 0.7, which is an inelastic response and shows some limitations in the ability to respond to market price incentives within that time span. The model explains roughly one third of the total short term variations in the capital to energy ratio.4

4.2. K/E ratios in heavy and light industry

Technology does not develop evenly among the different branches within industry. In light industries, energy is a minor cost item in relation to labour. Thus, in these industries any bias in technical change towards energy saving relative to capital is presumed to be of secondary importance. Capital is rather used in order to save labour. In heavy industries, on the other hand, both capital and energy are considerable cost items in relation to labour. Therefore, it is reasonable to assume that the bias towards energy-saving technical change is stronger within industries that are energy intensive. Furthermore, it is also reasonable that the inclination to use energy-economising techniques, i.e. substitution of capital for energy, is particularly strong within these industries.

Two hypotheses follow from this: firstly that overall the rate of increase in the capital/energy-ratio should be positively correlated to the degree of energy intensity in the branches, and secondly that the rate of increase in the capital/energy-ratio in energy intensive branches should vary more in accordance with variations in the relative price of energy.

To investigate these hypotheses, the branches of Swedish manufacturing industry were divided into the two groups of heavy and light industries for the period 1925–2000. The heavy industries are iron and steel works, pulp and paper industries and industries of construction materials such as cement, glass, bricks etc. Their energy to capital relation is three to four times higher than the light industries of engineering, saw mills, food industries, textiles and clothing. Since heavy industries are also relatively capital intensive, the weight of energy in total costs is comparatively even higher. Thus, the energy in relation to value added (energy intensity) is overall around 10 times higher in the heavy industries than in the light industries.

4 We tested the series for cointegration and they were found not to be cointegrated. Thus, a Granger causality test was performed and this confirmed the results of the OLS estimation (ordinary least square). Adjusted $R^2$ was the same, as was the elasticity for the 1-year lagged variable and the 3-year lagged variable. The elasticity of the 2-year lagged variable was 0.12, thus slightly different from the OLS.
The result of the disaggregation into these two groups is very much in accordance with the hypotheses. In the long run from the 1920s to 2000, the increase in the capital/energy ratio has been noticeably stronger in the heavy industries. The response has been rather elastic to the increase in the relative energy price (an elasticity of 1.8), while light industries show a markedly less elastic response (1.4). Furthermore, the relative responses between these types of industries have differed very much in periods of rising and falling energy prices. In the two periods of rising energy prices (the 1930s and 1940s on the one hand and the 1970s and 1980s on the other) the bias towards energy saving was definitely stronger in heavy industries, while the light industries actually had a stronger energy saving bias than heavy industries in the 1950s and 1960s as well as in the 1990s when energy prices were falling. The latter circumstance may be explained by the fact that wages increased more rapidly in those decades, which spurred a technological change that was mainly labour saving in labour intensive industries but had some capital for energy saving effects as a side consequence.

4.3. Biased technical change

The result of generally increasing $K/E$ ratios comes as no surprise, when we consider the strong thermal efficiency improvements that have taken place in machinery over this long period. Energy losses have been reduced in the conversion from heat to motion, something which acts to reduce the $E$ factor in the ratio, and more energy efficient capital has a higher value (ceteris paribus), which acts to increase the $K$ factor. The thermal efficiency increases therefore act twofold, both on the numerator and the denominator, to increase the $K/E$ ratio. These thermal efficiency improvements may be regarded as embodied biased technical change, saving energy more than capital, and being one way that the $K/E$ ratio is affected over time.

To investigate the size of the impact from embodied biased technical change on the $K/E$ ratio, we calculate the energy services (primary energy $×$ thermal efficiency ratio). One can certainly expect substantial consequences if we calculate energy services rather than primary energy: $K/energy$ services ratio is not going to increase as much (if at all!). The actual $K/energy$ services ratio for the total economy (KAPESER) and for industry (IKAPESER) over the period 1900–1998 is depicted in Fig. 4. The ratio shows large fluctuations, notably in the early 1920s, but the more interesting

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**Fig. 4.** The $K/energy$ services in the total economy (KAPESER) and in industry (IKAPESER), 1900–1998, lin-log scale. **Sources:** See Fig. 1 and Ayres and Warr (2005). **Note:** For construction, see Appendix A.
finding for our discussion here is that the energy services to capital ratio shows no clear time trend over this long time period, although there is a weak U-shape form with a low-point in the 1970s.\(^5\)

For part of the period there is even a reverse in the long run development of the KAPESER. Thus, from the early 20th century up to the early 1970s, there was a weak tendency for energy services to increase in relation to capital, both in industry and economy-wide. In both KAPESER and IKAPESER the long run annual decrease is 0.6%. Then, from the mid-1970s energy services were relatively reduced—abruptly in industry (1.1% annually) and more gradually at the GDP level (0.8%), due to energy saving and to structural/technical change.

Summing up the results so far we notice that the two kinds of capital to energy ratios: \(K/E\), and \(K/\text{energy services}\), produce very different results during the 20th century; from a fourfold increase for the baseline \(K/E\) ratio of GDP and a six-fold increase for the industry ratio, to nearly time stationary KAPESER and IKAPESER series. We have also demonstrated a strong price effect on the \(K/E\) ratio. A relevant question then is how the relative price of energy services has developed (see Fig. 5).

The relative price of energy services to machinery shifts downwards very substantially over the twentieth century, since machines have become much more effective in using energy. Thus, from a doubling of the relative price of energy, the relative price of energy services has been halved. In particular the period from 1920 to 1970 saw both a technological change and a development of the energy supply that reduced the price of energy services—a trend that was broken, however, in the 1970s with a marked increase in the relative price.

At this stage it is relevant to ask which of the two measures of capital/energy ratios is most useful for the discussion of how difficult it is to replace energy with capital. We suggest that the baseline \(K/E\) ratio is most useful in a discussion on constraints due to limitations in natural resources, because this ratio shows how much energy (in quantitative terms) has actually been used by the economy in relation to its capital stock. The \(K/\text{energy services}\) ratio, on the other hand, is highly relevant in a production function context, when it comes to modelling the economy and

\(^5\) The Augmented Dickey Fuller test with five lags rejects the hypothesis of a unit root in both series at the 1% significance level. However, this test can be unreliable in the presence of structural breaks like the one we can notice around 1970.
its dependence on energy services and technological progress, since it is those energy services that actually contribute to production.

We suggest that in addition the \( K'/E \) ratio may be used for analyzing the determinants of the \( K/E \) ratio (biased technical change versus substitution). For example the long run increase in the \( K/E \) ratio in combination with a nearly stationary \( K'/E \) ratio, allows the interpretation that all of the long run increase in the \( K/E \) ratio is due to thermal efficiency improvements of the capital stock. This is first of all because the conversion factor used for calculating energy services on the basis of primary energy is an empirically and historically based series that sums up all the technical efficiency improvements of machinery, and is thus a factor that catches the embodied energy saving technical change in capital. Second, if this recalculation of the energy into actually employed energy services makes the series time stationary, there is no need for additional explanations. Then the technical energy efficiency improvements are all that have mattered for the long term increase in the \( K/E \) ratio.\(^6\)

5. Concluding discussion

As a basic result, the Swedish capital to energy ratio is clearly increasing in the long-run (over 100 years). This is another example of stylised facts in the energy-capital context, besides the one previously available for the US, used by, for instance, Smulders and de Nooij (2003) for modelling of European development.

A long-term increase in the \( K/E \) ratio may be an effect of either biased technical change or factor substitution. Without any more information than the actual \( K/E \) ratio, it is not possible to determine which of these changes were at play or to what degree (if they were both operating). We have, however, been able to conclude that most, and perhaps even all, of the increase in the \( K/E \) ratio was due to embodied biased technical change. This was made possible by comparing the \( K/E \) ratio with the \( K'/E \) ratio, which proved to be nearly time-stationary over a hundred years period. In the very long run capital has made use of almost the same relative amount of energy services, indicating that energy is a crucial resource and not to any significant degree possible to exchange for man-made capital. Capital and energy services are highly complementary. A stationary or even slightly declining \( K'/E \) ratio, together with an increasing \( K/E \) ratio, shows that all of the increase in the \( K/E \) ratio is due to technical efficiency improvements of machinery, which is a clear case of biased technical change, where energy is saved at the same time as the value of the machines increase. These results indicate that all the biased technical change in an energy saving direction is due to embodied technical change in new, more efficient machinery, and thus confirm what Berndt et al. (1993) suspected, but were not able to show with advanced econometric methods.

Furthermore, the results shown here for the industrial branch level confirm our hypothesis that cost shares matter for energy saving incentives in technical change. Heavy energy intensive branches showed an elastic response to changes in energy prices, while energy savings in the light industries were a side effect of labour savings and technological change in general.

\(^6\) It should be emphasized, though, that this result is dependent upon the conversion figures for the entire US economy, including the generation of electricity in the power industry. Thus the results may be more directly valid at the Swedish GDP level while improvements in the conversion factor in the manufacturing industry (exclusive of the power industry) may be overstated. That would mean that there is some scope for substitution or energy-economizing behaviour. Cf. Schön (2004) that from different methods concludes that 3/4 of the change in the \( K/E \) ratio in the manufacturing industry is due to biased technical change and 1/4 is due to substitution.
From a natural resource and environmental perspective it is important to stress that the economy so far has managed to cope with relatively less primary energy in relation to capital, thanks to impressive improvements in the thermodynamic efficiency of machinery. There are, however, limits to further progress of this kind, because much of the theoretically possible improvements have already been achieved. It is thus not sensible to forecast a similar development for the future as the one we have witnessed in the past. It may, however, be the case that the trend break in the 1970s, with a reduction of energy services to capital, indicates a new long-run trend with a weakened complementarity between energy and capital. This new trend may indicate changes in societal behaviour and consumption pattern that may continue to reduce our dependence on energy for further growth.

Uncited references


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Appendix A


Energy series for the manufacturing industry are from Schönh (1990, 1992) and for the entire economy from Kander (2002). For the earliest decades the series rely upon benchmark estimates, but from the 1910s there are annual official statistics that for the manufacturing sector become

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7 The theoretically highest possible efficiency when converting heat into mechanical energy is expressed as the Carnot process: \( \eta = (T_1 - T_2)/(T_1) \). The burning of fuel to achieve mechanical power is a circular process, where the efficiency is determined by the highest and lowest temperature in the process, \( T_1 \) = the maximal heat (very reliant on the materials), \( T_2 \) = the heat of the cooling medium. The temperatures are given in absolute values (Kelvin). When Carnot formulated this theory in the early 19th century he believed that the maximum efficiency for converting heat to motive power was around 30%, but subsequent development has pressed the figures up to almost 50% efficiency to date.
comprehensive in terms of energy carriers from the 1920s and more detailed at sub-branch levels from the 1930s. In the present context both the capital and the energy series are indexed, which means they have no specific unit.

Energy services are calculated by multiplying primary energy with the US conversion factor (Ayres and Warr, 2004). Their conversion factor is for the entire economy including the generation of electricity. Thus, electricity must be calculated by its primary energy content, which has been done for our energy quantity series at the GDP level used for KAPENERGY. Thus, the US conversion factor can be obtained by dividing KAPENERGY by KAPESER. However, at the industry level, the IKAPENERGY series is constructed from the point of view of the users of electricity (i.e. as a secondary energy carrier), which means that in constructing IKAPESER we had both to recalculate electricity by its primary energy content and to convert it into energy services. As a consequence the relation between IKAPENERGY and IKAPESER diverges from the US conversion factor.

Price series for energy are constructed from price series for the individual energy carriers weighted with quantities for different periods (Laspeyre index with fixed weights within the periods)—see Schöen (1995). The price series are from Jörberg (1972), Ljungberg (1990) and Statistics Sweden. For the price of machinery, see above deflators for machinery.

References


