Electrification and productivity growth in Korean manufacturing plants

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ABSTRACT

This paper presents a theoretical model of firm-specific productivity growth that incorporates technological knowledge by electrification and tests the model empirically. Our theoretical explanations suggest that the energy-transformation from fossil fuel to electricity by electrification could cause a decrease in the short-term level of productivity but an increase in the long-term rate of productivity growth in firms. Our empirical evidence from a large panel of Korean manufacturing plants is generally consistent with the theoretical predictions on the relatedness of technological knowledge by the electrification to the level and rate effects of the firm’s productivity. The electrification measured by the share of electricity results in lowering the short-term productivity level but in raising the long-term rate of productivity growth of firms.

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1. Introduction

The share (weight) of electricity in the world’s total energy consumption increased from 9.4% in 1973 to 17.7% in 2010 (International Energy Agency, 2012). The importance of electricity in the energy use is also evidenced in Korea. There has been a strong increase in electricity’s share of total energy use for decades while fuel’s share of total energy use in Korea has decreased (Fig. 1). For example, the share of electricity in total energy use in Korea grew from 7.2% in 1978 to 19.7% in 2010. The overall efficiency of energy use, as measured by GDP per total energy use, has also been persistently improving from 4.23 in 1978 to 5.38 in 2010. The improvement in the efficiency of energy use with the increase in electricity’s share of total energy use plays an important role in the advancement of the production and hence it helps an economy grow. For example, in their study covering over 100 countries Ferguson et al. (2000) showed that electricity usage is highly associated with economic growth.

Since the work by Kraft and Kraft (1978) and Akarca and Long (1979, 1980), the causal relationship between energy consumption and output has been an important topic in energy economics. Most of these studies employed a neo-classical aggregate production model where the use of energy, in particular, the use of electricity, is treated as a separate input in production in addition to capital and labor inputs. However, causal examination of the relationship between electrical energy use and output has not reached a consensus on the direction of causality between the two because the results differ depending on approaches, time horizons and countries employed in the various empirical analyses (See Apergis and Payne (2011) for a detailed summary). Some empirical evidence is in favor of a positive effect of electrification on productivity while others are not. It is important to point out that empirical results are also affected by whether the analysis is based on short term or long term.

Apart from the causality issues, Schurr et al. (1983) and Jorgenson (1984) found that the electrification in the U.S. industry sector accounted for the rise in productivity and output. Schurr et al. (1980) also pointed out that the inter-relationships among electrification, productivity growth, and energy efficiency (Fig. 2). The electrification of plants and equipment has contributed to technological progress and helps account for the rising use of electricity relative to total energy. This technological progress has been a major factor supporting productivity and output growth. Productivity growth, in turn, has saved total input relative to output, including savings in energy input. The electrification and technological progress take place almost simultaneously and affect each other. The increase in electricity use by electrification and productivity gains by technological progress are linked to energy efficiency in the long run.

Several studies have explained the contribution of electrification to the improvement of productivity. For example, Berndt (1983) found that energy quality, specifically the electrification ratio in total energy, has had a positive and statistically significant impact on productivity growth in American manufacturing from 1958 to 1977, even though...
this energy quality effect was found to be small for multi-factor productivity growth. Moreover, Berndt (1990) surveyed the most important aspects underlying the relationships among technical progress, productivity growth, and energy use. He found that the concepts of embodiment, diffusion, and learning are critical for understanding the forces linking energy use, technical progress, and productivity growth. Kahane and Squitieri (1987) and Schön (2000) argued that productivity growth, and energy use. He found that the concepts of embodiment, diffusion, and learning are critical for understanding the forces linking energy use, technical progress, and productivity growth. Kahane and Squitieri (1987) and Schön (2000) argued that productivity growth is reduced. In addition to the link between productivity and energy efficiency, and conversely, when energy is abundant, its effect on economic growth is reduced. In addition to the finding that the elasticity of the substitution of energy and capital is likely to be low, he emphasized that energy used per unit of output has declined in developed countries and in some developing countries because of both technological change and a shift from poor quality fuels to higher quality fuels, especially electricity. In particular, the improvement in energy efficiency in both developed and developing economies may be partly due to the shift to higher quality fuels and thus different energy qualities have differing levels of productivity.

The above studies, however, are limited in determining a clear relationship between electrification and productivity in that they analyzed the effect of electrification on economic growth aggregated data. To overcome this limitation, Doms and Dunne (1995) and Boyd and Pang (2000) employed plant-level data to examine the role of energy use in production. On the one hand, Doms and Dunne (1995) found that when using plant-level data plants using AMT (Advanced Manufacturing Technology) are less energy-intensive than plants not using AMT, although the former consume proportionately more electricity as an energy source. Additionally, older plants are generally more energy intensive and rely on fossil fuels to a greater extent than younger plants. The results by Doms and Dunne (1995) indicate that technology affects energy and electricity usage in a statistically and quantitatively critical manner. However, they are silent on the effects of electricity usage on productivity of plants. Boyd and Pang (2000) examined the link between productivity and energy efficiency, and tested this link empirically using plant-level data. They found that productivity differences are important determinants of energy efficiency and supported the proposition that energy intensity and productivity have at least a proportional link. However, their analysis does not explain the role of electrification in the advancement of technology even though they generally explain the relationship between energy efficiency and productivity, using plant-level data.

Moreover, the adoption of technical progress by electrification is not immediate. Schmidt (1987) asserted that the electrification of industry is a long-term process, occurring over decades and that the intensity, precision, and controllability of electrically-based processes become increasingly important factors in improving industrial productivity, lowering cost, and reducing energy consumption. Schön (2000) commented that productivity growth by electrification is resource-demanding in the short term but it depends on innovation in the long term. Goldfarb (2005) also argued that electrification as a general purpose technology could be delayed by the technical bottlenecks, but it could proceed rapidly upon finding solutions to particular technical problems.

In keeping with the analysis of electricity consumption and technology by Doms and Dunne (1995) and the study of productivity and energy efficiency by Boyd and Pang (2000) using U.S. manufacturing plant-level data, this research contributes to the literature by investigating the

![Diagram](image-url)
relationship between productivity and energy efficiency through the channel of the electricity share over time, using Korean manufacturing plant-level data. Our second contribution is that we follow the arguments of long-term process and short-term demand of resources in the adoption of technical progress by Schmidt (1987), SchöN (2000) and Goldfarb (2005) and examine both the level effect in the short term, and the rate effect on productivity in the long term by using a plant-level dataset and various econometric techniques. This study finds a clear answer regarding whether and how electrification affects firm productivity. Our results provide new insights into policies associated with electricity, such as the price, demand and supply, and the industrial structure.

This paper is organized as follows: Section 2 presents a theoretical model of firm-specific productivity growth, incorporating both knowledge and information generated by electrification. Section 3 shows an empirical analysis for testing the important predictions derived from the theoretical model. We conclude the study with a discussion on the relationship between electrification and productivity growth in Section 4.

2. Theoretical model of electrification with firm-specific capital

Electrical energy is of a higher quality than just fossil fuel energy, and its use as an energy source requires more technologically advanced equipment than fossil fuels. A firm turning to the use of electrical energy would be seen as acquiring new technological knowledge. Such technological knowledge functions as an intangible productive asset to the energy-transforming firm. The use of electricity requires a higher technological knowledge than using just fossil fuel. The increased share of electricity to total energy reflects the inflow of a greater stock of private knowledge accessible to the firm, and hence the acquisition of more technological knowledge and the enhancement of the firm’s organization capital.

We incorporate the technological knowledge gap among firms, implied by the difference in the level of energy-transformation from fossil fuel to electricity among firms, into the firm-specific endogenous growth model developed by Ehrlich et al. (1994) and Liu (2008). Following Liu (2008), we treat firm-specific productivity growth as endogenous to the firm and hence firm-specific capital accumulated continuously is also an endogenous variable. Firm-specific capital depends on advancement in technological knowledge by the degree of energy-transformation from fossil fuel to electricity, which is an external “engine of growth” and the managerial allocation of effort and time of the firm. Given the existing firm-specific capital, the technological knowledge gap among firms by electrification is measured by the ratio of electricity to total energy consumption. The higher the ratio of electricity to total energy consumption, the more advanced technological knowledge needed to implement it.

The enhancement of technological knowledge by electrification is a costly process for it affects the optimal investment of managerial time or effort to embody any information acquired through the energy-transformation from fossil fuel to electricity that enhances firm-specific capital. This additional time and effort can be regarded as the costs of learning to the accumulation of firm-specific capital. The advance in the technological knowledge by the energy-transformation from fossil fuel to electricity raises marginal product of the accumulation of firm-specific capital more than that of current production. A new equilibrium for the allocation of managerial time and effort would be reached with the increased technological knowledge acquired by electrification.

We identify firm-specific and non-reproducible managerial time as a scarce resource that is allocated between two activities: the production of current physical outputs and the accumulation of firm-specific organizational capital. The time and effort of the managerial level in the firm must be allocated efficiently between the current output production and the accumulation of firm-specific capital to maximize the firm’s value function. Accordingly, the optimal allocation of non-reproducible managerial time and effort between the two activities comes from successfully accumulating firm-specific capital with physical output production.

In our theoretical framework, technology is assumed to be separable from valued-added and intermediate goods, output market is to be imperfect, and real value of factor price is to be constant at a steady state. We specify current physical production as the following Cobb–Douglas production function,

$$Q_t = A_t L_t^\alpha K_t^\beta [H_t M_t]^\gamma,$$

for $\alpha + \beta + \gamma < 1$, \hspace{1cm} (1)

where $A_t$ represents exogenous, common technical factors; $L_t$ and $K_t$ are labor and capital inputs, respectively; $H_t$ denotes the stock of firm-specific capital; $M_t$ is the fraction of managerial time devoted to current production; and the subscript $t$ denotes time. Managerial time is normalized to one because we are interested in the allocation ratio of managerial time between the current production and the accumulation of firm-specific capital.

To focus on the determinants of firm-specific productivity growth, $A_t$ is treated as a constant and $L_t$ and $K_t$ are defined in efficiency units that can be purchased in perfect rental markets at price $\omega$ and $c$ respectively.

The production of firm-specific capital requires the inputs of managerial time as the allocation ratio, $(1 - M_t)$ and knowledge from two sources. The first factor $(1 - M_t)$ is the portion of managerial time devoted to accumulating firm-specific capital. The first source of knowledge is the current stock of firm-specific capital ($H_t$). The second source of knowledge is technological knowledge gap among firms in the degree of energy-transformation from fossil fuel to electricity, and its value to the firm depends on the firm’s ability to convert the technological knowledge of the energy-transformation from fossil fuel to electricity into firm-specific capital even if every firm can transform its energy type from fossil fuel to electricity. Therefore, the accumulation of firm-specific capital is defined as follows:

$$H_t = H_{t-1} M_t + r E_t^F.$$

where $r$ is either an efficiency parameter of the production or a learning productivity parameter, and $0 < \delta \leq 1$ indicates whether managerial inputs are subject to diminishing returns. We assume that $\delta$ is equal to 1, strictly for analytical convenience because it allows for closed-form dynamic solutions of our model. $E$ denotes electrification, while $\omega \geq 0$ represents the intensity of learning from electrification.

Consider a representative firm operating in a competitive market. The firm decides the amount of managerial time and effort to devote to current production ($M^F$). Then $1 - M^F$ is the portion of managerial time and effort to accumulate firm-specific capital and to determine the amounts of labor and capital to hire so that the firm maximizes the present values of the objective function specified below over an infinite horizon. We assume $\omega = 1$ for closed-form dynamic solutions of our model without the distortion of generality. From the first-order optimal conditions for an interior solution, in the steady-state, we have growth rate relations: $Q = \lambda , ~ Q = \delta , ~ Q = \lambda - \omega$ and $\frac{1}{\lambda} = \lambda = \rho $, where $\rho$ is the discount factor, and $\lambda$ denotes the time derivative of the shadow price of firm-specific capital. Since we have $Q = \omega \lambda + \delta E^F$ from Eq. (1), we can obtain the following equation for the growth rate of firm-specific capital:

$$V_t = A_t L_t^\alpha K_t^\beta [H_t M_t]^\gamma - \omega L_t - c K_t + \lambda H_t [1 - M_t]^\gamma E_t^F \hspace{1cm} (3)$$

$$\dot{H} = \frac{(E_t^F - \rho)(1 - \alpha - \beta)}{(1 - \lambda - \beta - \gamma)} . \hspace{1cm} (4)$$
With Eqs. (2) and (4), the optimal managerial time and effort devoted to the current steady-state production is solves as follows:

\[ M_t = \frac{-\gamma}{(1-\alpha-\beta-\gamma)} + \frac{\rho(1-\alpha-\beta)}{(1-\alpha-\beta-\gamma)}E_t. \tag{5} \]

To identify the level and rate effects separately by electrification we need to conduct a comparative analysis for the level and rate of firm-specific capital \( (H_t \text{ and } M_t) \) with the technological knowledge due to electrification. The above results show that at a steady state, the amount of managerial time devoted to current production is negatively related to \( E \) but that the growth rate of firm-specific capital is positively related to \( E \), where \( E \) represents the ratio of electricity to total energy used as electricity. In addition, the firm’s total factor productivity \( (TFP) \) is \( TFP = A_t[H_tM_t] \) from Eq. (1) and thus its growth rate is \( \dot{TFP} = \dot{A} + \dot{Y}_H \), which is a positive linear combination of the steady state growth rates of technical change and firm-specific capital. The higher is \( E \), the higher the slope of productivity growth will be through their positive effect on the accumulation of firm-specific capital. However, the increase in \( E \) is negatively associated with the productivity level in the short term.

The theoretical model presented here has an important implication. The level effect of the firm-specific capital generated by electrification can differ from its rate effect. The rate effect could dominate the level effect from the rate effect of electricity. The above results show that the level or the growth rate of productivity could yield misleading results. Therefore, an empirical model that allows for the separation of the level effect from the rate effect of electrification must be specified.

3. Empirical analysis

3.1. Data and key variables used

We used the Korean manufacturing census data from 1990 to 1999. This dataset includes various inputs and output variables and considers plants operating in Korea. The panel dataset includes all plants with more than five workers and information such as production, total shipment, value-added, export, workers, capital, and inventory. Cost variables include electricity cost and fuel cost, and wage, among others. Plant identification numbers are used as the basis for the panel data.

The sample used in the empirical analyses is an unbalanced panel consisting of 771,760 observations over a period of 10 years, which was a sufficient duration to measure the rate effect of electrification on productivity. Production, total shipment, value added, and wage are deflated by the producer price indices at two-digit KSIC disaggregated level to alter variables from nominal to real terms. At the beginning and ending of the year, the tangible fixed assets as the capital stock are deflated by the capital goods deflator computed in the national account of the Bank of Korea. It should be noted that this type of capital stock is a rough proxy for capital input. Indeed, McGuckin and Nguyen (1993) pointed out that the appropriate measure of capital input is capital services rather than capital stock. Since data required to measure capital services are not available we assume that capital services are proportional to capital stock, which could be used as a proxy for capital input.

The variables relating to cost (direct or indirect) are deflated by the intermediate input price index. However, the variables of electricity and fossil fuel cost relating to energy are deflated by the electricity price index and the energy price index respectively, because the energy price in Korea is managed by government policy. Both electricity and energy price indices show a totally different trend than other price indices.

Table 1 presents definitions and summary statistics of the key variables used in the empirical estimations. Output is measured in terms of real value added, capital is measured by real year-end tangible fixed assets, and labor is the total number of workers. Using the variables of output, labor, and capital, total factor productivity \( (TFP) \) is measured in a semi-parametric estimation under the assumption of the Cobb-Douglas production function. Export shares in the plant and in the same industry are measured as the control variables to estimate the level and rate effects of electrification on the total factor productivity. We measure the electricity share for each plant as the proxy of electrification. Through this variable, we verify the existence of the level and rate effects by electrification on total factor productivity. The electricity share of a firm \( i \) at time \( t \) is measured by:

\[ E_{it} = \frac{\text{Electricity}_{it}}{\text{Total Energy}_{it}}. \tag{6} \]

We also considered skills, return to scale, export, age and foreign direct investment (FDI) as other sources of productivity advantages in an effort to isolate the effect of electrification on productivity. Following Atrostic and Nguyen (2005), we use the ratios of non-production worker to total labor cost and of non-production workers to total workers in the plant as a proxy for skills. As Van Biesebroeck (2005) stated, return to scale is the most important factor for increasing the productivity of exporters in absorbing some of the size effect. The market share of a plant in the same industry is regarded as a measure of the return to scale and is calculated in every scope of the industry. Finally, the volume of FDI in two-digit industries is used to explain the productivity gain.

3.2. Econometric strategy

We now turn to our empirical model, which is based on the equations for the growth rate of firm-specific capital and for the optimal managerial time and effort devoted to the steady-state production given by Eqs. (4) and (5). Since TFP is \( TFP = A_t[H_tM_t] \) from Eq. (1) and evolutions of exogenous technical factor and endogenous firm-specific capital are \( \dot{A}_t = \dot{A}_0 e^{\delta t} \) and \( \dot{H}_t = \dot{H}_0 e^{\delta t} \), where \( \dot{A}_0 \) and \( \dot{H}_0 \) are initial value of \( A_t \) and \( H_t \).
and \( H_0 \) respectively, we derive a TFP equation by plugging Eqs. (4) and (5) into Eq. (1) as follows:

\[
TFP_t = A_0 e^{\gamma t + \gamma E_t} [H_0 e^{-(\alpha_1 t + \alpha_2 T + \alpha_3 T^2 + \alpha_4 X_1 + u_t + e_t)}],
\]

(7)

where \( M(E_t) = \frac{\gamma}{(1-\alpha_2 - \gamma)} + \frac{(\alpha_1 - \alpha_2) \gamma}{(1-\alpha_2 - \gamma) x_t^2} \). The association of \( E \) with TFP through \( M \) given by the last term in the above equation is non-linear and thus a linear Taylor series approximation can be applied to estimate the non-linear term. The log-linear Taylor series expansion of the term for small \( \gamma \) is

\[
\gamma \ln M(E_t) \approx \gamma \ln \frac{E_t}{rE_t^*}.
\]

Thus the log-transformation of the above TFP equation has the following TFP:

\[
\ln TFP_t = \alpha_0 + \alpha_1 t + \alpha_2 E_t^* t + \alpha_3 \ln E_t,
\]

(9)

where \( \alpha_0 = \ln [A H_0^* \gamma] + \gamma E_t^* \), \( \alpha_1 = A - \gamma^{(1-\alpha_2-\beta)} \), \( \alpha_2 = -\gamma \) and \( \alpha_3 = -\gamma c \). The above equation shows \( \ln TFP \) is a function of \( t, E \) and interaction term between \( t \) and \( E \).

While our empirical work does not directly estimate analytical model presented in this paper, it estimates a derived model that specifies TFP as a function of \( t, E \) and \( t \times E \). Our empirical model captures the important implication of the theoretical model that electrification has a negative level effect in the short run (coefficient \( \alpha_3 \) in Eq. (9)) and a positive rate effect in the long run (coefficient \( \alpha_2 \) in Eq. (9)) on TFP.

Obtaining unbiased and efficient estimates for plant productivity levels from establishment-level panels is a necessary and important first step for analyzing the relationship between firm productivity and other variables or policy change. To solve the problems that occur in the process of extracting firm level productivity, this study used the approach of Olley and Pakes (1996) to extract total factor productivity (TFP) from the observed variables of establishments. This procedure was also implemented by Pavcnik (2002) and Javorcik (2004). This estimator solves the simultaneity bias for the choice of capital. The estimation procedure involves the two steps. In the first step, the coefficient of log capital is consistently estimated, and the estimates for labor and capital are then used to compute firm-specific total factor productivity, which is the difference between the actual and predicted outputs.

The differentiation of the level effect from the rate effect of electrification on TFP is very important to clearly identify the role of electricity in the empirical model as predicted by our theoretical model. A natural starting point to identify predictions related to electrification in the theoretical analysis is to estimate a model in which the logarithm of firm’s productivity (\( \ln TFP \)) is assumed to depend on the electricity share of the firm \( (E_t) \), a proxy for electrification, a time trend \( (T) \), an interaction term between \( T \) and \( E \), and other relevant control variables \( (X_i) \). That is,

\[
\ln TFP_t = \alpha_0 + \alpha_1 t + \alpha_2 E_t + \alpha_3 T + \alpha_4 X_1 + u_t + e_t,
\]

(10)

where \( u_t \) denotes the unobservable firm-specific effect, and \( e_t \) denotes the remainder stochastic disturbance. The parameter \( \alpha_2 \) captures the effects of electrification on the short-term level of productivity, whereas \( \alpha_3 \) captures the effect of electrification on the long-term rate of productivity growth of the firm.

We assume that each firm generates knowledge and information to improve its firm-specific capital through electrification. Thus, the increase in electricity share in each firm implies the increment of knowledge and information to enhance firm-specific productivity growth. Another implicit assumption of the regression is that the time trend of productivity can serve as an indicator of the long-term rate of firm-specific productivity growth. The electricity share of the firm is partly endogenously determined. In the regression, the fixed-effects specification is important to avoid the possible reverse causality and to mitigate the impacts of some forms of non-random measurement error.

3.3. Empirical results

We implement the regression model in Eq. (10), which allows us to estimate two effects separately in one regression equation. That is, we estimate the level effect and the rate effect on productivity. In all cases, we controlled for various sources of productivity gain and econometric problems. After presenting the main results related to electrification, we review other sources of productivity gain and econometric estimation issues that must be considered for clearly identifying the extent of the effects of electrification on productivity.

Table 2 presents the estimates based on the full sample, considering the level and rate effects of electrification on firm productivity. The coefficients of \( E \) and \( T \times E \) represent the level and rate effects of electrification, which are statistically significant at the 1% level. These coefficients, however, have consistently opposite signs; that is, the \( E \) variable has significantly negative coefficients, and the coefficient of the \( T \times E \) variable is significantly positive. These results indicate that electrification has significant and different effects on the short-term level and the long-term rate of the productivity growth of firms as our theoretical model predicts.

From column 2 in Table 2, the level effect, \( -0.0329 \), implies that the productivity level of average firms would decrease by approximately 0.3% following an increase of 10% in electrification. The rate effect, \( 0.0061 \), suggests that the rate of productivity growth of average firms would increase by approximately 0.06% in response to the same amount of change in electrification. According to these estimates, the increase in the rate of productivity growth will make up a firm’s initial loss in the productivity level in approximately 5 or 6 years, and thereafter, the net effect of electrification becomes positive and grows over time.

Table 2

<table>
<thead>
<tr>
<th>Regression results.</th>
<th>Total</th>
<th>Total</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>(-0.0074^{**})</td>
<td>(-0.0325^{***})</td>
<td>(-0.0477^{***})</td>
</tr>
<tr>
<td>(0.00061)</td>
<td>(0.00590)</td>
<td>(0.00746)</td>
<td></td>
</tr>
<tr>
<td>T + E</td>
<td>(0.00724^{***})</td>
<td>(0.00610^{**})</td>
<td>(0.00934^{***})</td>
</tr>
<tr>
<td>(0.00107)</td>
<td>(0.00104)</td>
<td>(0.00129)</td>
<td></td>
</tr>
<tr>
<td>Market_share(5-digit)</td>
<td>(3.119^{***})</td>
<td>(0.403^{**})</td>
<td>(0.392^{***})</td>
</tr>
<tr>
<td>(0.0230)</td>
<td>(0.0292)</td>
<td>(0.0333)</td>
<td></td>
</tr>
<tr>
<td>Non-production ratio</td>
<td>(0.919^{***})</td>
<td>(0.0614^{***})</td>
<td>(0.0674^{***})</td>
</tr>
<tr>
<td>(0.00459)</td>
<td>(0.00643)</td>
<td>(0.00810)</td>
<td></td>
</tr>
<tr>
<td>FDI_2digit</td>
<td>(-6.92e-08^{**})</td>
<td>(-4.93e-08^{**})</td>
<td>(-4.75e-08^{**})</td>
</tr>
<tr>
<td>(2.54e-09)</td>
<td>(1.88e-09)</td>
<td>(2.27e-09)</td>
<td></td>
</tr>
<tr>
<td>Herfindahl–Hirschman index</td>
<td>(-0.347^{***})</td>
<td>(-0.0655^{***})</td>
<td>(-0.0740^{***})</td>
</tr>
<tr>
<td>(0.0130)</td>
<td>(0.0121)</td>
<td>(0.0149)</td>
<td></td>
</tr>
<tr>
<td>Export</td>
<td>(0.288^{***})</td>
<td>(0.0362^{**})</td>
<td>(0.0342^{**})</td>
</tr>
<tr>
<td>(0.00228)</td>
<td>(0.00282)</td>
<td>(0.00338)</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>(0.00122^{***})</td>
<td>(-0.000173)</td>
<td>(-0.000298)</td>
</tr>
<tr>
<td>(0.000188)</td>
<td>(0.000318)</td>
<td>(0.000384)</td>
<td></td>
</tr>
<tr>
<td>Age^{2}</td>
<td>(0.00000101^{**})</td>
<td>(1.71e-08)</td>
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<tr>
<td>(0.00000469)</td>
<td>(0.00003538)</td>
<td>(0.00000664)</td>
<td></td>
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<tr>
<td>Time</td>
<td>(0.0592^{***})</td>
<td>(0.0533^{***})</td>
<td>(0.0505^{***})</td>
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<td>(0.000834)</td>
<td>(0.000828)</td>
<td>(0.000963)</td>
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<td>Industry Fixed Effects</td>
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<td>No</td>
<td>No</td>
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<td>Firm Fixed Effects</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>N</td>
<td>562,861</td>
<td>562,861</td>
<td>393,323</td>
</tr>
<tr>
<td>R2</td>
<td>0.348</td>
<td>0.740</td>
<td>0.769</td>
</tr>
</tbody>
</table>

a. All independent variables are used as the 1 year lagged variables to treat the endogeneity. b. In the regression of the last column, we excluded the plants used only electricity as energy. c. Standard errors in parentheses.

* \( p < 0.05 \)

** \( p < 0.01 \)

*** \( p < 0.001 \)
We also consider skills, return to scale, export, age and foreign direct investment (FDI) as other sources of productivity advantages in an effort to isolate the effect of electrification on productivity. Therefore, the above sources of productivity gain are used as control variables. The firm’s worker skills are computed by the ratio of non-production worker cost to total labor cost or by non-production workers to total workers. Return to scale is measured by the market share of firm to the industry average. The measure of electrification could reflect industry specific production techniques. Some industries, by the nature of their product, are more electric intensive. Thus, alternatively, normalizing the electricity cost share to the industry average is considered. Table 3 shows the regression results (normalizing the electricity cost share to the industry average).

The measure of electrification cost share may explain industry level but an increase in the long-term rate of productivity growth of firms. The empirical evidence from a large panel of Korean manufacturing plants was generally consistent with the theoretical predictions.

The negative level effect of electrification emphasizes the fact that technology transfer is a costly learning process. Electrification at the firm level requires new capital investment of equipment. When there is a new organization or capital in the firm, managers have to learn how to organize the new system and to manage the new capital or equipment to get the improved productivity. On the other hand, the positive rate effect of electrification is in accordance with the central thesis of the endogenous growth literature that identifies human capital or knowledge as the ultimate engine of economic growth. By serving as a source of knowledge, electrification promotes sustainable productivity growth among firms in the long run.

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### References


### 4. Conclusions & policy implications

Within the endogenous growth framework, we offered an explanation for how the energy-transformation from fossil fuel to electricity improves the firm productivity. Our theoretical analysis suggested that electrification could cause a decrease in the short-term productivity level but an increase in the long-term rate of productivity growth of firms. The empirical evidence from a large panel of Korean manufacturing plants was generally consistent with the theoretical predictions.

The negative level effect of electrification emphasizes the fact that technology transfer is a costly learning process. Electrification at the firm level requires new capital investment of equipment. When there is a new organization or capital in the firm, managers have to learn how to organize the new system and to manage the new capital or equipment to get the improved productivity. On the other hand, the positive rate effect of electrification is in accordance with the central thesis of the endogenous growth literature that identifies human capital or knowledge as the ultimate engine of economic growth. By serving as a source of knowledge, electrification promotes sustainable productivity growth among firms in the long run.