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Energy efficiency in the automotive industry evidence from Germany and Colombia

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Abstract This paper presents an analysis of energy efficiency performance in the automotive industry from evidence of Germany and Colombia in order to show important features in energy use between countries with the different income between 1998 and 2007. We found that the automotive industry improved its energy efficiency in each country. In order to understand the driving forces behind these trends, the concept of the production function is used to obtain the elasticities of substitutions and the relationships between several variables and energy efficiency performance in German and Colombian motor vehicle industries. In both countries, we found that the variables of energy prices and sizes of companies each have a positive influence on the efficiency of the gross production/energy ratio. These results show that, in the motor vehicle industry, energy efficiency performance depends on different factors. Hence, variables such as energy prices, energy taxes, economies of scale and technology changes have played a crucial role in the improvements in productivity and rational energy use.

Keywords Automotive industry · Energy efficiency · Production function

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1 Introduction

An increasing concern for energy efficiency has been emphasised by different organisations around the world. In 2005, the European Parliament took a step towards making energy efficiency a subject of highest priority in Europe.[1] Moreover, in 2006, the parliament stated that energy efficiency is the "greatest, fastest and cheapest reaction to energy security worries, rising and volatile energy prices and environmental concerns".[2] Other organisations have followed suit. In its 2007 report, the Intergovernmental Panel on Climate Change (IPCC 2007) declared that "all assessed stabilisation scenarios concur that 60–80% of the greenhouse gas emission reductions over the course of the century would come from energy supply and use and industrial processes" and that "energy efficiency plays a key role across many scenarios for most regions and time scales". Nevertheless, the development and implementation of policies that guarantee energy efficiency requires a thorough understanding of the role of different factors in changing energy consumption and energy efficiency trends in the society. In general, energy analyses are performed on energy-intensive sectors (EISs), whereas non-energy-intensive sectors (NEISs) have been neglected. This may be caused, among other reasons, by the fact that measures to improve energy efficiency are directed towards EISs because the results of the strategies to increase energy efficiency performance are more evident in this sector. Further, EISs provide detailed and readily available data on energy consumption and productive factors. In contrast, NEISs are more heterogeneous in their processes and products, and therefore more research covering a wide range of processes and products that produces reliable data is necessary to identify the energy consumption and efficiency trends within this sector. Such research should develop consistent time series data to be used in cross-country or cross-sector comparisons.

In the motor vehicle industry, the main research trends in energy efficiency have focused on two topics: First, fuel efficiency and the decrease in carbon dioxide emissions in automobile usage (Koopman 1997; Sakaguchi 2000; Known 2006; Zachariadis 2006; Dergay and Gately 1997; Blesl et al. 2007; Meyer et al. 2007) and second alternative fuel sources in transportation (Teotia et al. 1999; Ogden et al. 2004; Ramesohl and Merten 2006; Bomb et al. 2007). Therefore, studies about energy consumption and energy efficiency in the motor vehicle manufacture industry are limited, and the studies that do exist have been limited to descriptive analyses of energy efficiency potentials, of clean production and of strategies to improve energy efficiency (Maxwell et al. 1997; Galitsky and Worrell 2008; Boyd 2005; Moavenzadeh 2006).

Against this background and taking into account the concern for climate change and its relationship with energy efficiency, this paper presents an analysis pattern of energy efficiency in the German and Colombian motor vehicle industries (ISEC 34) at the 3 digit level[3] of statistical aggregation. The second stage determines several factors that have

[1] The European Parliament supported the European Commission's call for mandatory reductions in energy use across the EU and, in so doing, gave a needed push to rationalise to energy use in Europe.

[2] The report notes that if existing legislation (e.g., on the energy performance of buildings, combined heat and power, eco-design, emissions trading and energy end-use efficiency) was fully implemented, the EU would already be halfway to meeting its target of reducing energy use by 20% by the year 2020, in line with the Commission's Energy Efficiency Action Plan.

[3] ISEC classifies data according to the kind of economic activity; German and Colombian statistical data are within this classification. The automotive industry is comprised of the manufacture of motor vehicles for transporting people or goods (341), manufacture of trailers and semi-trailers (342) and parts and accessories (343).

influenced on energy efficiency through empirical analysis. The main contributions of this paper are the analysis of energy efficiency performance in a sector with high energy consumption and low energy intensity such as motor vehicle industry and define several factors that could determine energy efficiency performance in this industrial sector where the empirical studies are limited.

The German and Colombian motor vehicle industry sectors were chosen as case studies in order to show important features in energy efficiency between countries with the different income. This sector is highly important to both countries' economies: motor vehicle manufacture is the largest production industry in Germany, accounting for 21% of total industrial output, and is the sixth largest in Colombia, where it accounts for 5% of output. Most German motor vehicle industry is concentrated in the motor vehicles (341), accounting for 73% of the production of this manufacturing industry. In Colombia, the same sector accounted for 78% of the whole motor vehicle industry (See Fig. 1).

In this study, Germany is chosen because it is a world leader in energy efficiency and has shown important developments in energy-efficient technology. By using Germany as a case study, it is possible to evaluate different factors of energy efficiency in relation to the best practices in developed countries. The Colombian case is chosen because within the Latin American context, and especially during the period under study, the automotive

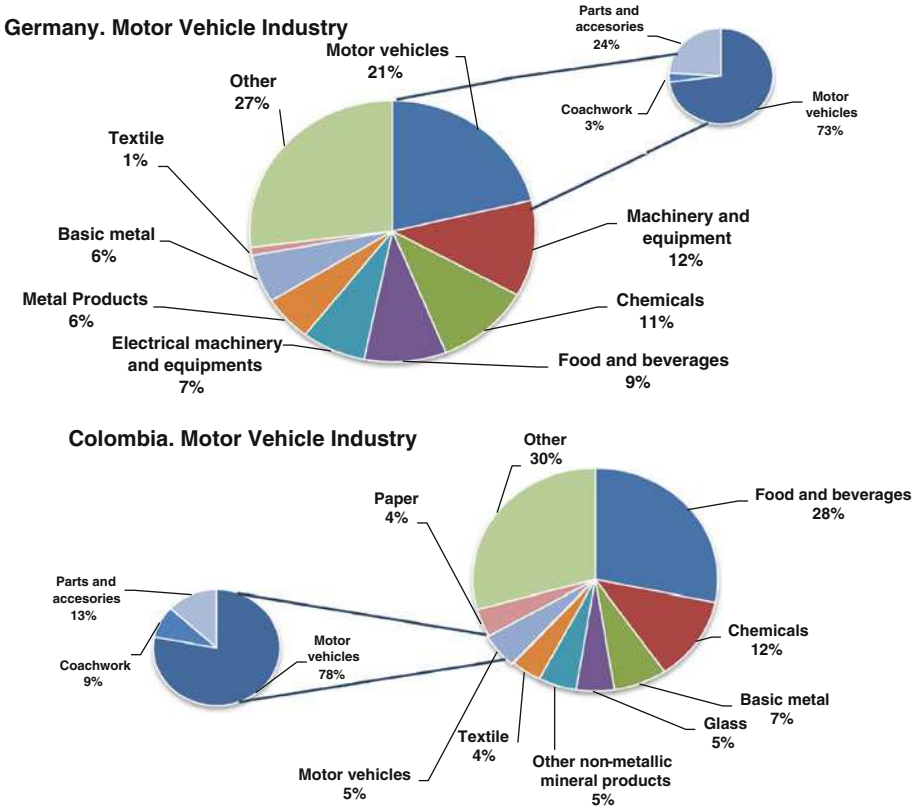


Fig. 1 Share of motor vehicle production in Germany and Colombia by type of product and its relation with other industrial sectors, 2007

industry of this country achieved improved energy efficiency. It now is an environmental leader among countries with comparable incomes. Therefore, the industrial sector of this country has best practice features of a developing country, making it possible to define and compare key factors of energy performance and define strategies to improve energy efficiency in developing countries.

The remainder of this paper is organised as follows. Section 2 provides a description of the German and Colombian motor vehicle industries, Sect. 3 describes the data and methodology, and Sect. 4 describes energy use and energy efficiency development in this industrial sector. In Sect. 5, we introduce an empirical analysis and discuss the main results. Section 6 offers some concluding remarks.

2 Description of German and Colombian automotive industries

The motor vehicle industry and the parts and accessories industry are each key components of the German and Colombian economies, accounting for a substantial percentage of direct and indirect employment, as well as overall industrial output. This sector produces an average of ten million cars per year in Germany and one hundred thousand cars per year in Colombia, generating an average gross product of €315 billion and nearly €2 million, respectively. In Germany, both cars and parts are among the country's top export products. It is also the world leader in automotive patents: German car companies spend €16 billion a year on research and development (VDA 2006a, b). In Colombia, the automotive industry is an important source of exports and generates qualified jobs as well as technological development and productive growth; it is also a leader in quality processes in national industry.

Germany is third among motor vehicle-producing nations: its factories produce between 1 million (e.g. Mercedes-Benz, BMW) and 1.2 million (e.g. Volkswagen) vehicles per annum; its average output is approximately 10–15 cars per employee per annum, calculated based on plants running an average of two daily shifts for a total of 16 h (ILO 2005). The key element in the success of the German automotive industry has been the creation of new jobs in production plants in order to deliver reasonable prices in the volume segment and technology and innovations in the premium market (today, a premium model is produced every second in Germany).

The Colombian automotive industry ranks fourth among Latin American producers. The Colombian assembly industry is an oligopoly of three powerful companies[4] with an installed capacity of 180,000 vehicles per annum (DNP 2004). This sector has achieved national and international acknowledgement for the quality of its products, for its innovations and for its export levels. Its share in the country's output has fluctuated in the last years between 4 and 7%, while its share of national employment was 4%, accounting for approximately 16,000 jobs. The key statistics for the German and Colombian automotive industries are presented in Table 1.

These data show the differences between a strong industry, such as the German motor vehicle industry, and one in development, such as its Colombian counterpart. Hence, while Germany looks for new technology developments patents, clear evidence of high

[4] These factories are CCA, (Compañía Colombiana Automortriz-Colombian Automotive Company, which assembles Mazda and Mitsubishi pick-ups), General Motors-Colmotores (assembles Chevrolet) and Sofasa (assembles Renault and Toyota). In bodywork, the monopoly is held by Monoblock (assembles chassis for Mercedes Benz).

Table 1 Development of the motor vehicle industry in Germany and Colombia

Industry ISIC Code	No. Companies				Employments (1,000)				Production (units)[a]			
	1998	2001	2005	2007	1998	2001	2005	2007	1998	2001	2005	2007
Germany												
34	837	931	997	1,005	806	854	856	838				
341	59	68	79	72	511	526	515	488	9.24	10.7	11.06	12.03
342	317	313	304	311	39	37	35	39	1.48	1.47	1.42	1.42
343	461	550	614	622	257	291	306	311	1,832	2,312	2,898	2,999
Colombia												
34	207	160	190	179	14.3	11	14	16.5				
341	22	18	17	17	4.4	3.5	3.8	5.2	89.1	111.3	146.8	150.4
342	65	54	69	66	3.3	2.4	4.3	4.7	10.2	5.8	73.4	75.5
343	120	88	104	96	6.6	4.7	6	6.6	21.6	28.7	95.1	100.3

[a] German production is given in millions of units, and Colombian production is given in thousands of units

investment in research, Colombia invests very little in research and innovation, instead seeking new markets in economies that guarantee demand for its products.

3 Data and methodology

3.1 Data

Based on the availability, consistency and disaggregation of energy data in both countries, the time period selected for was 1998–2007. In Germany, data in two and three levels of the ISEC classification were obtained from the Statistisches Bundesamt Deutschland (German Bureau of Statistics 2008a, b, c). In Colombia, data were taken from the Departamento Nacional de Estadística (Colombian Department of Statistics, DANE 2008); data of energy were taken from energy balances made by the International Energy Agency (IEA) and by the Unidad de Planeación Minero Energética (Unit of Mining and Energetic Planning, UPME). All monetary variables are measured by the appropriate quantity indices, with 1998 as the base year and price indices for individual variables used as the relevant input prices. Time series for production data and other variables were developed using data provided by national statistical offices and by industrial associations.

3.2 Methodology

3.2.1 Energy efficiency

Trends in energy efficiency can be measured by assessing energy use by unit of activity. In this study, two indicators of energy efficiency are used:

I. Energy intensity (EI) is defined as the energy used per unit of economic production (Eq. 1).

$$\mathrm{EI}_i = \frac{E_i}{P_i} \tag{1}$$

where EI_i = Energy intensity indicator (*Mj*/€), E_i = final energy consumption of the motor vehicle sector i (e.g. *Mj*), P_i = production of motor vehicle sector i (€)

II. Carbon emission intensity (CEI) measures the generation of greenhouses gases (in terms of CO_2 emissions) per unit of economic production (Eq. 2).

$$\mathrm{CEI}_i = \frac{\mathrm{CE}_I}{\mathrm{P}_i} \tag{2}$$

CEI_i = CO_2 emissions intensity based on economic production (tonnes of CO_2 emissions/€), CE_i = CO_2 emissions tonnes.

3.2.2 Production function

Following the work of Collard et al. (2005) and Bekmann and Sato (1969), we propose a model that will provide us with an interpretable relation between the production factors and energy consumption. We assume that the production function of the typical firm is a nested constant elasticity of substitution CES function:

$$\mathrm{Y}_t = \left[\omega\{E_t\}^{\frac{\sigma-1}{\sigma}} + (1-\omega)\{\mathrm{F}(\mathrm{K_t}, \mathrm{L_t}, \mathrm{M_t})\}^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma-1}{\sigma}} \tag{3}$$

Note that σ is the substitution parameter ($-1 < \sigma < \infty$) and it denotes the elasticity of substitution between production factors where E is energy, K is the capital, M is material and L is labour. The production/energy ratio can be partially controlled by the firm as it depends on the methods of production that is chosen to produce output.

The change in the production process is proxied by three variables: capital, materials and labour, normalised by energy consumption (K/E, L/E, M/E), and a log-linear time trend (τ_t), which accounts for exogenous energy-saving technological progress, is included. Moreover, we include a vector that explains other variables such as the price ratio (($\mathrm{P}_{\mathrm{E},t}/\mathrm{P}_t$) the ratio between the price of energy $\mathrm{P}_{\mathrm{E},t}$ and the total production price (P_t)) and the size of company variable (SC). Equation 3 leads to a log-linear equation from which estimates of the structural parameters can be obtained.

$$\begin{aligned}\mathrm{Log}\left[\mathrm{Y}_t/\mathrm{E}_t\right] =& \sigma \log(\omega) - \sigma \log\left(\frac{\mathrm{P_{Et}}}{\mathrm{P}_t}\right) \pm \phi \log(\mathrm{SC}_{it}) \\ &+ \sigma - 1\left[x\theta_0 + \tau_t t + \alpha_{\mathrm{kt}}\mathrm{Log}\left(\mathrm{K}_t/\mathrm{E}_t\right) + \beta_{\mathrm{Lt}}\mathrm{Log}\left(\mathrm{L}_t/\mathrm{E}_t\right) + \varphi_{\mathrm{Mt}}\mathrm{Log}\left(\mathrm{M}_t/\mathrm{E}_t\right)\right]\end{aligned} \tag{4}$$

As can be seen from Eq. 3, the Y/E (production by energy) ratio is the dependent variable. The equation is estimated using non-linear least squares regression methods. In the adopted panel approach, which combines the cross-section and time series dimension of the data, the production function is estimated using panel model with constant coefficients to determine the effect of input substitutions on energy efficiency in the German and Colombian automotive industries.

The data needed to apply the (CES) production function include energy consumption (E), gross output of production (Y), capital (K), materials (M), labour (L) and energy saving (τ_t). Moreover, the model includes other explanatory variables, such as energy price

(P_E), production price (P) and size of company (SC) as the share of gross production in medium and small enterprises.[5]

4 Energy use and energy efficiency in German and Colombian motor vehicle industries

4.1 Energy use

In 2007, the motor vehicle industry consumed about 138356 TJ and 3006 TJ in Germany and Colombia, respectively. Of this amount, 52.6 and 49.5%, respectively, were consumed by German and Colombian motor vehicle manufacture (341).

Figure 2 shows the energy consumption trends throughout the whole automotive industry in each country. In Germany and Colombia, all groups increased energy consumption over the period. Electricity was the main energy source used on-site in vehicle manufacturing, followed by natural gas and other fuels. Note that in Germany and Colombia, the increase in electricity and natural gas consumption indicates a shift in the structure of energy sources from lower end-use efficiency fuels (e.g. petroleum products) to higher end-use efficiency fuels (gas and electricity).[6]

Energy is employed in many end-use activities in vehicle assembly and parts and accessories[7] facilities (e.g. press line, body shell work, materials handling equipment, paint finishing system, casting, assembly, and inspection and testing). Other fuel sources are mainly used for space heating, steam applications and in the curing ovens of the painting lines, while some facilities may have been casting facilities for engines or other parts on-site.

4.2 Analysing energy efficiency developments

This section presents the analysis of energy efficiency development in the automotive industry. Figure 3 provides the results of energy intensity for German and Colombian motor vehicle industries. In both countries, energy intensity for the manufacture of parts and accessories for motor vehicles is higher than that for overall motor vehicle industry, whereas for the manufacture of motor vehicle, energy intensity is lower. The results also show that in the German and Colombian motor vehicle industries, energy intensity in terms of gross production decreased in all sectors. However, the numbers demonstrate that this indicator is three times higher in Colombian automotive industry than in the German automotive industry at the 2-digit level of aggregation, which means that Colombia requires more energy to obtain a money unit. This fact may explain the differences in technologies and production models: Colombian industries produce a variety of models and components that involve low standardisation, impeding the advantages of economies of scale[8] (Guterman 2000), while the German industry has high production volumes and

[5] See "Appendix" for more details on data.

[6] WRI (1987) showed that in developed countries, a strategy to improve energy efficiency was the shift in the structure of energy sources from lower end-use efficiency fuels to higher end-use efficiency fuels.

[7] This includes finished and semi-finished components. Approximately 8,000–10,000 different parts are assembled into approximately 100 major motor vehicle components, including suspension systems, transmissions and radiators (EPA 2003).

[8] Economies of scale refer to the decreased per unit cost as output increases. More clearly, the initial investment of capital is diffused (spread) over an increasing number of units of output, and therefore, the marginal cost of producing a good or service decreases as production increases of scale).

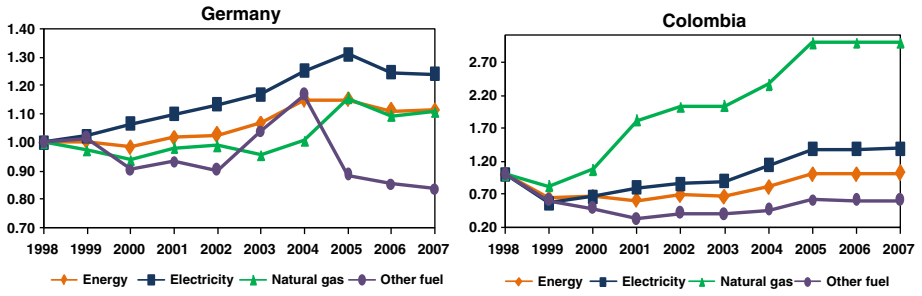


Fig. 2 Trends in energy consumption in the German and Colombian automotive industries by type of fuel (values have been indexed to 1998)

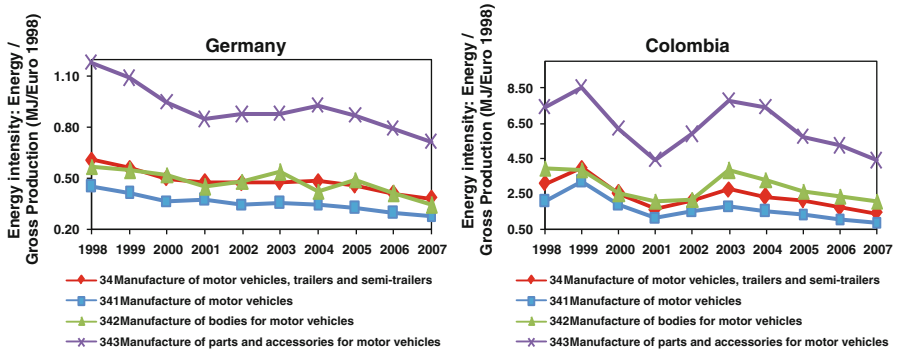


Fig. 3 The development of energy intensity in the German and Colombian motor vehicle industries

thoroughly standardised processes. Moreover, the Colombian motor vehicle industry has a low degree of automation[9] due to its limited production scale; however, these factories are flexible, and they adapt quickly according to market needs. Additionally, the machinery in this industry has a long lifespan, fluctuating from ten to twenty years. Investments in technology depend on decisions made in the company's main headquarters (Guterman 2000).

The second indicator assessed was carbon emission intensity (CEI), measured as the generation of CO_2 emissions by economic unit produced in each motor vehicle sector, i. In both countries, this indicator decreased in whole industry (see Fig. 4). However, the German and Colombian motor vehicle industries showed differences in the values and development of this indicator, which might be explained by the fuel substitutions made in Colombia during the sample period, especially in boilers from coal or diesel to natural gas. This demonstrates that fuel substitution is a good strategy in developing countries to decrease CO_2 emissions, and these results concur with WEC (2008) in the context of energy efficiency around the world and ENERDATA and ODYSEE (2007) in the context of the industrial sector.

Moreover, these results in both countries indicate that the automotive sector achieved a reduction in or at least maintained their greenhouse emissions, something that occurred not

[9] The automation in of motor vehicle manufacture is concentrated in the movement of cars along working stations, where coachwork is cut and welded.

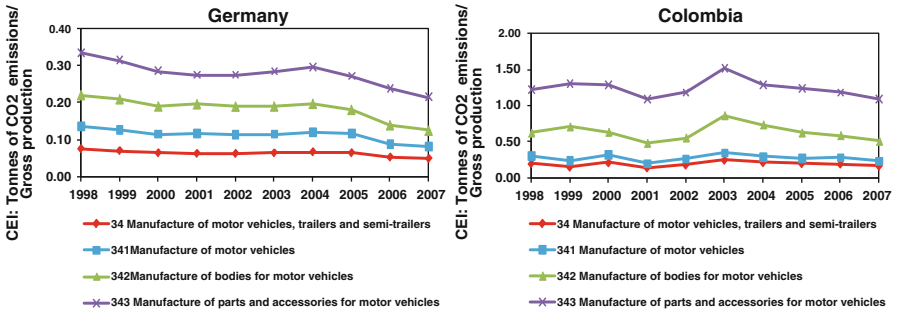


Fig. 4 The development of carbon emission intensity in the German and Colombian motor vehicle industries

only in the assembly industry, but also along the whole production chain. This might demonstrate that the effort of assembly industries to improve their environmental performance during the analysed period, with successful strategies of technology transfer, yielded positive results. Such results could further demonstrate that one of the strategies to improve energy efficiency in the industry might be the alliance between customers and suppliers, which guarantees the exchange of productive needs while looking towards continual improvement in quality, environmental, security and social performance. These results also show that the improvements in energy efficiency indicators were directly related to the decrease in the generation of green house emissions,[10] which is a key element of energy policy within the industry; if energy efficiency is not achieved, greenhouse emissions may not decrease, thereby increasing global warming.

The results indicate also that the main assemblers of the world have achieved an appropriate technology transfer not only in their industries, but also in most of their suppliers with whom they share the productive chain, with high requirements such as QS 9000 or ISO/TS 16949:2002, ISO 14001 certifications and international licence of production specific to some parts and accessories (Rothenberg et al. 2005; ISO 2003).

5 Empirical analysis

So far, our results show that the automotive industry improved its energy efficiency in each country. However, the explanation for these results in the German and Colombian motor vehicle industries may be complex and multifaceted. Therefore, we analyse the role of input substitution on energy efficiency used an empirical model where the production function is estimated.

Table 2 provides a synopsis of the estimation results obtained for the German and Colombian motor vehicles industries, for the indicators capital (K), labour (L), materials (M), energy prices (EP), energy savings (ES) and size of company (SC).

As can be seen, the materials, capital, energy prices and size of company variables had a positive influence, whereas the influence of the labour variable was insignificant. The elasticities can be interpreted in such a way that any 1% increase in the energy prices led to

[10] The IEA, in its report tracking Industrial Energy Efficiency and CO_2 Emissions (2007), shows that improvements in energy efficiency generated a decrease in CO_2 emissions in the industrial sector.

Table 2 Estimation results of the production functions for the motor vehicle industry

Parameter	(1)	(2)	(3)	(4)
Germany				
Intercept	1.014*** (6.20)	0.611** (3.09)	0.331 (1.38)	1.001** (3.26)
Capital α_K	0.067*** (7.40)	0.079*** (7.05)	0.323*** (4.27)	0.067*** (6.49)
Labour β_L	0.296 (0.45)	0.316 (1.38)	0.242 (1.01)	0.298 (1.05)
Material φ_M	0.649* (2.25)	0.618** (3.15)	0.526*** (12.29)	0.647*** (6.48)
Energy prices σ (P_E)		0.089*** (4.04)		
Energy saving (τ_t)			0.372*** (4.19)	
Size of company (ϕ)				0.004*** (3.46)
Colombia				
Intercept	1.329*** (5.12)	−0.620 (0.91)	−0.508 (1.40)	−0.067 (0.06)
Capital α_K	0.067 (0.47)	0.474* (2.08)	0.392* (1.97)	0.299 (1.33)
Labour β_L	0.091* (1.68)	0.320* (2.01)	0.551* (1.95)	0.077* (1.48)
Material φ_M	0.718*** (23.40)	0.753*** (24.96)	0.611*** (22.48)	0.682*** (16.30)
Energy prices σ (P_E)		0.238** (2.93)		
Energy saving (τ_t)			0.672*** (5.84)	
Size of company (ϕ)				0.207** (2.28)

Figures in parentheses are *t*-statistics

*, **, *** imply significance at the 10, 5 and 1% level, respectively

a 0.089 and 0.238% increase in the gross production/energy ratio in the German and Colombian motor vehicle industries, respectively.

The results for energy prices are important for a sector where the share of energy cost in terms of total cost varies between 0.5 and 1%. A reduction in energy costs reduces the unpredictability associated with variable energy prices in today's marketplace, which could negatively affect predictable earnings, an important element for publicly traded companies such as those in the motor vehicle industry (Galitsky and Worrell 2008). Likewise, an increase in energy prices results in the higher levels of energy efficiency, and in several industrial sectors, the decrease in energy intensity is an effect of higher energy prices (Samuel 2008; WEC 2008). Similar results were found in NEISs such as textile industry and food industry by Pardo (2010a, b), indicating that an adequate energy price policy is key to improve energy efficiency in NEISs.

The results for the capital variable could be explained by a close relationship to investment because several studies have demonstrated that energy efficiency investments[11] are the largest, fastest and cheapest ways to reduce energy costs and environmental impacts and increase productivity in the industrial sector (EIE 2004; Hanson et al. 2004; Mahone et al. 2009).

Moreover, the results for the capital also indicate that in both countries, there is evidence for energy savings augmenting technological progress, which should be explaining

[11] The main investments made by the motor vehicle industry to improve energy efficiency are focused in technology applications for use of waste heat, heat recovery systems, life-cycle assessments of energy consumption during processing and distribution, energy recovery on-site or off-site, natural energy of groundwater cooling, production of electricity and heat from hydrogen using fuel cell technology, cogeneration and biomass and photovoltaic cells (Sustainability Report 2006).

in the automotive industry by the change in technological level and the change in the management style. In the first case, automotive industry has achieved technology improvements through the automation, robotics systems, integrated processes, investment in research and development and changes in machinery and equipment generating simultaneously improvements on energy efficiency, productivity and product quality.[12] In the second case, automotive industry has achieved consolidation of the process management through continuous improvement methods like six sigma or ISO and the development of supplying firms through training and networks with the aim to increase the productivity across the value chain-based quality control, technology improvements, energy efficiency and best management practices.[13]

The results for the size of company variable (the share of gross production in medium and large enterprises) could be related to the fact that the innovations in one area of the automotive industry generate far-reaching technological spillover effects in other industries and especially in other sectors of its own industry, as it requires parts and accessories that guarantee quality and clean processes[14] that simultaneously improve energy efficiency in this sector.

We conclude the following from the results of the production function for the German motor vehicle industry: (1) Capital, materials, energy prices and sizes of company variables have a positive influence on the efficiency of the gross production/energy ratio. (2) There is evidence for energy savings augmenting technological progress. For the Colombian case, we conclude the following from the results of the production function: (1) materials, energy price and size of company variables have a positive influence on the efficiency of the gross production/energy ratio. (2) There is evidence for energy savings augmenting technological progress.

5.1 Correlation analysis

In order to take another approach to data analysis and taking into account the results of production function where energy prices and materials had a statistically significant effect on energy efficiency, a correlation analysis was performed using energy taxes and materials as variables. Energy intensity estimated in previous section and two new variables were employed in this analysis.

First, the tax variable was measured as the percentage of annual increase in taxes on energy expenditures during the sample period in each sector of automotive industry. In 2005, the motor vehicle industry took in total revenues of €1.9 trillion around the globe and paid €430 billion in taxes, making up the majority of global tax revenues. A high percentage of these revenues were generated from energy taxes (BMW Sustainability Report 2006).

[12] Both vehicle manufacturers and suppliers have achieved important improvements in technology, where engineering efficiency, competitive environment and energy efficiency have played an important role (Moavenzadeh 2006; Galitsky and Worrell 2008).

[13] Assemblers and suppliers develop parallel networks across the world generating initiatives for optimally integrating the quality management interfaces at the various stages of the supply chain or at a technical level achieving important improvements in the production process with principles for sustainable development (Humphrey and Memedovic 2003).

[14] The most important motor vehicle assemblies require certification in different management systems according to key suppliers or normal suppliers. Likewise, assembly companies, together with their suppliers, offer technical assistance, seminars, conferences, second party auditing, requests of certification and others.

Table 3 Correlation between different measures of energy efficiency and economic and technical variables in the German and Colombian motor vehicle industries

Measure of energy efficiency	Tax	Mat
Germany		
EI_i	−0.431*	−0.714**
Colombia		
EI_i	−0.231	−0.660**

*, ** imply significance at the 5 and 1% level, respectively

Second, the materials variable was measured as the average amount of plastic used annually in each sector of the motor vehicle industry during the sample period.[15] This variable was used to study the impact of a change of materials on energy efficiency performance. Previously, automobiles were primarily made of iron and steel,[16] but in the past 10 years, the use of iron and steel steadily decreased while the use of plastics increased in response to demands for more fuel efficient cars and energy-efficient manufacture processes. These changes in materials may have influenced energy efficiency performance since iron and steel are heavier than plastic and thus require more processing and energy consumption in the assembly process and in the manufacture of parts and accessories.

Table 3 shows the results of the correlation analysis. As expected, the tax and materials variables had significant and negative effects, indicating that the increases on energy tax and more use of plastics in automotive industry have improved energy efficiency.

In Germany, these results coincided with an increase in taxes of around 30% during the period. Moreover, the German motor vehicle industry was likely affected by the burden of state-imposed charges to the German industrial electricity market: 1.51 billion Euros in 2004 in renewable energy levies; 1.42 in electricity tax; 0.26 in concession charges; and 0.12 in combined heat and power levies (VDA 2006a, b). In the Colombian case, energy prices and taxes during the sample period increased by 35% and taxes[17] increased by 20% (UPME and ANDI 2003).

The results also showed that the change of materials in the motor vehicle industry had significant effect in the improvements of energy efficiency, which concurs with studies of EPA (1995) and VDA (2006a, b) showing that raw material selection plays a vital role in the production process and in energy efficiency in the motor vehicle industry because this selection is based on key factors such as performance (strength vs. durability, corrosion resistance and requirements of assembly), manufacturing components, costs, consumer preferences, recycling capacity[18] and type of waste. Moreover, cars made with plastic have the advantages of being lighter and of avoiding the use of energy-intensive light-metal components.

[15] This variable was measured for the German automotive industry by taking into account VDA and sustainable report, and in the Colombian case as the percentage of plastic bought by this industry that is reported in the manufacturing survey.

[16] Steel guarantees structural integrity and the ability to maintain dimensional geometry throughout the manufacturing process.

[17] The Colombian industrial sector pays a 20% contribution on the Service Provision Cost, which is designed to cover the subsidies granted to the users with lower incomes.

[18] The use of recycled materials is important in this sector but especially in Europe because EU legislation (Directive 2000/53/EC) will require as from 2015 that only five percent of an automobile's weight may be brought to landfill.

Finally, these results showed that in a global industry such as the automotive sector, energy efficiency performance depends on both economic and technical variables. Hence, variables such as energy price, energy tax, economies of scale, technology, organisation, proximity to suppliers and clients and access to human and technological resources have played a crucial role in improving the productivity and while simultaneously rationalising energy use.

6 Conclusions

The purpose of this paper was to analyse energy efficiency in the automotive industry from evidence of Germany and Colombia in order to show important features in energy use between countries with the different income between 1998 and 2007. The results showed that during the period of study, there is an increase in energy efficiency performance in both countries, indicated by a decrease on the average of energy use per monetary unit.

The results of energy efficiency showed that in the German and Colombian motor vehicle industries, energy intensity and carbon emission intensity decreased in all sectors. However, the numbers demonstrate that these indicators are higher in Colombian automotive industry than in the German automotive industry. This fact may explain the differences in technologies and production models: Colombian industries produce a variety of models and components, which involve low standardisation, impeding the advantages of economies of scale, while the German industry has high production volumes and thoroughly standardised processes.

Moreover, the results in both countries indicate that the automotive sector achieved to improve energy efficiency, something that occurred not only in the assembly industry, but also along the whole production chain. This might demonstrate that the effort of assembly industries to improve their environmental performance, with successful strategies of technology transfer, yielded positive results. Such results could further demonstrate that one of the strategies to improve energy efficiency in the industry might be the alliance between customers and suppliers, which guarantees the exchange of productive needs while looking towards continual improvement in quality, environmental, security and social performance.

In order to understand the driving forces behind these trends, we analyse the role of input substitution on energy efficiency used an empirical model where the production function was estimated. The results indicated that input substitution had a significant effect in energy efficiency improvement in the German and Colombian motor vehicle industry during the sample period.

The authors conclude that for the German motor vehicle industry, the production function demonstrates the following: (1) that capital, materials, energy prices and size of company variables had a positive influence on the efficiency of the gross production/energy ratio and (2) that there is evidence for energy savings augmenting technological progress. For the Colombian case, the authors conclude that the production function demonstrates that: (1) materials, energy price, and size of company variables had a positive influence on the efficiency of the gross production/energy ratio and (2) there is evidence for energy savings augmenting technological progress. These results could be explained by energy prices dynamic, energy efficiency investments, and the innovations in one area of the automotive industry generate far-reaching technological spillover effects in other industries and especially in other sectors of its own industry that simultaneously improve energy efficiency in this sector.

The results for the capital variable could be explained by a close relationship to investment because energy efficiency investments are the largest, fastest and cheapest ways to reduce energy costs and environmental impacts and increase productivity in the industrial sector. Moreover, the change in technological level and the change in the management style have played an important role in the energy efficiency improvement.

The results for the size of company (the share of gross production in medium and large enterprises) variable could be related to the fact that the innovations in one area of the automotive industry generate far-reaching technological spillover effects in other industries and especially in other sectors of its own industry, as it requires parts and accessories that guarantee quality and clean processes that simultaneously improve energy efficiency in this sector.

The tax and materials variables had significant and negative effects, indicating that the increases on energy tax and more use of plastics in automotive industry have improved energy efficiency.

The results showed that in the motor vehicle industry, energy efficiency performance depends on different factors. Hence, variables such as energy costs, energy taxes, economies of scale and technology change have played a crucial role in the improvements in productivity and rational energy use in the German and Colombian motor vehicle industries.

The results of this paper are of particular interest in the formulation and development of energy policies for the automotive industry to improve energy efficiency and reduction in carbon dioxide emissions. These policies should include an appropriate combination of policy instruments that take into account technical and economic strategies to improve energy efficiency. Moreover, it is important to strengthen the relationship between assemblers and suppliers for scaling-up of sustainable energy solutions across autoindustry value chains.

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Appendix

See Table 4.

Table 4 Summary of the main data used for German and Colombian motor vehicle industries

Variable	Main sources
Germany	
Monetary gross output of production in the motor vehicle industry	Destatis (GENESIS-Table: 42251-0002)
Labour—the total number of persons employed	
Materials—input	
Capital—stock by taking the value of fixed capital (Annual mean value)	Destatis (Table: 3.2.16)

Table 4 continued

Variable	Main sources
Energy price—Relationship between expenditure on energy and energy consumption	Destatis and author's calculations
Production price	Destatis (GENESIS-Table: 61241)
Size of companies—the share of gross production in medium and large enterprises for each industrial sector by year taking into account the categories established by German statistics office based on the number of workers and output levels for every industrial sector	Destatis (Serie 4—Vol. 4.3)
Energy consumption (TJ)	Destatis Chapter 5—Table: 5.2.2.1–5.3.11
Energy sources (electricity, natural gas, petroleum products and other in TJ)	
CO_2 emissions: IPCC carbon emission factors: Natural gas 56.1 tCO_2/TJ, petroleum products: 73.7 tCO_2/TJ, Other fuel (coal and coke): 84.0 tCO_2/TJ and electricity according to Federal Environment Agency, 2007.	Destatis Chapter 5 and author's calculations
Colombia	
Monetary gross output of production in the motor vehicle industry	DANE (Table: 3.1)
Labour—the total number of persons employed	
Materials—input	
Capital—stock by taking the value of fixed capital (Annual mean value)	
Energy price—Relationship between expenditure on energy and energy consumption	DANE, UPME and author's calculations
Production price	DANE (Table: 0.26)
Size of companies—the share of gross production in medium and large enterprises for each industrial sector by year taking into account the categories established by Colombian statistics office based on the number of workers and output levels for every industrial sector.	DANE (Table: 3.2)
Energy consumption (TJ)	UPME (Energy balance)
Energy sources (electricity, natural gas, petroleum products, and other in TJ)	
CO_2 emissions: IPCC carbon emission factors: Natural gas 56.1 tCO_2/TJ, petroleum products: 73.0 tCO_2/TJ, Other fuel: 81.8 tCO_2/TJ, and electricity according to Resolution 181401/2004.	UPME (Energy balance) and author's calculations

In order to ensure comparability between countries and over time, we therefore transformed the series as follows: (i) the variables were deflated using the respective wholesale price index (1998 = 100) (ii) we use exchange rates to account for monetary variables in Euros in the Colombian case.

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