International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

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Energy-productivity convergence across developed and developing countries in 10 manufacturing sectors

Asami Miketa (miketa@iiasa.ac.at)
Peter Mulder (mulder@iiasa.ac.at)

Approved by

Leo Schrattenholzer (leo@iiasa.ac.at)
Environmenally Compatible Energy Strategies (ECS) Project

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Contents

Abstract

This paper provides an empirical analysis of energy-productivity convergence across 56 developed and developing countries, in 10 manufacturing sectors, for the period 1971 to 1995. We find that, except for the non-ferrous metals sector, cross-country differences in absolute energy-productivity levels tend to decline, particularly in the less energy-intensive industries. Testing for the catch-up hypothesis using panel data confirms that in all manufacturing sectors energy-productivity growth is, in general, relatively high in countries that initially lag behind in terms of energy-productivity levels. At the same time, cross-country differences in energy-productivity performance seem to be persistent; convergence is found to be country-specific rather than global, with countries converging to different steady states and several failing to catch up. Finally, we find that country-specific factors, such as energy price and investment ratio, do explain the observed cross-country differences in energy-productivity performance, but only to a very limited extent. Hence, further research is needed to identify what accounts for the observed persistence in cross-country energy-productivity differentials.

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About the Authors

Asami Miketa is a Research Scholar at IIASA's Environmentally Compatible Energy Strategies (ECS) Project. She was a participant in the IIASA Young Scientists Summer Program in 1997. Before joining the ECS Project in 2000, she worked as a short-term consultant to the World Bank in 1999.

Peter Mulder is an Associate Research Scholar at IIASA's Environmentally Compatible Energy Strategies (ECS) Project. He was a participant in the IIASA Young Scientists Summer Program in 1997. Before joining the ECS Project in 2003, he worked with the Institute for Environmental Studies (IVM) of the Free University Amsterdam.

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Asami Miketa and Peter Mulder

1 Introduction

The changing picture of world energy use illustrates that economic development and environmental problems have become global issues. Whereas energy consumption used to be an issue mainly for the developed world, countries that are not members of the Organization for Economic Co-operation and Development (OECD) are becoming more and more important in this respect: their share of world primary energy consumption increased from 33 percent in 1971 to 42 percent in 2001 (UN, 2001) and is expected to rise substantially in the coming decades. Consequently, it is becoming a matter of increasing international concern that economic growth and environmental pressure should be decoupled, as evidenced by international agreements on environmental policy such as the Kyoto Protocol that aims for a worldwide reduction in greenhouse gas emissions. As energy use is a major source of greenhouse gases, this not only implies a need for carbon-free energy sources but also argues for a further improvement in energy efficiency or energy productivity across the world.

Important questions thus arise concerning the international dimension of energy-productivity dynamics. Are cross-country differences in energy-productivity performance decreasing or is the gap between leading and 'backward' countries widening? Do relatively energy-inefficient countries catch up with technological 'leaders' and, if so, how quickly and by what means? To answer these questions, this paper addresses two closely related concepts: 'convergence' and 'catch-up'. By convergence, we mean the phenomenon of decreasing cross-country differences in energy-productivity levels. By catch-up, we refer to the mechanism expressed by the hypothesis that "being backward in level of productivity carries a potential for rapid advance" (Abramovitz, 1986). The rationale behind this hypothesis is that countries lagging behind in terms of productivity levels can benefit from the experience and technologies developed by countries operating at the forefront, a process that might, of course, lead to convergence of cross-country productivity performance. In this paper we provide an empirical investigation of cross-country energy-productivity convergence and the catch-up hypothesis, within 10 manufacturing sectors, using a new dataset for the period between 1971 and 1995 that covers 56 countries, including 32 less-industrialized or developing countries.

The concept of productivity convergence has its roots in the traditional Solow-Swan neoclassical growth model (Solow, 1956; Swan, 1956) with its central notion of a transitional growth path toward a steady state. The model postulates convergence of income per worker driven by the assumption of diminishing returns to capital accumulation at the economy-wide level. In addition, new or endogenous growth theory (e.g., Lucas, 1988 and Romer, 1986, 1990) stresses the role of international knowledge spillovers in driving convergence, as this allows less-productive countries to catch up with more advanced economies by exploiting their ‘advantage of backwardness’ (Gerschenkron, 1952). At the same time, however, new growth theory suggests that growth differentials may persist, or even increase, because learning effects, externalities, and market imperfections allow for increasing returns to capital accumulation and the existence of multiple steady states on an economy-wide basis. These various approaches, in combination with the availability of new cross-country datasets, have caused the convergence hypothesis to be subjected to extensive empirical research and debate. In this literature, the principal focus has been on cross-country convergence of per capita income (e.g., Baumol, 1986; Abramovitz, 1986; DeLong, 1988; Barro, 1991; Barro and Sala-i-Martin, 1992, 1995; Mankiw *et al.*, 1992; Islam, 1995) and labour- and total-factor productivity (e.g., Baumol *et al.*, 1994; Islam, 2003a; van Ark and Crafts, 1996; Miller and Upadhyah, 2002)[1].

In spite of many existing cross-country studies on energy-productivity or energy-intensity developments and their determinants (e.g., Jorgenson, 1986; Howarth *et al.*, 1991; Miketa, 2001; Schipper and Meyers, 1992; Unander *et al.*, 1999), systematic analyses of convergence and catching up have, to date, been rare in the field of energy economics. An example can be found in Mulder and De Groot (2003b), who provide a comparison of energy- and labor-productivity convergence at a detailed sectoral level for a number of OECD countries. We follow their approach, but our study is different in that it includes a range of non-OECD countries[2], an exclusive focus on energy productivity, and a more elaborate analysis of cross-country energy-productivity dynamics. Except for its focus on energy productivity, our study differs from most empirical convergence studies in the empirical growth literature in considering a relatively high degree of sectoral detail. This is important because a convergence analysis of aggregate productivity developments may mask substantial differences in convergence patterns at the sectoral level, as has been pointed out by the few detailed sectoral convergence analyses available (Dollar and Wolff, 1988, 1993; Bernard and Jones, 1996a, 1996b; Mulder and De Groot 2003b).

The paper proceeds as follows. In Section 2, we give a brief description of the data used in this study and document some stylized facts, including average annual growth rates both in developed (OECD) and developing (mostly non-OECD) countries. In Section 3, we present a convergence analysis to measure the development of cross-country variation of energy-productivity levels over time. In Section 4, we use a panel-data approach to test, for each manufacturing sector, the proposition that energy-productivity growth rates are inversely related to initial energy-productivity levels, indicating possible patterns of catching up. Section 5 concludes the paper.

[1] For more complete surveys of this literature, refer to Durlauf and Quah (1999), Economic Journal (1996), and Islam (2003b), among others.

[2] In this respect, our study also differs from most cross-country studies of energy-intensity developments, which are mainly confined to OECD countries. An exception is Park *et al*. (1993).

2 Data and stylized facts

The analysis presented in this paper is based on a newly constructed database of manufacturing energy-productivity data covering the period between 1971 and 1995, and includes 56 countries. Among those countries, we characterize 24 as industrialized or developed countries and 32 as less-industrialized or developing countries. The first group consists of the OECD countries of North America, Western Europe and the Pacific, while the second group includes mostly non-OECD countries. See Table A.1 in the *Appendix* for a detailed overview of the countries in each sector. Furthermore, we distinguish 10 manufacturing industries, classified according to the International Standard Industry Classification (ISIC) (Rev. 2), as shown in Table 1. Below, we briefly describe the dataset.[3]

Energy productivity is defined as output divided by final-energy use and is thus the inverse of energy intensity. Final energy-consumption is expressed in tons of oil equivalents (toe) and taken from the International Energy Agency (IEA) publication series, *Energy Statistics and Balances.* Sectoral output is measured in 1990 US dollars. They have been constructed using 1990 output values in combination with the production (output) index at sub-industry level (at a three-digit level of ISIC), subsequently aggregated into 10 manufacturing sectors (at the two-digit level). The production index was taken from the *Industrial Statistics Database* at the three-digit classification level, published by the United Nations Industrial Development Organization (UNIDO). Missing data in this data source have been estimated at the three-digit level using the production data from the United Nations *Industrial Commodity Statistics*.

Table 1: Sector classification.

	Sector		**ISIC Rev. 2 code**
1	Food and Tobacco	FOD	31
2	Textiles and Leather	TEX	32
3	Wood and Wood Products	WOD	33
4	Paper, Pulp and Printing	PAP	34
5	Chemicals	CHE	35
6	Non-Metallic Minerals	NMM	36
7	Iron and Steel	IAS	371
8	Non-Ferrous Metals	NFM	372
9	Machinery	MAC	381+382+383+385*
10	Transport Equipment	TRM	384

*MAC = Fabricated metal Products (381) + Machinery except electrical (382) + Machinery, electrical (383) + professional and scientific equipment (385)

In this paper we also use data on energy prices and investment ratios, presuming they are important fundamentals of productivity growth. Country-specific, industrial energy end-use price series have been calculated as a weighted average of aggregate industrial

[3] A separate, unpublished document with a more detailed description of the database is available upon request.

energy prices for the four main energy carriers: petroleum products, natural gas, coal, and electricity. The country-specific weights of these energy carriers in total energy consumption in the industrial sector were taken from *Energy Statistics and Balances* of the IEA. The price for petroleum products is calculated as a weighted average of liquefied petroleum gas (LPG), naphtha, gas/diesel oil and heavy fuel oil. Industrial energy prices for natural gas, coal, and electricity were taken from the IEA *Energy Prices and Taxes* series, the *Energy Indicators of Developing Member Countries of ADB* published by the Asian Development Bank (ADB) and *Energy, Economic Statistics and Indicators of Latin America and the Caribbean* published by the Latin American Energy Organization (OLADE). Investment data represent gross capital formation and are taken from the aforementioned UNIDO *Industrial Statistics Database*. Both energy price and investment data series are deflated using the wholesale price index taken from the *International Financial Statistics* (IFS) database of the International Monetary Fund (IMF).

Finally, all currency-denominated variables are in constant 1990 U.S. dollars and have been converted using 1990 market exchange rates taken from the IFS database of the IMF. In the context of our study, market exchange rates are the theoretically most appropriate conversion factor, particularly because we analyze the manufacturing sector and, hence, mainly deal with tradable goods. Moreover, contrary to other conversion factors such as Purchasing Power Parity (PPP), they are available both for OECD and non-OECD countries.[4] Obviously, the results presented in this paper should be interpreted with caution, bearing in mind that market exchange rates might suffer from the impact of speculation or other specific peculiarities in the base year. In the remainder of this section we document a few stylized facts derived from our dataset.

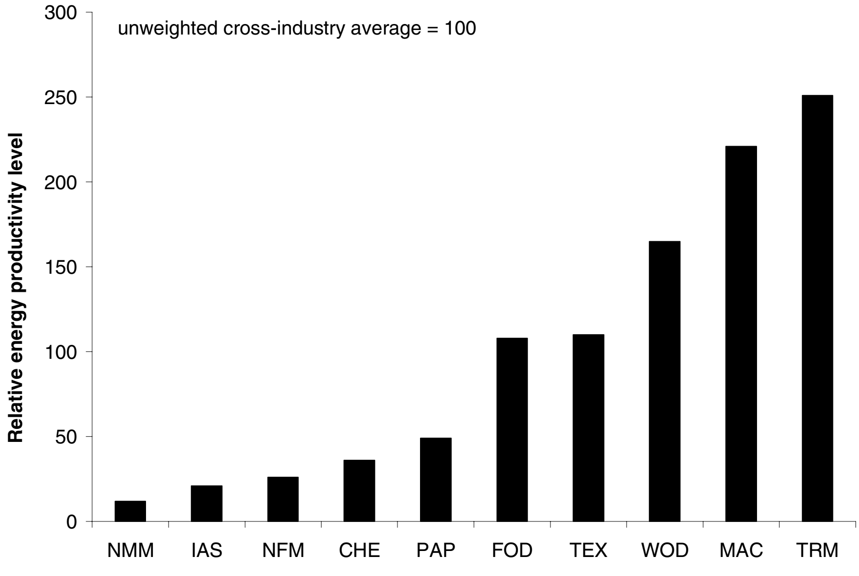

Figure 1: Comparison of the relative level of energy productivity (cross-industry average normalized to 100).

[4] See van Ark (1993), van Ark and Pilat (1993), Pilat (1996) for a discussion of different conversion factors in cross-country analyses as well as Sørensen (2001) and Bernard and Jones (2001) for a discussion of this issue in the context of empirical convergence analyses at the sectoral level.

The manufacturing sector is characterized by substantial differences in energy productivity across its various sub-sectors. This is illustrated in Figure 1 which shows, for each manufacturing sector, an index of the cross-country average energy-productivity levels in 1990, normalized to the unweighted cross-sector average (=100) in our database.

The figure shows that roughly three groups of sectors can be distinguished within manufacturing: (i) the energy-intensive sectors, non-metal products (NMM), iron and steel (IAS), non-ferrous metals (NFM), chemicals (CHE) and paper (PAP); (ii) the energy-extensive sectors, transportation equipment (TRM), machinery (MAC), and wood (WOD); and (iii) a medium group consisting of food (FOD) and textiles (TEX). These substantial (structural) differences are mainly a consequence of some activities requiring more capital and higher labor skills and/or technology than others, the result being that some sectors produce more value added per unit of input than others. For that reason, the impact of a shift in sectoral distribution of energy consumption (often referred to as structural change) on aggregate energy-productivity growth can be substantial (e.g., Greening *et al.*, 1997; Howarth *et al.*, 1991; Eichhammer and Mannsbart, 1997; Unander *et al.*, 1999, Mulder and De Groot 2003a). Our sectoral approach implies that the sectoral energy-productivity growth rates we report below result from technological change and *intra*-sectoral structural change only, which implies a closer link with issues concerning international technology diffusion, as raised in the convergence debate induced by the new growth theory.

In Table 2 we summarize, for each manufacturing sector, the cross-country average growth rate of energy productivity for the period between 1975 and 1990, weighted by each country's 1990 share of total output per sector, according to our classification of industrialized countries ('Industrialized'), less-industrialized countries or developing countries ('Rest of World') and all countries in our database ('World').

Table 2: Weighted average annual growth rates 1975-1990.

	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD	MAN*
Industrialized	1.20	1.22	2.69	0.27	2.26	0.39	1.46	0.07	0.98	1.07	1.16
Rest of World	-0.84	-0.95	1.54	3.68	1.70	0.48	1.38	0.83	-3.96	-0.67	0.32
World	0.86	0.81	2.40	0.63	2.14	0.41	1.45	0.26	0.90	0.88	1.07

The average is weighted with each country's 1990 share of total output per sector.
* Unweighted average of all manufacturing sectors

From the table it can be seen that the sectors differ substantially in terms of the dynamics of energy-productivity levels over time. In general, the highest growth rates of energy productivity are to be found in energy-intensive sectors rather than less energy-intensive sectors, and within the Industrialized regions rather than within the Rest of World. In particular, the energy-intensive sectors, iron and steel (IAS), non-ferrous metals (NFM), and paper (PAP) experienced rapid energy-productivity growth in both regions. An important exception to this pattern, however, is the most energy-intensive sector, non-metallic minerals (NMM), which experienced rather slow energy-productivity growth, particularly in the Industrialized regions. In the sectors, chemicals (CHE), food (FOD), transport equipment (TRM), and wood (WOD), modest energy-productivity growth took place in the Industrialized region, and negative-to-almost-zero growth in the Rest of World. In the textile industry (TEX), energy-productivity growth has been relatively slow in both regions. Machinery (MAC) is unique in showing much higher energy-productivity growth in the group of less-industrialized or developing countries than within the Industrialized region. In the remaining part of the paper, we will explore what these dynamics mean for the development of cross-country differences in energy-productivity performance.

3 Cross-country differences

Our analysis of cross-country energy-productivity differences builds upon the methodological framework provided by the convergence analyses in the empirical growth literature, as briefly discussed in the introduction. From this literature, it follows that convergence can be understood in terms of levels and growth rates, which translates into a distinction between so-called σ-convergence and β-convergence (e.g., Barro, 1991; Barro and Sala-i-Martin, 1992). The former refers to a decreasing variation of cross-country differences in productivity levels, while the latter suggests a tendency of countries with relatively low initial productivity levels to grow relatively fast, substantiating the catch-up hypothesis. In section 4 we further explain the notion of β-convergence. In this section, we analyze the development of the variation of energy-productivity *levels* across countries within each manufacturing sector. The variation is measured by σ, defined as the cross-country standard deviation for the log of energy productivity[5]. A decreasing cross-country variation is therefore referred to as σ-convergence. Figure 2 displays the degree of cross-country variation in energy-productivity levels per manufacturing sector for the period 1980 to1990, again classified by our sample of Industrialized countries and Rest of World respectively[6].

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[5] In the literature on convergence analysis, two measures of σ-convergence are used interchangeably: 1) the SD of the log of productivity (y) and 2) the SD of productivity (*y*) divided by the sample average. They are defined, respectively, as follows: 1) $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\log y_i - \overline{\log y}\right)^2}$, $\overline{\log y} = \frac{1}{n}\sum_{i=1}^{n}\log y_i$ 2) $\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i - \bar{y}}{\bar{y}}\right)^2}$, $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y$. The latter is usually referred to as the coefficient of variation. Dalgaard and Vastrup (2001) have shown that these measures may lead to different conclusions because they assign different weights to individual countries' performance. For this reason we also calculated the coefficient of variation to test for the robustness of our results. We find both measures to yield an overall similar pattern of σ-convergence, although there are some differences in various sectors. Moreover, the coefficient of variation yields differences in the size of cross-country variance. In Table A.3 in the *Appendix* we present, analogue to Table 3 the percentage change of the coefficient of variation of energy productivity per sector over the period 1980-1990.

[6] It should be noted that throughout the period the sample of countries is kept the same to avoid a potential bias of convergence evidence due to change in the list of countries included. See *Table A.1* in the Appendix for an overview of countries included per sector. We also performed the analysis for the period 1975-1990 where we had to drop a number of countries because of restricted data availability. Moreover, we did the analysis for a somewhat different sample of countries, making a strict distinction between OECD and non-OECD countries. The results of these analyses revealed that although in some sectors the level of dispersion is somewhat different as shown in Figure 2 the overall pattern is similar. Details are available upon request.

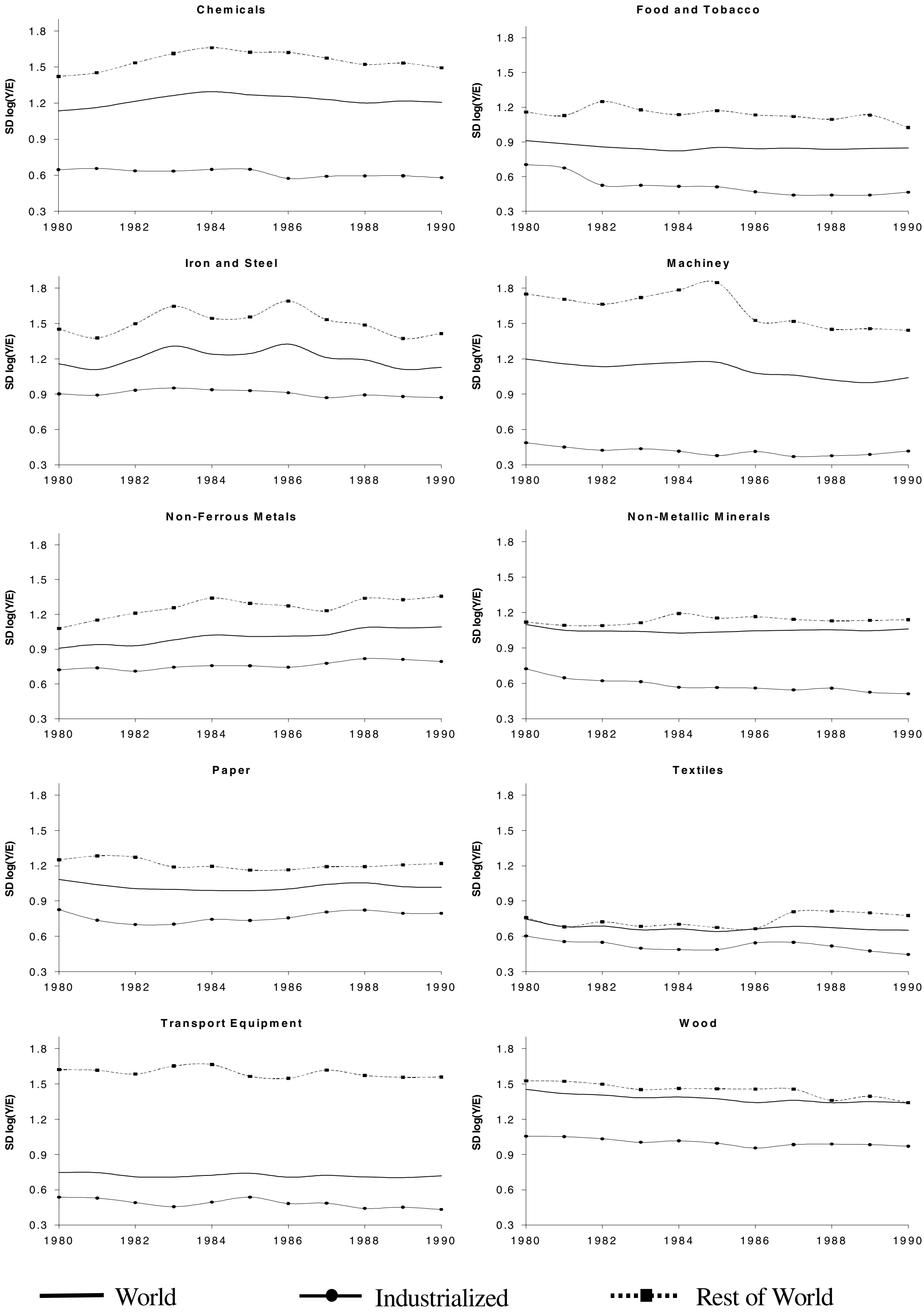

Figure 2: Standard Deviation of log Energy Productivity per sector over the period 1980-1990.

It can be seen from Table 3 that, in most sectors, the cross-country differences in absolute energy-productivity levels are declining in the Industrialized region as well as in the Rest of World (and thus in the World sample as well). In other words, most sectors show a pattern of σ-convergence. This appears particularly so in less energy-intensive industries, such as food (FOD), textile (TEX), wood (WOD), and machinery (MAC). The most important exception is the non-ferrous metals sector (NFM) where cross-country differences in energy-productivity levels have increased considerably in both regions. The overall picture for the Industrialized countries in Figure 2 accords well with the findings of Mulder and De Groot (2003b), who conducted the same analysis for a limited number of OECD countries, although they did, in fact, find a somewhat lower level of cross-country variation in the Iron and Steel sector. This can be explained from the larger number of countries included in our sample.

Table 3 Percentage change in standard deviation of log energy productivity per sector over the period 1980-1990.

	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD
Industrialized	-10.1	-33.8	-3.4	-14.4	10.1	-29.2	-3.9	-25.9	-19.6	-8.1
Rest of World	5.1	-11.6	-2.5	-17.6	25.7	1.8	-2.3	2.4	-4.0	-12.2
World	6.4	-6.9	-2.6	-13.2	20.1	-3.4	-6.3	-12.8	-3.9	0.88

Figure 2 also shows that, in all sectors, the cross-country variation in energy productivity is lower among Industrialized countries than among the countries in the Rest of World. Moreover, for both the Industrialized region and the Rest of World, the highest cross-country productivity differentials can be found in the energy-intensive sectors – iron and steel (IAS), non-ferrous metals (NFM), paper (PAP) and chemicals (CHE), as well as in the wood sector (WOD)[7].

In Table 3 we summarize the results shown in Figure 2 in terms of the total percentage change in standard deviation (SD) of the log of energy productivity during the same decade. In addition to the above-mentioned conclusions, the table shows that in chemicals (CHE), non-metallic minerals (NMM) and textiles (TEX), the variation in energy-productivity levels has increased (slightly) among the developing countries (see also footnote 6), while in the energy intensive sectors, iron and steel (IAS) and paper (PAP), the decline in cross-country variation has been relatively small in all regions.

Finally, Figure 2 leads to the conclusion that, in spite of the overall pattern of σ-convergence in nine manufacturing sectors, substantial cross-country variation in energy-productivity levels remains in existence, in particular in several energy-intensive sectors such as chemicals, iron and steel, and paper. In the next section, therefore, we will further explore the mechanisms behind these developments and the apparent lack of absolute cross-country convergence.

4 Advantage of backwardness

In this section we focus on the catch-up hypothesis by analyzing cross-country convergence of energy productivity in terms of *growth rates*. Below, we adopt a panel-

[7] We view the high cross-country variation in transport equipment (TRM) for the Rest of World as a special case as it is based on a sample of two countries only (see Table A.2 in Appendix).

data framework to regress, for each sector, average energy-productivity growth rates on initial energy-productivity levels, generating an estimate of the coefficient β. A negative coefficient β indicates the existence of so-called β-convergence, suggesting that countries with relatively low initial energy-productivity levels catch up to more advanced countries, possibly because they can benefit from the experience and technologies developed by countries operating at the forefront. In addition to an analysis of σ-convergence, therefore, a β-convergence analysis contributes to a better understanding of the driving forces behind convergence patterns and the cross-country differences in energy-productivity growth. Obviously, catching up is a necessary condition for convergence to the same productivity level across countries, i.e. for σ-convergence. As has been argued by Quah (1993), however, it is not a sufficient condition because lagging countries can still catch up where there is a constant or even an increasing cross-country variation in energy-productivity levels, a statistical phenomenon known as Galton's fallacy of regression toward the mean[8].

The concept of β-convergence can be refined by distinguishing unconditional (or absolute) convergence from conditional (or relative) convergence. The first is said to be present if cross-country productivity exhibits a tendency to converge toward a uniform level, while the second concerns convergence of (subsets of) different countries toward different levels, implying that convergence is conditional on similarities in countries' characteristics. The idea of conditional convergence has been formalized by Durlauf and Johnson (1992) and confirmed by several empirical convergence studies, some of which suggest the existence of convergence clubs: groups of countries converging to different levels (e.g., Barro, 1991; Chatterji, 1992; Chatterji *et al.*, 1993; Quah, 1997). Below we will apply both concepts to analyzing energy-productivity developments across countries.

We start our β-convergence analysis by testing for unconditional convergence, assuming that energy productivity converges toward the same long-term level for all countries included in the dataset. Subsequently, in section 4.2, we include unspecified country-specific factors by allowing the intercept of the regression equation to vary across countries (fixed-effect model). In doing so, we test for the assumption that countries converge to country-specific growth paths and analyze whether this supports the existence of convergence clubs. Finally, in section 4.3, we include country-specific data on energy prices and investment ratios as factors that could cause cross-country productivity differences.

4.1 Unconditional convergence

We test for unconditional β-convergence by regressing, for each sector, the average annual growth rate (g) of energy productivity (y) on its initial level (and a constant α), thus generating an estimate of β according to:

$$g_{it} = \alpha + \beta \ln(y)_{i,t-1} + \gamma_t + \varepsilon_{it} \qquad (1)$$

[8] This can be the case, for example, if the gap in productivity level between leading and lagging countries is big, such that an even higher growth rate in the lagging countries cannot prevent the absolute difference in productivity levels from increasing. See Quah (1993) and Durlauf and Quah (1999) for a more elaborate discussion of this point.

with i and t denoting, respectively, the cross-country and the time-series dimension of the panel-data structure, while η_t denotes period-specific fixed effects (period dummies) and ε_{it} is the standard error. Following Islam (1995), we divide the total period into several shorter periods using five-year time intervals so that the error term is less influenced by business-cycle fluctuations and serial correlation than it would be in a yearly set-up[9]. The estimation results are summarized in Table 4.

Table 4: Unconditional β -convergence for energy productivity.

	CHE	**FOD**	**IAS**	**MAC**	**NFM**	**NMM**	**PAP**	**TEX**	**TRM**	**WOD**
World										
β	-0.01	-0.02	-0.01	-0.03	-0.02	-0.03	-0.01	-0.03	-0.04	-0.01
	(-2.83)	(-3.66)	(-2.43)	(-5.74)	(-2.52)	(-6.78)	(-3.04)	(-4.79)	(-4.73)	(-3.06)
implied λ	0.0029	0.0036	0.0024	0.0058	0.0033	0.0063	0.0026	0.0068	0.0072	0.0027
R^2	0.09	0.08	0.03	0.25	0.07	0.22	0.08	0.16	0.24	0.11
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	45	37	52	34	35	42	36	33	22	28
totalobs	205	161	240	147	151	181	158	141	97	120
Industrialized										
β	-0.02	-0.04	-0.01	-0.05	0.01	-0.06	-0.02	-0.06	-0.05	-0.01
	(-2.14)	(-4.78)	(-1.66)	(-5.66)	(1.03)	(-9.08)	(-3.10)	(-5.07)	(-4.29)	(-1.12)
implied λ	0.0043	0.0072	0.0019	0.0110	-0.0014	0.0126	0.0041	0.0115	0.0094	0.0017
R^2	0.09	0.22	0.05	0.33	0.07	0.48	0.11	0.25	0.27	0.08
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	23	23	23	23	20	23	22	22	18	20
totalobs	110	103	112	103	91	107	103	100	86	90
Rest of World										
β	-0.02	-0.02	-0.01	-0.03	-0.04	-0.02	-0.01	-0.02	-0.03	-0.02
	(-2.60)	(-2.50)	(-1.74)	(-3.19)	(-3.34)	(-2.95)	(-1.32)	(-1.70)	(-1.24)	(-2.95)
implied λ	0.0036	0.0032	0.0024	0.0057	0.0079	0.0049	0.0018	0.0039	0.0058	0.0038
R^2	0.15	0.21	0.05	0.29	0.20	0.16	0.15	0.13	0.55	0.33
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	22	14	29	11	15	20	14	11	4	8
totalobs	95	58	127	44	60	77	55	41	11	30

T-statistics in parentheses. Estimated values for the constant and the period-specific fixed effects are not reported.
regobs: number of time points included; ncrossest: number of countries included; and totobs: total number of observation.

The table displays a negative estimate of β in virtually all sectors, for the total sample as well as for the Industrialized region and the Rest of World, while in most sectors these estimates are statistically significant. An exception to this result is the non-ferrous metals (NFM) sector within the Industrialized region, which shows a positive β-coefficient. Its estimate, however, is statistically insignificant, which also applies to the iron and steel (IAS) sector in the Industrialized region as well as the paper (PAP) and transport equipment (TRM) sectors in the Rest of World.

In short, the results of our test for β-coefficient provide evidence of lagging countries catching up in terms of energy-productivity performance within most industrial sectors. It may be noted that our estimates are rather similar to the two percent convergence coefficient reported by Barro and Sala-i-Martin (1992) in their seminal work on per capita income convergence. Moreover, on the whole, our results for the Industrialized countries are in line with the findings of the convergence analysis for 14 OECD countries in Mulder and De Groot (2003b). These values indicate that the catch-up

[9] As our dataset covers the period 1971-1995 and 1971 is the initial year in our regression analysis, we took the first interval to be a 4-year period from 1971-1975, followed by 4 periods of 5 year.

process is rather slow. Using the estimated values of β, the speed of convergence can be calculated as follows (Barro and Sala-i-Martin, 1992; Mankiw *et al.*, 1992; Islam, 1995): let y^* be the productivity level to which countries are supposed ultimately to converge and $y(t)$ its actual value at any time t. Approximating around this 'steady-state level', the speed of convergence λ is given by

$$\frac{d\log(y(t))}{dt} = \lambda[\log(y^*) - \log(y(t))] \tag{2}$$

which implies that

$$\log(y(t)) = (1 - e^{-\lambda t})\log(y^*) + e^{-\lambda t}\log(y(0)) \tag{3}$$

where (y(0)) is the energy-productivity level at some initial date. Subtracting log (y(0)) from both sides yields

$$\log(y(t) - \log(y(0)) = (1 - e^{-\lambda t})[\log(y^*) - \log(y(0))] \tag{4}$$

in which $(1 - e^{-\lambda t}) = \beta$.

Hence, the speed of convergence λ is given by $\lambda = -[(1/T)\log(\beta - 1)]$ with T denoting the time interval under consideration[10]. A convenient way of expressing this speed of convergence is the time t needed for the energy-productivity level to move its initial level halfway (y(0)), and the steady state productivity level y^*. This period of time is commonly referred to as the 'half life' (H), derived from $e^{-\lambda H} = 0.5 \Leftrightarrow H = \log(2)/\lambda$. Table 4 presents the values of the implied λ as they follow from the estimates of β. They confirm the finding of a slow rate of convergence: the half life that can be derived from these values varies from 55 years in the non-metallic minerals sector (NMM) to 397 years in the wood sector (WOD) in the Industrialized region.

A comparison of these results with the patterns of σ-convergence, as reported in Section 3, confirms that those sectors showing evidence of σ-convergence also display evidence of β-convergence. This is obvious because a decreasing cross-country variation in energy-productivity levels implies that countries with a relatively poor initial productivity performance tend to grow relatively fast. As we noted previously, however, the converse does not necessarily hold true; hence, evidence of catching up can be consistent with increasing cross-country variation in energy-productivity levels. This can be illustrated by the non-ferrous metal (NFM) sector which, in the previous section, we found to show increasing cross-country variation in energy-productivity levels (i.e., σ-divergence) but which nevertheless also demonstrates evidence of β-convergence (see Table 4 and, particularly, Tables 5 to 7 below). This can be caused by cross-country differences in energy productivity being governed not just by the catch-up mechanism alone but also by other (country-specific) exogenous factors. Moreover, even if we control for the appropriate exogenous differences, the combination of β-

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[10] T=5 in our analysis, as we use five-year time intervals. The fact that our first period is 4 years will bias β and thus λ. We believe this effect to be very small, however, because in our regression model we use an average annual growth rate and include period dummies to control period-specific fluctuations in growth. Moreover, it should be noted that in Islam (1995), $\lambda = -[(1/T)\ln(\beta)]$ as he takes ln $(y)_{it}$ instead of [ln $(y)_{it}$ – ln $(y)_{it-1}$] as dependent variable, after rewriting equation (4).

convergence and σ-divergence can be subject to Galton's fallacy, as discussed earlier. In any case, it should be noted that the extremely low R-squares indicate that the explanatory value of equation (1) is very limited, suggesting the existence of factors determining cross-country differences in energy-productivity growth other than those included in equation (1). In the next section we deal with these issues by exploring patterns of conditional convergence.

4.2 Conditional convergence

Conditional convergence presumes that (groups of) countries converge to different energy-productivity growth paths, depending on country-specific conditions, rather than evolving toward the same ultimate level of energy-productivity growth. To analyze conditional convergence, therefore, we allow the intercept (α) of equation (1) to vary across countries, applying a so-called fixed-effect model. We do so by reformulating equation (1) into a panel-data model with individual country effects, according to:

$$g_{it} = \alpha_i + \beta \ln(y)_{i,t-1} + \gamma_t + \varepsilon_{it} \qquad (5)$$

with α_i representing unspecified country-specific (fixed) effects, and all other symbols identical to equation (1). These country effects might include all sorts of country-specific tangible and intangible factors affecting energy-productivity growth that have not been included in equation (1) or, to put it differently, factors that have been subsumed in the error term. The model formulation of equation (5) enables us to test for the hypothesis that, in the long run, the energy-productivity growth rates of nations tend to slow down as they approach *their own* long-run growth path, thus implying the existence of multiple 'steady-state' levels of energy productivity. Hence, this formulation accords well with the possibility that substantial cross-country differences remain in existence, presuming that determinants of energy-productivity growth may well vary across countries. Table 5 summarizes the results of the unspecified conditional convergence estimation according to equation (5).

The results confirm the evidence of β-convergence: except for wood (WOD) in the Rest of World, all estimated β coefficients are negative and highly significant. Moreover, the values of the R-squares improved considerably, suggesting that country effects indeed play an important role, and thus making equation (5) a much better model for explaining energy-productivity growth across countries than equation (1). From the higher values of the implied λ in Table 5 it can be seen that allowing for country-specific effects also leads to a substantial increase in the speed of convergence. It can be calculated that the resulting half life (H) decreases to a period that lies between 11 and 47 years (for, respectively, TEX in the Rest of World region and WOD in the World region).

In short, our results show support for the hypothesis that, in terms of sectoral energy productivity, lagging countries tend to catch up with advanced nations, with convergence tending to be conditional on country-specific characteristics rather than unconditional or absolute. Of course, this raises the question as to which underlying mechanisms cause 'followers' to grow faster than 'leaders'. It may be recalled from the introduction that there are various mechanisms; for example, advanced economies may suffer from diminishing returns, lagging countries may benefit from knowledge spillovers (technology transfer), production processes may converge because of increasing competition, and so forth. To date, our results do not provide much information to clarify this. From Table 5 it can be concluded that, in most sectors, the estimated values for β are higher among less-industrialized or developing countries (the Rest of World region) than for the Industrialized region. This may be taken as a sign that developing countries are realizing their potential for rapid growth, benefiting from the advantage of backwardness. At the same time, however, it is again to be noted that these results do not necessarily imply that cross-country differentials in energy-productivity performance are vanishing, which is also best illustrated in Table 5 by the non-ferrous metals sector (NFM) which shows robust statistically significant evidence of β-convergence in combination with a pattern of σ-divergence (see Section 3). Hence, it is worth taking a closer look at actual energy-productivity performance per sector and per country. Our panel estimation permits us to analyze, for each sector, the estimated coefficients of the country-specific intercepts μ_i themselves. They can be interpreted as a rough measure of a country's initial energy-productivity performance in so far as it captures the unspecified country characteristics within a sector.

Table 5: (Unspecified) conditional β -convergence for energy productivity.

	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD
World										
β	-0.10	-0.10	-0.12	-0.12	-0.15	-0.14	-0.15	-0.15	-0.10	-0.07
	(-7.37)	(-6.31)	(-9.31)	(-7.10)	(-9.69)	(-12.83)	(-10.28)	(-8.96)	(-5.72)	(-3.47)
implied λ	0.0215	0.0219	0.0263	0.0249	0.0315	0.0293	0.0330	0.0326	0.0205	0.0148
R^2	0.50	0.41	0.43	0.53	0.62	0.68	0.57	0.53	0.60	0.46
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	45	37	52	34	35	42	36	33	22	28
totalobs	205	161	240	147	151	181	158	141	97	120
Industrialized										
β	-0.11	-0.12	-0.11	-0.08	-0.15	-0.12	-0.14	-0.13	-0.09	-0.08
	(-5.60)	(-5.83)	(-6.09)	(-4.56)	(-4.93)	(-11.86)	(-8.03)	(-7.20)	(-5.14)	(-3.62)
implied λ	0.0239	0.0248	0.0235	0.0162	0.0319	0.0250	0.0307	0.0283	0.0184	0.0167
R^2	0.44	0.43	0.41	0.53	0.42	0.79	0.56	0.54	0.60	0.48
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	23	23	23	23	20	23	22	22	18	20
totalobs	110	103	112	103	91	107	103	100	86	90
Rest of World										
β	-0.11	-0.10	-0.13	-0.17	-0.15	-0.19	-0.18	-0.27	-1.03	0.12
	(-5.15)	(-3.28)	(-6.74)	(-4.82)	(-7.44)	(-7.73)	(-6.19)	(-6.24)	(-1.80)	(1.44)
implied λ	0.0240	0.0206	0.0270	0.0377	0.0332	0.0429	0.0387	0.0617	---	-0.0230
R^2	0.55	0.55	0.45	0.61	0.73	0.61	0.63	0.66	0.85	0.55
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	22	14	29	11	15	20	14	11	4	8
totalobs	95	58	127	44	60	77	55	41	11	30

T-statistics in parentheses
regobs: number of time points included; ncrossest: number of countries included; and totobs: total number of observation.

As a next step in our analysis, therefore, we analyze the country-specific intercepts included in equation (5). Table 6 shows, for each sector, the top five and bottom five countries in terms of energy-productivity performance, defined by the estimated values of α_i relative to the highest value α_{max} per sector. For an overview of the ranking of all countries per sector, refer to Table A.4 in the appendix.

Table 6: Best and worst performance in energy productivity. Relative estimated intercepts.

	CHE			FOD			IAS			MAC			NFM	
	Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$
1	Kuwait	(1.0)	1	Switzerland	(1.0)	1	Malaysia	(1.0)	1	Thailand	(1.0)	1	Chin. Taipei	(1.0)
2	Switzerland	(.86)	2	Chile	(.81)	2	Bangladesh	(.96)	2	Belgium	(.99)	2	S. Korea	(.00)
3	Philippines	(.84)	3	USA	(.81)	3	Uruguay	(.96)	3	Japan	(.97)	3	Mexico	(.95)
4	Denmark	(.84)	4	Canada	(.80)	4	Argentina	(.91)	4	Austria	(.97)	4	Austria	(.92)
5	Greece	(.82)	5	India	(.79)	5	Peru	(.86)	5	Ireland	(.97)	5	Belgium	(.90)
41	Mexico	(.50)	33	Hungary	(.45)	48	N.Zealand	(.47)	30	Colombia	(.79)	31	Iceland	(.62)
42	Bangladesh	(.47)	34	Poland	(.33)	49	Iceland	(.45)	31	Hungary	(.77)	32	Venezuela	(.61)
43	USSR	(.47)	35	Mexico	(.33)	50	China	(.44)	32	Poland	(.67)	33	USSR	(.54)
44	Trinidad	(.47)	36	USSR	(.27)	51	USSR	(.40)	33	China	(.65)	34	Bahrain	(.49)
45	China	(.30)	37	China	(.20)	52	Venezuela	(.38)	34	USSR	(.54)	35	Ireland	(.33)
	NMM			**PAP**			**TEX**			**TRM**			**WOD**	
	Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$		Country	$\frac{\alpha_i}{\alpha_{\max}}$
1	Switzerland	(1.0)	1	Ireland	(1.0)	1	S. Africa	(1.0)	1	Japan	(1.0)	1	UK	(1.0)
2	France	(.97)	2	S. Africa	(.99)	2	N. Zealand	(.95)	2	Italy	(.98)	2	Belgium	(.99)
3	Turkey	(.94)	3	Switzerland	(.94)	3	Belgium	(.88)	3	Canada	(.98)	3	Italy	(.99)
4	Austria	(.92)	4	N. Zealand	(.91)	4	Finland	(.86)	4	Finland	(.97)	4	Slovenia	(.99)
5	Ireland	(.91)	5	Denmark	(.90)	5	USA	(.86)	5	France	(.97)	5	Germany	(.98)
38	Colombia	(.59)	32	Canada	(.63)	29	Luxembourg	(.71)	18	Australia	(.85)	24	Poland	(.92)
39	USSR	(.52)	33	Mexico	(.62)	30	Hungary	(.70)	19	Belgium	(.80)	25	Turkey	(.92)
40	China	(.51)	34	China	(.57)	31	India	(.70)	20	Hungary	(.77)	26	China	(.90)
41	Pakistan	(.47)	35	Poland	(.55)	32	Colombia	(.69)	21	Czech Rep.	(.72)	27	USSR	(.90)
42	Poland	(.46)	36	USSR	(.52)	33	China	(.63)	22	Poland	(.67)	28	N. Zealand	(.89)

The ranking of countries is based on the estimated values of μ_i from equation (5) in the text. The values in parentheses denote a country's values of μ_i relative to the highest estimated value μ_{max} per sector.

First, from Table 6 it can be seen that, not surprisingly, industrialized OECD countries dominate the top five ranking whereas most bottom five countries are less-industrialized or developing countries. An important exception, however, is the iron and steel (IAS) sector where all top five countries are developing countries. Second, it seems that several countries have a similar position in the ranking across different industrial sectors. According to our analysis, for example, China, Hungary, Poland and the former Soviet Union do belong to the bottom five category in several sectors, while Austria, Belgium and Switzerland are listed among the top five countries in several sectors. This tendency of intercepts across sectors to be correlated with the relative ranking of countries underlines that country-specific factors affecting energy-productivity growth, rather than sector-specific factors, seem to be dominant in causing (the persistence of) cross-country energy-productivity differentials.

To further investigate the energy-productivity dynamics, we break down the period 1971-1995 in an initial period 1971-1985 and a subsequent period 1985-1995 and compare, for each sector, the relative energy-productivity performance of the various countries between those two periods. We do so by performing the regression analysis according to equation (5) for both periods and examine per sector the estimated country-specific effects α_i relative to the average intercept value $\overline{\alpha}$ (cf. Islam, 2003a).

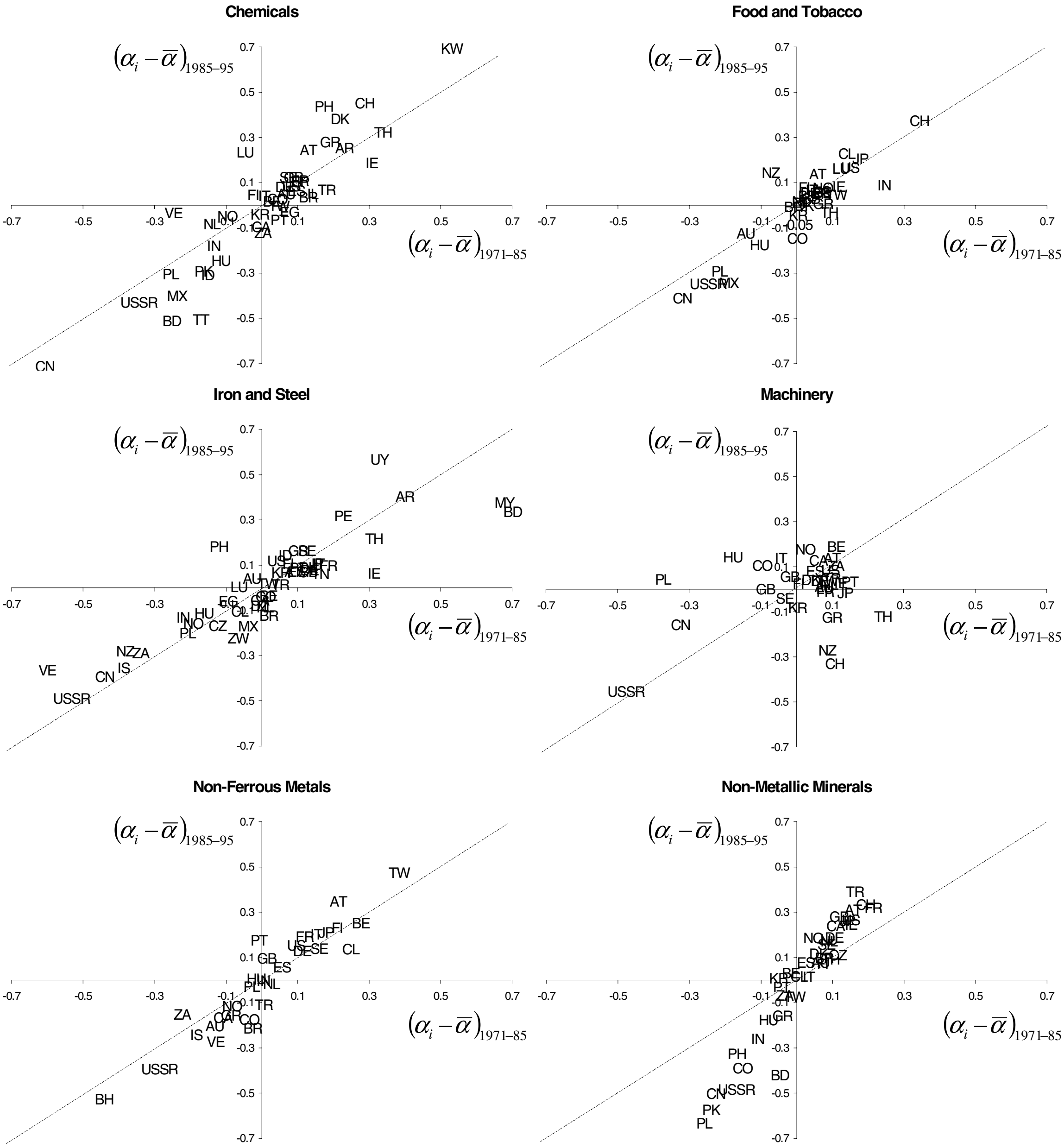

Figure 3: Sectoral energy productivity dynamics in the ‘world’ sample of countries.

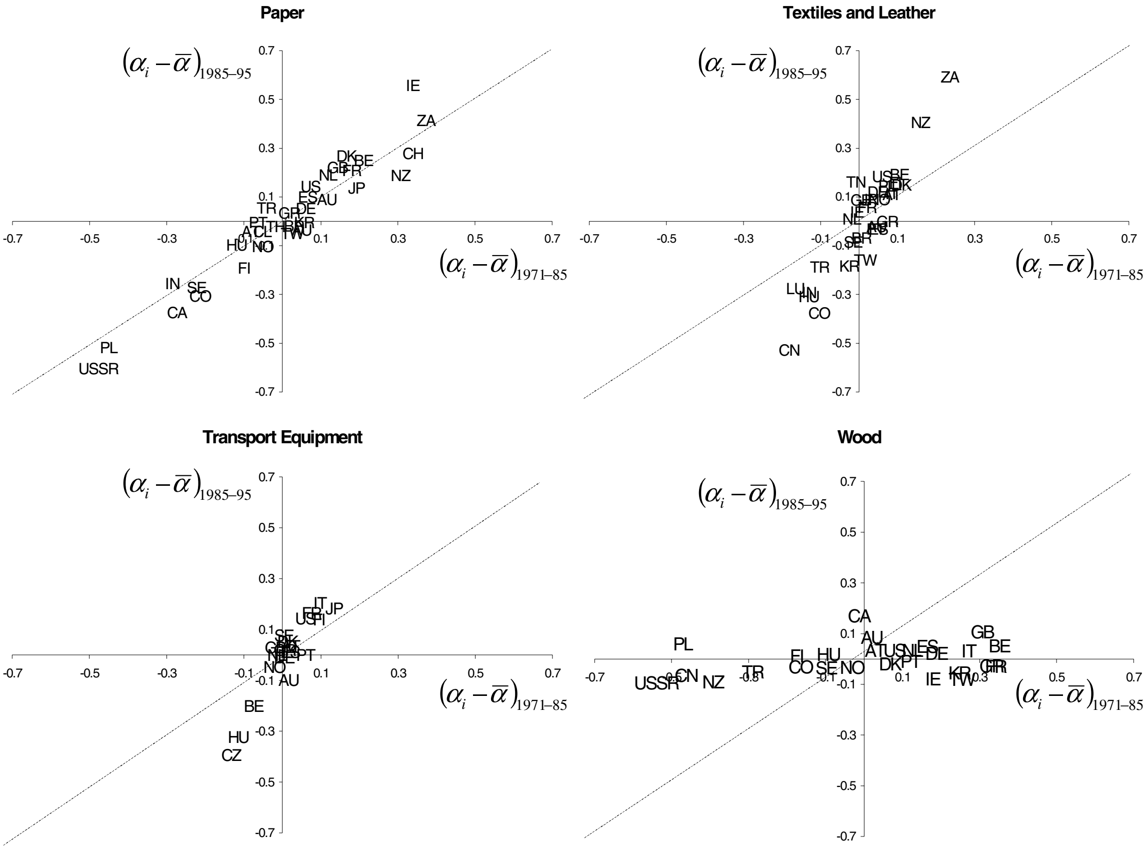

Figure 3 (continued).

The results are plotted in Figure 3, with the *x*-axis and *y*-axis representing the relative energy-productivity level in, respectively, the initial and subsequent period. The 45-degree line represents points where the relative levels in the two periods are the same. Hence, the countries that have improved their relative (to the average) energy-productivity performance in the second period as compared with the first period are plotted above the 45-degree line. Vice versa, those countries that experienced a fall in relative energy-productivity performance between the two periods are plotted below the 45-degree line.

Figure 3 leads to the following observations. First, some sectors display a more dynamic picture than others, as can be seen from the number of countries deviating from the 45-degree line, indicating differences in their relative productivity performance between the two periods. In this respect, chemicals, and iron and steel are among the most dynamic sectors, while in paper and food particularly, the relative performance of most countries is relatively stable over time. Second, in several sectors, various countries with above-average performance in the first period increased their relative performance in the subsequent period while, at the same time, the opposite is true for various countries lagging behind in the first period. This pattern is most notable in the non-metallic mineral sector, but can also be observed in chemicals, textiles, and transport equipment. Third, that we found no evidence of β-convergence for the wood sector within the Rest of World region is mainly due to the substantial drop in relative productivity performance of Chinese Taipei (TW) in the second period from its above-average performance in the first period. All other developing countries in the wood sector display a clear pattern of catching up, as all are plotted above the 45-degree line.

The main conclusion emerging from this analysis is that notwithstanding the evidence that countries characterized by relatively low energy-productivity levels generally tend to have relatively high energy-productivity growth rates, there are countries in several sectors failing to catch up to advanced economies. This results in persistent and sometimes even widening cross-country differences in energy-productivity performance. These differences are clearly driven by country-specific characteristics, as indicated by the considerable positive impact of fixed country effects on the panel estimation. Therefore, a final step in our analysis consists of an attempt to identify these country-specific characteristics.

4.3 Conditional convergence: identifying country effects

In this section we test for the hypothesis that cross-country differences in energy prices and investment ratios are a main source for the observed (persistence in) cross-country differences in energy-productivity performance. To this aim we add to the unspecified country-effects α_i equation (5), specified fixed-effects x_i, according to:

$$g_{it} = \alpha_i + \beta \ln(y)_{i,t-1} + \sum_{j=1}^{2} \gamma_j x_{it}^j + \eta_t + \varepsilon_{it} \qquad (6)$$

with x_{it}^1 and x_{it}^2 representing, respectively, the country-specific industrial energy price and investment ratio (i.e., the share of investment relative to output)[11]. We expect energy prices to be positively correlated with energy-productivity growth, as higher energy prices provide an incentive to improve energy efficiency. By including the investment share as an explanatory variable, we test for the so-called embodiment hypothesis or vintage effect, assuming that higher investment will contribute to increasing energy-productivity growth via technological change embodied in new capital goods (e.g., Howarth *et al.*, 1991; Mulder *et al.*, 2003).

The results of the regression analysis of equation (6) are presented in Table 7. It can be seen that in most sectors the estimated β coefficients are still negative and statistically significant. Moreover, the values of the R-squares suggest equation (6) to be an appropriate model to describe cross-country energy-productivity patterns. Nevertheless, the results also show very limited support for the hypothesis that energy prices and investment ratios are important determinants of (cross-country differences in) energy-productivity performance. The expected positive correlation between energy prices and energy-productivity growth is found in a limited number of sectors only, while it is statistically significant nowhere except for the wood (WOD) sector in the World sample. A similar result is obtained for the impact of the investment ratio, with a statistically significant positive effect in the textile (TEX) sector only.

It can, however, be argued that it is not so much the level but rather the increase in energy prices and investment share that will contribute to higher energy-productivity growth. We have, therefore, slightly modified equation (6) by reformulating x_{it}^1 in terms

[11] Refer to section 2 for a more detailed description of these variables.

of energy price *growth* and x_{it}^2 in terms of *growth* of the investment ratio. The results are shown in Table 8.

Table 7: Conditional β -convergence for energy productivity, specifying levels of energy price and investment ratio.

	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD
World										
β	-0.14	-0.16	-0.23	-0.11	-0.18	-0.15	-0.15	-0.17	-0.11	-0.09
	(-6.77)	(-6.17)	(-11.53)	(-5.72)	(-5.68)	(-7.81)	(-6.93)	(-7.75)	(-4.54)	(-3.31)
implied λ	0.0306	0.0344	0.0518	0.0234	0.0409	0.0321	0.0334	0.0362	0.0225	0.0178
P_E	-0.15	0.00	-0.05	0.16	0.27	-0.33	-0.04	0.14	-0.27	0.48
	(-0.87)	(-0.01)	(-0.25)	(0.72)	(0.66)	(-1.35)	(-0.15)	(0.50)	(-0.69)	(1.96)
I/Y	0.29	-0.39	-0.09	-0.46	0.01	0.03	0.02	0.94	0.11	0.16
	(1.04)	(-0.62)	(-1.55)	(-0.98)	(0.03)	(0.26)	(0.09)	(2.43)	(0.25)	(0.48)
R^2	0.68	0.55	0.77	0.79	0.56	0.68	0.55	0.62	0.59	0.55
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	35	31	34	28	26	33	30	27	19	24
totalobs	117	103	116	98	86	111	103	96	71	85
Industrialized										
β	-0.15	-0.22	-0.18	-0.11	-0.19	-0.14	-0.15	-0.16	-0.10	-0.09
	(-7.12)	(-8.28)	(-7.99)	(-5.44)	(-4.75)	(-8.09)	(-5.36)	(-6.74)	(-4.48)	(-3.59)
implied λ	0.0335	0.0500	0.0407	0.0243	0.0424	0.0313	0.0332	0.0344	0.0210	0.0198
P_E	0.04	0.24	-0.20	-0.07	0.03	-0.26	-0.04	0.39	-0.30	0.58
	(0.15)	(0.99)	(-1.18)	(-0.26)	(0.06)	(-1.33)	(-0.14)	(1.18)	(-0.79)	(2.07)
I/Y	0.48	-0.45	-0.12	-1.17	-0.17	0.32	-0.03	1.42	0.14	0.32
	(1.50)	(-0.72)	(-2.97)	(-2.11)	(-0.40)	(1.30)	(-0.07)	(2.07)	(0.36)	(0.84)
R^2	0.71	0.69	0.71	0.70	0.51	0.82	0.49	0.62	0.63	0.54
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	21	22	19	22	19	19	21	21	17	20
totalobs	78	75	70	78	65	72	77	76	66	71
Rest of World										
β	-0.10	-0.14	-0.25	-0.06	-0.24	-0.17	-0.20	-0.29	NA	0.12
	(-1.44)	(-2.21)	(-6.22)	(-0.80)	(-3.39)	(-3.54)	(-3.89)	(-5.93)	--	(0.80)
implied λ	0.0200	0.0302	0.0573	0.0116	0.0539	0.0379	0.0441	0.0675	--	-0.0231
P_E	-0.20	0.45	-0.09	1.29	0.55	-0.37	-1.11	-0.96	NA	0.36
	(-0.59)	(0.65)	(-0.18)	(1.11)	(0.58)	(-0.44)	(-1.19)	(-2.35)	--	(0.76)
I/Y	-0.03	-2.43	-0.23	-0.63	-0.22	0.09	0.03	1.10	NA	-0.56
	(-0.04)	(-1.11)	(-0.96)	(-0.38)	(-0.51)	(0.49)	(0.10)	(2.98)	--	(-0.92)
R^2	0.66	0.66	0.83	0.92	0.88	0.63	0.82	0.84	--	0.68
regobs	5	5	5	5	5	5	5	4	4	4
ncrossest	14	9	14	6	7	14	9	8	4	5
totalobs	39	28	41	20	21	39	26	20	5	14

T-statistics in parentheses
regobs: number of time points included; ncrossest: number of countries included; and totobs: total number of observation.

It can be seen that the overall result is similar to that in Table 7: although the evidence of β-convergence is confirmed in virtually all sectors and the explanatory value of equation (6) seems to be considerable, we again found only very limited evidence of a statistically significant positive correlation between energy-productivity growth on the one hand and growth of energy prices and investment share on the other. Contrary to the previous results, however, in various sectors such as iron and steel (IAS), food (FOD), non-metallic minerals (NMM) and paper (PAP), energy price increases do have a positive effect on energy-productivity growth, although this is, in general, statistically insignificant. The overall picture for the effect of investment share remains similar, although the results slightly change for individual sectors[12].

[12] We also did the regression analysis including a three-year moving average for the energy price to avoid capturing the effect of short-term price fluctuations, assuming that investments in energy- and labor-

Table 8: Conditional β -convergence for energy productivity, specifying growth of energy price and investment ratio.

	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD
World										
β	-0.15	-0.13	-0.17	-0.15	-0.17	-0.17	-0.15	-0.20	-0.13	-0.07
	(-3.57)	(-3.48)	(-6.39)	(-5.60)	(-3.85)	(-7.91)	(-7.25)	(-7.67)	(-4.04)	(-2.62)
implied λ	0.0327	0.0285	0.0361	0.0323	0.0374	0.0374	0.0315	0.0454	0.0267	0.0138
P_E	0.03	0.12	0.37	-0.17	-0.36	0.09	0.09	-0.32	-0.32	-0.04
	(0.18)	(0.70)	(2.81)	(-1.05)	(-1.06)	(0.69)	(0.62)	(-1.38)	(-0.97)	(-0.20)
I/Y	0.04	0.03	-0.04	-0.09	-0.06	0.00	-0.07	0.01	-0.08	0.18
	(0.52)	(0.28)	(-1.61)	(-0.63)	(-0.69)	(0.07)	(-1.21)	(0.05)	(-0.63)	(1.72)
R^2	0.60	0.60	0.85	0.71	0.51	0.81	0.80	0.70	0.62	0.80
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	34	30	31	27	25	31	29	27	19	24
totalobs	86	78	84	74	68	85	79	74	56	64
Industrialized										
β	-0.20	-0.27	-0.19	-0.19	-0.20	-0.17	-0.15	-0.20	-0.12	-0.06
	(-4.63)	(-5.06)	(-6.18)	(-6.82)	(-3.57)	(-6.97)	(-5.79)	(-7.38)	(-3.91)	(-2.25)
implied λ	0.0454	0.0620	0.0430	0.0425	0.0445	0.0383	0.0330	0.0457	0.0245	0.0131
P_E	-0.17	0.26	-0.05	0.42	-0.37	-0.07	0.11	-0.61	-0.21	-0.05
	(-0.54)	(1.14)	(-0.26)	(2.07)	(-0.86)	(-0.32)	(0.54)	(-1.95)	(-0.63)	(-0.20)
I/Y	0.00	-0.07	-0.06	-0.37	0.10	-0.09	-0.24	0.04	-0.07	0.25
	(-0.02)	(-0.54)	(-2.61)	(-1.36)	(0.37)	(-1.16)	(-2.04)	(0.15)	(-0.53)	(1.67)
R^2	0.63	0.69	0.77	0.79	0.52	0.80	0.80	0.73	0.64	0.76
regobs	5	5	5	5	5	5	5	5	5	5
ncrossest	21	22	18	22	18	19	21	21	17	20
totalobs	60	58	54	60	52	57	60	60	52	54
Rest of World										
β	-0.03	-0.10	-0.10	-0.12	-0.27	-0.15	-0.15	-0.33	NA	-0.22
	(-0.30)	(-1.59)	(-1.55)	(-1.92)	(-2.98)	(-3.19)	(-4.45)	(-3.23)	--	(-2.41)
implied λ	0.0062	0.0216	0.0208	0.0266	0.0638	0.0333	0.0333	0.0808	--	0.0495
P_E	0.17	0.42	0.31	-0.73	-0.17	0.27	-0.26	0.05	NA	-0.62
	(0.65)	(1.32)	(0.96)	(-2.21)	(-0.27)	(1.42)	(-1.08)	(0.18)	--	(-1.03)
I/Y	0.02	0.06	0.12	-0.23	-0.04	0.03	0.02	-0.09	NA	-0.04
	(0.12)	(0.42)	(0.71)	(-1.01)	(-0.31)	(0.41)	(0.22)	(-0.34)	--	(-0.31)
R^2	0.67	0.58	0.81	0.69	0.70	0.85	0.81	0.76	--	0.98
regobs	4	4	4	4	4	4	4	4	3	3
ncrossest	17	11	21	8	10	18	11	8	4	5
totalobs	26	20	26	14	16	28	19	14	5	10

T-statistics in parentheses
regobs: number of time points included; ncrossest: number of countries included; and totobs: total number of observations.

That we find energy prices and the investment ratio playing only a very limited role in explaining energy-productivity growth might, to some extent, be due to these being estimated at the level of aggregate manufacturing, because of limited data availability. Consequently, they do not take into account sector-specific mixes of energy carriers used or particular sector-specific energy prices. Although accounting for these sectoral differences will probably improve the estimation results to some extent, we do not, however, expect the additional variation in energy price series to account fully for the observed cross-country differences. In their convergence analysis for 14 OECD countries, Mulder and De Groot (2003b) constructed sector-specific energy prices but found these to have a statistically significant impact on energy-productivity growth in a few energy-intensive industries only (iron and steel, chemicals, and paper), although the impact is positive in virtually all manufacturing sectors. In closing our examination of

augmenting technologies do respond to a structural trend in energy price/wage developments rather than to short-term fluctuations. Moreover, we tested for the effect of a lagged investment share, assuming that it takes some time for new technologies to become effective, for example through various learning and adaptation effects. These alternative specifications (in different combinations), however, did not substantially improve the estimation results. Details are available upon request.

the country-characteristics driving energy-productivity growth, we therefore emphasize that our analysis points to the role of country-specific factors other than prices and investment shares being crucial in determining cross-country productivity differentials.

5 Conclusions

In this paper we examined the dynamics of energy-productivity performance for 56 countries, including 32 less-industrialized or developing countries, in 10 manufacturing sectors, during the period 1971 to 1995. We calculated average annual growth rates of energy productivity and performed a convergence analysis to examine patterns of international energy productivity developments at a detailed sector level. We found that, in most sectors, cross-country differences in absolute energy-productivity levels tend to decline. This appears particularly so in the less energy-intensive industries; the energy-intensive sector, non-ferrous metals, is a major exception in that it shows substantial divergence of energy-productivity levels across countries. Testing for the so-called β-convergence hypothesis using panel data confirms that, in all sectors, energy-productivity growth is relatively high in countries that initially lag behind in terms of energy-productivity levels. This suggests that lagging countries catch up with advanced economies. At the same time, however, cross-country differences in energy-productivity performance seem to be persistent, for convergence is found to be local rather than global, with countries converging to different steady states that depend on country-specific characteristics. Moreover, an analysis of sectoral energy-productivity dynamics showed several lagging countries failing to catch up. In a first attempt to identify the country-specific factors determining cross-country (differences in) energy-productivity growth rates, we found that the energy price and the investment ratio affected country-specific energy-productivity growth rates to a very limited extent only.

The task ahead is to identify what accounts for the observed persistence in cross-country energy-productivity differentials. Our results suggest that international flows, associated mostly with manufacturing, may not be contributing substantially to convergence of energy productivity across countries in different parts of the world. It may be that patterns of international specialization and relocation of industries, accommodated by increasing international trade, or all sorts of market imperfections, outweigh the influence of increasing competition, capital accumulation, technology transfer, and knowledge spillovers in driving international patterns of energy-productivity developments. Another possible explanation is that countries lagging too far behind are not able to catch up with advanced economies because the technology gap (distance to technology leader) proves to be too large to actually exploit the advantage of backwardness through, for example, knowledge spillovers or technology transfer (Gomulka, 1971; Chatterji, 1992, 1993). This suggestion is very much in line with the Abromivitz notion of ‘social capabilities’ (Abromivitz, 1986) required for successful catching up. Finally, there is some reason to believe that technology diffusion and knowledge spillovers are local rather than global (Keller, 2002). As technological change is a major source for energy-productivity growth, this suggests that there is a need to pay specific attention to the spatial dimension of technology gaps and technology diffusion in driving energy-productivity patterns in different world regions.

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Appendix

Table A.1: Industrialized countries included in the sigma-convergence analysis 1980-90 per sector.

Country	Code	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD
1 Austria	AT	x	x	x	x	x	x	x	x	x	x
2 Australia	AU	x	x	x	x	x	x	x	x	x	x
3 Belgium	BE	x	x	x	x	x	x	x		x	x
4 Canada	CA	x		x		x	x	x			x
5 Switzerland	CH	x	x		x		x	x			
6 Germany	DE	x	x	x	x	x	x	x	x	x	x
7 Denmark	DK	x	x	x	x		x	x	x	x	x
8 Spain	ES	x		x	x	x	x	x	x	x	x
9 Finland	FI	x	x	x	x	x	x	x	x	x	x
10 France	FR	x	x	x	x	x	x	x	x	x	x
11 United Kingdom	GB	x	x	x	x	x	x	x	x	x	x
12 Greece	GR	x	x	x	x	x	x	x	x	x	x
13 Ireland	IE	x	x	x	x		x	x	x		x
14 Iceland	IS			x		x					
15 Italy	IT	x	x	x	x	x	x	x	x	x	x
16 Japan	JP	x	x	x	x	x	x	x	x	x	
17 S. Korea	KR	x	x	x	x		x	x	x		x
18 Luxembourg	LU	x	x	x	x		x		x		
19 Netherlands	NL	x	x	x	x	x	x	x	x	x	x
20 Norway	NO	x	x	x	x	x	x		x	x	x
21 New Zealand	NZ		x	x	x			x	x		x
22 Portugal	PT	x	x	x	x	x	x	x	x	x	x
23 Sweden	SE	x	x	x	x	x	x	x	x	x	x
24 United States	US	x	x	x	x	x	x	x	x	x	x

Table A.2 Rest of World (developing) countries included in the sigma-convergence analysis 1980-90 per sector.

Country	Code	CHE	FOD	IAS	MAC	NFM	NMM	PAP	TEX	TRM	WOD
1 Argentina	AR	x		x							
2 Bangladesh	BD	x		x			x		x		
3 Bahrain	BH					x					
4 Brazil	BR	x	x	x		x	x	x	x		
5 Chile	CL		x	x		x	x	x			
6 China	CN	x	x	x	x		x		x		x
7 Colombia	CO	x	x	x	x		x	x	x		x
8 Czech Republic	CZ			x			x			x	
9 Algeria	DZ			x							
10 Egypt	EG	x	x	x							
11 Hungary	HU	x	x	x	x	x	x	x	x	x	x
12 Indonesia	ID	x		x							
13 Israel	IL	x									
14 India	IN	x	x	x	x	x	x	x	x		
15 Kuwait	KW	x									
16 Malaysia	MY			x			x				
17 Mexico	MX	x	x	x							
18 Peru	PE			x							
19 Philippines	PH	x		x			x				
20 Pakistan	PK	x		x			x				
21 Poland	PL	x	x	x	x	x	x	x	x		x
22 Slovenia	SI										
23 Thailand	TH	x	x	x	x		x	x			
24 Tunisia	TN			x					x		
25 Trinidad & Tobago	TT	x									
26 Chinese Taipei	TW	x	x	x	x	x	x		x		x
27 USSR (former)	USSR	x	x	x	x	x	x	x			x
28 Uruguay	UY			x							
29 Venezuela	VE	x		x		x					
30 South Africa	ZA	x		x	x	x	x	x			
31 Turkey	TR	x	x	x	x	x	x		x		x
32 Zimbabwe	ZW			x							

Table A.3: Percentage change in the coefficient of variation of energy productivity per sector over the period 1980-1990.

	CHE	**FOD**	**IAS**	**MAC**	**NFM**	**NMM**	**PAP**	**TEX**	**TRM**	**WOD**
Industrialized	50.9	-51.4	0.2	-2.2	55.0	-40.0	-4.2	-3.9	-7.4	-7.4
Rest of World	6.0	-60.6	-20.5	1.9	28.2	-55.2	2.2	-17.9	-30.7	-15.8
World	54.2	-21.0	3.2	-19.7	76.8	-35.4	-27.7	-7.1	11.6	2.6

Table A.4: Estimated country effects per sector for different countries (ranking in parenthesis).

	CHE	**FOD**	**IAS**	**MAC**	**NFM**	**NMM**	**PAP**	**TEX**	**TRM**	**WOD**
Country Code	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$ x	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$ x	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$	$\frac{\alpha_i}{\alpha_{\max}}$
AR	.79 (8)		.91 (4)							
AT	.77 (9)	.71 (9)	.71 (23)	.97 (4)	.92 (4)	.92 (4)	.75 (24)	.84 (12)	.89 (15)	.97 (9)
AU	.68 (24)	.47 (32)	.68 (26)	.91 (17)	.64 (30)	.81 (19)	.78 (18)	.80 (21)	.85 (18)	.97 (13)
BD	.47 (42)		.96 (2)			.60 (36)				
BE	.68 (23)	.66 (19)	.66 (29)	.99 (2)	.90 (5)	.74 (26)	.88 (8)	.88 (3)	.80 (19)	.99 (2)
BH					.49 (34)					
BR	.69 (20)	.61 (27)	.63 (36)		.67 (25)	.82 (18)	.78 (19)	.78 (25)		
CA	.64 (30)	.80 (4)	.64 (35)	.93 (13)	.66 (26)	.89 (9)	.63 (32)	.86 (6)	.98 (3)	.97 (10)
CH	.86 (2)	1.0 (1)		.97 (7)		1.0 (1)	.94 (3)			
CL		.81 (2)	.62 (37)		.86 (7)	.77 (24)	.76 (23)			
CN	.30 (45)	.20 (37)	.44 (50)	.65 (33)	.65 (27)	.51 (40)	.57 (34)	.63 (33)		.90 (26)
CO	.69 (22)	.50 (31)	.66 (31)	.79 (30)	.65 (28)	.59 (38)	.66 (30)	.69 (32)		.94 (23)
CZ			.57 (42)			.80 (21)			.72 (21)	
DE	.70 (19)	.65 (22)	.73 (16)	.94 (11)	.81 (12)	.87 (10)	.82 (14)	.83 (14)	.89 (14)	.98 (5)
DK	.84 (4)	.63 (24)	.73 (17)	.91 (16)		.83 (15)	.90 (5)	.85 (7)	.91 (9)	.97 (12)
DZ			.65 (33)							
EG	.62 (33)		.61 (38)							
ES	.70 (18)	.68 (15)	.72 (18)	.91 (18)	.77 (15)	.80 (22)	.83 (13)	.80 (22)	.89 (16)	.98 (8)
FI	.67 (25)	.67 (16)	.72 (20)	.90 (21)	.88 (6)	.83 (16)	.72 (28)	.86 (4)	.97 (4)	.94 (21)
FR	.72 (15)	.67 (17)	.75 (11)	.91 (20)	.83 (10)	.97 (2)	.88 (7)	.81 (17)	.97 (5)	.98 (6)
GB	.73 (14)	.64 (23)	.72 (19)	.88 (25)	.77 (16)	.91 (7)	.89 (6)	.81 (18)	.89 (12)	1.0 (1)
GR	.82 (5)	.65 (21)	.76 (9)	.94 (12)	.67 (24)	.69 (30)	.80 (16)	.84 (11)	.89 (13)	.98 (7)
HU	.58 (37)	.45 (33)	.59 (40)	.77 (31)	.73 (18)	.68 (32)	.74 (26)	.70 (30)	.77 (20)	.95 (19)
ID	.54 (39)		.78 (7)			.68 (31)				
IE	.80 (7)	.75 (8)	.77 (8)	.97 (5)	.33 (35)	.91 (5)	1.0 (1)	.83 (15)		.95 (18)
IL	.72 (16)									
IN	.58 (36)	.79 (5)	.57 (44)	.86 (28)	.73 (19)	.64 (34)	.66 (31)	.70 (31)		
IS	.60 (35)		.45 (49)		.62 (31)					
IT	.69 (21)	.66 (18)	.75 (12)	.87 (27)	.85 (9)	.78 (23)	.84 (12)	.84 (10)	.98 (2)	.99 (3)
JP	.73 (12)	.79 (6)	.75 (13)	.97 (3)	.86 (8)	.91 (8)	.88 (9)	.82 (16)	1.0 (1)	
KR	.64 (29)	.59 (28)	.72 (22)	.88 (24)	1.0 (2)	.76 (25)	.79 (17)	.74 (27)		.96 (16)
KW	1.0 (1)									
LU	.73 (10)	.77 (7)	.66 (30)	.87 (26)		.87 (11)		.71 (29)		
MX	.50 (41)	.33 (35)	.61 (39)		.95 (3)	.65 (33)	.62 (33)			
MY			1.0 (1)			.80 (20)				
NL	.61 (34)	.62 (25)	.65 (34)	.91 (19)	.74 (17)	.85 (14)	.87 (10)	.79 (24)	.90 (10)	.96 (15)
NO	.63 (32)	.69 (12)	.57 (43)	.90 (22)	.69 (22)	.85 (13)	.75 (25)	.84 (13)	.87 (17)	.94 (20)
NZ		.69 (11)	.47 (48)	.97 (6)			.91 (4)	.95 (2)		.89 (28)
PE			.86 (5)							
PH	.84 (3)		.70 (25)			.61 (35)				

Table A.4: continued

Country Code	CHE $\frac{\alpha_i}{\alpha_{\max}}$	FOD $\frac{\alpha_i}{\alpha_{\max}}$	IAS $\frac{\alpha_i}{\alpha_{\max}}$	MAC $\frac{\alpha_i}{\alpha_{\max}}$	NFM $\frac{\alpha_i}{\alpha_{\max}}$	NMM $\frac{\alpha_i}{\alpha_{\max}}$	PAP $\frac{\alpha_i}{\alpha_{\max}}$	TEX $\frac{\alpha_i}{\alpha_{\max}}$	TRM $\frac{\alpha_i}{\alpha_{\max}}$	WOD $\frac{\alpha_i}{\alpha_{\max}}$
PK	.58 (38)		.67 (28)			.47 (41)				
PL	.54 (40)	.33 (34)	.56 (45)	.67 (32)	.73 (20)	.46 (42)	.55 (35)	.85 (9)	.67 (22)	.92 (24)
PT	.67 (26)	.62 (26)	.72 (21)	.94 (10)	.79 (14)	.73 (28)	.76 (22)	.80 (19)	.90 (11)	.96 (14)
SE	.73 (13)	.68 (14)	.76 (10)	.88 (23)	.83 (11)	.85 (12)	.67 (29)	.79 (23)	.91 (8)	.94 (22)
SI		.69 (13)	.71 (24)	.85 (29)	.67 (23)		.73 (27)	.80 (20)		.99 (4)
TH	.80 (6)	.65 (20)	.82 (6)	1.0 (1)		.82 (17)	.78 (21)			
TN			.73 (14)					.85 (8)		
TR	.73 (11)	.54 (29)	.68 (27)	.92 (14)	.70 (21)	.94 (3)	.81 (15)	.73 (28)		.92 (25)
TT	.47 (44)		.54 (46)			.60 (37)				
TW	.67 (27)	.70 (10)	.66 (32)	.92 (15)	1.0 (1)	.74 (27)	.78 (20)	.76 (26)	.94 (7)	.96 (17)
US	.71 (17)	.81 (3)	.73 (15)	.95 (9)	.81 (13)	.91 (6)	.84 (11)	.86 (5)	.96 (6)	.97 (11)
USSR	.47 (43)	.27 (36)	.40 (51)	.54 (34)	.54 (33)	.52 (39)	.52 (36)			.90 (27)
UY			.96 (3)							
VE	.64 (31)		.38 (52)		.61 (32)					
ZA	.64 (28)	.53 (30)	.50 (47)	.95 (8)	.64 (29)	.73 (29)	.99 (2)	1.0 (1)		
ZW			.58 (41)							
$\alpha_{\max}$	.97	.52	1.05	1.15	1.20	.98	1.31	1.42	.93	3.32
$\alpha_{\min}$	.29	.11	.40	.62	.40	.45	.69	.89	.62	2.97