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Fossil energy in economic growth: A study of the energy direction of technical change, 1950-2012*

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Abstract

Climate change mitigation challenges national economies to increase productivity while reducing fossil energy consumption. Fossil energy-saving technical change has been assumed to accomplish this, yet empirical evidence is scarce. This paper investigates the long-run relationship between the rate and direction of technical change with respect to fossil energy and labor in the world economy. Growth rates of labor productivity and the fossil energy-labor ratio are examined for more than 95% of world output between 1950 and 2012. The average elasticity of the energy-labor ratio with respect to labor productivity is close to one, implying highly energy-using technical change, but no trade-off between factor productivity growth rates. This stylized fact suggests the importance of a cheap, abundant energy supply for robust global growth, and a more important role for renewable energy. Integrated assessment models do not incorporate this restriction which may result in poorly specified baseline scenarios.

JEL: N10, O44, O47, Q43

Keywords: labor productivity, fossil energy productivity, energy-using technical change, decoupling, long-run trends, stylized facts, direction of technical change

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1 Introduction

Fighting climate change and stagnant economic growth are the biggest challenges currently facing the world economy (Group of Twenty Major Economies 2015; United Nations 2015). Responses to both challenges have identified technical change as an important component of a solution. Mitigating greenhouse gas emissions is predicated on highly fossil energy-saving technical change, that allows 'decoupling' of economic growth from fossil energy consumption growth (Gillingham et al. 2008; Schandl et al. 2015). Growing the world economy is predicated on fast per capita income growth, which in turns necessitates high labor productivity growth rates (Baumol 1986; Maddison 2006). What is unclear is the degree to which labor productivity growth can be achieved at the same time as fossil energy-saving technical change (Bowen and Hepburn 2014; Csereklyei et al. 2016).

Theories of factor-augmenting technical change are obvious candidates for answering how labor and energy productivity hang together. In models of induced (Di Maria and Valente 2008) and directed (Acemoglu et al. 2012) technical change with fossil fuels, technical change has both a rate and a direction, regulated by relative factor prices and scarcity.[1] Although this body of research has furnished impressive empirical evidence at the sectoral and micro-level about the direction of technical change with respect to fossil energy, among others in this journal (Sue Wing 2008; Noailly and Smeets 2015; Aghion et al. 2016), little empirical research has been conducted into the aggregate relationship between different productivity growth rates (Nordhaus 2002). One obstacle to aggregate empirical research appears to be scarce data, especially on energy prices. Another theory, ecological macroeconomics (Rezai and Stagl 2016), also predicts how rate and direction of technical change interact, but based on biophysical rather than price considerations (Rezai et al. 2013). Although this theory is operationalized more easily, no empirical studies have tested its predictions for the world economy.

[1]Technical change, or equivalently technological change, refers to changes and improvements of productivity, represented by ratios of output over input(s), that are either single-factor productivities such as labor productivity or fossil energy productivity, or cost-weighted multifactor productivities such as total factor productivity. Technical change with two inputs, x and y, has a direction to input factor x if y-productivity grows faster than x-productivity and x becomes a more important factor in production relative to y; equivalently, this technical change is x-using and y-saving.

Absent empirical studies informed by an explicit theory of production, a plethora of empiricist studies have searched the data for 'Environmental Kuznets Curves' and Granger correlation based solely on GDP and energy consumption data. Yet, this literature has failed to reach a consensus about the nature of the world economy's long-run correlation between economic growth and fossil energy consumption; this claim will be substantiated below through a literature review. On balance, no extant empirical work seems able to satisfactorily inform about energy's role in world productivity growth. But this information is particularly relevant because the results of integrated assessment models (integrating models of the climate and global economic growth) regarding the compatibility of economic growth and climate change mitigation are driven mainly by varying assumptions about labor productivity growth and the evolution of fossil energy intensity at the global level (IPCC 2014, p. 426). A clearer understanding of the historical relationship of such basic magnitudes as labor productivity and fossil energy productivity growth would help the parametrization of these forecasting models as well as supply a stylized fact for any economic model of energy in economic growth.

This study investigates the long-term empirical correlation between the rate and direction of technical change with respect to labor and fossil energy in the world economy. The investigation is firmly rooted in a theory of production. The ecological macroeconomic approach is used as a lens of analysis, for its easier operationalization, without necessarily committing to its theoretical conclusions. Using only variables for output (X), employment (L), and fossil energy (FE), aggregate fossil energy intensity (FE/X) is expanded by aggregate employment

$$\frac{FE}{X} \equiv \frac{FE}{X} \times \frac{L}{L} \equiv \frac{X}{L} \times \left(\frac{FE}{L}\right)^{-1} \tag{1}$$

into the product of realized labor productivity – that is, the ratio of output to employment (X/L) – and the fossil energy labor ratio (FE/L). Growth in realized labor productivity represents the rate of technical change, while the fossil energy-labor ratio represents its direction. A functional relationship between labor productivity and the fossil energy-labor ratio is imposed, which in turn determines fossil energy intensity or its inverse – realized energy productivity

– by accounting identity. This approach thus analyzes the role of fossil energy in economic growth as following from the rate and direction of technical change in production.

Long-term trends for the global economy made up of its component countries are considered since this is the relevant level to analyze 'decoupling', but individual countries' and regions' trajectories are also considered. A long-run perspective is particularly important to distinguish secular trends that are important for growth and development from cyclical fluctuations and shorter-term disruptions such as the fall in crude oil output during two OPEC crises.[2] The study focuses on *fossil* primary energy supply. Not only can technical change improve energy efficiency, but also substitute fossil with other, non-greenhouse gas emitting energy sources.[3] A dataset of compound annual growth rates is constructed from annual national observations of fossil and non-fossil primary energy in production, output and employment for 1950-2012 for over 95% of world domestic product. Energy and output data are from the International Energy Agency data and UN data before 1971, employment data is from the Total Economy Database (IEA 2014b,a; Darmstadter et al. 1971; Conference Board 2014).[4] The combination of length and coverage is more comprehensive than in previous studies.

The analysis employs a combination of quantitative and qualitative methods. Both global and regional level results are visually inspected, before the elasticity of the energy-labor ratio with respect to labor productivity is estimated in cross-sections for global, and the and entire panel, for regional and national growth. Outliers are explained in their economic-historic context. The global level results will be discussed as providing a stylized fact about energy and labor productivity for economic growth models and in particular for integrated assessment model assumptions, the country-level results as pointing to the need for cheap, abundant

[2]In 1973, five years after crude oil overtook coal as the most important energy source, the Organization of Petroleum Exporting Countries (OPEC) imposed an oil export embargo against the US and later other Western countries that supported Israel in the 1973 Arab-Israeli War. In late 1978, the Iranian Revolution led to a 10% drop in OPEC's crude oil production (EIA 2002). The Iran-Iraq War that began in 1980 reduced oil production also in other OPEC members and in 1981 OPEC crude output stood one quarter below its pre-revolution 1978 level. Global crude production only recovered its 1978 level in 1989 (IEA 2014a).

[3]The fossil energy-labor productivity relationship will nevertheless be representative for energy in general since more than 80% of global energy use has been supplied by fossil fuels during the period of analysis (IEA 2014a).

[4]Only 15% of global primary energy consumption in 2012 was due to non-production, 'residential' usage for heating, lighting, and powering home appliances.

energy for future rapid growth in developing countries.

The next section reviews the empirical literature on economic growth and fossil fuels. Section 3 develops the study's analytical framework and introduces the data. Section 4 presents results, and section 5 discusses their implications for modeling and policies supporting fossil-energy saving productivity growth. Section 6 concludes and suggests avenues for further research. Appendices provides details on estimation methods, data, and results.

2 The economic literature on energy and growth

2.1 Non-production studies

Most empirical contributions to the debate about the role of energy in economic growth have considered the relationship between a measure of energy consumption and output, without starting from a theory that explains energy use as an input into production. One strand of this literature, called the energy-growth nexus, applies the Granger correlation test (Granger 1969) to national time series of output and energy in order to test the direction of causality between the two series.[5] The underlying assumption is that the role of energy in production can be found from the structure of the two time series and without reference to a theory of production.[6]

The literature began after the OPEC oil embargo of 1973, when scarce crude oil was suspected to be a cause of a US productivity growth slowdown. Kraft and Kraft (1978) found that in the post-war US economy (from 1947 to 1974), the Granger correlation ran only from output to energy, but not the other direction. In the Granger interpretation of causality, this implies that energy was not a causal factor in US economic growth and economic growth would be unimpeded by lesser energy consumption. Subsequent studies found no Granger

[5]The Granger test regresses an observation of a random variable X on lags of itself and a random covariate Y. If Y's coefficient is zero, X is said to be exogenous with respect to Y. If, additionally, Y is not exogenous with respect to X, then X is said to be causally prior to Y (Cooley and Leroy 1985).

[6]Implicit in the hypothesis of no causation is a growth model with a high elasticity of substitution between energy and other inputs.

correlation at all (Akarca and Long 1980; Hwang and Yu 1984), and also found a lack of co-integration between energy, output, and employment (Yu and Jin 1992).

The 2000s saw an explosion in the number of nexus studies for countries other than the United States. Although this literature continues to grow, it has failed to reach any consensus on the existence and/or direction of causality. Ozturk (2010) surveyed 72 studies of the energy-growth relationship in a variety of countries typically for periods after 1971 (International Energy Agency data) or 1980 (Energy Information Agency data) and found all 2^2=4 Granger causal patterns. In particular, all types of causation were found for almost every country, which Ozturk attributed to the sensitivity of the results to time period and variables included.[7] Similar inconclusiveness is found in a review of studies considering electricity in lieu of total energy (Payne 2010). Absent an economic theory underlying this approach, the only recommendation that both reviews can offer is to use better econometric methods and increase the number of covariates, without questioning the theoretical preconceptions.

Another strand of this literature, the 'Environmental Kuznets Curve' (EKC) for CO_2 emissions, examines the hypothesis that the sign of the change in CO_2 intensity of production is dependent on a country's per capita income (Panayotou 1993). Because of the high positive correlation between CO_2 and fossil fuel use (Schmalensee et al. 2001), this translates into a fossil energy EKC. This hypothesis has been discussed controversially (Dasgupta et al. 2002; Stern 2004) and without leading to a consensus about its existence (Franklin and Ruth 2012; Stern 2011). Out of 41 studies that have estimated the CO_2/GDP per capita relationship, one-quarter have found evidence for the hypothesis of an EKC, with turning points ranging between \$5,000 and \$33,000 (in 2000 USD), while the other three-quarters have not (Hervieux 2014). It has also been shown that EKC evidence is sensitive to country sample, time period selection, and model specification (Yang et al. 2014).

Those studies that have examined energy directly have tended to find a nonlinear relationship for national trajectories, some of which are of the EKC type. Schurr (1984) found the

[7]Nevertheless, individual studies make strong policy recommendations, including that India would grow faster if it reduced its total energy consumption (Narayan and Popp 2012); at least one study has claimed that, in the long-run, growth *in general* is independent of energy consumption, based on data only from OECD countries (Coers and Sanders 2013).

time series of aggregate energy intensity in the US between 1880 and 1980 to be an inverted U-shape for GDP per capita, peaking in 1920. An EKC pattern was revealed for an energy-material aggregate intensity for a panel of 31 European countries over the period 1970-1985 (Jänicke et al. 1989), and in cross-sections for energy for 100 countries by comparing the change between 1975 and 1997 (Ang and Liu 2006). Evidence has also been furnished that *per capita energy consumption* is an s-shaped function of per capita GDP in national time series (Wolfram et al. 2012; Fouquet 2014). A general problem with time series findings is that they cannot control for what part of changes in energy intensity are due to relocation of sectoral activity to other countries.

2.2 Production studies

Studies explaining energy as an input into production start with an explicit theory of aggregate production and factor productivity, which guides empirical measurement. A variety of theories of growth with energy were developed in the late 1970s and 1980s, mainly as a reaction to rising oil prices from the OPEC crises (Berndt 1990). The one most relevant for the question of the direction of technical change is based on assuming a trade-off between augmenting different factor-specific productivity such as labor and energy productivity. This is resolved by assuming profitability guided behaviour of producers, where more expensive factors 'induce' faster factor- specific growth rates (Kennedy 1964). Originally developed to explain constant factor shares in spite of labor-saving technical change in the US, the theory of price-induced technical change was also used to explain why rising energy prices coincided with faster energy productivity growth, but slowing overall productivity growth (Jorgenson 1984). A more recent vintage of 'directed' technical change, starts from changes in relative factor supplies that affect profitability (Acemoglu 1998). Both induced and directed technical change have been modeled with fossil energy or 'dirty inputs' (Di Maria and Valente 2008; Acemoglu et al. 2012, 2015).[8] Although a recent study found a trade-off between productivity growth

[8] Di Maria and Valente are in the spirit of the induced innovation literature by assuming an elasticity of substitution below one between fossil fuels and other inputs, whereas the papers by Acemoglu and co-authors focus on the results with an elasticity no less than one. The latter enables a long-run upward sloping demand curve for the more abundant factor, the 'market size effect'.

rates of energy and a capital-labor composite for the US after 1950 (Hassler et al. 2012), this literature produced hardly any empirical work at the aggregate level (Nordhaus 2002; Sue Wing 2006).

Endogenous growth theory has suggested mechanisms besides directed technical change for endogenizing changes in the CO_2 emissions' (and hence fossil fuel) intensity. The most common variants explain reductions in emission intensity as consequences of R&D or scale effects from learning by doing (Gillingham et al. 2008). One challenge for empirical estimation of the strength of these forces at the level of the world economy is a lack of data (Pizer and Popp 2008), while results for the US or other advanced countries cannot be generalized due to trade linkages. Therefore, most of the models that forecast world economic growth and fossil energy consumption continue to rely on exogenous labor productivity growth and make separate assumptions about the evolution of the energy intensity of output, as well as the composition of the energy mix (IPCC 2014, p. 426).

The correlation between labor productivity and energy intensity has also been addressed by theories based on 'ecological macroeconomics' (Rezai and Stagl 2016), which predicts that rising labor productivity comes with increased energy use per worker, and therefore constrains the ability of energy intensity to fall (Rezai et al. 2013). An elasticity of the fossil energy-labor ratio with respect to labor productivity close to one was found for the US economy in the period between 1905 and 1980 (Cleveland et al. 1984), and an elasticity of 0.6 in a cross-section of compound annual growth rates from 1990-2004 for some three-quarters of the world economy (Taylor 2009). Despite the comparatively modest demands on data (no prices, no micro-data on R&D etc.), no empirical studies have followed up more comprehensively on the correlation between labor productivity and the direction of technical change.

3 Method and data

The above review shows that the variety of approaches have produced little consensus about the relationship between productivity growth and fossil energy for the world economy. Empirical studies that eschew a theory of production have reported contradictory types of correlations and directions of causation, and econometric results are sensitive to sample and model selection. Economic theories of growth can explain empirical regularities with technical change in specific countries, but have not yet examined the world economy as a whole. The current study takes a production perspective, but examines a larger dataset in order to reveal the long-term, global role of fossil energy in productivity growth.

3.1 Method

In order to investigate a global, long-term dataset, the study adopts the most easy to operationalize approach from ecological macroeconomics. This theory predicts a stable relationship between rates of change in realized labor productivity, $X/L = \lambda$, and the fossil energy-labor ratio $FE/L = e$. The proportional rate of change of labor productivity, denoted by a hat, $(\partial\lambda/\partial t)/\lambda = \hat{\lambda}$ represents the rate of productivity growth, while the proportional rate of change of the fossil energy-labor ratio, $\hat{e}$, represents the direction of technical change. In particular, technical change is fossil energy-saving when $\hat{e} < 0$ and labor becomes a more important factor in production relative to fossil energy, and fossil energy-using otherwise. With fossil energy being an input into production, the inverse of the fossil energy intensity is the realized energy productivity, $X/FE = \phi$. The relationship between $\hat{\lambda}$ and $\hat{e}$ determines the change in the economy's energy productivity by accounting identity as a result of the rate and direction of technical change. To see this, expand fossil energy productivity with labor

$$\frac{X}{FE} \equiv \frac{X}{L} \times \frac{L}{FE} \qquad \text{equivalently} \qquad \phi \equiv \lambda \times e^{-1} \quad . \tag{2}$$

Taking logarithmic derivatives and rearranging gives

$$\hat{\phi} \equiv \hat{\lambda} - \hat{e} \quad . \tag{3}$$

Growth theories also determine a direction of causation. The assumption that causation runs from higher $\hat{\lambda}$ to higher $\hat{e}$ arises theoretically when reasoning that economic agents strive for higher output and labor productivity growth, but do not consciously attempt to change the energy-labor ratio. Learning by doing and knowledge spill-overs (Arrow 1962; Romer 1986), or increasing returns to output expansion from external economies of scale (Young 1928; Kaldor 1961), all follow this view by explaining faster labor productivity growth as a result of faster output growth. The growing energy-labor ratio is then a reflection of the growing energy needs of the larger scale of production. Induced technical change also assumes this direction as innovations geared at factor augmenting change lead to changes in the input ratio. The alternative direction of causation – that changes to the energy-labor ratio cause changes in labor productivity – sees productive activity as resulting from useful energy inputs. This human ecology perspective dates back to shortly after the discovery of the laws of thermodynamics in the 19th century (Martinez-Alier and Schlüpman 1990), and its causal reasoning has recently been applied in a model of growth with greenhouse gases (Taylor et al. 2016).

The literature review has shown that disentangling causality empirically is difficult with aggregate data, and this study of empirical correlations cannot examine or justify a direction of causation. Its purpose is to document the correlation between the rate and direction of technical change with respect to energy for the world economy. Yet, where appropriate, results will be interpreted through the lens of agents attempting to increase labor productivity, which leads to changes in the aggregate energy-labor ratio. This view connects to the majority of the theoretical literature. Hence, for purposes of plotting and regression, the analysis will consider the rate of change in the energy-labor ratio as an increasing function, f, of that of labor productivity

$$\hat{e} = f(\hat{\lambda}) \tag{4}$$

which ecological macroeconomics predicts should be linear. Hence the analysis lends itself to linear regression of the form $\hat{e} = \alpha + \beta\hat{\lambda}$, which is done both for multi-year cross-section weighted least squares to estimate the global relationship of countries, complemented by nonlinear local polynomial regression, and a country and time fixed effect estimate for national growth rates. The role of non-fossil energy is also considered. Appendix A details the specifications used.

The main objects of the study are elasticities, but as the literature on the energy-growth nexus and the EKC has shown, the exact econometric relationship between changes in the aggregate measures of output, energy, and labor is plagued by ambiguity. The present study keeps the econometric analysis to a minimum and instead follows Hassler et al. (2012) and Taylor (2009) to complement it with a visual analysis. This helps contextualize outliers by locating them in their economic-historic period. Visual analysis is also particularly appropriate because the analysis proceeds in two dimensions ($\hat{\lambda}$ and $\hat{e}$). Recalling that identity (3) can be rearranged as $\hat{\lambda} \equiv \hat{\phi} + \hat{e}$, energy productivity growth is positive whenever $\hat{e} < \hat{\lambda}$.

3.2 Data

A global, long-run dataset is constructed of annual observations of national output, employment, and fossil energy data in countries representing more than 95% of GDP for the years 1950-2012, and compound annual growth rates of labor productivity and the energy labor ratio are calculated. Fossil energy use data is from the International Energy Agency's World Energy Balances dataset for 1971-2012 (IEA 2014b,a).[9] It excludes energy use for residential purposes (home heating, lighting, and power for home appliances), to focus on

[9]One advantage of focusing solely on fossil fuels for the data construction is the ability to dispense with an ambiguous conversion factor between thermal energy from fossil fuels and electricity from hydro or other renewable energy (Martinot et al. 2007). Where renewable energy sources are considered, however, the IEA conversion factor is used.

the relationship between fossil energy and production.[10] Non-residential non-fossil energy estimates are also taken from the IEA. Fossil fuel consumption (including for residents, which cannot be separated) for 1950 and 1960 is taken from tabulations of national fossil energy use for 1950-1965 by adding solid, liquid, and gaseous fuels from the tables in section 10 of by Darmstadter et al. (1971), which is based on UN data.

Employment data from the Conference Board's (2014) Total Economy Database (TED) is used, that counts average number of persons employed per year. Although the number of hours worked per year would be a more accurate measure of employment, coverage for this measure is only available for a subset of countries and time and is unsuitable for the purpose of a long-term global analysis. Output is represented by GDP at market exchange rates reported by the IEA. Prior to 1971, TED data is used, including GDP at Gheary-Khamis conversion factors if no market exchange rate GDP is available. Since the bilateral Gheary-Khamis (and other purchasing power parity measures) conversion factor is the same every year, the *growth rates* of GDP, which will be used exclusively, do not differ between various measures of GDP.

The calculation of compound annual growth rates for countries and regions is detailed in Appendix B. Table I displays regional compound annual growth rates for the pre-IEA period 1950-1971 and the IEA period 1971-2012 typically used by extant studies. The summary statistics reveals that, in this dataset, labor productivity growth was faster in the 1950s and 1960s on average than in the later decades, and technical change was more energy-using in the earlier period. No regions displays energy saving technical change in the earlier period, three do in the later period. The 'Golden Age' of capitalism, 1950-73 (Maddison 2006, p. 125), coincided with highly energy-using technical change, which led to falling energy productivity in seven out of ten regions. The results section of this paper will analyze how these regional patterns hang together at the world level, and split up the two long 21 and 41 year intervals into shorter ones. This structures the data into decadal intervals starting

[10] Approximately 6% of fossil energy is used for non-energy purposes, such as feedstock in the chemical industry or lubricants in refineries. To the extent that these products are incinerated after use, the fossil fuels embodied in the material still emit carbon dioxide, approximately half of what would have been caused by combustion (Weiss et al. 2009). Because of their carbon emissions, fossil fuels for non-energy use are included in the dataset.

1950 where interval endpoints are adjusted to reach the IEA starting data (1971), separate the periods before and after the second oil crisis (1979) and accommodate the most recent data (2012).

Table I: Regional compound annual growth rates of labor productivity $\hat{\lambda}$, fossil energy-labor ratio $\hat{e}$, and fossil energy productivity $\hat{\phi}$ during the pre-IEA and IEA data periods.

Region	1950–1971			1971–2012		
	$\hat{\lambda}$	$\hat{e}$	$\hat{\phi}$	$\hat{\lambda}$	$\hat{e}$	$\hat{\phi}$
North America (NAM)	0.024	0.015	0.009	0.014	-0.010	0.024
Western Europe (WEU)	0.043	0.035	0.008	0.016	-0.006	0.022
Pacific OECD (POECD)	0.063	0.076	-0.013	0.020	0.008	0.012
Economies in Transition (EIT)	0.032	0.043	-0.011	0.019	0.004	0.015
Latin America (LAM)	0.028	0.038	-0.010	0.006	0.005	0.001
Sub-Saharan Africa (SSA)	0.024	0.014	0.010	0.003	-0.001	0.004
Middle East & North Africa (MNA)	0.047	0.054	-0.007	0.007	0.036	-0.029
East Asia (EAS)	-0.004	0.066	-0.062	0.066	0.043	0.023
Pacific Asia (PAS)	0.023	0.057	-0.034	0.031	0.040	-.0009
South Asia (SAS)	0.017	0.037	-0.020	0.027	0.040	-0.013

4 Results

This section shows visually and with regression analysis that labor productivity growth was highly correlated with growth in the fossil energy-labor ratio for the world except after the OPEC oil shocks and during the transition of planned economies to the market; the elasticity was close to one. The results carry over to some extent to national growth experiences. Low-carbon energy sources have substituted for fossil energy in the most recent decade.

4.1 The world economy's energy direction of technical change

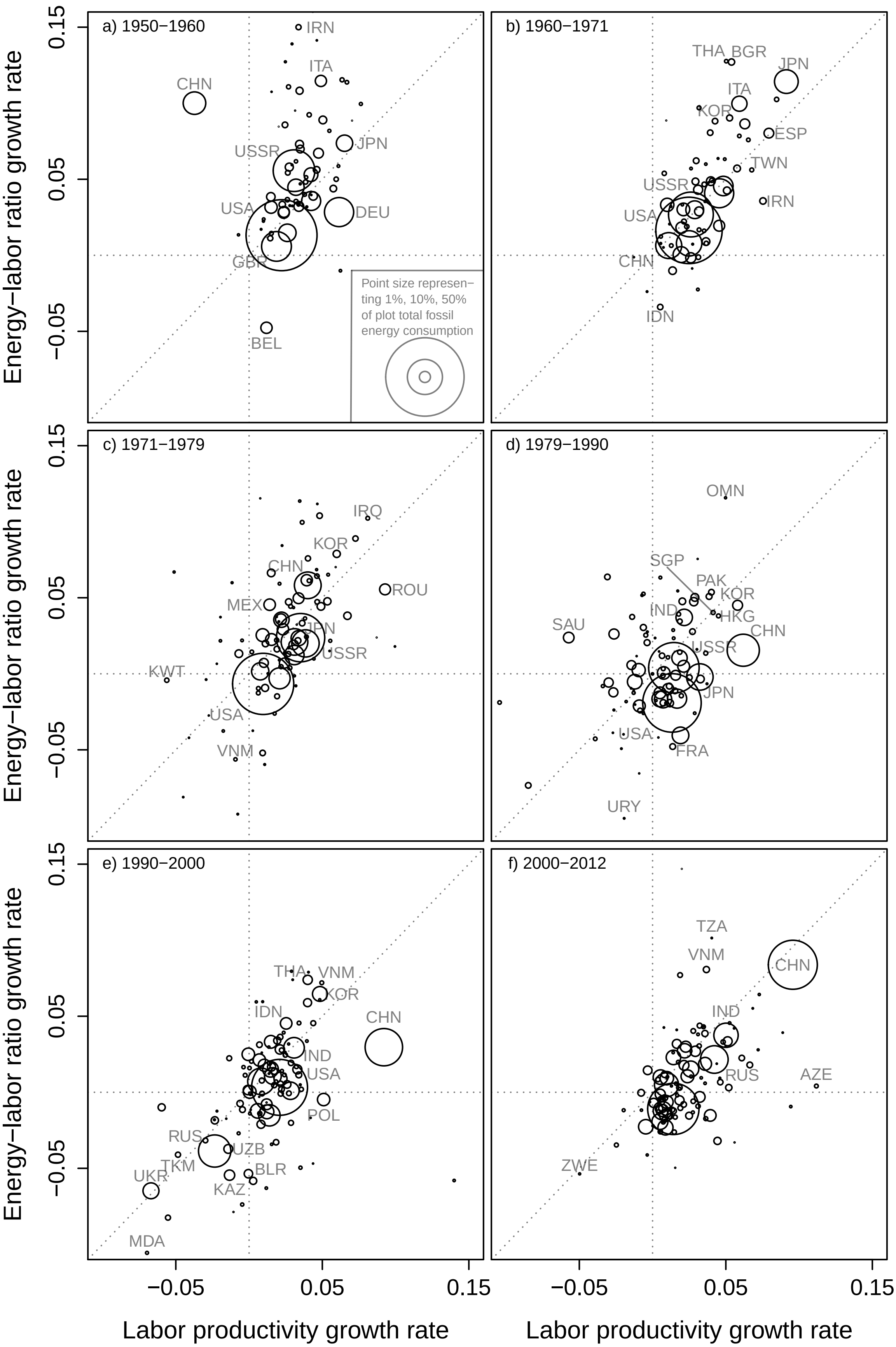
In any decade, national economies together form the world economy. Six plots of decadal compound annual growth rates in Figure 1 show the entire dataset in cross sections and trace the world economy's growth. The most striking pattern is the south-west to north-east direction of the data cloud in most plots. National differences in labor productivity growth rates, $\hat{\lambda}$, were associated with proportional differences in the fossil energy-labor ratio in production, $\hat{e}$. The proximity of many observations to the 45 degree line in most plots indicates that faster labor productivity growth led to a similarly faster change in the direction of technical change, where points above the 45 degree line imply that $\hat{e} > \hat{\lambda}$, i.e. a falling energy productivity. Quickly growing countries often find themselves in the northeast of the plot, close to the 45 degree line (Japan in the 1960s, Korea in the 1970s-90s, China in the 2000s). As a consequence, national energy productivity remained nearly constant, regardless of the corresponding national growth of labor productivity.

The one exception to this pattern is plot *d*. It shows that the correlation collapsed in the 1980s as a significant part of the world economy moved to stagnating growth with slightly energy-saving technical change (below the horizontal dashed line). To put this in context, at one point or another in this period, almost every part of the world found itself in an economic crisis more severe than in the previous three decades (Kindleberger 1988; Maddison 2006; Gourinchas and Obstfeld 2012), a trend that continued into the 1990s (Kindleberger and Aliber 2005). As a result per capita income growth halved in the last quarter of the century, compared with the golden age (Maddison 2006, Table 8b, p. 643). Few average national labor productivity growth rates for this decade exceeded 2%; more will be said on the exceptional performance of China below. The more energy-saving technical change than in previous decades is typically attributed to price-induced technical change from the 1970s oil crises (Berndt 1990). This plot emphasizes that the lower rate of productivity growth coincided with less-energy using technical change.

The negative tail of the 1990s data cloud in plot *e* is also remarkable, as it achieves unprecedented energy-saving technical change by countries mired in depression. A closer look at the countries in the third quadrant shows that these are Russia, Ukraine, Belarus and other former USSR republics in transition from planned production. China, the other country in transition is an outlier on the positive side. Together, the countries in transition from plan to market give this decade an uncommon pattern, too.

With a dataset starting in 1971 or even 1980, the most recent period in plot f might appear as an exceptional correlation in lieu of the continuation of a pattern from the 1950

Figure 1: Scatters of compound annual growth rates of labor productivity vs. energy-labor ratios, marker area corresponds to share of global fossil fuel consumption in production during plot period. Horizontal, vertical axes, and 45 degree line are dashed lines.



to the 1970s that was interrupted in the 1980s. Indeed, such a short dataset might invite concluding that no stable pattern exists in the relationship between $\hat{\lambda}$ and $\hat{e}$. However, the longer data series suggests that the 1980s are an exception, and the 1990s witnesses the repercussions from a change in the mode of production of a significant part of the world economy. Otherwise, the world economy displays a remarkably tight positive correlation between labor productivity growth and the direction of technical change.

4.2 Elasticity in the world economy

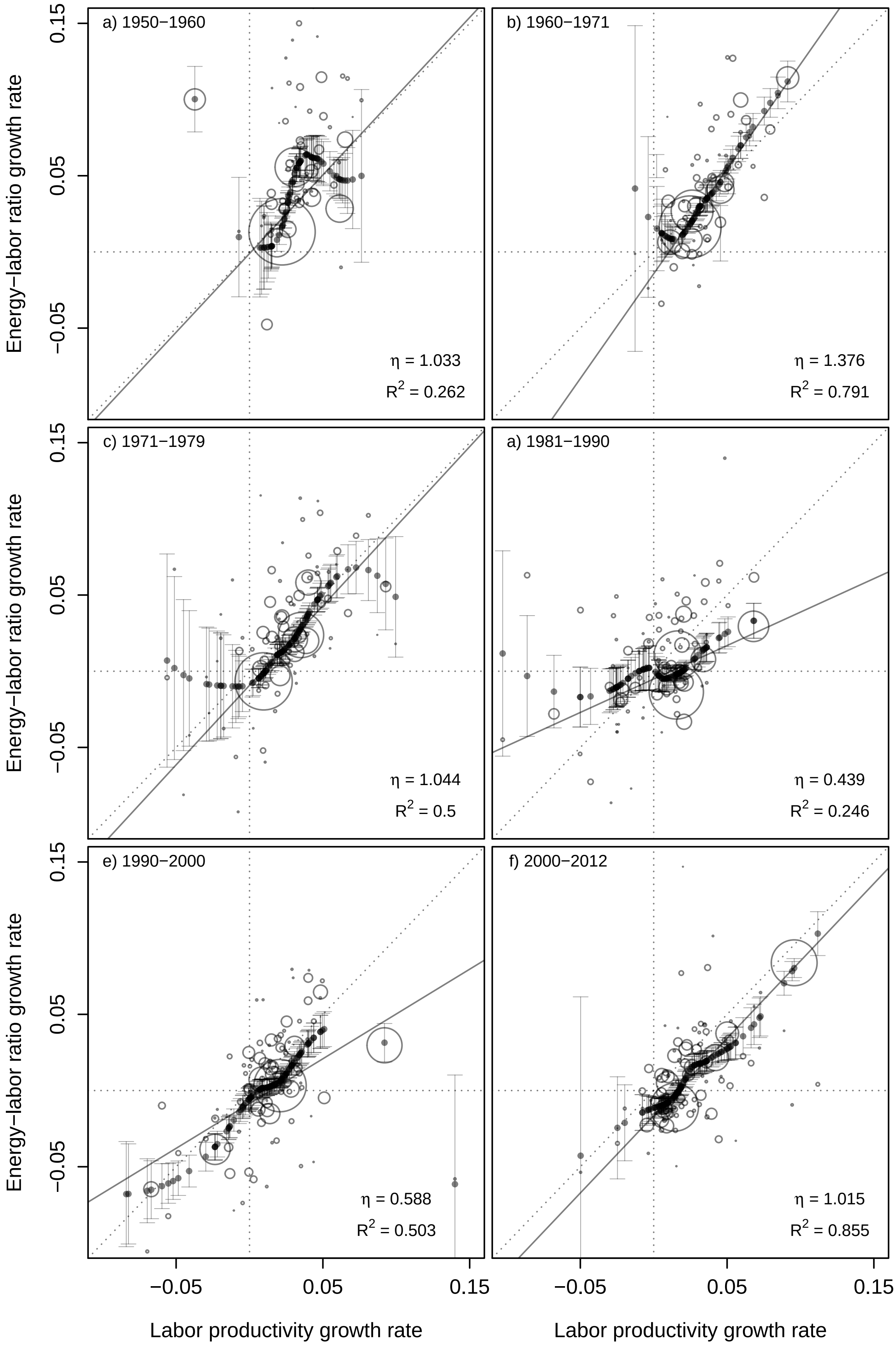
A regression analysis makes this correlation more precise. Linear and loess fits to equations (A.1) and (A.3) are estimated for every period, and superimposed on the scatters in Figure 2. The linear fits are solid lines, loess fits are points with 1.96 times standard deviation error bars. The slope of the weighted linear fits, η, which is the elasticity of the energy-labor ratio with respect to labor productivity, can be seen to be around unity in plots a-c and f. Plots d, with data slightly shortened to the period 1981-1990 to exclude the oil price shock, and plot e have a lower slope, and all are significant at the 99.9% confidence level.[11] Seen as a whole, the world economy operated with energy-using technical change that left energy productivity growth nearly constant and near zero over a wide range of labor productivities, in the four out of six decades that were also the most successful in terms of labor productivity growth (Maddison 2006, p. 125). A rolling regression in Appendix C reports all ten year cross section estimates and confirms the regular pattern and exceptions identified here.

Most linear fits leave a large part of the information in the data unexplained (low R^2). Loess fits help understand the residual information. Weighing neighboring datapoints more heavily, the loess fits show that the vast majority of the data is aligned along the 45 degree line, nearly linearly.[12] Surprisingly, this is even true for the 1990s, as all major countries

[11] The slope coefficient is not significant for the period 1979-1990. Acting on the prior knowledge that the anomalous correlation in the 1980s is related to the oil price shocks of 1979 (rather than the economic crises occurring throughout the decade), and seeing that real US oil prices only started falling in 1983 (Berndt 1990), the period is shortened successively to recover the correlation in the 1980s. It is first shortened to 1980-1990 and then to 1981-1990, at which point zero is excluded from the slope estimator's 99.9% confidence interval.

[12] The elasticity above one in the 1950s and 1960s may be partly caused by a substitution of traditional

Figure 2: Scatters of compound annual growth rates of labor productivity vs. energy-labor ratios. Linear fit represented by solid line, with slope and R^2 estimate, *loess* fit represented by dots with 95% confidence interval whiskers.



but China followed the unit elasticity pattern. The important non-linearities occurred in the 1950s and 1980s. Apart from these two outliers, non-linearities dominate only at the left and right fringes caused by small countries in deep depression or expectional growth spurts. Hence, most of the world economy operated under a technical change regime that substituted energy for labor at the same rate as it improved its labor productivity. The next subsection examines whether this also held for individual regions and countries over time.

4.3 Regional and country experience over time

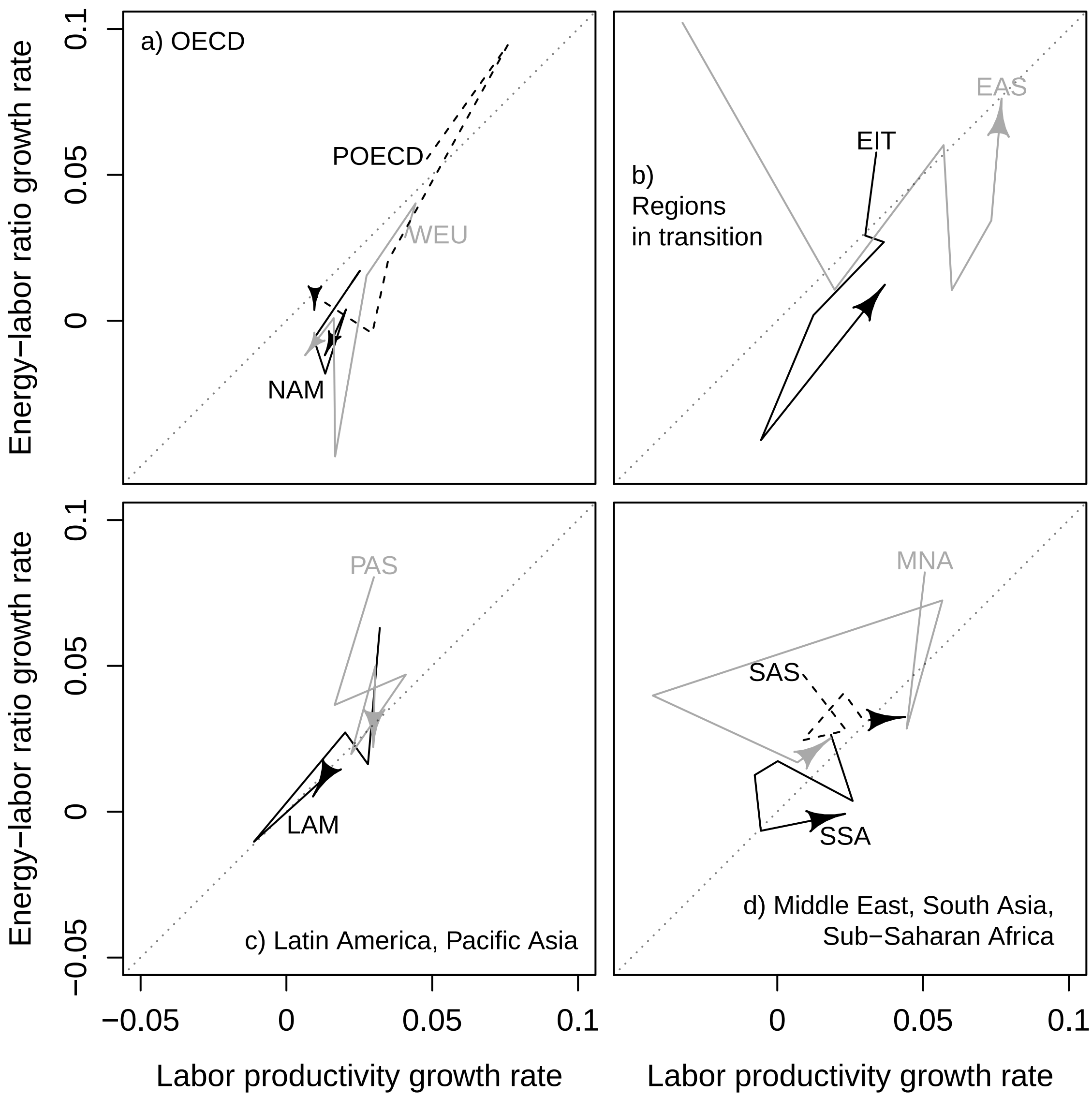
To examine trajectories over time, regional growth rates in the six decades are plotted, where contemoraneous $\hat{\lambda} - \hat{e}$ compound annual growth rate vertices are connected by edges. An arrowhead indicates the time direction. Figure 3 displays time series for all regions and shows that the positive elasticity holds not only cross-sectionally for the world, but also over time for individual regions in plots *a* and *c*, where plot a represents more than half the world's economy until 2000.

The plots on the right-hand side, *b* and *d*, display exceptional patterns. One is East Asia, in which China experienced large-scale introduction of fossil energy in the 1950s (Smil 2004); at the same time China's Great Leap Forward and the subsequent famine depressed output and employment, miring the region in falling labor productivity for the period (Hobsbawm 1994). This was followed by two regular decades until the end of the 1970s. The 1980s and 1990s were characterized by high energy productivity growth from an initially very low level, which took place in the context of a series of 'exceptionally successful' energy efficiency measures in the course of that country's economic reforms (Smil 2009; Sinton et al. 1998, p. 813), which made it the most successful country in terms of productivity growth in the world (Hu and Khan 1997). After 2000, growth in China returned to the energy-using growth of the 1960s and 1970s based on heavily expanding manufacturing industry, large infrastructure projects and growing net exports of embodied energy in products (Zeng et al. 2014).[13]

biomass with fossil fuels in fast growing economies, as the world share in biomass dropped from 25% to 10% (data underlying Fouquet 2009).

[13]Given that the engineering energy efficiency of more decentralized final goods production tends to be

Figure 3: Time series of regional $\hat{\lambda}$ and $\hat{e}$ couples.



Plot *b* also displays the remaining economies in transition from planning, which is the only region in the 1990s that moves to more energy-saving technical change.[14] Unlike China, those newly existing former Soviet republics experienced a deep depression in the 1990s. Russia's GDP in 1998, the year the government defaulted on its debt to the IMF (Boughton 2012), was only 57% of its 1990 GDP in real terms, while Ukraine's was only 41% of its 1990 value. In the 2000s this region returned to its labor productivity growth rate of the 1970s with a proportional increase in its energy-labor ratio, leading to neutral technical change.

The regions in panel *d* had a negative elasticity, η between at least two decades. South Asia's trajectory may be explained by pointing to net imports of energy intensive products or a low resource service-driven growth, while the Middle East and North Africa consist mostly of fossil fuel producers, which are expected to deviate from typical energy use patterns. The figures on sub-Saharan Africa are especially difficult to interpret because the accuracy of historical growth rate statistics for some countries included in the dataset are questionable (Jerven 2010). Another reason for an irregular relationship in these regions may be that they operated with inefficient energy productivity changes, which fell in most decades. In summary, while some regions diverge from the near-unity elasticity, which can be partly explained by their historic economic circumstances, the positive elasticity is pervasive also for individual regions' trajectories over time.

Finally, a country and time fixed effect estimate of equation (A.4) for the entire dataset summarizes average developments at the *national* level, while controlling for decades' different growth environments. It does not weight countries for their share in total energy consumption but treats each of them equally as a datapoint. Table II shows that the highly positive slope coefficient is confirmed even by focusing on national growth rates and assuming a linear relationship. This is also true for subsets of the world, the OECD, non-OECD countries and the economies in transition (EIT). In the last column, excluding the 1980s from the estimate confirms that this decade was a pervasive shock to national economies patterns of technical

lower than for highly concentrated industrial production, the fact that China's move towards a 'consumer economy' is unlikely to improve the ratio of $\hat{\lambda}$ to $\hat{e}$ in the near future (Brockway et al. 2015).

[14] All other regions rebounded from a drop in the energy-labor ratio growth rate from the 1970s to the 1980s, the third edge, in the aftermath of the OPEC oil crises.

change. The panel also highlights that the 1950s and 60s display a higher intercept, relative to the later periods, implying that in the later periods energy productivity growth tended to be more positive for low rates of labor productivity growth.

In sum, the constantly high, positive elasticity of the fossil energy-labor ratio with respect to labor productivity observed at the world level, is also reflected on average in national development. Faster growth tends to require proportionately more energy, putting the onus for reducing carbon emissions in growth on substituting fossil fuels with renewable sources, as opposed to harnessing energy-saving technical change.

Table II: Panel country and time fixed effects estimates.

	World	OECD	non-OECD	EIT	World$_{-1980s}$
η	0.727 **	0.868 **	0.695 **	0.627 **	0.808 **
	(0.067)	(0.151)	(0.080)	(0.137)	(0.079)
1950s	0.048**	0.030 **	0.055 **	0.073 **	0.045**
	(0.006)	(0.007)	(0.008)	(0.018)	(0.006)
1960s	0.022**	0.033 **	0.016 *	0.042 *	0.021 **
	(0.006)	(0.007)	(0.008)	(0.018)	(0.006)
1970s	0.014*	0.015 *	0.013	0.011	0.014
	(0.005)	0.006	(0.007)	(0.015)	(0.005)
1980s	0.007	0.009	0.006	0.004	
	(0.005)	(0.005)	(0.007)	(0.016)	
1990s	-0.003	0.009	-0.007	-0.034 *	-0.002
	(0.005)	(0.005)	(0.006)	(0.011)	(0.005
R-squared	0.404	0.693	0.388	0.669	0.420
Adj R-squared	0.308	0.542	0.288	0.395	0.302
N	550	138	412	88	455

** significant at the 99.9% confidence level.

* significant at the 95% confidence level.

4.4 Substitution with non-fossil energy

Before discussing the results' implications, a brief estimate of the substitutability of fossil with low carbon energy sources is made. It has been argued that the much higher energy density (power per area) of fossil fuels compared to traditional biomass made them superior engines of

Table III: Effects of changes in low carbon sources in the energy mix.

Dependent Variable	Fossil $\hat{e}_{2000-12}$	Total $\hat{e}_{2000-12}$
$\hat{\lambda}$	1.029**	1.023**
	(0.038)	(0.037)
$\tilde{\gamma}$ (renewables	-1.394**	-0.226
percentage change)	(0.287)	(0.284)
Intercept	-0.016**	-0.016**
	(0.002)	(0.002)
N	112	112
Adj. R^2	0.871	0.870
Log Likelihood	222.010	240.896

** Significant at the 99.9% confidence level

productivity growth (Sieferle 2001; Wrigley 2010); and their density is also higher than that of new low-carbon alternatives (Smil 2010, ch. 4). This would suggest that although renewable energy is now the preferred alternative energy source, it is not clear whether substitutes perfectly for fossil fuels. To check whether low-carbon sources are qualitatively different from fossil fuels, and have an impact on the *total* energy labor ratio, $\hat{e}$ is additionally regressed on the annual percentage change of the non-fossil energy, γ in the energy mix. In particular, if they are less efficient at providing energy, increasing their share may have a significantly positive effect on the total energy-labor ratio. Table III shows that this is not the case. It reports the coefficient values and standard errors from equation (A.2) for the period 2000-2012. Column 1 shows that that a 1 percentage point increase per year in non-fossil energy for production is associated with an average of 1.39 percentage point less growth in fossil $\hat{e}$, suggesting low-carbon sources are replacing fossil fuels when used. But they do not seem to do so at the cost of an overall more energy using technical chnage, for an increased share of low-carbon energy has no significant effect on the total energy-labor ratio, as column 2 shows. Where low-carbon energy has been implemented, it has led to more fossil-energy saving technical change in recent years, without changing the correlation between *overall* energy use and the rate of productivity growth.

5 Discussion of results

The implications of the results for growth models and climate change mitigation policies are discussed. The near unit elasticity at the global level suggests a stylized fact for energy in economic growth that links the direction of technical change to (labor) productivity growth.[15] This complements the fourth of Nicholas Kaldor's stylized facts, that the capital output ratio is constant (Kaldor 1961), and hence labor productivity growth is achieved by a growing capital-labor ratio. Here, we have seen that growing labor productivity is also accompanied by a rising fossil energy-labor ratio. While fossil energy output ratio *has* fallen at the global level, this has happened predominantly in the 1980s and 1990s which were shown to deviate from other periods due to shocks that were exogenous to the economy.

Can economic growth models with energy inputs explain this regularity? Growth models that see a trade-off between different factor productivity growth rates, such as those with induced technical change, are *prima facie* too 'pessimistic' about the simultaneous productivity growth potential in labor and energy. Careful studies that incorporate factor shares would be necessary in order to be more precise about the consequences for single-factor productivity of changes in relative factor prices. Models of endogenous technical change with increasing returns to scale, on the other hand, discussed in Section 2.2, can explain this relationship, where the increased labor productivity from scale economies leads to a higher throughput of energy resources. Similarly, the ecological economic growth models that see increases in energy per worker driving labor productivity would predict this relationship. Models, on the other hand, that assume simultaneously faster labor and energy productivity growth are likely to overestimate the ability to 'decouple' growth from fossil energy.

Significantly, more than 95% of baseline scenarios in the integrated assessment models of the IPCC or the IEA fall into this optimistic category. Baseline scenarios sketch future developments in per capita GDP, driven by exogenous labor productivity growth, and energy

[15] Studies that have drawn a large part of their sample from these two decades - an inevitable procedure if readily available data from the IEA (starting in 1971) or the EIA (starting in the 1980s) are used - run the risk of missing this regularity. This may go some way to understanding the contradictory conclusions reached by the studies reviewed in Section 2.1.

intensity without mitigation policies (IPCC 2014, p. 426), and the IEA forecast does the same (International Energy Agency 2014, p. 40). Future growth scenarios are ultimately based on extrapolation of past trends; however, the median scenario for the years 2010-2050 assumes both a 1.5 times faster labor productivity growth and a 1.5 times faster decline in the energy intensity than the trend in the period 1970-2010. These are based ostensibly on separately specifying labor productivity and energy intensity trends (IPCC 2014, p. 426). The results of the present study suggest that while labor productivity growth rates may plausibly increase, this will not be accompanied by significantly faster energy intensity decreases. The worrying implication is that policy advice based on these scenarios may rest on a spurious empirical basis for how labor productivity growth interacts with energy intensity through the direction of technical change.

A second implication bears on national climate change mitigation policies. The results show that the period of rapid growth in the world economy was predicated on highly fossil energy-using technical change. The most recent period saw the most concerted efforts yet to mitigate carbon emissions, and yet growth depended on increased fossil fuel consumption for faster productivity growth, reminiscent of the 'Golden Age' of the 20th century. It is clear that robust economic growth will require abundant and cheap energy supplies. Policies aimed at decoupling should focus more on substituting the energy supply with low-carbon alternatives rather than primarily on overall energy savings.

In the absence of sufficiently fast innovation in renewable energies or alternative low-carbon energy supplies, however, attempting to achieve fast productivity growth and decoupling from fossil fuels may prove frustrating. National economic development has relied on rapid increases in the consumption of fossil fuels. In particular, few countries have sustained high rates of growth of labor productivity with fossil energy-saving technical change anywhere in the data. Often the successful growers – such as Thailand and South Korea in the 1990s and Japan and Italy in the 1960s – had falling fossil energy productivities. The historical record is also in sharp contrast to IPCC projections that see energy productivities of non-OECD countries growing at 2-4% per year on average for the next four decades, while increasing their per capita growth rate relative to the 1970-2010 period (IPCC 2014, Figure 6.2, p. 426). The need for continued growth in fossil energy consumption in countries that seek quick growth in per capita income puts the confrontations between OECD and developing countries at recent United Nations climate mitigation conferences in perspective (Financial Times 2015).

6 Conclusion

This study has investigated the long-run relationship between the rate and fossil energy direction of technical change in the world economy. Growth rates of labor productivity and the fossil energy-labor ratio were examined for more than 95% of world output and fossil energy consumption in production in the period between 1950 and 2012. It was found that, for an additional percentage point of labor productivity growth, the fossil energy consumed per unit labor also grew by one percentage point on average, and left energy productivity close to constant over a wide range of labor productivity growth rates. This near unit elasticity was remarkably constant over time and regions, and deviations in the 1980s and to a lesser degree the 1990s were shown in their historical context to be one-time exceptions that are unlikely to reflect a change in the long-term technical change pattern. In recent years, low-carbon sources have been used to substitute fossil energy without changing the relationship between labor productivity growth and the direction of technical change with respect to total energy inputs. The discussion about the implications emphasized that growth models with increasing returns to scale may be useful for explaining the relationship, while policies attempting to achieve fast, decoupled growth will likely have to ensure access to an abundant, cheap non-fossil energy supply rather than aiming for overall energy savings.

Avenues for research using growth models are sketched. First, models of growth with increasing returns to scale could incorporate the labor productivity elasticity of the fossil energy-labor ratio and examine the plausibility of varying chains of causation. Second, integrated assessment models could be re-run with a baseline informed by the historical correlation between labor productivity and energy intensity. Third, embodied energy trade flows could be examined to determine in how far they can explain deviations from the unit elasticity trend, and could be used to underpin input output results (Wiedmann et al. 2013) about the interdependence of countries' energy consumption with economic theory.

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Appendix A: Econometric specifications used

The regression techniques are straightforward linear and nonlinear cross section regressions and a panel time and country fixed effects regression. For the global relationship, weighted least square regression is applied in a cross section of N countries from year t to year s

$$\hat{e}_{its} = \alpha_{ts} + \eta_{ts}\hat{\lambda}_{its} + \nu_{its} \quad \text{for } i = \{1, ..., N\} \tag{A.1}$$

where ν is the i.i.d. normal standard error weighted by country i's share of global fossil energy consumption for production. The weights are used to estimate the role of fossil fuel in *world* production, which is more heavily determined by large countries. Giving the same weight to every country would lead to a summary of national experiences, without representing the picture for the world as a whole. Using fossil fuels as a weight instead of GDP confers the advantage that no ambiguous exchange rate - market or purchasing power weighted - has to be selected.

In order to examine the impact of a changing share of non-fossil energy in the energy mix, another regression adds the annual change in percentage points of non-fossil energy in the mix, $\tilde{\gamma}$. Percentage points are used instead of growth rates of shares in order to give equal weights to a marginal change to any energy mix composition. This leads to the equation

$$\hat{e}_{its} = \alpha_{ts} + \eta_{ts}\hat{\lambda}_{its} + \rho_{ts}\tilde{\gamma}_{its} + \nu_{its} \quad \text{for } i = \{1, ..., N\} \tag{A.2}$$

Additionally, locally weighted regression, *loess*, (Cleveland 1979; Cleveland and Devlin 1988) captures nonlinearities in the conditional correlation estimated by the linear fit. *loess* estimates the value of the fit at observation i as a polynomial fit that weighs neighboring observations k by their distance from $\hat{\lambda}_i$, conditional on a weight function $w_k(\hat{\lambda}_i)$ for a share ζ of the nearest observations to i, so that $k = \{1, ..., i, ..., n\}$. Setting $\zeta = 0.75$, a polynomial of degree two is estimated

$$\hat{e}_i = \beta_{0,\hat{\lambda}_i} + \beta_{1,\hat{\lambda}_i}\hat{\lambda}_i + \beta_{2,\hat{\lambda}_i}\hat{\lambda}_i^2 + \nu_{its} \quad \text{for } i = \{1, ..., N\} \tag{A.3}$$

where $\beta_{\hat{\lambda}_i}$ are the local estimators that arise from minimizing the distance using the neighboring observations weighted by $w_k(\hat{\lambda}_i)$.

Finally, a country and time fixed effects model is estimated to control for unobserved variable biases in the cross sections as

$$\hat{e}_{its} = \alpha_i + \eta_{ts}\hat{\lambda}_{its} + \tau_{ts} + \nu_{its} \quad \text{for } i = \{1, ..., N\},\ t = \{1, ..., T\} \tag{A.4}$$

where α is the country-fixed effect and τ the time fixed-effect.[16]

Appendix B: Supplementary data information

Countries are indexed by i and years by t. Output and the measures of energy use are divided by employment to yield annual observations of labor productivity λ_{it} and the non-residential fossil energy-labor ratio, e_{it}. The variables used in the analysis are then generated by calculating compound annual growth rates, $\hat{\lambda}_{its}$ and e_{its}.[17] Indices are omitted in the main text where unambiguous. Regional growth rates are computed for the ratios of the sums of member countries' labor, output and energy variables. Therefore, regional growth is weighted by the member countries' size and the growth rates for North America, for instance, reflect mainly those of the United States.

Merging the IEA and TED datasets leaves 113 countries, some of which were part of Yugoslavia or the Soviet Union before the 1990s. These countries comprise 98% of global GDP at market exchange rates, more than 95% of global fossil fuel consumption, and 95% (falling to 93%) of global population for the period 1971-2012, compared to the IEA world estimate.[18] Merging Darmstadter et al.'s energy data with TED output and employment leaves 70 countries, for 1950 and 1960, which covers more than 95% of GDP and population in the TED database. Using the intersection of countries in Darmstadter and IEA to compute growth rates from 1960 to 1071 produces growth rates for 68 countries from 1960 to 1971. Table IV shows which countries belong to which region according to the IPCC Region Categorization 10 (IPCC 2014, 1286).

[16] Fits were estimated in R using the functions *lm()*, *loess()* and *plm()*.

[17] The compound annual growth rate of variable y at time t over s years is defined as $\left(\frac{y_{i,t+s}}{y_{i,t}}\right)^{1/s} - 1 = \hat{y}_{its}$.

[18] The IEA omits estimates of energy use if nationally reported data quality is judged unreliable. Since this routine mostly excludes countries with low per capita GDP, the IEA data is biased to leaving out a larger share of population than GDP (IEA 2014a).

Table IV: Regions and their member countries. Country names are abbreviated with their three letter codes (ISO 2014).

Region	Member countries
North America	USA, CAN
Western Europe (WEU)	AUT, BEL, DNK, FIN, FRA, DEU, GRC, ISL, IRL, ITA LUX, NLD, NOR, PRT, ESP, SWE, CHE, GBR , TUR
Pacific OECD (POECD)	AUS, JPN, NZL
Economies in Transition (EIT)	HRV, CYP, CZE, EST, LVA, LTU, MLT, POL, RUS, SVN SVK, KGZ, KAZ, TJK, TKM ARM, GEO, UKR, UZB, ALB AZE, BLR, BIH, BGR, HUN, MKD, ROU, SRB, MDA *
Latin America (LAM)	CHL, COL, CRI, TTO, URY, BOL, GTM, ARG, BRA, DOM ECU, JAM, MEX, PER, VEN †
Sub-Saharan Africa (SSA)	COD, ETH, GHA, KEN, MOZ, NGA , SEN, TZA, ZMB, ZWE CMR, AGO, ZAF †
Middle East & North Africa (MNA)	BHR, ISR, IRQ, IRN, JOR, KWT, TUN, DZA, EGY, MAR SDN, SYR, ARE, YEM, OMN, QAT, SAU †
East Asia (EAS)	CHN, KOR, HKG **
Pacific Asia (PAS)	SGP, KHM, MMR, IDN, PHL, VNM, MYS, THA
South Asia (SAS)	BGD, IND, PAK, LKA

* until 1990: USSR ,YUGOS.

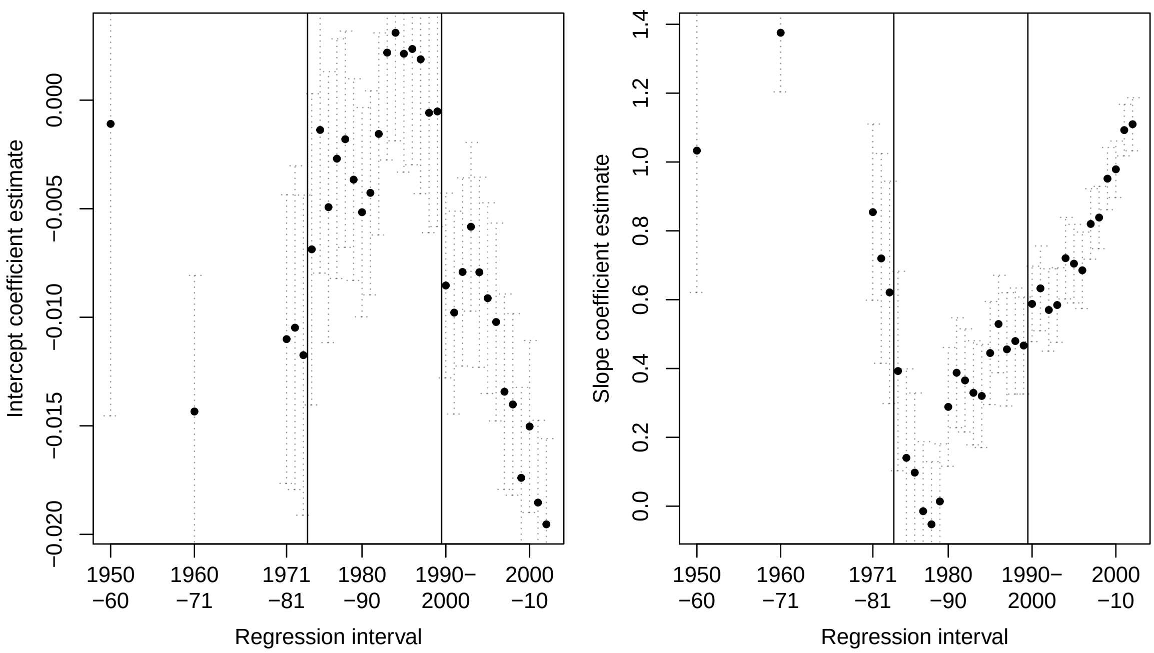
** until 1971: CHN is ‘Communist Asia’ and includes North Korea and North-Vietnam, while separate data for Taiwan is available.

† Data for a subset of countries in this region is available only from 1971.

7 Appendix C: Linear fit endpoint variation

A rolling regression estimate of equation (A.1), where start t is increased by increments of one year while the interval s is held constant at ten years from 1971 without exclusions of any years, summarizes the linear estimate the elasticity over the entire data period. Periods before 1971 are not rolled, due to data reported only every few years. Shown in Figure 4, the intercept estimate (left) and slope estimate (right) show an inverse u-shaped and u-shaped pattern respectively, which indicate that in more recent years the relationship between changes in labor productivity and the direction of technical change returns to its character of the 1950s and 1960s, before it was shocked from the late 1970s through the early 1990s.

Figure 4: Coefficients of a linear fit to cross-sections of growth rates: ten-year-moving averages of a rolling window regression with 95% confidence intervals. The vertial lines enclose the estimates from 1974-1983 through 1989-1998, which show significantly higher intercept and lower slope estimates.



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