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Electrification and energy productivity

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Abstract

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Keywords: Energy, electricity, sustainable development, productivity

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1. Introduction

Efficiency, i. e. producing more from a certain amount of inputs, is a driving force for economic development. It involves productivity increases in relation to labour, but also in relation to capital and other inputs such as energy and material. Increases in energy productivity are particularly relevant these days, when energy prices peak due to growing demand and insufficient supply. It has been suggested that one way of actually increasing energy productivity is to increase the share of electricity in the energy consumption basket.

Historical investigations of the relation between electricity and productivity in the US economy have primarily been focused on the breakthrough period of the electrical motor from the 1890s to the 1920s. Schurr and Netschert (1978) have noticed that there were not only a general productivity surge in the 1920s, but also a steep increase in energy productivity, which they conjecture was related to the electrification of industry. Devine (1983) connected the general productivity growth with the energy productivity growth. He explicitly explained the productivity effects that arose from the electrification of industry, when steam and water powered prime movers were replaced by electric motors that first drove groups of machines and later individual machines. Not only did this mean that energy was saved, because of reduced losses in the transmission of power within the industrial factories; it also improved the working conditions and the control of machines and enabled the gradual expansion of plants. Together, this improved the productivity of labour and capital. It was not just the electric motor that had these productivity effects, but also electric light which improved the working conditions. The productivity effects were further emphasized by David (1990) in a discussion of "productivity paradoxes", when he regarded the productivity increase in the first decades of the 20th century as a delayed effect of the introduction of the electric dynamo in the 1880s.

Moser and Nicholas (2004) question that the surge in US productivity growth in the 1920s is attributed to electrification. Using the patent statistics, they find that electricity does not stand out as exceptional in comparison with other technology fields. They use a sample of American patents in the 1920s and the citations that these patents received much later: in the period between 1976 and 2002. They find that although electricity patents were broader in scope and more original on the date of grant, they had lower generality scores than other sectors (due to fewer forward citations per patent and lower range of different industries that cite the patents) and a shorter impact period (the mean time between the grant date of a patent and the date of all its forward citations). This may well be true, but the question is if patent statistics is the appropriate means for evaluating productivity effects. We think that Moser and Nicholas (2004) play down the role of electricity inventions, by only counting technical inventions within the electricity producing sector as "real" electricity inventions, and neglect the inventions within electricity-using sectors. However, in a discussion of electricity from an economic growth perspective it is absolutely essential to look at the productivity effects of *using* electricity. A second problem with their analysis is that patent citations are unsuitable for testing whether electricity is a widely adopted technology or not. This is simply because when something is general enough it becomes common knowledge, so there are no longer any citation requirements for subsequent patents. This means that all machines that use electricity as a power source between 1976 and 2002, or all lighting equipment, or heating by means of electricity do not cite electricity patents from the 1880s. Neither do all micro-electronic patents of the 1970s cite the basic electricity patent, although integrated circuits make use of low current electricity. Electricity is so deeply embedded in our society that hardly anything functions without it, exactly because it is a general purpose technology, and to paraphrase Solow (1987): "We find electricity everywhere but in the patent statistics".

This paper contributes to long term studies of productivity effects from electrification. We use Swedish industry as our case, not only because Swedish statistics are detailed back to the breakthrough period of the electrical motor, but also because electricity has been very influential in Swedish industry, which is still today very electricity intense compared to other countries. Sweden went for electricity early on in its industrial development, and thus it is a highly relevant case study of productivity impacts from electricity. The lack of domestic fossil fuels, but extensive access to waterfalls, made electricity a cheap and attractive choice for Sweden. Electrification was central in the decisive acceleration of Swedish industrialization from the 1890s onwards. The development of electrical utilities and electrical engineering industries was stimulated by the demand from energy-intensive industries. The Swedish state actively promoted the adoption and diffusion of electricity, establishing a national grid, connecting the sites of electricity generation in the far North with the consumption locations in the South, in the 1930s. The inter-relationship of electricity, productivity and structural transformation of industry was previously studied by Schön (1990, 1991, 2000). He showed that electrification was part of a broader structural transformation of industry that followed a specific pattern. Leaps in electricity use and in the share of electricity were taken in three periods of roughly 15-20 years, namely 1900-1920, 1940-1960 and 1975-1990. These periods coincided with technological breakthroughs in electricity equipment and utilities as well as with disruptions in the supply of fuels. Furthermore, electrification was part of a technological upgrading and the share of human capital increased more decisively in sub-branches that electrified (a case of technology/skill complementarity, cf Goldin and Katz 1995). In that sense, Schön identified electricity as a force behind long-term labour productivity growth in Sweden. The productivity effects were delayed, however, until the industrial organization was rationalized and the share of electricity stabilized. Productivity growth increased in the 1920s, 1960s and 1990s. Hence, the productivity paradox effect in relation to electricity repeated itself.

This article addresses a somewhat different question than previous studies by Schön. Instead of putting the productivity effects into a cyclical pattern and studying delayed effects of 15-20 years we here investigate more or less concomitant effects (with only a few years lag). We further investigate the impact from electrification on energy productivity (value added/energy quantities) and not on labour productivity. Energy productivity is highly relevant today in its own right, with the surging oil prices and threats of global warming. Furthermore, impacts on energy productivity that goes beyond the effects from using a more refined energy carrier, will demonstrate efficiency effects from electricity that have an impact on a country's energy balance. Further, one can assume that effects on energy productivity will have an effect also on on labour productivity, even though this may come with a more pronounced time lag, as suggested by previous studies by Schön and Devine.

We use the time-series method of cointegration to investigate the impact of electrification on energy productivity in some broad Swedish industrial sectors and we find a strong impact of electrification on energy productivity in the machinery and chemicals sectors. These sectors use electricity for multiple purposes. In a second step we sharpen the test to rule out the probability that all these energy productivity gains from electrification are due to electricity being a more refined energy source than oil or coal. We label the gains in a user industry from switching from coal or oil to electricity as "book-keeping effects", since energy losses in electricity production are borne by the electricity generating sector and not by the electricity using industry. Thus we check whether we can make certain that the energy productivity effects we find are of the spillover kind, really augmenting productivity, as suggested by earlier analyses like Devine (1983). We do actually find spillover effects of electrification on energy productivity in those sectors that use electricity for multiple purposes, but not in others, and propose a set of tests that can specify how long the time lags are in various energy using sectors.

2. Theory and conceptualization

2.1 Simply book-keeping effects or also spillovers?

There are two principal ways that electricity may affect energy productivity within a certain industrial sector: book-keeping effects and spillovers. The book-keeping effects are due to electricity being a secondary energy carrier, produced from primary sources, which has high technical efficiency in its final use compared to fuels. Using increasing amounts of electricity leads to lower energy demands and increased energy productivity in a specific sector, per se. However, this gain from electricity is not a real gain in terms of energy requirements in relation to output on the GDP level – as long as electricity is produced from fuels – since the transformation losses of converting the primary energy to the secondary energy are borne by the electricity-generating and transmitting industry. Such energy savings are in one sense illusionist and may thus be perceived as "book-keeping" gains.

A second possibility, and what we are interested in here, is that there are "dynamic" impacts, or spillovers, of electricity on energy productivity within the electricity-using sectors, impacts that go beyond the book-keeping gains. The dynamic effects have to do with new organizations of production, better working conditions for the workforce etc. Schurr and Netschert (1978) put forward this interpretation of the energy productivity development in the US and Devine (1983) claimed that there were total factor productivity (TFP) gains in industry from electrification. Furthermore, Schön identified TFP gains through the complementarity between electricity and skills in more sophisticated technology within Swedish industry for the period 1890 to 1990 (Schön 1990, 2004). These dynamic effects, or spillovers, are likely to be more prevalent within industrial sectors with multiple and extensive use of electricity, such as machinery, than in sectors of single-use, such as railways. The size of the spillovers should depend on whether electricity adoption entails the total transformation of the organization of motive power and work within a factory, or if it mainly means that a fuel-driven engine is substituted by an electricity-driven one.

We conceptualize the electricity-generating sector and the electricity-using sectors as forming development blocks that drive growth (Dahmén 1950, 1988). Major technological breakthroughs, like GPTs, are central to the idea of development blocks. However, the development block concept is much wider and encompasses not only the complementary activities and sectors that co-function with technologically more advanced sectors, but also the infrastructural changes of society. The existence of two partly overlapping development blocks in Swedish industry centered on electricity was quantitatively identified in Enflo, Kander and Schön (2008). That investigation identified development blocks based on sheer common movement in time series of value added of certain sectors. Here, we investigate if there are measurable linkages between electricity use per se and energy productivity of a sector.

We hypothesize that electricity consumption (in MWh) should affect energy productivity (value added/MWh). If this is the case, we expect to find a common stochastic trend between time series of electricity consumption and energy productivity within those industries that benefit most strongly from electrification. This common stochastic trend can be seen as the technology shocks affecting both electricity consumption and energy productivity. In addition, we expect electricity consumption to affect energy productivity rather than the other way around.

3. Methods and Data

The advantage of the Moser and Nicholas (2004) investigation is that they assess different technologies with a common method. Our investigation here, using cointegration techniques, is confined to electricity in Swedish industry, and hence we cannot draw the conclusion that electricity affects productivity more than any alternative candidates. We do not compare the productivity effects from electricity with those from the adoption of chemicals or combustion engines. It might be possible to adopt our method for more candidates, but it would require substantial empirical work to map out the input-output structure for relevant innovations and sectors over a long period of time. Electricity consumption by industrial sub-sectors is easily attainable in the industrial statistics. A long time period, such as the one employed here, is necessary because cointegration techniques require a minimum of 40 subsequent observations in time, which also poses limitations on the studies that may be carried out.

3.1 Energy productivity versus TFP

We choose to focus the analysis on the relation between electricity (expressed as its heat value in any physical energy unit, here in MWh) and energy productivity, rather than on the relation between electricity and TFP. Energy productivity is measured as the value added (in constant Swedish kronor) divided by all energy use (the heat value of electricity and fuels measured in MWh). There is still no consensus on how to model energy in a full production function approach where output and labour are also included. One major complicating factor for such modelling is that energy and capital are highly complementary. Adopting the production function approach means including restrictive assumptions concerning the nature of the production process and the linkages of the production factors that are all the more unsuitable when taking into account the length of the time period encompassed in our study. We argue that the impact of electricity on productivity can be made more compelling by investigating the more restricted issue of the role of electricity for energy productivity. We could have carried out a similar test of electricity and labour productivity, and this would have made sense too. However, according to Devine, both energy productivity and labour productivity increased as a consequence of electrification, and if we find spillover effects on energy productivity we are also likely to find it on labour productivity. This could be tested in a subsequent study.

3.2 Spillover effects or just book-keeping effects?

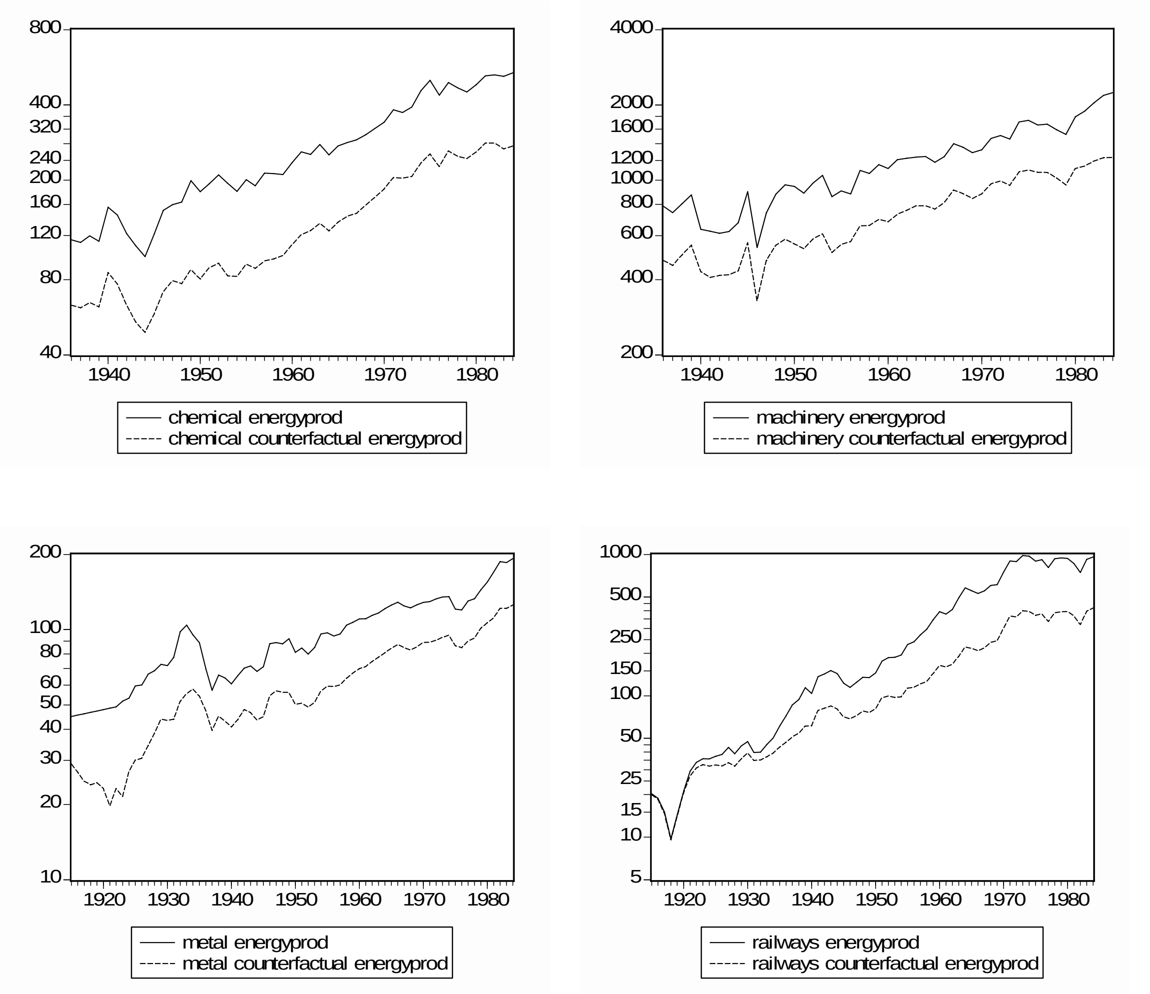
The basic method we use for identifying energy productivity effects from electricity use in an industrial sector is cointegration (see section 3.3). We conduct two tests. First, we investigate whether the actual electricity use of a sector is cointegrated with its energy productivity. Second we sharpen the test by constructing a counterfactual energy productivity measure and investigate whether this too is cointegrated with electricity use. If that is so, we consider spillover effects from electricity. The counterfactual energy productivity is based on the assumption that the electricity consumed in one sector is also produced within that sector by the use of fuels, and thus the energy value of electricity is calculated as the energy value of the fuels required for its production - also counterfactually assuming that all electricity is produced from fuels. In reality the bulk of Swedish electricity is generated from hydropower, and not from fuels. However, if the plants of the sectors have to produce the electricity themselves they will in most cases be forced to do so by means of fuels, if they are not located by a waterfall. Since electricity generation and transmission have become substantially more efficient over time, it is necessary to use a historically-founded factor for converting primary energy into electricity. The conversion factor we have used is taken from Kander (2002) and based on Etemad and Luciani (1991).

Thus, by our method we translate the energy value of electricity to the heat content of fuels necessary for its production for each and every year (according to the technology of the time). In the counterfactual energy productivity measure we have in fact deducted the book-keeping gains by transferring the energy that is needed for the production of electricity for the electricity-using sector. This means of course that the level of energy use will be raised and hence that the level of energy productivity will be lowered (see figure 1).The important characteristic is not the level but the rate of change in energy productivity in relation to electricity use. In principle, the difference between the growth rates of the original energy productivity and the counterfactual energy productivity will be the net effect of two opposing forces that takes place over time: the growing electricity shares that raise the counterfactual energy use and the declining transformation losses that lower the counterfactual use. Over this period the electricity share of total energy increases substantially, but at the same time the transformation losses of energy decrease a lot (which is expressed in the changing conversion factor).

If electricity use is cointegrated, not only with energy productivity, but also with the counterfactual energy productivity, an effect of electrification on energy productivity is indicated, which reaches beyond book-keeping gains, and thus is of a spillover character.

Figure 1 depicts the actual energy productivity and the counterfactual energy productivity in four main sectors of Swedish industry that are important electricity users. We have access to data for the period 1915-1987 for the metal industry and the railways, and the period 1936-87 for the machinery and chemical industries. 1936 is the earliest year for which there is a complete set of energy statistics at the industrial sector level in Sweden, and after 1987 the statistics change, so creating consistent time series after that year is much more labourious.

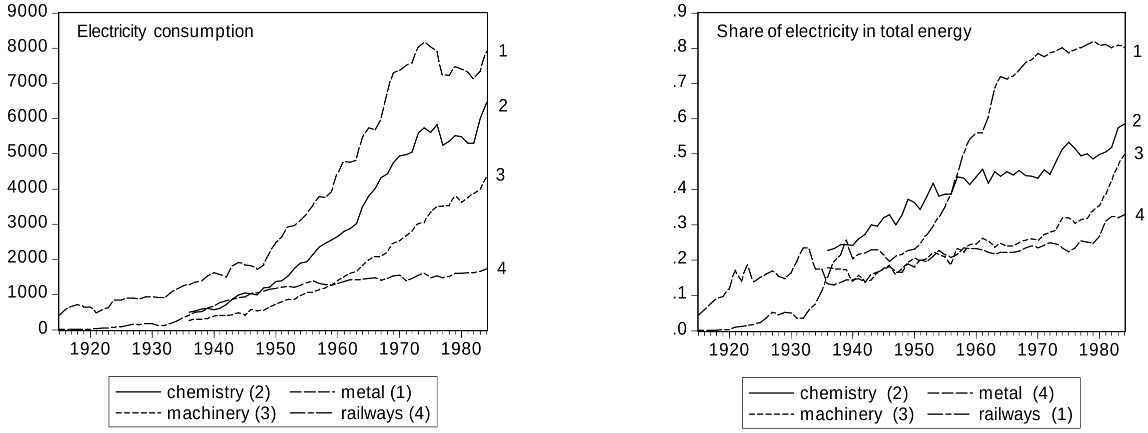
Figure 1. Energy productivity (Value added in 1969/70 SEK) divided by total energy use in MWh, logarithmic scale on the y-axis.



Sources: Schön (1990), SOS Järnvägar.

Longer time series would be beneficial for the cointegration test in general, but the results would probably not change, since the electricity conversion factor stabilizes in the early 1990s. Figure 2 displays electricity diffusion after 1915 for the metal industry and the railways, and after 1936 for the chemical and machinery industries. The left panel in the figure shows the total energy consumed and the right panel shows the share of electricity in total energy for the same industries.

Figure 2. Total electricity consumed in 1000s MWh (left) and the electricity share of total energy used (right) in four industries.



As seen from the figures, electricity consumption grew substantially during the 20th century. Total electricity consumed grew rapidly in the post-war period, foremost in the energy-intensive industries metal and chemistry. The share of electricity in total energy consumed increased in Swedish industry to varying degrees, showing the highest growth in the electrification of the railways. The chemical industry relied on electricity for more than half of its energy consumption in the 1980s and the machinery industry converged to similar levels after a rapid electrification during the 1970s and 1980s. The lowest and most stable electricity share is found for the metal industry for which electricity accounted for roughly 30 percent of total energy consumption at the end of the period. Fuel-based thermal processes dominated production in this latter sector.

3.3 Cointegration and VECM:s

We use cointegration methods to identify the long-term relationships between electricity use and energy productivity in the chemical, machinery and metal industries and the railways during the 20th century. The concept of cointegration can be defined as a systematic co-movement between two or more non-stationary variables over the long run. A variable is non-stationary when its mean, variance and covariance are time dependent. This implies that any shock to the variable will have a permanent effect, as the variable does not revert back to its mean. Before identifying cointegration relations between our variables, it is therefore crucial to test whether all the time series are non-stationary, i.e. whether they have a unit root. The unit root symbolizes that any shock to the variable multiplies with time in the series so that it never returns to its mean.

The reason for using cointegration methods when variables are non-stationary is that regressing non-stationary variables upon each other is likely to produce spurious results (Granger and Newbold: 1974). Many economic time series have been found to be non-stationary and in order to avoid producing spurious results, methods dealing with this property are a crucial tool. One method has been to first difference the variables to make sure that they are stationary before they are included in any regression. The drawback of such a procedure is however that any long run properties of the time series are removed and the analysis only carried out on the short term changes in the series.

In order to analyze long run properties of time series cointegration methods must be used. These methods rely on the result by Engle and Granger (1987), who showed that there may exist a linear combination of two non-stationary variables that produces a stationary time series. If there is such a linear combination, the two non-stationary time series are cointegrated, which means that they may drift away from their original means, but that they follow the same stochastic trend, so they never drift too far apart from each other in the long-run. This long-run relationship between the series can be analyzed in a cointegration equation. Thus, if X_t and Y_t are non-stationary but cointegrated, there will be some value, β, such that $Y_t - \beta X_t$ is stationary.

To investigate whether there is a systematic long-run relation between electricity use and energy productivity, we use the Vector Auto Regression (VAR)-based trace test for cointegration developed by Johansen (1988, 1991). The Johansen test is carried out in several steps where it first tests the null hypothesis of zero cointegration relations against the alternative of at least one cointegration relation using a differenced VAR-model. If the first null hypothesis is rejected, the test continues by testing the null hypothesis of one cointegration relation against the alternative of at least two cointegration relations. This procedure alleviates the identification of more than one cointegration relation, which is impossible with the simple Engle-Granger (1987)-cointegration test. The Johansen test is also chosen since it allows for the inclusion of exogenous variables, trend stationary variables, a constant and a trend in the cointegration relation. The test is, however, sensitive to the choice of lag length in the original differenced-VAR used for the test, so we use a combination of Akaike, Schwarz and Hannan-Quinn information criteria and lag exclusion tests to determine the appropriate number of lags before testing for cointegration (the chosen number of differenced lagged terms is displayed in table A1 in Appendix).

Since the asymptotic distribution of the test statistics for cointegration depends on the assumptions made with respect to deterministic trends in the data series and in the cointegration relations, we need to make an assumption regarding the underlying trends in our data. All specifications include an intercept in the cointegration relation, but we only include trends if the variables appear to be trend stationary and if the trend turns out to be significant. Again, details of the specification of the cointegration test are found in table A1 in Appendix.

If we find that electricity and energy productivity are indeed sharing a long-run cointegration relation, we can use this information to find out more about the nature of this long-run relationship, in addition to the short run relations between the variables, by estimating a Vector Error correction Model (VECM).

The Granger representation theorem (Granger: 1983, Engle and Granger: 1987) states that if the variables are cointegrated, there exists a valid error correction representation of the data. If X_t and Y_t are cointegrated, we may write the following Vector Error Correction Model of lag order p:

$$\Delta Y_t = \sum_{i=1}^{p} \Phi_{1,i} \Delta Y_{t-i} + \sum_{i=1}^{p} \Phi_{2,i} \Delta X_{t-i} + \alpha_1 (Y_{t-1} - \beta_1 X_{t-1}) + \varepsilon_{1,t}$$

$$\Delta X_t = \sum_{i=1}^{p} \theta_{1,i} \Delta X_{t-i} + \sum_{i=1}^{p} \theta_{2,i} \Delta Y_{t-i} + \alpha_2 (Y_{t-1} - \beta_2 X_{t-1}) + \varepsilon_{2,t}$$

where Δ is the first-difference operator, Φ and θ are the coefficients of the first-differenced terms. The VECM has the property of estimating the short-term relationship, denoted by the differenced terms, and its adjustment parameters separately from the long-term cointegration relationship. In the case of two variables, X_t and Y_t, their long-term relations are estimated by the β:s in the cointegration relation, within brackets. Note that the specification of the cointegration relation states that a negative sign of the β:s signifies a positive long-term relation. The α:s in both VECM measure the speed of adjustment of each variable to the cointegration relationship. If one α is not significantly adjusting to the cointegration relation, it can be said to be weakly exogenous to the variables in the system. This means that it is driving, rather than responding to, the shocks in the system. Finally, the ε:s are serially uncorrelated error terms.

4. Results

4.1 Testing for stationarity of the variables

We find that electricity consumption and energy productivity are non-stationary variables when testing with the Phillips Perrron-test. P-values for the null hypothesis that the series contain a unit root are found in tables 1 and 2. The Phillips Perrron-test is chosen since it uses a Newey-West heteroskedasticity and autocorrelation consistent estimate that agrees with the assumption of white noise residuals[1]. The tests are carried out using three different specifications to ensure robustness of the results: the first specification without constant and trend, the second with only constant and the third with both constant and trend. It turns out that the null hypothesis of a unit root can not be rejected with any specification so we can safely conclude that our series are non-stationary. In addition, the test shows very high p-values for all series (above 0.48) which indicates that the result of non-stationarity of the series is a fairly robust one. When the trend in the test equation is significant and the unit root is accepted, we conclude that the series are trend stationary.

One potential problem that may plague cointegration analysis with non-stationary time series is that some series may contain two unit roots. These

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[1] There are other unit root tests than the Phillips-Perron (PP) test that may be used, for example the Augmented Dickey Fuller (ADF) test. The ADF-test deals with the assumption of white noise residuals by adding lagged differenced terms to the test equation, and often return similar results as the PP test. Although the unit root test generally has low power (i.e. it may accept the null hypothesis of a unit root too often) our results with the PP-test so strongly indicate that the series are non-stationary that we argue that the results are not sensitive to which unit root tests were used.

series actually require to be differenced twice to ensure stationarity, and they are therefore referred to as integrated of order 2, I(2). Cointegration analyses with time series that are I(2) requires specific procedures, so we must carefully test whether our first differenced times series can be said to be stationary. When we run our PP-tests on the differenced level of the series, we however obtain p-values of 0.00 in all specifications. This means that we can reject the null hypothesis of a unit root in all the first-differenced series. This leads us to safely conclude that the time series data from our four selected industries are non-stationary, only contain one unit root and thus integrated of order 1, I(1).

Table 1. Phillips-Perron test for a unit root in energy productivity series.

Level					1st diff				Conclusion	N
	T-stat	P-val.	Trend	Const.	T-stat	P-val.	Trend	Const.		
Machinery	2.37	1.00	x	X	-6.26	0.00	x	x	I(1) trend	49
	1.00	1.00	x	0.84	-6.74	0.00	x	0.05		
	-2.00	0.59	0.02	0.02	-7.09	0.00	0.09	0.30		
Chemistry	4.48	1.00	x	X	-5.22	0.00	x	x	I(1) trend	49
	1.20	1.00	x	0.44	-6.66	0.00	x	0.00		
	-2.01	0.58	0.02	0.08	-6.92	0.00	0.12	0.77		
Railways	1.10	0.93	x	X	-7.71	0.00	x	x	I(1)	72
	-0.26	0.93	x	0.14	-8.10	0.00	x	0.20		
	-1.94	0.62	0.05	0.13	-8.28	0.00	0.17	0.97		
Metal	2.51	1.00	x	X	-5.69	0.00	x	x	I(1) trend	97
	0.91	1.00	x	0.93	-6.06	0.00	x	0.06		
	-1.77	0.71	0.06	0.76	-6.17	0.00	0.26	0.97		

Table 2. Phillips-Perron test for a unit root in electricity series.

Level					1^{st} diff				Conclusion	N
	T-stat	P-val.	Trend	Const.	T-stat	P-val.	Trend	Const.		
Machinery	7.58	1.00	x	x	-3.81	0.00	x	x	I(1) trend	49
	3.48	1.00	x	0.10	-6.82	0.00	x	0.00		
	-1.24	0.89	0.04	0.10	-8.62	0.00	0.00	0.18		
Chemistry	3.41	1.00	x	x	-4.12	0.00	x	x	I(1) trend	49
	0.58	0.58	x	0.08	-5.47	0.00	x	0.00		
	-2.20	0.48	0.03	0.08	-5.55	0.00	0.34	0.87		
Railways	2.62	1.00	x	x	-5.92	0.00	x	x	I(1)	72

	-0.60	0.86	x	0.01	-7.18	0.00	x	0.00		
	-1.16	0.91	0.34	0.07	-7.13	0.00	0.72	0.04		
Metal	2.89	1.00	x	x	-5.69	0.00	x	x	I(1) trend	97
	0.54	0.99	x	0.06	-6.06	0.00	x	0.06		
	-1.76	0.71	0.05	0.91	-6.17	0.00	0.26	0.97		

4.2 Electricity and energy productivity

After we have ensured that all our variables are non-stationary and integrated of order 1, we may proceed to test whether there are any cointegration relationships between electricity and energy productivity in the four industries. We detect significant relationships for the machinery and chemical industries. This result is in line with our expectations, since electricity in these sectors is used for multiple purposes, so the productivity-enhancing effects of electrification are especially large here. In the railways, and the metal industry, where electricity is used for fewer purposes (merely motive power and heating), we do not find any systematic long-term relations.

Since data availability forces us to use shorter time series for the chemical and the machinery industries than for railways and metals, we need to rule out the effects that the sample size may have on the outcome. Therefore, we also test for cointegration in these industries using a shorter sample from 1936 to 1987. We do not find a cointegration relationship in the railways and metal industries for the shorter time period and conclude that the results seem robust to changes in sample size.

The p-values of the Johansen Trace test for cointegration between electricity and energy productivity are summarized in the upper part of table 3. In the Johansen test, the null hypothesis of no cointegration relationships is first tested against the alternative hypothesis of at least one cointegration relationship. If this null hypothesis is rejected, the procedure is continued by testing the null hypothesis of at most one cointegration relationship against the alternative hypothesis of more than one relationship. P-values lower than 0.05 indicate that we can reject the null hypothesis at the 5 percent significant level, and draw the conclusion that electricity use and energy productivity are related. The Johansen test was chosen since it alleviates the identification of more than one cointegration relation, which is impossible with the simple Engle-Granger (1987)-cointegration test. In addition, the Johansen test is also chosen since it allows for the inclusion of exogenous variables, trend stationary variables, a constant and a trend in the cointegration relation. The test is carried out in the framework of a differenced VAR-model with the two time series, the chosen number of differenced lagged terms is based on Akaike's, Schwarz and the Hannan-Quinn information criteria and the log likelihood lag exclusion tests (details can be found in Appendix). In general we find a rather long dependence between the series; between 2 and 7 lags in differenced terms. This is perhaps not so surprising, since several of the productivity effects of electrification take time to mature.

To check that electricity really has a special effect on energy productivity, and that not just any energy input would have the same demonstrated effects, we carry out the same test for fuels (oil and coal). The bottom rows of table 3 display the p-values from the Trace tests for cointegration between fuels and energy productivity, indicating that we cannot reject the null hypothesis in any of our four industries. Thus, fuels do not affect energy productivity in the same way as electricity.

Table 3. Johansen Cointegration Trace Test.

		Machinery 1936-84*	Chemistry 1936-84*	Railways 1915-87	Metal 1915-87
A. Electricity and Energy productivity		p-values	p-values	p-values	p-values
Hypothesized no. of CE:					
	none	0.03	0.00	0.28	0.47
	at most one	0.95	0.10	0.95	0.58
B. Fuel and Energy productivity					
Hypothesized no. of CE:					
	none	0.85	0.74	0.40	0.84
	at most one	0.39	0.93	0.62	0.69

Note: P-values are calculated from critical values in MacKinnon-Haug-Michelis (1999). Tests are performed with linear deterministic trend specification in the VAR and intercept in the CE. Trends in CE are only included when significant.

* Data availability restricts the sample to 1936-84 for the machinery and chemical industries. See section 4.2 for issues concerning robustness to time specification.

The finding of a long-term cointegration relationship in the machinery and chemical industries requires further analysis using statistical methods. This relationship can be modeled econometrically, using the Vector Error Correction Model. The VECM is a useful way to establish the nature of the long-term relationship between the cointegrated variables. As outlined in the methodology section, the nature of the long-term cointegration vector is such that a negative sign of the β-coefficient in the cointegrating vector indicates that the relationship between the cointegrated variables is positive in the long run, i.e. that an increase in one variable gives rise to an increase in the other. In addition to determining the nature of the cointegrating relationship, the VECM also models how the variables adjust to a shock to the long-term relationship, for example an exogenous technology shock. If one variable is less likely to adjust to restore the long-term relationship, this is an indicative sign that it is driving the system, whereas the other one merely responds to the shocks.

Table 4. Bivariate Vector Error Correction Models (VECM) 1936-84.

	Machinery		Chemical Industry	
Dep. Var.	Electricity	Energy prod.	Electricity	Energy prod.
CE				
B	1.00	-7394	1.00	-14193
		[-3.01]***		[-35.43]***
Trend		197408.30		
		[2.73]***		
Constant		-7255896		1059502
Error correction				
A	0.0026	0.0001	-0.0117	0.0001
	[0.14]	[4.63]***	[-0.06]	[3.17]***
Adj R-sq	0.40	0.40	-0.16	0.39
No. of lags (diff. terms)	5		7	
N	43		41	

Note: T-values are given in parentheses below the estimated coefficient values
*= significance at 10 %-level, ** =significance at 5 %-level, ***=significance at 1 %-level. Electricity and energy productivity series are from Schön (1990), SOS Järnvägar.

If the cointegration relationship between electricity and energy productivity truly is a relationship determined by technology shocks, we would expect electricity to play such a driving role in relation to energy productivity.

Table 4 reports the estimated values from the VECM, where the first two columns give the values for the machinery industry and the last two columns report values for the chemical industry. Starting with the cointegration relationship in the machinery industry, we find that the β-coefficient displays the expected negative sign and that it is significant. The α-coefficients of the error correction show how the differenced terms of the two VECM:s adjust to the long-term cointegration relationship, and are only significantly different from zero in the equation where energy productivity is the dependent variable. In line with our expectations, this indicates that energy productivity is adjusting to restore the positive long-run relationship whenever the system is hit by a shock, whereas there is no significant adjustment in the electricity variable to shocks in energy productivity. Thus electricity is driving energy productivity rather than the other way around. The explanatory power of the VECM:s can be considered high, judging from the adjusted R-squares of 0.4 in both VECM:s.

The last two columns report the VECM estimated for the chemical industry. Again we find that electricity is driving energy productivity. The adjusted R-squares are high in the case of the Energy productivity VEC-equation (0.39) but turn negative (due to the high number of insignificant lags) in the electricity equation. The negative adjusted R-square in the electricity equation indicates that trying to explain electricity with lagged values of energy productivity does a worse job than a horizontal line for the chemical industry. This bad fit is not so worrying for our hypothesis, since we expect that electricity is driving energy productivity and not vice versa.

4.3 More than book-keeping gains?

Our second goal is to ensure that the productivity effects that we measure are not simply static, book-keeping effects. Table 5 reports the test for cointegration between our counterfactual energy productivity (where the pure thermal efficiency gains from electricity are omitted, assuming generation from fuels) and electricity use in the machinery and chemical industries. We find that the null hypothesis of no cointegration relationship is rejected at the 5 percent level for both the machinery and the chemical industries, which we take as an indication of dynamic spillover effects of electricity on energy productivity[2].

In order to ensure that the observed cointegration between electricity and the counterfactual energy productivity is not spuriously related to the introduction of the conversion factor when recalculating the electricity shares, we also test for cointegration between electricity use and the conversion factor. The results are found in the lower part of table 5 and show no sign of cointegration between electricity and the conversion factor. Thus, we may conclude that the long-term relationship between electricity and energy productivity is due to dynamic effects that go beyond the mere book-keeping gains from adopting electricity. Table 6 displays the VECM:s for the relationship between electricity and the counterfactual energy productivity in the machinery (the first two columns) and chemical industries (the last two columns).

Table 5. Johansen Cointegration Trace Test.

Hypothesized no. of CE:		Machinery 1936-84	Chemistry 1936-84
A. Electricity and Counterfactual Energy Productivity			
	none	0.04	0.03
	at most one	0.29	0.51
B. Electricity and the Conversion Factor			
	none	0.09	0.77
	at most one	0.59	0.93

Note: The counterfactual energy productivity is depicted in figure1 and explained in section 3.2. The conversion factor is based on Etemad and Luciani (1991) and taken from Kander (2002). Electricity and energy productivity series are from Schön (1990), SOS Järnvägar.

Table 6. Bivariate Vector Error Correction Models (VECM) 1936-84.

	Machinery		Chemical Industry	
Dep. var.	Electricity	Energy prod. (C)	Electricity	Energy prod. (C)
CE				
B	1.00	-7552.58	1.00	-18866.11
		[-8.58]***		[-7.91]***
Trend		45140.86		-29644.54

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[2] Details of the lag length choice can be found in Appendix.

		[2.73]***		[-2.25]***
Constant		621749.9		1636271
Error correction				
A	-0.1384	0.0003	-0.4243	0.0004
	[-1.42]	[3.86]***	[-1.80]	[4.13]***
Adj. R-sq	0.48	0.52	0.01	0.52
No. of lags (diff. terms)	6		6	
N	42		42	

Note: The counterfactual energy productivity is depicted in figure 1 and is referred to as "Energy prod. (C)" in this table. T-values are given in parentheses below the estimated coefficient values, * = significance at 10 %-level, ** =significance at 5 %-level, ***=significance at 1 %-level.

In the machinery industry the β-coefficient in the CE again indicates a positive and statistically significant long-term relationship. The α:s show that the counterfactual energy productivity is significantly adjusting to the long-run equilibrium, whereas the opposite is not the case, indicating that electricity is the driving force again. The adjusted R-squares are again high in both VECM:s (0.48 and 0.52).

The β-coefficient in the chemical industry also shows the expected negative and statistically significant sign, indicating a positive relation in the long run. The adjustment coefficients again show that there is only significant adjustment to equilibrium in the energy productivity variable. R-squares indicate again that electricity does a better job in explaining energy productivity (0.52) than the other way around (0.01).

Taken together, the VECMs indicate that there is a positive and significant long-term relation between electricity and energy productivity, even after controlling for the obvious book-keeping gains. Adjustment coefficients and R-squares seem to suggest that electricity is the exogenous variable in the system that energy productivity is adjusting to.

5. Conclusion

This article has demonstrated that electricity use has a significant impact on long-term energy productivity in those broad industries that use electricity for multiple uses (machinery and chemical industries).

In addition we have shown that this positive effect from electrification on energy productivity is not confined to “book-keeping” effects (electricity being a secondary energy carrier with low energy losses at the point of consumption), but entails spillover effects, and that the productivity lag typically is 2 to 7 years. This may indicate a productivity lag over an investment cycle, with new electrical machinery installed in the upswing phase and with concentration of productivity effects in the later downswing phase, when the structure is being rationalized, old technologies are driven out and organizational changes are maturing. We have also shown that in sectors with more single-purpose use of electricity (railways and metal industry) there is no measurable impact of electrification on energy productivity. In neither of the sectors do we find any causal impact of fuel use (coal and oil) on energy productivity, so electricity stands out as special.

We have used Swedish industry as our case, because Swedish industries were early adopters of electricity, but we believe the same results could be obtained for other countries as well.

Appendix

Table A1. Specification of the VAR in the Johansen Cointegration Trace Test.

	Machinery 1936-84	Chemistry 1936-84	Railways 1915-87	Metal 1915-87
Electricity and energy productivity				
Trend in CE	Y	N	N	N
No. of lags (diff. terms)	5	7	7	4
Fuel and energy productivity				
Trend in CE	Y	N	N	N
No. of lags (diff. terms)	2	4	7	4
Electricity and counterfactual energy productivity				
Trend in CE	Y	Y		
No. of lags (diff. terms)	6	6		
Electricity and the conversion factor				
Trend in CE	N	N		
No. of lags (diff. terms)	3	1		

Note: Whenever the different information criteria gave conflicting results regarding the number of lags that should be chosen for the lagged differenced terms in the VAR, the number indicated by the majority of the tests (Akaike, Swarz, Hannan-Quinn and the log likelihood lag exclusion test) were chosen. Trends in the cointegration relations were only added when significant at the 5%-level.

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