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# Energy in Economic Growth: Is Faster Growth Greener?*

Gregor Semieniuk†

April 5, 2018

**Abstract**

An influential theoretical hypothesis holds that if aggregate productivity growth accelerates, then so does the decline in energy intensity. Whether faster growth is greener in this sense is crucial for modeling future growth and climate change mitigation, but empirical evidence is lacking. This paper characterizes the global, long-run historical relationship between changes in energy intensity and labor productivity growth rates. Basing estimates on an unbalanced panel of 180 countries for the period 1950-2014 and the world as a whole, it captures a significantly larger historical window than previous studies. The paper finds a stylized fact whereby the rate at which energy intensity changes is constant or even increases as labor productivity accelerates. Faster growth is not greener. This provides important new information for calibrating integrated assessment models, many of which make a green growth assumption in near term projections.

JEL: O44, O47, Q43, E17

Keywords: energy intensity, labor productivity, decoupling, green growth, stylized fact

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# 1 Introduction

Is faster growth greener? This question connects two key global challenges of our time. The first is to lift billions of humans out of poverty and reduce material deprivation. The second is to avoid catastrophic climate change caused by anthropogenic greenhouse gas emissions. The main mechanism underpinning efforts to meet the first challenge is robust and inclusive economic growth to raise incomes (G20, 2017; UN, 2018). A key mechanism to meet the second is to reduce energy demand because greenhouse gas emissions are predominantly caused by combustion of fossil fuels to meet energy demand (Clarke et al., 2014; IEA, 2015a; UNEP, 2016).[1] Mitigating climate change is intrinsically in the interest of long term growth, because global warming and its consequences would damage global growth potential (Burke et al., 2015). Reasoning in the other direction is less straightforward. Historically, economic growth has been tightly correlated with increases in energy demand, so economic growth tends to increase the greenhouse effect. If, however, *faster* growth was correlated with the rate at which output growth decouples from energy demand, this would be an important factor in making progress towards addressing both challenges.

An influential theoretical hypothesis holds that if aggregate productivity growth accelerates, then so does the decline in energy intensity (energy used per unit value of output produced). The reasoning behind this argues that older and less energy-efficient technologies would be replaced faster with newer, more efficient ones, and hence the energy intensity is falling faster. This intuitively appealing claim, which is based on the vintage model of embodied technical change (Solow, 1960), implies that faster productivity growth itself delivers faster climate change mitigation conditional on growing incomes. Conversely, it implies that slower productivity growth detracts simultaneously from meeting both the income and mitigation targets. This “green growth hypothesis” thus proposes that the goal of poverty reduction can be reached faster, while at the same

[1]Depending on conversion ratios used to compare heat and electricity forms of energy, and treatment of non-commercial energy, fossil fuels were estimated to supply around 80-85% of the world’s primary energy in recent years (British Petroleum, 2017; Energy Information Agency, 2018; IEA, 2017), a ratio that has changed little since 1950 (Fouquet, 2009).

time using relatively less energy and making headway towards the climate mitigation target – a win-win situation.

The accuracy of this hypothesis is important for understanding whether economic growth may undermine its own basis via climate change (Taylor, 2009). This is highlighted by current integrated assessment models that chart scenarios of future growth and climate change for the regions of the world. In these models the crucial relation for the feasibility of climate change mitigation conditional on growth is the output elasticity of energy (Marangoni et al., 2017). These models typically produce an uptick in near future projected global productivity growth rates due to convergence of poorer regions with richer ones (Dellink et al., 2017; W. D. Nordhaus and Yang, 1996). If the green growth hypothesis holds, then convergence also induces faster decoupling and lessens the greenhouse gas emissions of growth. Bringing the models to the data in the growth-energy demand dimension is particularly important as more sophisticated accounts of technological change, relying on, machine varieties, learning rates and R&D expenditures are more difficult to validate empirically (Gillingham, Newell, et al., 2008), especially at the global level, the level that counts for the global challenges of growth and climate change.

Against this backdrop, it is surprising that little empirical work has investigated the green growth hypothesis. Energy intensity has tended to fall at the global level since the second half of the 20th century, but it is unclear whether faster growth would accelerate this reduction. Most empirical studies focus on nonlinearities in the *levels* relationship of output per capita and energy intensity or energy per capita due to the environmental Kuznets curve argument applied to energy (Ang and Liu, 2006; Kander et al., 2013; Luzzati and Orsini, 2009), household consumption patterns (Wolfram et al., 2012) or energy policies (Fouquet, 2016), but not on changes in growth rates. The careful study on stylized facts of energy in economic growth by Csereklyei et al. (2016) goes some way towards elucidating the correlation of the rates of change. They find that in a long-run cross section of compound annual growth rates for 99 countries over the years 1971-2010, energy intensity falls more quickly when productivity growth accelerates (an elasticity of around -0.3). However, the authors give the same weight to each observation with e.g. Singapore's position having the same influence as China's on the slope of the regression line. This is useful for international comparisons, but less so for understanding the global trajectory of energy intensity and growth. Moreover, they do not examine any variation within their 40 year cross section, nor a country's own elasticity as it increases or decreases its rate of productivity growth over time. Finally, although their dataset comprises 99 countries, they leave out the entire Soviet Union and its successor states, surely a component that must not miss due to its pivotal role in economic growth and energy demand in the 20th century.[2]

Empirical evidence for whether faster growth is greener is lacking, and current modeling relies mainly on a theoretically motivated prior. The present paper fills this gap and characterizes the global, long-run historical relationship between changes in the rates of change of productivity and energy demand. It goes beyond existing studies in three key aspects. Basing estimates on an unbalanced panel of 180 countries for the period 1950-2014, this research captures a significantly larger historical window than previous studies. Taking country size into account, it looks at global patterns, not just international comparisons. By tracing individual countries as well as the world as a whole for their own elasticity over time, this research moves beyond pooled cross sections. The aim is to provide robust insight into the relationship of productivity and energy demand changes, as this stylized fact is a crucial parameter in the debates about economic growth, energy demand and climate change.

This paper analyses a more comprehensive dataset than in greater detail than any previous study of the author's knowledge, and updates our prior about decoupling as productivity growth varies. The key finding is that the green growth hypothesis does not hold water: faster growth is not greener. Moreover, it is shown that the current suite of

[2]Some other noteworthy omissions, that are included in the present study, are Yugoslavia and its successor states, Myanmar, several African countries, the more populous of which are Burkina Faso, Chad, Madagascar, Malawi, Mali, Niger, Rwanda, Uganda, and a suite of Middle Eastern countries, namely Kuwait, Qatar, Saudi Arabia, United Arab Emirates and Yemen.

integrated assessment models used to inform climate policy tends to assume the refuted hypothesis to hold in near term projections of economic growth and energy demand, so this research provides new information for calibrating these models.

# 2 Literature Review and Hypothesis Development

Prior to starting the empirical analysis, it is useful to demonstrate how widespread the green growth hypothesis is, trace it to an underlying theoretical argument about embodied technical change, and to review extant empirical evidence.

## 2.1 Green Growth in the Modelling Literature

The green growth hypothesis, although not always spelled out explicity, is widespread in models of growth with energy. For instance, the latest assessment report of the International Panel for Climate Change (IPCC), assumes that faster labor productivity growth coincides with faster decline in energy intensity (Clarke et al., 2014, p. 426). A similar assumption can be found in the BP Energy Outlook (British Petroleum, 2018, p. 120), and in the two transition scenarios of the World Energy Council (2016, Tables 21 and 30), in all of which output per capita grows and energy intensity declines at accelerated rates over historical averages. In fact, Semieniuk et al. (2018) show that in most current models, whether baseline or policy scenarios, the green growth hypothesis plays an important role.

Many scenarios are not explicit about the rationale for this elasticity. More insight comes from earlier generations of models. For instance, the first IPCC assessment report argues that "a higher rate of economic growth makes it possible for capital stocks (e.g., power plants, factories, housing) to be refurbished or replaced more quickly, and makes the accelerated penetration of advanced technologies possible" (IPCC, 1991, p. 38) and a publication widely cited in later models assumes for its energy projection "the faster the economic growth, the higher the turnover of capital and the greater the nergy intensity improvements (Nakicenovic et al., 1998, p. 37). In fact, this refers to the theory of embodied technical change from the lat 1950s, whereby productivity growth occurs by installing newer, more productive vintages of capital (Johansen, 1959; Salter, 1960; Solow, 1960). Assuming new vintages of capital to be more energy efficient, accelerated productivity growth also implies faster energy efficiency growth (Jin and Zhang, 2016; Zon and Yetkiner, 2003). Embodied technical change is a common of incorporating technical change into models of growth with energy and climate change (Gillingham, Newell, et al., 2008; Popp, 2010) and perhaps the most direct theoretical justification for the green growth hypothesis.[3] How is the evidence for it causing green growth?

## 2.2 Embodied intensity reductions

The period of scarce oil and high oil prices in the 1970s and 80s (more on which in the results section) generated considerable interest in the problem of energy efficient embodied technical change (Berndt et al., 1993), and there have since been industry specific studies of it. Worrell and Biermans (2005) find that new vintages and retrofitting of US electric arc furnaces account for more than 90 percent of energy efficiency increases in the sector. In the cement sector Worrell, Martin, et al. (2000) reason capital stock turnover to be an important component of energy efficiency improvements, and (Sterner, 1990) show that capital-embodied technical change is the most important reason for energy efficiency improvements in the Mexican cement industry. A study for 35 US industries finds replacement of quasi-fixed inputs, in particular vehicles, to contribute to US energy efficiency since the 1980s (Sue Wing, 2008) and energy intensity reductions through embodied technical change are also to be found important in international technology adoption (Majumdar and Kar, 2017).[4] Considerable additional savings are possible (Worrell, Bernstein, et al., 2009). In fact, it has been estimated that if all practical

[3]A recent analytical contribution using Romer's (1990) expanding variety theory is Lennox and Witajewski-Baltvilks (2017).

[4]A related argument about technology-leapfrogging proposes that countries that catch up to the technological frontier should see less energy intensity growth throughout due to more energy efficient technology adoption (Goldemberg, 1998). This is not borne out by evidence (Benthem, 2015).

efficiency improvements in current energy consumption were used (down to 2nd Law of Thermodynamics lower bounds), energy demand would fall to 15% of its current level (Cullen, Allwood, and Borgstein, 2011). This figure falls further to 11% for energy conversion devices, such as equipment in factories (Cullen and Allwood, 2010). In all, little doubt exists that embodied technical progress is important for energy efficiency changes. However, no empirical studies were found that consider its correlation with changes in the (aggregate) rate of growth.

These results are qualified by the old observation that aggregate energy intensity is not the inverse of per unit energy efficiency (Jevons, 1865). Due to substitution effects, more energy-efficiently and thus more cheaply produced products may be consumed more by consumers, and an income effect may lead to additional purchase of energy intensive products, thus raising energy demand. These direct and indirect "rebound effects" explain why part of energy efficiency savings from capital-embodied technical change may be lost (Gillingham, Rapson, et al., 2016; Sorrell et al., 2009). An example is increased driving per person as cars become more fuel efficient; in the UK a one percent increase in fuel efficiency has led to an average increase of a quarter percent of distance driven (Stapleton et al., 2017). While energy efficiency thus grows by one percent, energy intensity only drops by three quarters of a percent. However, as with the previous set of studies no empirical studies were found that relate the rebound's magnitude to growth – in particular whether it becomes smaller as productivity growth picks up, thus serving as theoretical cause of green growth. In sum, there is little empirical evidence for the green growth hypothesis in terms of the underlying replacement of capital stock.

## 2.3 Empirical Evidence

This leaves us with evidence directly about the correlation between aggregate rates of change. The empirical literature on economic growth and energy demand has largely studied correlations of levels, not rates of change. However, there are exceptions. Hannesson (2002) finds a strong positive correlation between growth in energy and GDP in plots for 171 countries for the period 1950-1997. Hannesson (2009) further finds a GDP growth rate elasticity of the rate of energy growth of 0.84 and with an intercept of +4.6 percentage points (meaning a stagnating country is predicted to have a quickly growing EI) in a cross section of 67 countries for 1950-2004. The author controls for level of GDP per capita (negative insignificant) and oil price (negative significant); the fit is poor ($R^2 = 0.09$). Ocampo et al. (2009) report a labor productivity growth rate elasticity of the rate of energy-labor ratio growth rate of 0.4 and 0.6 for 47 countries grouped into 12 regions for 1979-1990 and 1990-2004 respectively. The most recent and comprehensive attempt is by Csereklyei et al. (2016) (see introduction). Their findings on growth rates correlations show that on average for 99 countries over 1971-2010 the elasticity of energy intensity rate of change with respect to output per capita growth rate is roughly one third (estimated from the plot in their Figure 6). All of these studies therefore seem to support the green growth hypothesis. But all of them also have in common that they leave out a number of important countries, do not distinguish (many) time periods and their relationship, and do not account for the different weights of countries in the world's relationship between energy and growth. In sum, good evidence on green growth is lacking, and the incorporation into models is predicated largely on a theoretical prior.

## 2.4 Updating our prior

The aim of this paper is to characterize the correlation of changes in growth rates of output and energy for the world economy and thus update our theoretical preconception with data. In short, we are looking for a stylized fact. There are a number of equivalent ways of doing this. In order to stress the idea that changes in energy intensity hang together with changes in production (productivity growth), we start from models of economic growth that consider the relationship between labor productivity and the capital-labor ratio. In those models, if the capital-labor ratio grows, economic growth is said to be capital deepening, as successive techniques of production use more capital for every unit of labor employed, with concomitant effects on the capital-output ratio

(Burmeister and Dobell, 1970). If we replace capital with energy, then energy intensity, $z$, which is just the energy-output ratio. $E/X$, depends on the relationship between labor productivity, $x$, and the energy-labor ratio, $e = E/L$. To see this decompose energy intensity

$$\frac{E}{X} \equiv \left(\frac{X}{L}\right)^{-1} \times \frac{E}{L} \iff z \equiv x^{-1}e \tag{1}$$

Taking logarithmic derivatives gives us the geometric rates of change

$$\hat{z} \equiv \hat{e} - \hat{x} \tag{2}$$

which are the object of our interest. These accounting identities show that the rate of change in energy intensity is simply the difference between rates of change of productivity $\hat{x}$, and of technique, that is the ratio of input factors, $\hat{e}$. In fact, whenever productivity growth is faster than the rate of energy deepening, relative decoupling of output from energy use occurs Ocampo et al. (2009).[5] This approach also maps – when replacing labor with population – directly onto the many studies investigating the energy per capita levels that sustain a certain level of affluence.

The question investigated here is whether an increase/decrease, in the growth rate of labor productivity, $\hat{x}$, corresponds to lesser acceleration/deceleration in the rate of change of the energy-labor ratio, $\hat{e}$. If so, then this supports the green growth hypothesis as this implies a drop in the rate of change of energy intensity, $\hat{z}$. Empirically, this occurs if the elasticity of the energy-labor ratio rate of change with respect to the labor productivity rate of change (henceforth simply the elasticity) is lower than one. The magnitude of this elasticity is what the following seeks to establish.[6]

[5] Absolute decoupling, $\hat{E} < 0$, occurs when the energy-labor ratio falls faster than labor's growth rate, since from $\hat{z} = \hat{E} - \hat{X}$ and rearranging (2) we have $\hat{E} = \hat{e} + \hat{L}$.

[6] It is important to stress that this paper is not explaining the patterns' drivers. We must first understand what the patterns are. The determination of causality is left to subsequent research.

# 3 Data and method

## 3.1 Data Description

The data serves to ground the investigation of the green growth hypothesis in a previously unavailable dataset that is more comprehensive than previous studies. As a result, a wide range of data sources have been consulted and merged. The result are historical national time series of GDP, employment, population, and total and non-residential primary energy demand at annual frequency for the period 1950-2014 for an unbalanced panel of 180 countries and the world as a whole;[7] to confront the stylised fact emerging from the historical data with near-term projections, data series for 2005, 2010 and 2020 generated by the models in the IPCC's 5th assessment report have also been used.

GDP data is from the Penn World Table (Feenstra et al., 2015). Market exchange rates (MER) are used for conversion to a common unit. The alternative would be to adjust exchange rates to achieve purchasing power parity (PPP). There are arguments for both types for aggregate exercises (W. D. Nordhaus, 2007; Pant and Fisher, 2007). We use MER mainly for comparability with extant IAM projections but revise three additional arguments for why MER are appropriate. First, there is no one right PPP. Significant changes in per capita incomes between PPP exercises reveal that it is very difficult to ascertain just what is the right parity (Deaton and Heston, 2008). Second, our focus is on output growth, much of which is traded at MER, rather than a measure of welfare. Even from a welfare perspective, the focus only on prices of consumption goods ignores differences in the consumption environment, where rich countries tend to provide more public goods that make the mere consumption of non-traded goods incomparable (Pant and Fisher, 2007). Third, because only long-term compound average growth rates (10 years) are used here, there are no distortions from short-term speculative fluctuations in MER. For countries not in the Penn World Table, the following sources were used: GDP data for the Soviet Union and Yugoslavia for 1950-1990 are from the gdpnapc series

[7] It's important to include global rather than sum of national energy demands as the about 2% of global energy demanded by international aviation and shipping is not attributed to any country.

in the Maddison project (Bolt et al., 2018). A number of country time series that begin in 1960 or later in the Penn World Table were spliced with Maddison project data, and, in a few cases, if not available there, with the Total Economy Database (Conference Board, 2016). World data was taken from the World Bank for 1960-2014. For 1950-60, the Maddison data were used, although these are in Geary Khamis dollars, and different estimates give diverging growth rates over this period (Institute for Health Metrics and Evaluation, 2012), so the world data for the 1950s are less reliable.

Total primary energy supply (TPES) was calculated from the United Nations Energy Statistics (UN, 2016) for 1950-1970 and taken from the IEA (2016) for 1971-2014, and from the UN for countries not covered by the IEA. The data include non-commercial energy sources, mainly fuelwood, crop residue, animal waste and charcoal, which have an important effect on energy intensities, in particular in developing countries (Nilsson, 1993).[8] And although it is notoriously difficult to estimate non-commercial energy use (Ang, 1986), the IEA data include these estimates. To complete the time series back to 1950, UN Statistics for non-commercial energy were used where available. For many developing countries, these statistics only begin in 1970 (Nilsson, 1993, p. 313). In that case, the non-commercial energy share in TPES data was interpolated between the 1970 UN figure and the estimates for 1949 in UN (1952), with additional data points in between supplied by estimates in (Ang, 1986; Desai, 1978; Planning Commission, 1999). World energy data was taken from Fouquet (2009) for 1950-1970 and the IEA for 1971-2014. Whenever data was spliced, the IEA series levels were extended. Finally, subtracting the IEA's estimate for household energy demand (Residential) from TPES generates an alternative energy series 1971-2014 that more closely approximates primary energy demand for production.

Population and employment data were taken from the Penn World Table, and supplemented from the Maddison (only for population) and the Conference Board data in the same way as for GDP. World population data was retrieved from the United Nations

[8] For instance, in India one quarter of primary energy came from mainly non-commercial biomass in 2013, but this share stood at 34% in 2000 (IEA, 2015b).

Population Division 2017 Update. Data on GDP, population and primary energy demand for 1184 scenarios that populate the output and emissions trajectories IPCC 5th assessment report are from its scenario database IAMC, 2014, version 26 May 2015.

Combining these data series, we construct six ratios and their growth rates, depicted in Table I. The ratios are for more than 90 per cent of the world's population, and more than 99 per cent from the 1990s onwards. We study compound annual growth rates over s periods, e.g. $\hat{x} = \left(\frac{x_{t+s}}{x_t}\right)^{\frac{1}{s}} - 1$, with typically $s = 10$ to average out business cycle fluctuations.

Table I: Indicators used in the analysis

| Ratios | | | |
|---|---|---|---|
| Indicator | Construction | Level | Rate of change |
| Labor productivity | $\frac{\text{GDP}}{\text{Employment}}$ | $x$ | $\hat{x}$ |
| Energy-labor ratio | $\frac{\text{TPES}}{\text{Employment}}$ | $e$ | $\hat{e}$ |
| Energy intensity | $\frac{\text{TPES}}{\text{GDP}}$ | $z$ | $\hat{z}$ |
| Output per person | $\frac{\text{GDP}}{\text{Population}}$ | $y$ | $\hat{y}$ |
| Energy per person | $\frac{\text{TPES}}{\text{Population}}$ | $f$ | $\hat{f}$ |
| Production energy-labor ratio | $\frac{\text{TPES–residential energy}}{\text{Employment}}$ | $q$ | $\hat{q}$ |

## 3.2 Method

We use a novel combination of graphic and econometric methods to examine the green growth hypothesis in unprecedented depth. First we consider the *levels* of labor productivity and the energy-labor ratio as in (1) to contextualize global productivity growth and the corresponding energy deepening in the economic history of the past six and a half decades. This gives insight into possible periodization, and helps interpret subsequent growth rate results.

In a second step, we examine cross sections of *rates of change* across countries as in (2) by plotting them in the $\hat{x}$ and $\hat{e}$ plane. Visual inspection of the angle of the data cloud gives an idea of the elasticity. A straightforward graphical way to check is to measure the distance from the 45 degree quadrant halving line. A data scatter parallel to this line spells unit elasticity would update the green growth hypothesis to non-green growth.

Following previous empirical studies, we also estimate the elasticity as the slope of a linear regression, but weight observations according to their importance in the global sample. The model is

$$\hat{e} \sim \mathcal{N}(\beta_1 + \beta_2 \hat{x}, \sigma^2 W^{-1}) \tag{3}$$

where $W$ is the diagonal matrix of weights using the share of each country in global energy demand in the period over which rates of change are computed. Assuming independently distributed errors we implement a Bayesian weighted linear regression analysis with non-informative priors, $p(\beta_1, \beta_2, \sigma^2) \propto 1/\sigma^2$ (Gelman et al., 2014). To capture non-linearities, we also estimate (3) with locally weighted estimates, "loess" (Cleveland and Devlin, 1988) and the same matrix of weights, W.[9]

In a third step, we analyze time series, in order to understand countries' own elasticities. This has not been done in the literature. We inspect individual countries' trajectories by plotting them again in the $\hat{x}$ and $\hat{e}$ plane. As trajectories appear as a set of directed acyclic graphs, the direction of each edge gives information about the green growth hypothesis. Unlike a slope, this also allows distinguishing the direction for accelerations and decelerations in the growth rate, so it gives a handle on whether the hypothesis cuts in both directions. We measure directions counterclockwise in angular degrees relative to an edge pointing straight east (zero degrees). Then the green growth hypothesis predicts edges' directions at most to lie in angular interval $[0°, 45°]$

[9]The estimates are made using the R version 3.4.2 implementation, sampling from the weighted linear estimate posterior densities with a self-programmed Gibbs sampler with 10,000 iterations where the first 2,000 burn-in samples are discarded, and using the function loess() for the loess estimate.

for countries accelerating growth, and at most in the angular interval $[180°, 225°]$ for countries decelerating growth.[10] Finding a large number of edges to lie outside these intervals, in particular if they are near to or above the 45° line, would necessitate revising our prior beliefs about the hypothesis. We also use this method, subsequently, to contrast the world's historical trajectory with that projected by IAMs in the current IPCC assessment report.

Together, the three steps of analysis lay the ground for pronouncing on a stylized fact about the elasticities and, if necessary, updating our beliefs about the green growth hypothesis.

# 4 Results

This section shows the results of applying the methods to country cross sections of growth rates, and trajectories over time. The aim is to crystallize a stylized fact about growth rate elasticities. To begin, though, it is helpful to look at the global level relationship between labor productivity and the energy-labor ratio to understand the possibly changing historical context.

## 4.1 Productivity and energy demand since 1950

Although generally positively correlated, the relationship of economic growth and energy demand since 1950 has gone through heterogeneous phases. In figure 1 we see two stretches of positive correlation, and one more complicated pattern sandwiched between them, corresponding two three distinct periods. The first is 1950 through 1973: rapid productivity growth along with fast energy deepening. These more than two decades are considered the most successful economic growth period in world history, the "golden age" (Maddison, 2001, p. 125).

[10]The idea to analyze directions based on angular degrees is due to Isabella Weber.

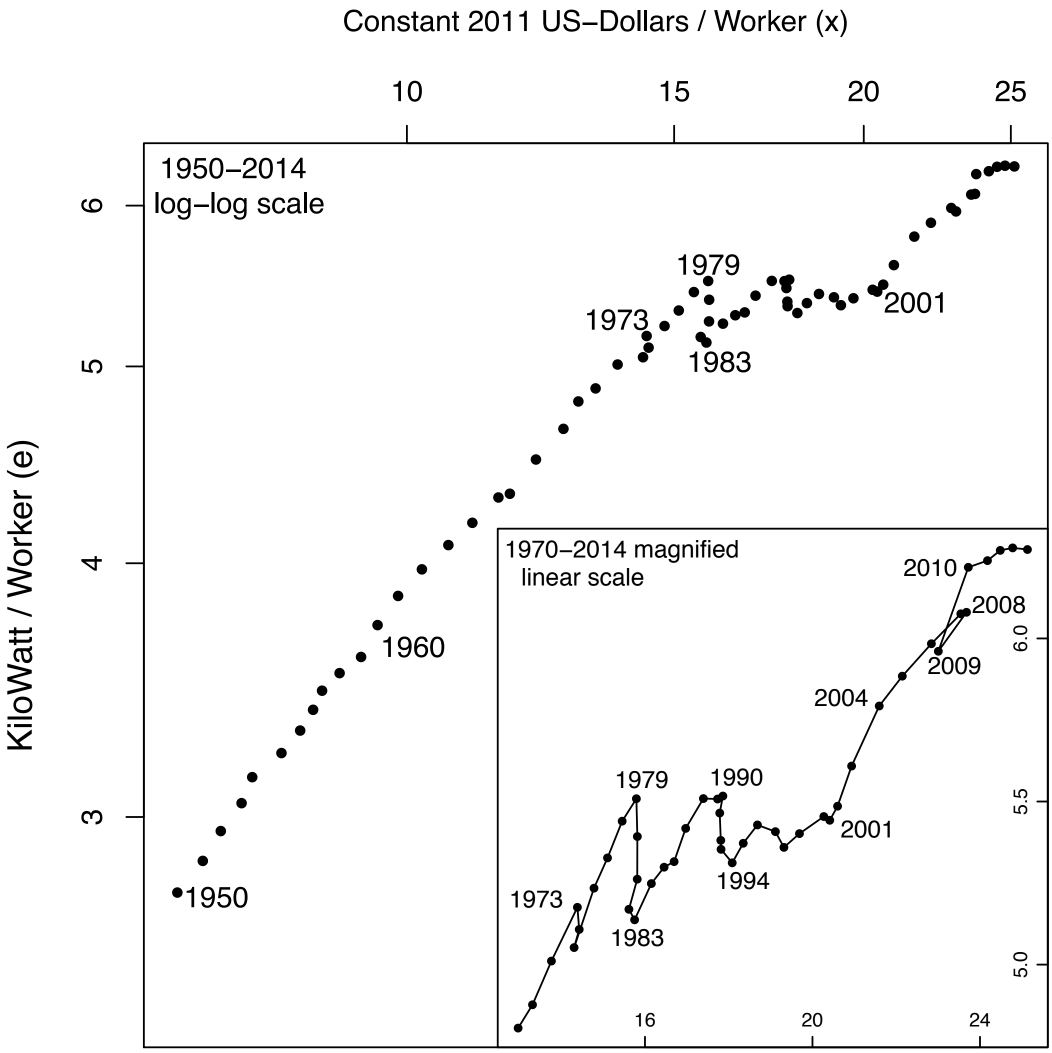



Figure 1: Scatter of annual levels of world average labor productivity and the energy-labor ratio, 1950-2012. The inset magnifies the period after 1970 and connects observations by line segments to clarify the non- monotone trajectory.

The second phase covers 1973 until the millennium, where productivity growth is more sluggish and periods of energy deepening are interspersed with two periods of labor deepening, as the inset of figure 1 highlights. It is characterized by two big shocks: the OPEC oil crises and the transition of socialist economies. Both are crucial to understanding this period. In 1973, five years after oil overtook coal as the most important energy source, the Organization of Petroleum Exporting Countries (OPEC) imposed an oil export embargo against the USA and later European countries, that supported Israel in the 1973 Arab-Israeli War. OPEC production curbs reduced world crude production temporarily by 7.5 percent (Hamilton, 2011), and the quadrupled price of oil is recognized to have contributed to a productivity growth slowdown in rich countries (Fischer, 1988; Hamilton, 1983; Jorgenson, 1988). The combined effect of the 1978 Iranian Revolution and the Iran-Iraq War, that began in 1980, again shrank oil production drastically. In 1981 OPEC output stood one quarter below its pre-revolution 1978 level; world oil production only surpassed its 1979 level again in 1993 (consumption already 1989 thanks to stock depletions); total primary energy production only surpassed the 1979 level in 1984 and demand in 1983, with gas and nuclear picking up part of the demand (calculated from IEA 2016). The slow growth in demand is due substitution away from energy (Hamilton, 2011), which shows up in figure 1 as the first bout of labor deepening technical change. On the productivity side, the early 1980s marked the most protracted global recession since the 1930s (UN DESA, 1984), and while causality is difficult and not the focus of this paper, high oil prices have been argued to have contributed to the developing countries' debt crises Sachs, 1985.

The second shock was the collapse of the Soviet Union and the economic reforms in the socialist countries in Eastern Europe and China. In the Soviet Union, output stagnated in the 1980s, then collapsed dramatically in its successor states during the transition in the 1990s. Energy demand dropped dramatically, although energy intensities did not necessarily improve until after 2000 due to equally collapsing output (Cornillie and Fankhauser, 2004). Due to the high levels of energy intensity of the Eastern European and Central Asian countries, however, the fall in energy had a larger impact on the world series than the growth side; the collapse coincides with the second labor deepening episode. In contrast, China's reform approach led to rapid economic growth alongside a dramatic reduction in energy intensity. The rest of the world grew more strongly in the 1990s than 1980s, until the 1997 Asian crisis, which shows up as a minor third labor deepening episode. Moreover, commentators adduce a lasting impact on technical change of energy efficiency improvements from the high prices in the 1970s/80s through a ratchet effect (Gately and Huntington, 2002). Clearly, the period 1973-2000 saw a very different energy-growth relationship than the golden age.

The third phase covers the years from the millennium. Apart from the 2001 dotcom crash, the period up to 2007 saw renewed rapid output and energy growth with the emergence of the BRICS countries. The Great Recession 2008-09, leads to the largest symmetric reduction in both indicators in the sample, although both bounce back in the next year. Indeed, this crisis is not typically linked to shocks to energy prices and/or scarcity, in spite of high oil prices in 2008 (but see Aminu et al., 2018). Since the Great Recession in 2008-09, productivity growth has been more sluggish and little energy deepening took place. In spite of the last few observations that are too few to constitute a trend, the pattern since 2000 looks more similar to that in the golden age' than the almost three shock decades in between.

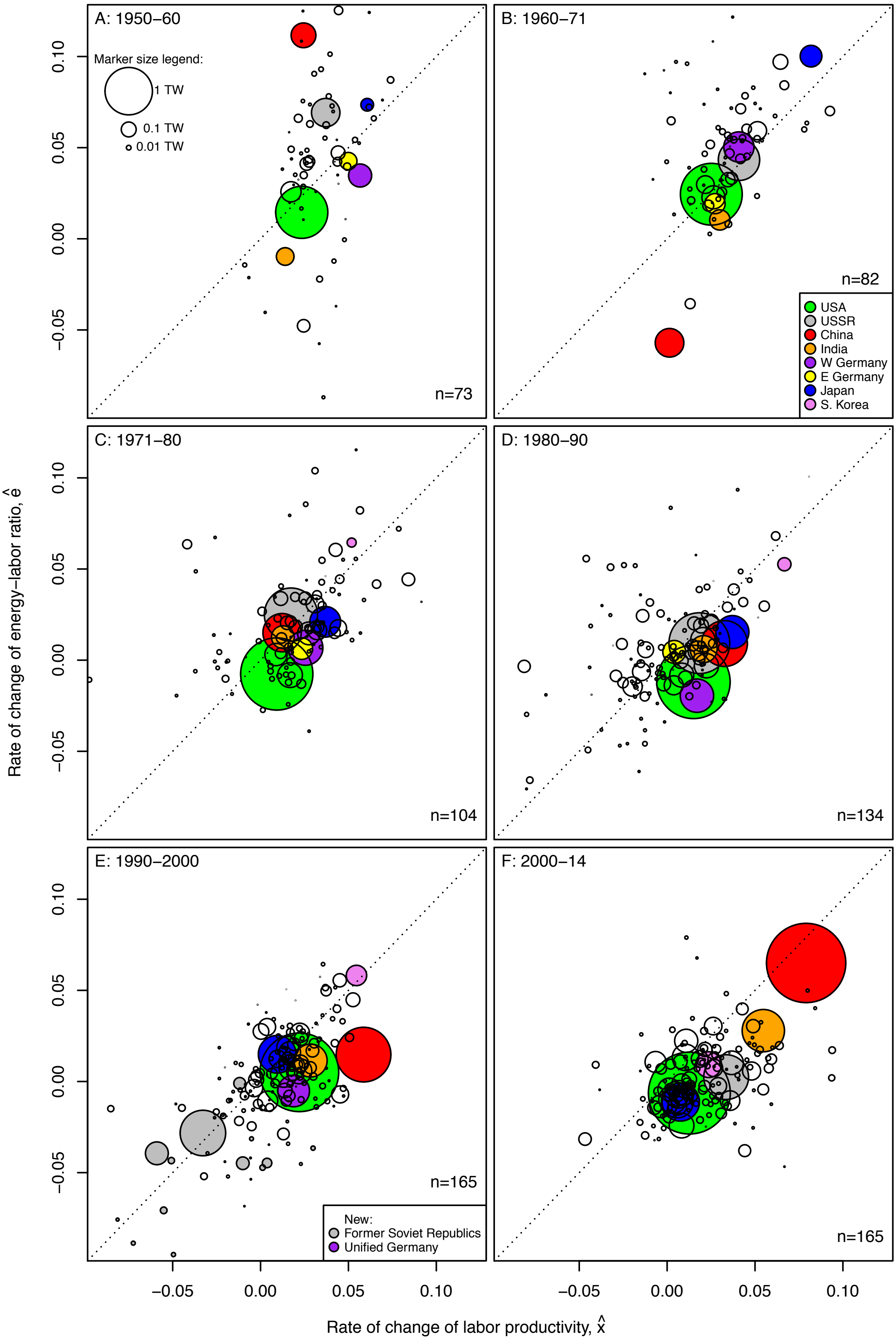
This first look at the data shows that the two big shocks in the second phase introduce variation over time into the series, and at least the second of the two is certainly unique. It is also important to note that studies of energy and growth with data from the IEA for 1971 to the early 2000s, or the US Energy Information Agency, starting only in 1980, will see their time series dominated by these two shocks. Our subsequent analysis will heed these differences in time by considering decadal average growth rates, that strike a balance between averaging out business cycle fluctuation, and tapering over the important structural changes between the three phases.

A last point to take away is that the relationship between growth rates does not follow straightforwardly from a consideration of levels, as it depends on the length as well as the direction of the edges connecting observational nodes. In the following, we study the relationship between the growth rates of the indicators directly.

### 4.2 Cross sections

We divide the country data into six roughly decadal periods and examine them for the green growth hypothesis in cross sections. Figure 2 shows a very strong organization of the data into a south-west north-east oriented cloud in all six periods. The relationship also approximates a linear one, with most of the observations near the 45 degree line, and thus suggesting an elasticity near one. This is true in particular of countries with large energy demand, marked by larger circles. Any rate of change of labor productivity supports a range of energy-labor ratio changes, that may be explained primarily by differences in size, climate, habits, level of income, production structure, energy mix and self-sufficiency (Smil, 2003, p. 75). However, there is an obvious tendency for faster labor productivity growth rates to accelerate the energy labor ratio rate of change roughly equally. Clearly, this speaks against green growth. For the data to confirm the green growth hypothesis, the cloud should be rotated more horizontally.

Figure 2: Cross-sectional growth rate scatters. Marker area corresponds to total energy demand. The 45 degree line is dashed.



Looking more closely, most observations are near the origin, but countries achieving fast productivity growth cluster in the top right corner of each plot. Japan, the two Germanys and the Soviet Union are examples of in the 1950s and 1960s. Other points during those periods in the top right are several Southern and Eastern European economies of the first wave of successful post-war economic development. South Korea exemplifies the "Asian Tigers" and their successful growth in the 1970s and 1980s. In the bottom two plots, China stands out for its extraordinary productivity growth in the 1990s and after 2000. For stagnating countries (zero or negative labor productivity growth) the constraint on the corresponding labor-energy ratio growth rate seems less binding, as some countries in recession also experience fast energy deepening.[11] Nevertheless most country observations are organized along a cloud with a slope near one. This betrays a strong tendency towards unit elasticity, not green growth.

Where exceptions appear, they tend to be countries in the early stages of switching from biomass to fossil fuels, e.g. in the 1950s, and those that stagnate or decline in any period. The 1980s show little variation horizontally except for some small countries in deep depression and with growing energy intensities (many of which Middle Eastern oil exporters), which coincides with the aftermath of two oil crises – the first shock identified in the previous subsection. The 1990s reflect the second shock of the disappearance of socialist governments, where Eastern European, former Soviet transition economies and China pivot the cloud clockwise.[12] However, this anomaly is not sustained in the subsequent period. Nothing in this visual inspection of the data suggests that faster growing countries are particularly effective at lowering their energy intensity. In the next step we consider what elasticities are determined by econometric estimates.

For the weighted linear regression, the posterior density both for slope and intercept

[11] The Chinese energy demand figures for 1956-60 during the Great Leap Forward are deemed too high by several commentators (Cheng, 1984, p. 8), and consequently the drop from 1960 to 1970 too deep. We use UN data based on the Chinese figures here, but exclude China from the linear regression results Figure 3 in these two decades.

[12] Naughton (2007, p. 335) claims significant underreporting of coal demand in China in 1996-2000, and overreporting in 2000-2004, which, if true, implies that the Chinese observations in plots E and F should be a convex combination and thus more similar to each other. This would make the 1990s position less of an outlier.

Figure 3: Posterior distributions of of decadal weighted linear estimates and ten year rolling window estimate of highest posterior density estimates with 1.96 standard deviation whiskers (insets) for slope (top: $\beta_2$) and intercept (bottom: $\beta_1$) parameters. Rolling $R^2$ dashed in top inset.

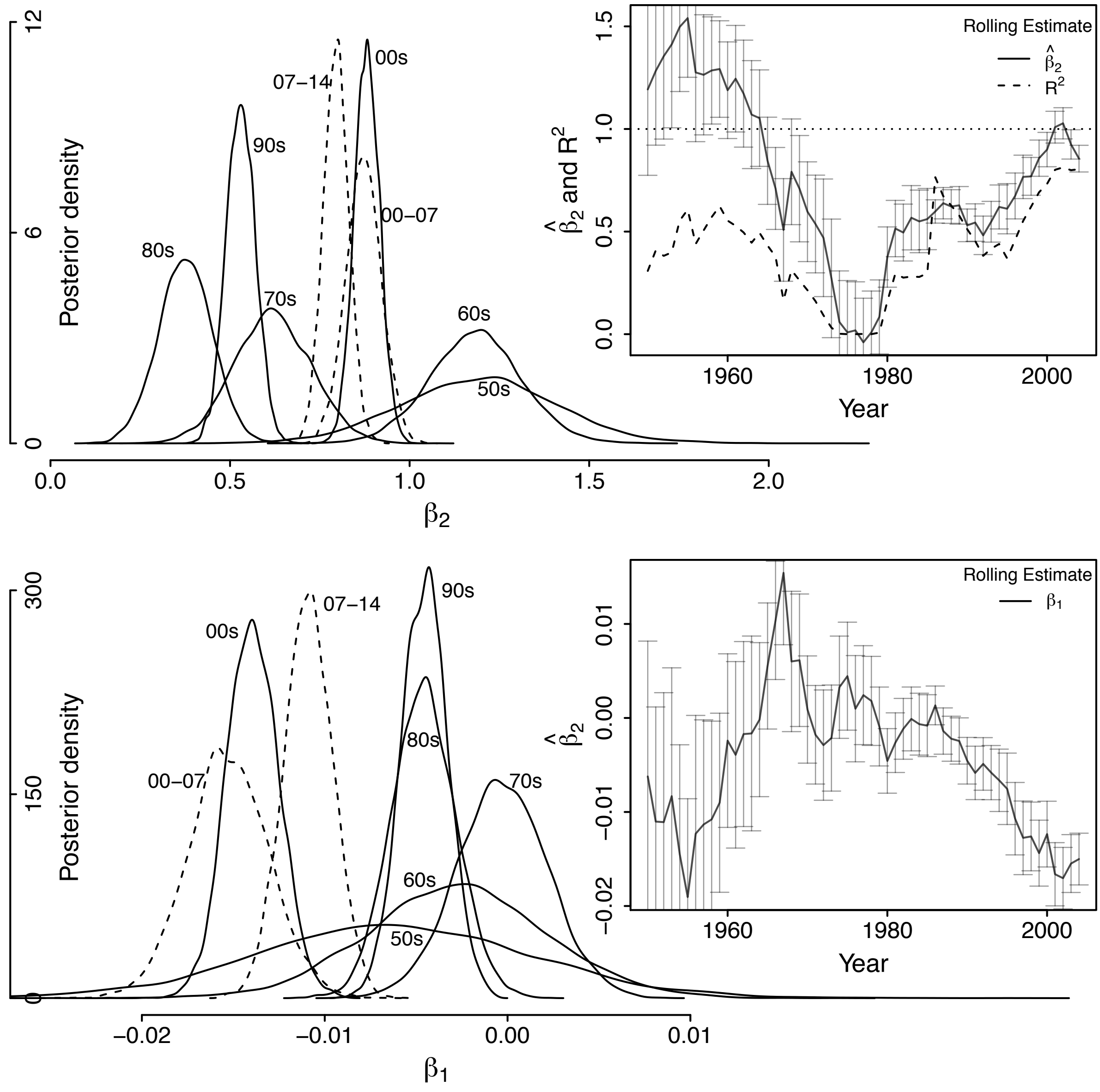



Table II: Highest posterior density estimates in each period of the slope parameter $\beta_2$ for various models. Subscripts indicate the number of observations in the estimate.

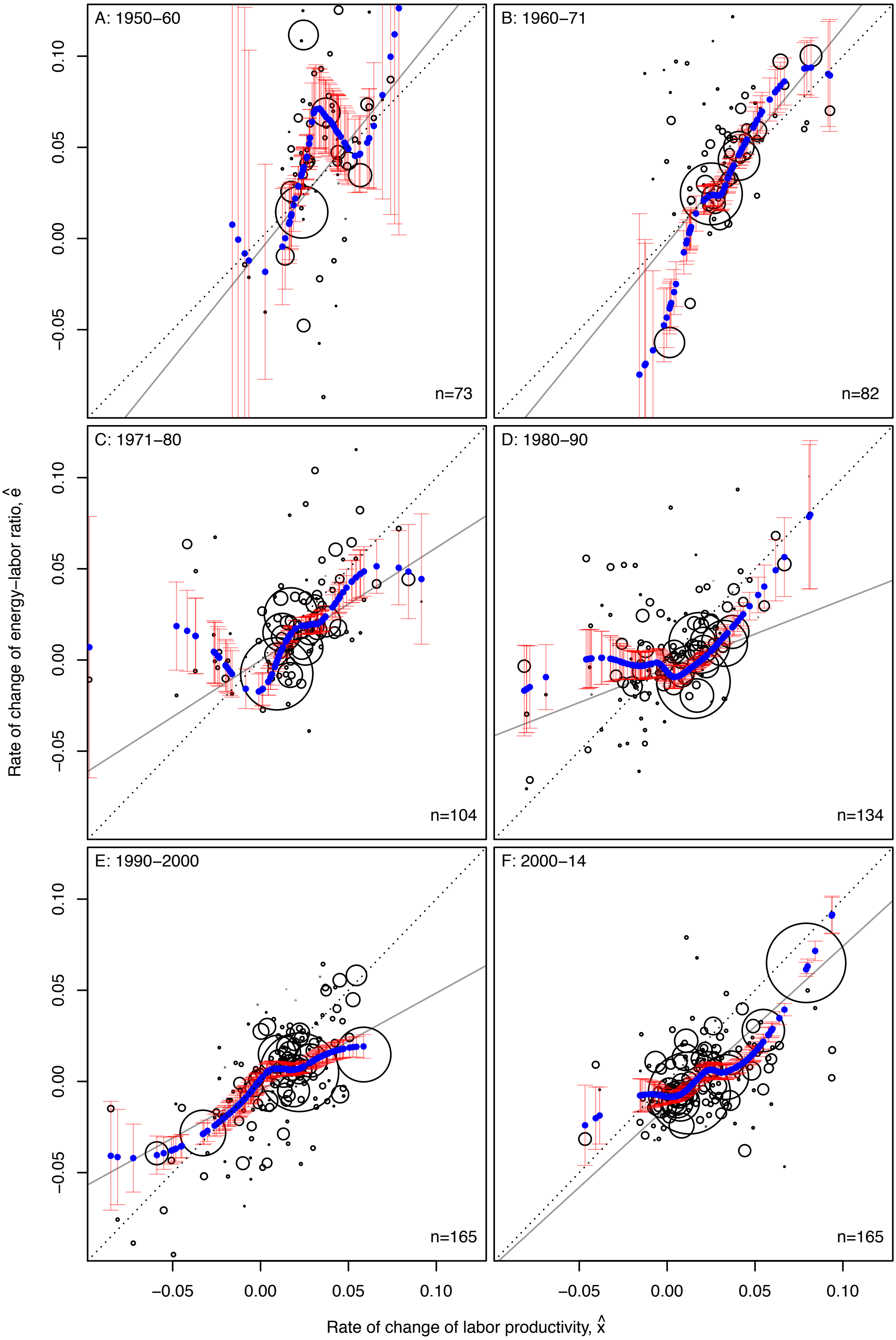
| Regression | 50s | 60s | 70s | 80s | 90s | 00s | 2000-07 | 2007-14 |
|---|---|---|---|---|---|---|---|---|
| $\hat{e}$ on $\hat{x}$ | $1.19_{73}$ | $1.18_{81}$ | $0.62_{104}$ | $0.37_{134}$ | $0.53_{165}$ | $0.88_{165}$ | $0.87_{166}$ | $0.80_{165}$ |
| $\hat{y}$ on $\hat{f}$ | $1.09_{84}$ | $1.16_{100}$ | $0.56_{145}$ | $0.35_{146}$ | $0.62_{176}$ | $0.90_{176}$ | $0.87_{176}$ | $0.75_{180}$ |
| $\hat{q}$ on $\hat{x}$ | — | — | $0.70_{96}$ | $0.48_{104}$ | $0.76_{130}$ | $0.82_{134}$ | $1.07_{134}$ | $0.73_{135}$ |

is graphed in Figure 3. Starting with the slope (top plot), the posterior density of the elasticity is mainly above one for the 1950s and 60s, somewhat below for the 70s, low for the 80s and 90s, and again near unity for the 2000s. The 2000s are further subdivided into two seven year periods (pre and post Great Recession), which are similar to the whole period. These results update the previous findings with weights, more detailed periods and a larger sample. The global elasticity is higher than previous, international estimates (0.4-0.7) for half the sample, and the low elasticity corresponds mainly to the shocked decades of the 1980s and 1990s. This is also the first result that reports estimates for the 1950s and 1960s separately and finds much higher slopes than Hannesson does for his 50 year cross section.

A rolling window regression of the highest posterior density estimate (equal to maximum likelihood due to uninformative priors) confirms these estimates for every possible ten year interval, as shown in the upper inset: the elasticity moves like a wave, from more diffuse to a sharply peaked near unit elasticity estimates. A parallel wave is described by the corresponding $R^2$ coefficient, which shows that the high elasticity estimates are a good fit, while the low elasticity estimates explain the data only very poorly. These results (including the $R^2$, not shown) carry over to estimates using population instead of employment or removing non-residential energy, as reported in Table . On the whole, the data show strong support for a near unit elasticity in those periods where the linear model has explanatory power, with a striking similarity between the first golden age period and the most recent period. The golden age and the 2000s are also similar in their lower intercept estimate (Figure 3 bottom) suggesting that in those periods with a high elasticity, stagnating countries also displayed labor deepening.

Additional insight particularly into the periods with a low fit comes from the non-linear loess approach. The loess fit is superimposed on the data in Figure 4, and we also draw the higest posterior density estimates of the weighted linear model. We can clearly see that in all data plots, the majority of the locally weighted conditional mean estimates lies on a straight line with a slope close to one. In particular, in plots C,

Figure 4: Growth rate scatters. Loess fit with 0.7 span represented by dots with 1.96 standard deviation whiskers. Weighted linear maximum likelihood fit represented by solid lines.



D and E, the periods with a lower slop in the linear fit, we can see that most of the data actually abides by a unit elasticity, but outliers or a lack of horizontal variation confound the linear fit (hence the low $R^2$). In C and D, the linear fit is confounded by little variation plus outliers, while in the 1990s Russia on one end, and China on the other, pivot the linear fit. The loess plot emphazises that but for the outliers, most data in these shocked periods is as in the others. The loess strengthens the evidence that for most of the sample, the elasticity is close to one, while lower slopes are induced by outliers. This evidence clearly goes against the green growth hypothesis, and in favor to updating it to a unit elasticity in cross sections.

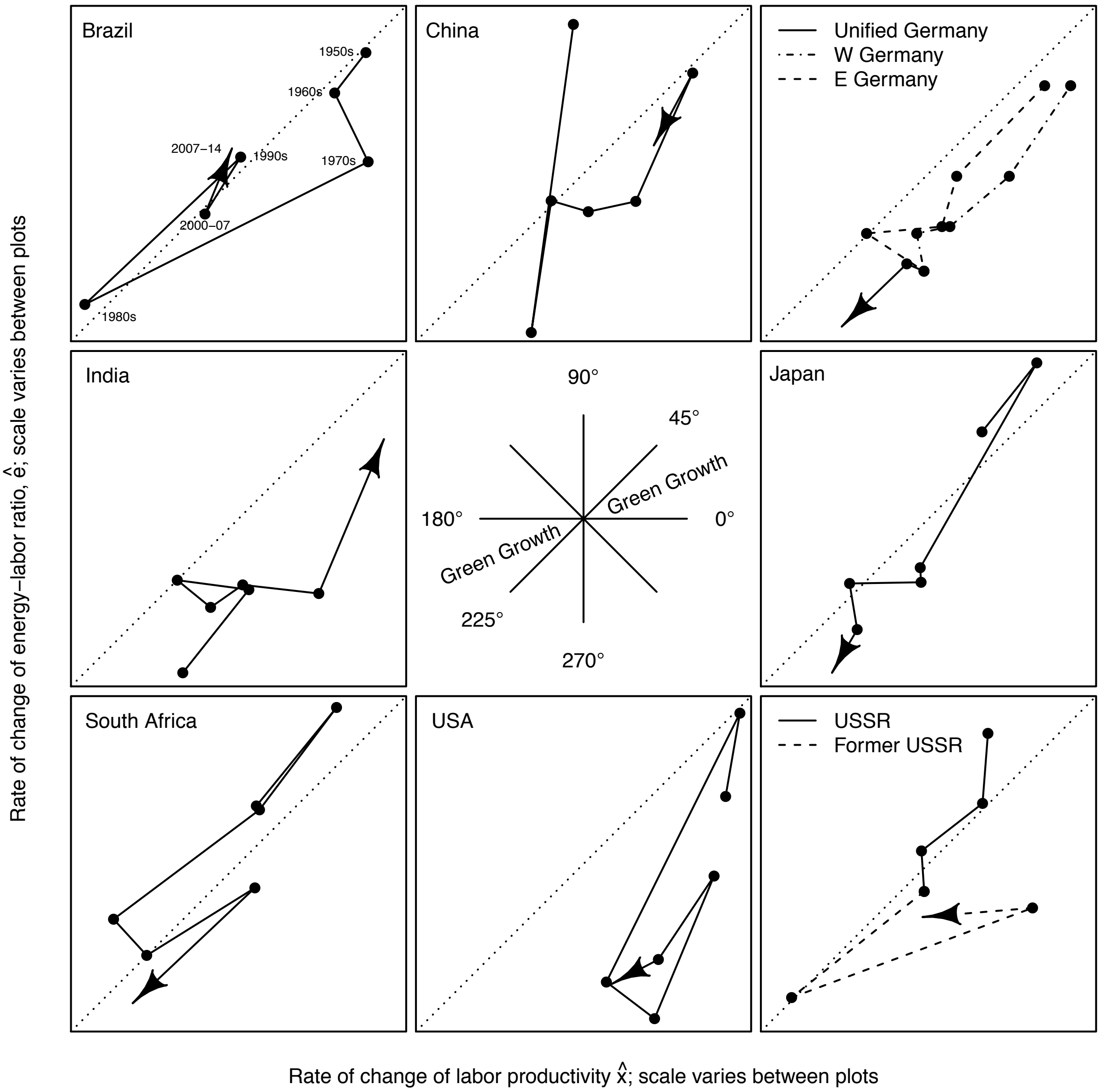
## 4.3 Time series

To examine whether countries have achieved green growth in their own growth path, we start with a visual inspection of large economies. The 7 biggest economies in terms of energy use in 2014 and all BRICS countries are plotted in figure 5. It is immediately clear that these countries's trajectories correspond to an own elasticity of around unity. Indeed, for several countries lower growth rate nodes have a faster falling energy intensity. For instance, the plots for the USA and the USSR prior to 1990 are pivoted anti-clockwise against the 45 degree line, and these countries together accounted for nearly half the global energy consumption at the time. using the angular vocabulary, their edges' directions are outside the green growth intervals, depicted in the middle panel of figure 5. The one time exception in direction from the 1970s to 1980s when oil shortages bit, and for the former USSR when it rebounded from depression following its dissolution cannot obscure the fact that the overall pattern follows a near unit elasticity both for productivity acceleration and deceleration. The result also in the other countries shows the need to revise the green growth hypothesis for time series.[13]

These patterns carry over to the other countries in the sample. Figure 6 left plot

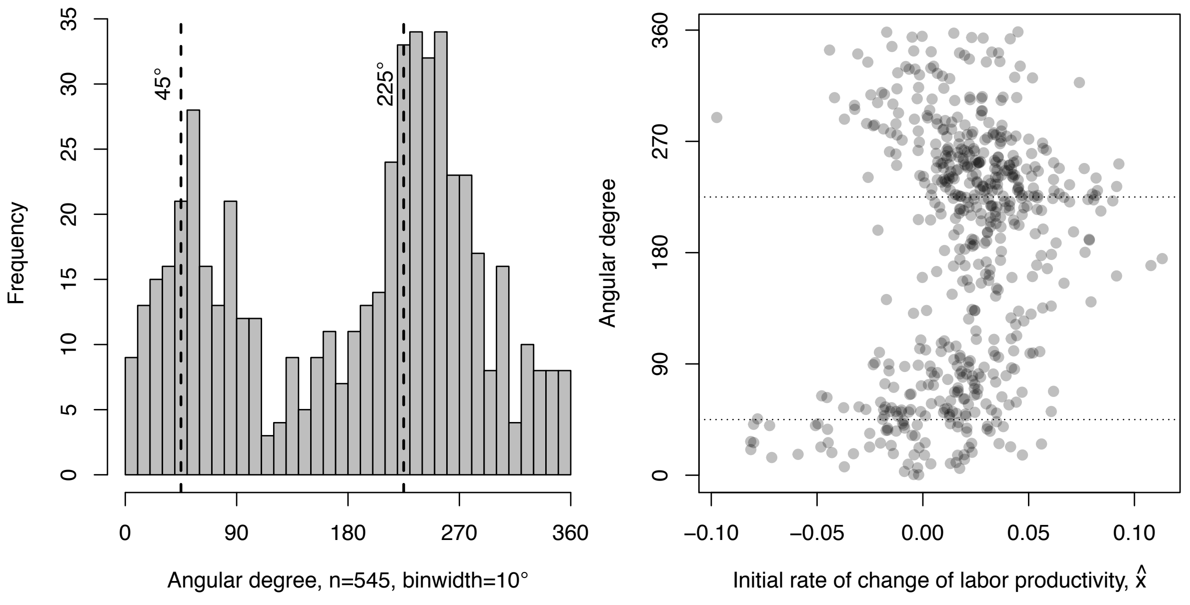
[13]The least regular pattern is displayed by India. India's relatively agricultural and services oriented economy (Amirapu and Subramanian, 2015), demands further research into the relationship between service energy use and economic growth.

Figure 5: Time series country growth rates in 7 periods (2000-2014 subdivided in two equilong periods). Each node represents a period's growth rates; the six edges connect subsequent periods and show the direction of change. Plots are scaled to countries' growth rates; the 45 degree line is dotted



shows the unweighted frequency distribution of angles of the entire sample's 545 edges. Most countries move in the intervals $[45°, 90°]$ and $[225°, 270°]$, implying slower growth is greener most of the time. The presence of every direction in the sample indicates that there are heterogeneous factors across time and countries which impact the growth-energy trajectory. However two modes are near the unit elasticity. The right plot of figure 6 makes the marginal distribution of angles conditional on an edge's origin in the labor productivity growth dimension. This shows from what level of productivity growth any edge departed. Most of the countries with near and above unit elastic trajectory start from a position of healthy productivity growth. Countries moving at an angle of less than 45° on the contrary tend to start from initial position of stagnation or depression, such as the countries of the former Soviet Union, Brazil, or (not shown) a number of other Latin American countries in the 1980s, as well as Arab oil exporting countries. A similar observation holds for very high angular degrees, which occur also predominantly in stagnating economies, such as South Africa in the 1980s in Figure 5. This confirms the observation in the cross sections, that in stagnating countries, there are fewer constraints on energy deepening, while a tight constraint binds for fast economic growth, which these trajectories show is incompatible with green growth.

Figure 6: Frequency distribution of the angle of edges indicating the direction of countries' change in growth rates (left); and joint distribution of initial rate of productivity growth and the angle to the next position (right), both plot for full sample.

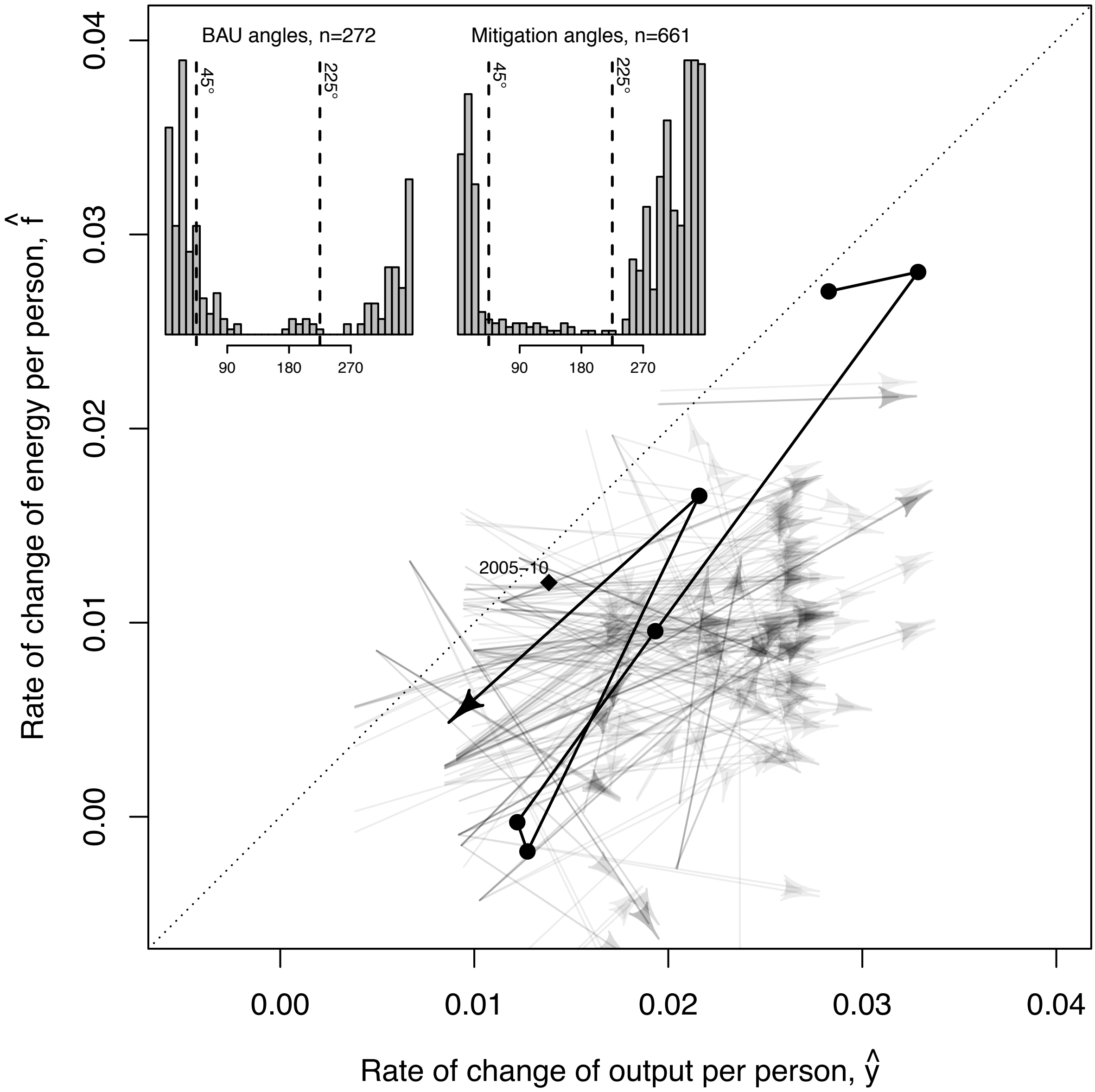


We can take this analysis one step further and consider the whole world's trajectory, which also permits a comparison with global projections. For comparability, we use population instead of labor, and we recalculate the IEA's world energy balance using the IPCC's direct equivalent energy accounting method (Krey et al., 2014, p. 1294). Focus first on the world historical trajectory. Figure 6 shows that the world's trajectory operates on an elasticity around one. Faster growth has no impact on energy intensity improvements. The only possible conclusion from this and the foregoing country analysis is that the idea of faster economic growth hanging together with more efficient energy usage in the aggregate, which underpins the green growth hypothesis, is not confirmed by any historical data. Projections based on extrapolations of past trends should reflect this.

The rest of the plot concerns such projections. The arrows are the edges connecting the first two nodes of all reference scenarios of the 5th Assessment Report's (Clarke et al., 2014) scenario database. The first node corresponds to historical growth rates between 2005-2010 with the caveat that the data is from shortly after 2010, and is likely to have been revised since. The second node at the arrow's point depicts the projected growth rates for 2010-2020. The elasticities are low in comparison with historical ones. Most reference scenarios achieve fast productivity growth like in the golden age, but combined with a very slow rate of energy deepening, unseen in history and implying rapid decline in the energy intensity. 88% of BAU scenarios, 239 out of 272, project a trajectory with an angle below 45° or above 90°. As the top left inset of Figure 7 shows, 30% of reference scenarios even assume a particularly optimistic "super green growth" direction in the interval $[270°, 360°]$, whereby the growth trajectory moves to the bottom right of the plot. As mitigation of climate change measures kick in, that are expected to deviate more from past trends, the share projecting super green growth rises to 64% (top right inset histogram).[14] Near term reference projections depart significantly from

[14]From the 1148 scenarios, BAU scenarios were selected by taking those scenario names containing the strings 'bau', 'ref', 'bas' (as in reference or baseline), and discarding strings that also contain '450' or '500' indicating mitigation policies. The 'mitigation' scenarios were selected as the complement of the BAU scenarios. The total number of scenarios used is less than 1148 because some do not supply the necessary three data points in all three periods.

Figure 7: World growth rate trajectory, 1950s through 2007-2014. The diamond is the 2005-10 position, that corresponds to the origins of the transparent arrows showing the trajectories of growth rates in business as usual (BAU) scenarios integrated assessment models from 2005-10 to 2010-2020. Insets show the frequency distribution of angles in BAU (left) and mitigation (right) scenarios over the same period.



the just documented historical trend, and near term mitigation measures place a heavy emphasis on even deeper energy intensity reductions, breaking completely with past trends. The directions become more aligned with the historical record in subsequent periods (although at unprecedentedly fast rates of energy intensity reductions), but as developments in the near future are particularly crucial for meeting mitigation targets, the models' ability to reflect likely trajectories here is crucial.

# 5 Discussion

The results from this analysis show that green growth assumptions in models of the global economy, have no empirical basis in the past growth record. Apparently, past growth spurts were not predicated on an uptick in the introduction of more productive and energy efficient machines. Or if they were, then the energy cost of replacing machines, or a strengthened rebound effect, prevented the translation from per unit energy efficiency into aggregate energy intensity. Whatever the underlying reasons for this result, which were not the object of the present investigation, we have a stylized fact that the productivity elasticity of the energy labor ratio is around one.

The result is a negative one in the sense that there is no technological win-win solution to reconciling economic growth and climate change, as the unitary elasticity undermines hopes of energy intensity reductions simply through faster technological progress. It also concerns projections of growth and energy and by extension green house gas emissions, as near term future growth is likely to require a similar combination of labor and energy inputs as that of the past. While there may be hopes for structural changes that upend the historical correlations in the long-run, these take time to materialize. Due to the importance of cumulative emissions limits, the short term is also precisely the time span that matters for implementing climate change mitigation measures (Figueres et al., 2017). Our juxtaposition of the world's trajectory with IAM projections suggests that the latter assume green growth in the near term future, and greater scrutiny of these near term results may be a useful exercise to fix realistic expectations particularly about business as usual scenarios. To the extent that the energy intensity channel is less suited for reducing green house gas emissions, a bigger onus falls on other channels of mitigation.

One radical alternative is to focus not solely on energy demand, but also on economic growth. A surprising result in the data showed that it was often slow growth, which allowed faster reductions in energy deepening. Slower growth would then both accelerate the decline in energy intensity and reduce the rate at which the total grows, making a reduction of total energy demand more likely. Such a strategy, with most of projected growth now in low income countries, would require significant (additional) redistribution to ensure everyone has a claim to an income sufficiently high to participate in global output's consumption (Foley, 2012). However, while this seems a topical issue in a world of high inequalities, international transfers are an intractable political economy problem. One has to look no farther than the non-ratification by the US of the Kyoto protocol, where estimates of costs of international transfers (W. Nordhaus and Boyer, 1999) as well as fear of adverse consequences for domestic industry contributed to its rejection by Congress (Byrd and Hagel, 1997). The Paris treaty, significantly, binds parties to their self-announced measures only. Even if transfers were possible, it is unclear how growth would be "slowed" in an orderly fashion and without creating an economic crisis. Engineering *global* low growth seems even less likely than green growth.

The other major channel concerns changing the energy mix. If energy demand cannot be reduced, it needs to be decarbonized faster. One encouraging fact is that actual developments of renewable energy supply have been consistently growing faster than in projections (Metayer et al., 2015). There is a portfolio of policy measures that, if implemented, could accelerate deployment further (Aldy et al., 2010; Broome and Foley, 2016; Mazzucato and Semieniuk, 2017). But this route is not devoid of political economy problems either, as lost revenues from stranded fossil assets also raise knotty questions about redistribution, with costs estimates in the tens of trillions of US dollars (IRENA, 2017). Nor are problems of energy storage (Larcher and Tarascon, 2014) or material availability (Ali et al., 2017) solved. Nevertheless, the present results suggest that a focus on faster low-carbon energy supply is even more important for mitigating climate change than current scenarios, with in-built green growth, project.

# 6 Conclusion

This paper has answered the question whether faster growth is greener. More specifically, it has investigated whether an additional percentage point labor productivity growth is accompanied by significantly less than an additional percentage point increase in the energy-labor ratio, or an elasticity below one, as predicted by the green growth hypothesis. An analysis of a data sample of 180 countries over the period 1950-2014 as well as for the world as a whole helped update the theoretical prior about green growth: it is not supported by the data. Instead the paper finds a stylized fact of a unit unit elasticity. This raises difficult questions for near-term climate change mitigation because the historical data imply that the energy demand reduction channel may prove less capable of emission reductions than many scenarios assume.

The result has consequences for energy and growth modeling. First, we must stress that the stylized fact 1.c in Csereklyei et al. (2016, p. 249) that "[t]he growth rate of energy intensity is negatively correlated with the growth rate of income" should be rephrased to: the growth rate of energy intensity is uncorrelated with the growth rate of income per capita. This rephrasing does not affect the validity of the authors' other stylized facts about level relationships. Second, the new information should be incorporated into projections of near term economic growth and green house gas emissions, especially in integrated assessment models.

For further research, it would be useful to explore the effect of a unit elasticity also in analytical models, and ways of reducing it.[15] To do so, the models need to be informed by empirical analysis of the relationship's drivers. One obvious step is to examine how

[15] Two models that already incorporate non-green growth are Rezai et al. (2018) and Dafermos et al. (2017), the latter restricted to its "conventional capital".

capital, a complement of energy inputs (Csereklyei et al., 2016), and energy prices, negatively correlated with growth in energy use (Hannesson, 2009), play into the relationship. Another is to revisit micro-level studies and explicitly analyze drivers of the interplay between accelerations in growth and energy demand. Overall, the results here point to a gap in our understanding of correlations in growth rates, which have been neglected in favor of levels in the research on energy and economic activity.

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