Measuring Energy-saving Technological Change: International Trends and Differences*

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Abstract

Technological change is essential to balance economic growth and environmental sustainability. This study documents energy-saving technological change to understand the trends and differences therein in OECD countries. We estimate sector-level production functions with factor-augmenting technologies using cross-country and cross-industry panel data and shift–share instruments, thereby measuring energy-saving technological change for each country and sector. Our results show how the levels and growth rates of energy-saving technology vary across countries, sectors, and time. In addition, we evaluate the extent to which factor-augmenting technologies contribute to economic growth and how this contribution differs across countries and sectors.

KEYWORDS: Non-neutral technological change; capital–labor–energy substitution; growth accounting; sectoral productivity.
JEL CLASSIFICATION: E23, O33, O44, O50, Q43, Q55.

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1 Introduction

One of the greatest challenges facing society is the achievement of economic development and environmental conservation. Technological change has been in the past, and will be in the future, the most promising way to balance economic growth and environmental sustainability. Society has been developing and adopting new technology to make more efficient use of energy and natural resources in the face of serious environmental problems, including climate change, environmental pollution, and resource depletion. Given the global nature of environmental problems, the development and adoption of new technology need to expand worldwide. However, it has been difficult to assess how energy-saving technology has evolved across countries over time due to the lack of adequate measurements. The aim of this study is to measure and document the level and growth rate of energy-saving technological change for each country and sector, thereby developing an understanding of international trends and differences in energy-saving technological change.

Measuring energy-saving technological change is challenging. Environmentally friendly technological change is typically measured in the literature using data on research and development (R&D) spending and patent counts (Popp, 2019). These measures, however, have some drawbacks. R&D spending is a measure of input into the innovation process rather than its outcomes. Patent counts are a measure of product innovation, but not of process innovation. In this study, we measure energy-saving technology in terms of output and factor inputs along the lines of the Solow (1957) residual, also known as total factor productivity (TFP). Similar to TFP, but different from R&D spending and patent counts, our measure captures the actual circumstances of national income and technology adopted in the economy, including not only patented product technology but also unpatented product and process technology. At the same time, our measure differs from TFP in that it allows technological change to be factor-augmenting.

We measure factor-augmenting technological change using sector-level production functions and firm’s optimality conditions. Our method builds upon the seminal work of Caselli and Coleman (2002, 2006). The advantage of this method is that it allows us to quantify the level and growth rate of energy-saving technology for a given value of the elasticity of substitution in production without assuming the functional forms of technological change. Our analysis extends that of Caselli and Coleman (2002, 2006) by using the gross-output production function at the sector level, allowing for imperfect competition, and estimating the elasticity of substitution between energy and non-energy inputs. Our study is the first to measure and compare the levels and growth rates of energy-saving technology across countries and sectors.

Although numerous studies have estimated the elasticity of substitution between energy and non-energy inputs, this study differs from those studies in that we take into account the cross-sectional and time variation in the unobserved components of factor-augmenting technologies. To do so, we use cross-country and cross-industry panel data from 12 OECD countries and construct shift–share instruments. Our results indicate that the elasticities of substitution among capital, labor, and energy inputs are significantly less than one.
We utilize our measure of energy-saving technology in two ways. First, we examine the nature of energy-saving technological change and its differences across countries. Our results show that the levels and growth rates of energy-saving technology vary substantially across countries over time for the year 1978 to 2005 both in the goods and service sectors. Cross-country differences in energy-saving technology are greater than those in capital- and labor-augmenting technologies. Moreover, in line with theoretical predictions, energy-saving technology tends to progress in countries or years in which energy resources are scarce. Technological change tends to be directed toward energy as government spending on energy-related R&D increases. Second, we evaluate the quantitative contribution of energy-saving technology to economic growth. Our results demonstrate that energy-saving technological change contributes to economic growth in the goods or service sectors of many countries.

The remainder of this paper is organized as follows. The next section reviews the literature. Section 3 introduces the method for measuring energy-saving technological change using sector-level production functions. Section 4 considers the identification and estimation of substitution parameters in the production functions. Section 5 describes the data used in the analysis. Section 6 presents the empirical results. Section 7 discusses the interpretation and implications of the results when the model is extended. The final section summarizes and concludes the paper.

2 Related Literature

This study is related to three strands of the literature. First, it contributes to the literature that measures factor-augmenting (non-neutral) technological change. The direction and magnitude of factor-augmenting technological change can be measured by estimating either a production or a cost function. Brown and Cani (1963) and David and van de Klundert (1965) develop an approach that uses a constant elasticity of substitution (CES) production function (see León-Ledesma, McAdam and Willman, 2010 for a list of related studies). van der Werf (2008) adopts this type of approach to measure energy-saving technological change in 12 OECD countries from the year 1978 to 1996. Binswanger (1974) develops an alternative approach that uses the factor-share equations derived from a translog cost function (see Jorgenson, 1986 for a survey). Sanstad, Roy and Sathaye (2006) adopt this type of approach to measure energy-saving technological change in India from the year 1973 to 1994, the Republic of Korea from the year 1980 to 1997, and the United States from the year 1958 to 1996. The advantages of the former approach are that it does not require the estimation of many parameters (or dealing with many endogenous regressors) and can estimate the key parameters in computable general equilibrium models to analyze climate and energy policies. However, both approaches have a common limitation in that factor-augmenting technologies is treated as a parametric and deterministic component in the production or cost function. Most studies assume that factor-augmenting technologies grow at a constant rate.

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1 Klump, McAdam and Willman (2007) measure capital- and labor-augmenting technologies in the United States from the year 1953 to 1998. Herrendorf, Herrington and Valenti (2015) measure capital- and labor-augmenting technologies in the agriculture, manufacturing, and service sectors in the United States from the year 1947 to 2010.
Caselli and Coleman (2002, 2006) develop an approach that measures factor-augmenting technologies using the aggregate production function and the firm’s optimality conditions. They do so without specifying the functional forms of technological change for the given values of the substitution parameters in the production function. Caselli and Coleman (2006) measure non-neutral technologies that augment skilled and unskilled labor in 52 countries in the year 1988, while Caselli and Coleman (2002) measure non-neutral technologies that augment capital as well as skilled and unskilled labor in the United States from the year 1963 to 1992. Hassler, Krusell and Olovsson (2021) employ this type of approach in the first part of their analysis to document fossil energy-saving technological change in the United States from the year 1949 to 2018. However, as Caselli (2005) notes, the intrinsic pitfall of this type of approach is that the elasticities of substitution are not estimated in a way that takes into account the variation in unobserved factor-augmenting technologies across observations.

Second, this study contributes to the literature that estimates the elasticity of substitution between energy and non-energy inputs. The substitution parameter in the CES production function is a key parameter in the analysis of climate and energy policies using computable general equilibrium models (Jacoby, Reilly, McFarland and Paltsev, 2006). Among others, Prywes (1986), Chang (1994), Kemfert (1998), van der Werf (2008), and Henningsen, Henningsen and van der Werf (2019) estimate the elasticities of substitution among capital, labor, and energy inputs based on the CES production function, while Berndt and Wood (1975) and Griffin and Gregory (1976) estimate them based on the translog cost function (see Koetse, de Groot and Florax, 2008 for a survey). Although this literature provides various estimates of the elasticities of substitution between energy and non-energy inputs, it ignores the endogeneity problem associated with factor-augmenting technological change. Consequently, there may be a bias in previous estimates of the elasticities of substitution between energy and non-energy inputs. Recently, Raval (2019) estimates the elasticity of substitution between capital and labor in the manufacturing sector of the United States from the year 1987 to 2007. Raval (2019) addresses the endogeneity problem associated with factor-augmenting technological change using shift–share instruments. We also adopt this type of approach to consistently estimate the elasticities of substitution among capital, labor, and energy inputs.

Finally, this study contributes to the literature on sectoral growth accounting. Jorgenson, Gollop and Fraumeni (1987) develop a growth accounting framework to decompose the rate of growth in sectoral gross output into the contribution of capital, labor, and intermediate inputs and TFP in the United States for the year 1948 to 1979. O’Mahony and Timmer (2009) apply this framework to measure the contribution of capital, labor, and intermediate inputs and TFP to the gross output growth in business service industries in seven OECD countries for the year 1995 to 2005. Both studies demonstrate a significant contribution of intermediate inputs to economic growth. While these studies focus on the growth in gross output, many other studies focus on the growth in value-added output (see Caselli, 2005 and Herrendorf, 2019).

Some studies estimate the elasticities of substitution between energy inputs. Papageorgiou, Saam and Schulte (2017) estimate the elasticity of substitution between clean and dirty energy inputs in 28 industries of 19 OECD countries for the year 1995 to 2007.
Rogerson and Valentinyi, 2014 for surveys). As far as we are aware, none of the studies evaluate the quantitative contribution of factor-augmenting technologies to economic growth.

3 Model

We assume that gross output (\(y\)) is produced from capital (\(k\)), labor (\(\ell\)), and energy (\(e\)) in the goods and service sectors. We denote by \(r\), \(w\), and \(v\) the prices of capital, labor, and energy inputs, respectively, that are normalized by the output price. The representative firm in each sector chooses the quantities of inputs \((k, \ell, e)\) so as to maximize its profits:

\[
y - rk - w\ell - ve
\]

subject to production technology:

\[
y = f(k, \ell, e; a_k, a_\ell, a_e),
\]

where \(a_k\), \(a_\ell\), and \(a_e\) are capital-, labor-, and energy-augmenting technologies, respectively. We interchangeably use the terms “energy-augmenting technology” and “energy-saving technology” throughout the paper since a rise in \(a_e\) results in a fall in the cost of production as well as a rise in the output in the model presented here.

We start our analysis by considering the standard one-level CES production function. We then extend it to the two-level nested CES production function.

3.1 One-level CES

The standard one-level CES production function is in the form of:

\[
y = \left[ (a_k k)^\sigma + (a_\ell \ell)^\sigma + (a_e e)^\sigma \right]^{\frac{1}{\sigma}} \quad \text{for} \quad \sigma < 1.
\]

The parameter \(\sigma\) governs the degree of substitution among capital, labor, and energy inputs. The elasticity of substitution among capital, labor, and energy inputs is \(\varepsilon_{xy} \equiv 1/(1-\sigma) > 0\). If the elasticity of substitution is one, the CES production function reduces to the Cobb–Douglas production function, in which case the relative use of inputs is invariant to technological change. We assume a constant returns to scale technology but confirm the robustness of results to this assumption in the appendix.

We consider factor-augmenting technologies to be unobserved and stochastic components in the production function. In this case, it is difficult to estimate the parameter directly using equation (3) since the production function is not only non-linear in the parameters but also non-additive in the unobserved components.

Profit maximization entails equating the ratio of input prices to the marginal rate of technical substi-
tution:

\[
\frac{w}{r} = \left( \frac{a_\ell}{a_k} \right)^{\frac{\epsilon_\ell}{\epsilon_\ell - 1}} \left( \frac{\ell}{k} \right)^{\frac{1}{\epsilon_\ell}},
\]

(4)

\[
\frac{w}{v} = \left( \frac{a_\ell}{a_e} \right)^{\frac{\epsilon_\ell}{\epsilon_\ell - 1}} \left( \frac{\ell}{e} \right)^{\frac{1}{\epsilon_\ell}}.
\]

(5)

These equations hold irrespective of the degree of markup or the degree of returns to scale. Equations (4) and (5) imply that the relative use of inputs varies according to the relative factor-augmenting technologies. When the elasticity of substitution is less (greater) than one, the relative quantities of inputs decrease (increase) with a rise in the relative factor-augmenting technologies. The elasticity of substitution can be estimated using equations (4) and (5), as described in the next section. The ratios of factor-augmenting technologies can then be calculated as residuals, but their levels cannot be calculated using these two equations alone.

As noted by Caselli and Coleman (2002, 2006), the system of three equations (3)–(5) contains three unknowns \((a_k, a_\ell, \text{ and } a_e)\). Factor-augmenting technologies can be derived from these equations as:

\[
a_k = \left( \frac{r k}{r k + w \ell + v e} \right)^{\frac{\epsilon_\ell}{\epsilon_\ell - 1}} \left( \frac{y}{k} \right),
\]

(6)

\[
a_\ell = \left( \frac{w \ell}{r k + w \ell + v e} \right)^{\frac{\epsilon_\ell}{\epsilon_\ell - 1}} \left( \frac{y}{\ell} \right),
\]

(7)

\[
a_e = \left( \frac{v e}{r k + w \ell + v e} \right)^{\frac{\epsilon_\ell}{\epsilon_\ell - 1}} \left( \frac{y}{e} \right).
\]

(8)

Equations (6)–(8) imply that factor-augmenting technology is log proportional to the factor income share and output per factor input. Gross output is equal to the sum of factor incomes multiplied by markup \((\omega)\); that is, \(y = (r k + w \ell + v e) \omega\). Energy-saving technological change can be measured as:

\[
\Delta \ln a_e = \Delta \ln \left( \frac{y}{e} \right) + \frac{\epsilon_\ell}{\epsilon_\ell - 1} \Delta \ln \left( \frac{v e}{r k + w \ell + v e} \right),
\]

(9)

The first term is a change in output per energy input. The second term is inversely (directly) proportional to a change in the energy share of income when the elasticity of substitution is less (greater) than one. As is clear from the derivation, this approach does not require specifying the functional forms of factor-augmenting technologies.

### 3.2 Two-level CES

In the one-level CES production function, the elasticity of substitution between energy and non-energy inputs is assumed to be identical to the elasticity of substitution between non-energy inputs. This as-
A consumption can be relaxed by considering the following two-level nested CES production function:

\[
y = \left[ (a_kk)^{\varphi} + (a_{\ell}\ell)^{\varphi} \right]^{\frac{\varphi}{1-\varphi}} + (a_e e)^{\varphi} \quad \text{for} \quad \varphi, \varphi < 1.
\] (10)

The elasticity of substitution between capital and labor is \( \varepsilon_{\varphi} \equiv \frac{1}{1-\varphi} > 0 \), while the elasticity of substitution between energy and non-energy inputs is \( \varepsilon_{\zeta} \equiv \frac{1}{1-\zeta} > 0 \). When the two substitution parameters \( \varphi \) and \( \varphi \) are identical, the two-level CES production function (10) reduces to the one-level CES production function (3). This nesting structure is most commonly used in the literature and tends to fit the data best (van der Werf, 2008).

Profit maximization entails equating the ratio of input prices to the marginal rate of technical substitution:

\[
\frac{w}{r} = \left( \frac{a_k}{a_{\ell}} \right)^{\varphi} \left( \frac{\ell}{k} \right)^{\varphi-1}, \quad (11)
\]

\[
\frac{w}{v} = \left[ \left( \frac{a_k}{a_{\ell}} \right)^{\varphi} + 1 \right]^{\frac{\epsilon_{\varphi}}{1-\varphi}} \left( \frac{a_{\ell}}{a_e} \right)^{\zeta} \left( \frac{\ell}{e} \right)^{\zeta-1}. \quad (12)
\]

The first equation retains the same form as equation (4), while the second equation becomes more involved than equation (5).

The system of three equations (10)–(12) contains three unknowns \( a_k, a_{\ell}, \) and \( a_e \). Factor-augmenting technologies can be derived from these equations as:

\[
a_k = \left( \frac{r k + w \ell}{r k + w \ell + v e} \right)^{\frac{\zeta}{1-\zeta}} \left( \frac{r k}{r k + w \ell} \right)^{\frac{\varphi}{1-\varphi}} \left( \frac{y}{k} \right), \quad (13)
\]

\[
a_{\ell} = \left( \frac{r k + w \ell}{r k + w \ell + v e} \right)^{\frac{\zeta}{1-\zeta}} \left( \frac{w \ell}{r k + w \ell} \right)^{\frac{\varphi}{1-\varphi}} \left( \frac{y}{\ell} \right), \quad (14)
\]

\[
a_e = \left( \frac{v e}{r k + w \ell + v e} \right)^{\frac{\zeta}{1-\zeta}} \left( \frac{y}{e} \right). \quad (15)
\]

Equations (13)–(15) imply again that factor-augmenting technology is log proportional to the factor income share and output per factor input. Energy-saving technological change can be measured as:

\[
\Delta \ln a_e = \Delta \ln \left( \frac{y}{e} \right) + \frac{\varphi}{\zeta} \Delta \ln \left( \frac{v e}{r k + w \ell + v e} \right). \quad (16)
\]

This equation takes the same form as equation (9) but with a different parameter.
4 Estimation

We first consider how we identify and estimate the elasticity of substitution. We then describe how we evaluate the quantitative contribution of specific factor inputs and factor-augmenting technologies to economic growth.

4.1 Elasticity of substitution

The optimality conditions (4) and (5) form the basis for estimating the substitution parameter in the one-level CES production function (3). The optimality conditions (11) and (12) form the basis for estimating the substitution parameters in the two-level CES production function (10).

One-level CES

Let \( c, s, \) and \( t \) denote the indices for countries, sectors, and years, respectively. After taking logs in equations (4) and (5) and taking differences over time, the estimating equations can be derived as follows:

\[
\Delta \ln \left( \frac{w_{CST}}{r_{CST}} \right) = - (1 - \sigma) \Delta \ln \left( \frac{\ell_{CST}}{k_{CST}} \right) + \Delta \nu_{1CST}, \quad (17)
\]

\[
\Delta \ln \left( \frac{w_{CST}}{v_{CST}} \right) = - (1 - \sigma) \Delta \ln \left( \frac{e_{CST}}{e_{CST}} \right) + \Delta \nu_{2CST}. \quad (18)
\]

where the error terms comprise the relative factor-augmenting technologies; that is, \( \nu_{1CST} = \sigma \ln \left( \frac{a_{\ell, CST}}{a_{k, CST}} \right) \) and \( \nu_{2CST} = \sigma \ln \left( \frac{a_{e_{CST}}}{a_{e_{CST}}} \right) \).

Three facts about the estimating equations are worth noting. First, the observed and unobserved terms are additively separable in equations (17) and (18), which makes it possible to estimate the substitution parameter. Second, any time-invariant country- and sector-specific effects are eliminated by first differencing. Even though there are persistent and substantial differences in the unobserved characteristics across countries and sectors, such differences are fully controlled for. Finally, the substitution parameter can be over-identified when using the two equations, which makes it possible to test the validity of the equations.

One more estimating equation can be derived from the optimality conditions with respect to capital and energy inputs as follows:

\[
\Delta \ln \left( \frac{r_{CST}}{v_{CST}} \right) = - (1 - \sigma) \Delta \ln \left( \frac{k_{CST}}{e_{CST}} \right) + \Delta \nu_{3CST}, \quad (19)
\]

where \( \nu_{3CST} = \sigma \ln \left( \frac{a_{k, CST}}{a_{e, CST}} \right) \). We additionally estimate this equation for the purpose of robustness checks.
Two-level CES  One of the estimating equations can be derived from equation (11) in the same way as above:

\[
\Delta \ln \left( \frac{W_{cst}}{r_{cst}} \right) = -(1 - \varphi) \Delta \ln \left( \frac{\ell_{cst}}{k_{cst}} \right) + \Delta v_{4cst},
\]

where \( v_{4cst} = \varphi \ln \left( \frac{a_{c,cst}}{a_{k,cst}} \right) \).

Another estimating equation cannot be derived directly from equation (12) since the observed capital and labor quantities are not separated from the unobserved capital- and labor-augmenting technologies. However, equation (11) implies that the ratio of capital- to labor-augmenting technology is log proportional to the relative price and relative quantity of capital to labor; that is, \( (a_k/k)\ell = r_k/w\ell \). After substituting this into equation (12), the additional estimating equation can be derived as follows:

\[
\Delta \ln \left( \frac{W_{cst}}{v_{cst}} \right) = -\frac{\varphi - \zeta}{\varphi} \Delta \ln \left( \frac{W_{cst} \ell_{cst}}{r_{cst} k_{cst} + W_{cst} \ell_{cst}} \right) - (1 - \zeta) \Delta \ln \left( \frac{\ell_{cst}}{v_{cst}} \right) + \Delta v_{5cst},
\]

where \( v_{5cst} = \zeta \ln \left( \frac{a_{c,cst}}{a_{e,cst}} \right) \).

Consequently, the observed and unobserved terms are additively separable, and any time-invariant effects are differenced out in both equations (20) and (21). By virtue of these equations, it is possible to estimate the substitution parameters even when factor-augmenting technologies are neither observed nor deterministic. The substitution parameters can be over-identified from the two equations since there are three regressors for the two parameters in the system of equations (20) and (21).

Identification  Since the relative input quantities are presumably correlated with relative factor-augmenting technologies, the estimating equations are likely to involve endogenous regressors. If this is not taken into account, the estimated elasticities of substitution will be biased.$^3$

We address the endogeneity problem in three ways. First, we control for time-invariant country- and sector-specific effects, as mentioned above. Second, we control for non-linear time trends specific to each country-sector pair in the relative factor-augmenting technologies. These considerations amount to decomposing each error term as:

\[
v_{cst} = \alpha_c + \alpha_s + \sum_q \psi_{q,cst} t_q + u_{cst},
\]

where \( \alpha_c \) is a country fixed effect, \( \alpha_s \) is a sector fixed effect, \( u_{cst} \) is an idiosyncratic shock in country \( c \), sector \( s \), and year \( t \), and \( q \) is the order of polynomials. We omit the first subscript of the error terms in equations (17)–(21) to avoid notational clutter. If time-series data from a single country were used, it would be difficult to isolate the effect of the relative input quantities on the relative input prices from

$^3$The regressor in equation (17) or (18) is likely to be positively correlated with the error term. The reason for this is that, when \( 0 < \epsilon_{cr} < 1 \) (\( \epsilon_{cr} > 1 \)), the relative input quantities should theoretically be negatively (positively) correlated with the relative factor-augmenting technologies, and each relative factor-augmenting technology has a negative (positive) coefficient in the error term. The coefficient of the regressor is the negative of the inverse of \( \epsilon_{cr} \). The elasticity of substitution \( \epsilon_{cr} \) will be overestimated regardless of whether \( 0 < \epsilon_{cr} < 1 \) or \( \epsilon_{cr} > 1 \).
general time trends. However, since panel data from many countries are used in our analysis, it is possible to identify the elasticity of substitution among inputs by exploiting the cross-sectional and time variation in the relative input quantities.

Finally, we use the shift–share instrument, also known as the Bartik (1991) instrument, to allow for correlations between the changes in the relative input quantities and idiosyncratic shocks to the relative factor-augmenting technologies. We treat all right-hand-side variables, except time trends, as endogenous regressors. For each endogenous variable, we use the shift–share instrument:

$$\Delta \ln z_{c,s,t} = \sum_{i \in I_s} \frac{z_{c,s,i,t_0}}{\sum_{i' \in I_s} z_{c,s,i',t_0}} \Delta \ln \left( \sum_{c \in C} z_{c,s,i,t} \right)$$ \quad for \quad \{k, \ell, e, w, \ell, r + w, \ell\}, \quad (23)$$

where $i$ is an index for subsectors (or industries), $C$ is a set of countries, $I_s$ is a set of subsectors in sector $s$, and $t_0$ is the first year of observation. The shift–share instrument for the endogenous regressor in the goods (service) sector is constructed using the data from the service (goods) sector. Basically, we exploit demand shocks in the service (goods) sector as a source of exogenous variation in factor supply in the goods (service) sector (Raval, 2019; Oberfield and Raval, 2021). The shift–share instrument is the interaction between the initial industry shares of inputs for each country and the growth rates of inputs for each industry. The former measures local exposure to industry shocks, while the latter measures global shocks to industries. The identification assumption is that either the industry shares or growth rates in one sector are uncorrelated with idiosyncratic shocks to relative factor-augmenting technologies in another sector (conditional on non-linear time trends specific to each country-sector pair).\textsuperscript{4}

GMM The elasticity of substitution in the one-level CES production function can be estimated using equations (17) and (18), while the elasticities of substitution in the two-level CES production function can be estimated using equations (20) and (21). In both cases, the same parameter appears in different equations, and the error terms are correlated across equations. Hence, it is more efficient to estimate the system of equations jointly using the generalized method of moments (GMM). In doing so, all the right-hand-side variables except time trends are treated as endogenous variables using the shift–share instruments, five-year differences are used, and standard errors are clustered at the country-sector level to allow for heteroscedasticity and serial correlation. The GMM estimator is consistent as the sample size approaches infinity.

\textsuperscript{4}Goldsmith-Pinkham, Sorkin and Swift (2020) show that the two-stage least squares estimator with the shift–share instrument is numerically equivalent to the generalized method of moments estimator using industry shares as excluded instruments. Borusyak, Hull and Jaravel (2020) show that it is also numerically equivalent to the two-stage least squares estimator using industry shocks as an excluded instrument in the exposure-weighted industry-level regression. These results imply that the shift–share instruments can be valid under certain conditions if either initial local industry shares or global industry growth rates are exogenous.
4.2 Growth accounting

We utilize our measure of factor-augmenting technologies to evaluate the quantitative contribution of specific factor inputs and factor-augmenting technologies to economic growth for each country and sector. Technological change is typically measured as the Solow residual, which is the portion of growth in output not attributable to changes in factor inputs. The limitation of this standard approach is that it does not tell us the type of technological change. We take the approach one step further by leveraging our measure of factor-augmenting technologies as follows.

We decompose the rate of growth in gross output (\(y\)) into changes due to the three components in factor inputs (\(k, \ell,\) and \(e\)) and three components in factor-augmenting technologies (\(a_k, a_\ell,\) and \(a_e\)). Furthermore, we measure the contribution of the three pairs of factor inputs and factor-augmenting technologies (\(a_kk, a_\ell\ell,\) and \(a_e e\)) to economic growth. Given the way in which we estimate the elasticities of substitution and measure factor-augmenting technologies, the decomposition results are invariant to the normalization of input quantities. The issue that arises in the implementation of the decomposition is that there is no simple transformation to make the CES production functions additively separable in those components. In such a case, the decomposition results depend on the order of the decomposition. To address this issue, we use the Shapley decomposition (Shorrocks, 2013). Appendix A.1 details the decomposition procedure.

5 Data

The analysis described so far requires data on the prices and quantities of capital, labor, and energy inputs. The data used for the analysis are drawn from the EU KLEMS database and the International Energy Agency (IEA) database. The EU KLEMS database collects information on the quantities of and incomes from capital, labor, and energy services in major OECD countries from the year 1970 to 2005, while the IEA database (World Energy Prices) collects information on energy prices inclusive of taxes since the year 1978. The wage rate can be calculated as the ratio of labor income to hours worked. The rental price of capital can be calculated in standard ways. The internal rate of return approach is used as in previous analyses of data from the EU KLEMS when markup is assumed to be absent, whereas the external rate of return approach is used when markup is considered to be present. Appendix A.2 details the calculation procedure. All the variables measured in monetary terms are converted into the value of U.S. dollars in the year 1995.

The EU KLEMS database is created from information collected by national statistical offices and is grounded in national accounts statistics. The March 2008 version is used for the analysis because later versions contain no information on energy. All countries, industries, and years, for which the data needed for the estimation are available, are included in the sample. The economy is composed of two sectors. The goods sector consists of 17 industries, while the service sector consists of 12 industries.\(^5\)

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\(^5\)The goods sector includes five broad categories of industries: agriculture, hunting, forestry, and fishing; mining and
Consequently, our sample comprises 610 country-sector-year observations from 12 countries: Austria, the Czech Republic, Denmark, Finland, Germany, Italy, Japan, the Netherlands, Portugal, Sweden, the United Kingdom, and the United States.\footnote{The results remain almost unchanged if the Czech Republic is excluded from the sample.}

When we calculate the gross output, we use the estimates of markup by De Loecker and Eeckhout (2020). When we calculate the input prices and quantities, we adjust for the variation in input composition over time to the extent possible. For this purpose, we make full use of detailed information on capital, labor, and energy input components in the EU KLEMS and IEA databases. Appendix A.3 details the adjustment procedure, including further description of the data used.

When we compare our measure and conventional measures of energy-saving technological change, we construct the conventional measures using the amount of government spending on energy-related R&D and the number of energy-related patents (i.e., patents on climate change mitigation). Both types of information are readily available from the OECD.Stat database. When we examine the relationship between energy-saving technological change and energy resource abundance, we measure the abundance of energy resources using the self-sufficiency rate of energy supply, defined as the ratio of the indigenous production of total primary energy to the total primary energy supply. The self-sufficiency rate of energy supply can be calculated from the IEA database (World Energy Balances).

6 Results

We start this section by presenting the estimates of the elasticities of substitution among capital, labor, and energy inputs. We then discuss the international trends and differences in energy-saving technological change. We end this section by evaluating the quantitative contribution of energy input and energy-saving technology to economic growth.

6.1 Production function estimates

Table 1 reports the estimates of the elasticities of substitution in the one- and two-level CES production functions. The estimates vary slightly depending on the way in which time trends are controlled for. The estimated elasticities of substitution ($\epsilon_{\sigma}$) are, however, less than one in all specifications, ranging from 0.43 to 0.68, in the one-level CES production function. The same applies to the two-level CES production function. The estimated elasticities of substitution between energy and non-energy inputs ($\epsilon_{c}$) range from 0.27 to 0.44, while the estimated elasticity of substitution ($\epsilon_{q}$) between capital and labor ranges from 0.41 to 0.75. Since it is desirable to add extensive controls for time trends to ensure instrument exogeneity, our preferred specification is the one in which quadratic trends specific to each country-sector pair are

 quarrying; manufacturing; electricity, gas and water supply; and construction. The service sector includes nine broad categories of industries: wholesale and retail trade; hotels and restaurants; transport and storage, and communication; financial intermediation; real estate, renting, and business activities; public administration and defense and compulsory social security; education; health and social work; and other community, and social and personal services.
added. In this specification, the estimated elasticity of substitution in the one-level CES production function is 0.43, while the estimated elasticities of substitution in the two-level CES production function are 0.41 both between energy and non-energy inputs and between capital and labor. Thus, the estimated elasticities of substitution between energy and non-energy inputs are approximately the same between the one- and two-level CES production functions. Overall, our estimates are within the range of estimates reported in van der Werf (2008) and Raval (2019).\footnote{van der Werf (2008) provides the estimates of the elasticities of substitution among capital, labor, and energy inputs by country or industry. His estimates range from 0.17 to 0.65 in the two-level CES production function similar to equation (10). Raval (2019) provide the estimates of the elasticity of substitution between capital and labor by industry or year in the manufacturing sector of the United States. Most of his estimates fall within the range between 0.15 and 0.75.}

| Time Trends | One-level CES | Two-level CES |
|-------------|---------------|---------------|
|              | $\epsilon_{\sigma}$ | $\epsilon_{\gamma}$ |
|              | 0.681 (0.193) | 0.274 (0.200) |
| country      | 0.532 (0.133) | 0.441 (0.131) |
| linear       | 0.432 (0.087) | 0.408 (0.108) |
| sector       |               |               |
| linear       |               |               |
| quadratic    |               |               |

Notes: Standard errors in parentheses are clustered at the country-sector level. All specifications use the shift–share instruments. The specification in the first column controls for linear time trends specific to each country. The specifications in the second and third columns control for linear and quadratic time trends specific to each country-sector pair, respectively.

The estimated elasticities of substitution differ significantly from one in the one-level CES production function. The Wald statistic under the null hypothesis that the elasticity of substitution equals one is 42.6 with a $p$-value of zero in the preferred specification. This result indicates that the Cobb-Douglas production function can be rejected against the CES production function. At the same time, the estimated elasticities of substitution between capital and labor do not differ significantly from those between energy and non-energy inputs in the two-level CES production function. The Wald statistic under the null hypothesis that the two substitution parameters are identical is 0.001 with a $p$-value of 0.975 in the preferred specification. This result indicates that the one-level CES production function cannot be rejected against the two-level CES production function.

The estimated elasticities of substitution are similar irrespective of which equation is used for estimation. Table 2 reports the estimates of the elasticities of substitution in the one-level CES production function when equations (17), (18), and (19) are used separately. The estimated elasticities of substitution among capital, labor, and energy inputs fall into a tight range of 0.41 to 0.44 in the preferred specification. The Wald statistic under the null hypothesis that the estimated elasticities of substitution are the same between the first (second) and second (third) columns is 0.04 (0.04) with a $p$-value of 0.85.
Table 2: Elasticities of substitution estimated with different equations

|          | One-level CES | Two-level CES |
|----------|---------------|---------------|
| $\epsilon_{\sigma}$ | 0.410 (0.151) | 0.444 (0.099) |
|          | 0.422 (0.125) |               |

Notes: Standard errors in parentheses are clustered at the country-sector level. All specifications use the shift–share instruments and control for quadratic time trends specific to each country-sector pair.

(0.84). These results suggest the robustness of the estimates across different CES nesting structures.

Two types of test statistics indicate that the shift–share instruments used in our analysis are valid if quadratic trends specific to each country-sector pair are included. First, the first-stage $F$ statistics under the null hypothesis that the shift–share instruments are irrelevant are 11.3 for $\ell/k$, 14.7 for $\ell/e$, and 23.0 for $k/e$ in the one-level CES production function, while they are 11.3 for $\ell/k$, 8.3 for $\ell/e$, and 4.6 for $w\ell/(rk + w\ell)$ in the two-level CES production function. Second, the $J$ statistics under the null hypothesis that over-identifying restrictions are valid are 0.10 with a $p$-value of 0.746 in the one-level CES production function and 0.12 with a $p$-value of 0.725 in the two-level CES production function.

We end this subsection by mentioning that the marginal rate of technical substitution equals the ratio of input prices even if the product market is not competitive. Accordingly, the estimating equations hold irrespective of the presence or absence of markup. Technically, however, many specifications assume the absence of markup so that the rental price of capital can be calculated using the internal rate of return approach under the assumption of competitive markets. Nevertheless, estimating equation (18) is robust to the presence of markup since it does not depend on the rental price of capital. Reassuringly, the estimated elasticities of substitution change little irrespective of whether both equations (17) and (18) are used or only equation (18) is used. Moreover, the first-stage $F$ statistic is fairly large in the latter case. Consequently, our estimates are robust to product market imperfections. We also report the results when estimating the elasticity of substitution by sector in the appendix.

6.2 Energy-saving technological change

6.2.1 International trends

We measure factor-augmenting technological change in the presence of markup for each sector. Figures 1 and 2 display factor-augmenting technological change in the goods and service sectors of 12 OECD countries. Factor-augmenting technological change can be measured using data on output per factor input and factor income shares for a given value of the elasticity of substitution, as seen in equations (6)–(8). Given the results above, the elasticity of substitution is set to 0.444 in the one-level CES production function. We allow for the presence of markup when we calculate gross output. Appendix A.4 describes
the trends in output per factor input and factor income shares.\textsuperscript{8,9}

Figure 1: Factor-augmenting technological change in the goods sector

Notes: The solid, dashed, and dotted lines represent capital-, labor-, and energy-augmenting technologies ($a_k$, $a_l$, and $a_e$), respectively. The shaded area represents the 90 percent confidence interval for $a_e$. All series are expressed as log differences relative to the first year of observations.

\textsuperscript{8}The inverse of output per energy input (energy input per output) is referred to as energy intensity. \textit{Mulder and de Groot} (2012) document trends in energy intensity by industry in 18 OECD countries for the year 1970 to 2005.

\textsuperscript{9}Karabarbounis and Neiman (2014) document trends in the labor share of value added in 59 countries for the year 1975 to 2012.
Technological change is not factor-neutral. Changes in capital-, labor-, and energy-augmenting technologies are noticeably different for each country and sector. Capital-augmenting technology does not exhibit a clear trend in the goods and service sectors of most countries, but exhibits an increasing trend in the goods sector of a few countries and a modest decreasing trend in the service sector of a few countries. Labor-augmenting technology exhibits an increasing trend in the goods sector of all countries and in the service sector of almost all countries. The rate of increase in labor-augmenting technology is greater in the goods sector than in the service sector for all countries. Labor-augmenting technology tends to increase more than capital-augmenting technology in the goods and service sectors of all countries. This result is consistent with those of Klump et al. (2007) and van der Werf (2008). Energy-saving technology
exhibits different trends across countries and over time for each sector. Energy-saving technology tends to increase more than capital-augmenting technology but less than labor-augmenting technology in the goods and service sectors of most countries. However, the rate of increase in energy-saving technology is similar to that in labor-augmenting technology in the goods sector of the United Kingdom and in the service sector of Denmark, Germany, and Sweden, and greater than that in labor-augmenting technology in the goods and service sectors of the United States and in the service sector of Italy. Our results indicate greater variation in energy-saving technological change across countries and over time than those of van der Werf (2008).

Energy-saving technological change is neither linear nor monotonic over time. This result confirms the importance of not imposing the functional forms of technological change. Moreover, energy-saving technological change differs substantially across countries over time. The rate of change in energy-saving technology was greater in the United States than other OECD countries except Italy during the period between the years 1978 and 2005. In the United States, energy-saving technology started to rise after the mid-1980s and increased from the year 1978 to 2005 by 89 and 85 log points in the goods and service sectors, respectively. This result implies that when the years 1978 and 2005 are compared, new energy-saving technology would require only 41 and 43 (\(= 100 \times (a_e,1978/a_e,2005)\)) percent of energy in the goods and service sectors, respectively, to produce the same amount of output. The main reason for the difference between the United States and other countries is the steady increase in output per energy input in the United States (see Figures A1 and A2). In Denmark and Italy, energy-saving technology also increased from the 1980s to the 1990s, especially in the service sector. In Finland, Japan, and the United Kingdom, energy-saving technology progressed in the 1980s but stagnated in the 1990s and 2000s. In Germany and Sweden, energy-saving technology progressed in the 1990s but stagnated in the 2000s. The results imply that when the first and last years of observations are compared, new energy-saving technology would require only 77, 71, 85, 52, 60, 87, 68, and 41 percent of energy to produce the same amount of output in the goods sector of Denmark, Finland, Germany, Italy, Japan, Sweden, the United Kingdom, and the United States, respectively. At the same time, new energy-saving technology would require only 48, 76, 29, 90, 84, and 43 percent of energy to produce the same amount of output in the service sector of Denmark, Germany, Italy, Sweden, the United Kingdom, and the United States, respectively. In Austria, energy-saving technology modestly increased in the goods sector in the 1990s but decreased both in the goods and service sectors in the late 1990s and the 2000s. In the Czech Republic, energy-saving technology did not change much during the period. In the Netherlands and Portugal, energy-saving technology decreased during the period. Energy-saving technology might have progressed in more countries if the technology developed in other countries could be adopted.

Appendix A.5 provides additional results. The magnitude and direction of energy-saving technological change can vary significantly according to the value of the elasticity of substitution (see Figures A5 and A6). However, they remain almost unchanged regardless of whether we allow the elasticity of substitution to vary across sectors (see Figures A7 and A8). The magnitude and direction of energy-saving
technological change do not vary significantly according to the degree of returns to scale (see Figures A9 and A10). Factor-augmenting technological change remains essentially unchanged even if material inputs are taken into account (see Figures A11 and A12).

Table 3: Factor-augmenting technologies relative to the United States

(a) Goods sector

| Country         | Period      | $a_k$ | $a_\ell$ | $a_e$ | $t_0$ | 2005 |
|-----------------|-------------|-------|----------|-------|-------|------|
| Japan           | 1978–2005   | 0.42  | 0.17     | 4.12  | 0.35  | 0.40 |
| Italy           | 1978–2005   | 0.64  | 0.43     | 2.47  | 0.81  | 1.26 |
| Denmark         | 1980–2005   | 0.44  | 0.38     | 3.51  | 0.45  | 0.64 |
| Sweden          | 1994–2005   | 0.63  | 0.65     | 1.37  | 0.71  | 0.87 |
| Germany         | 1992–2005   | 0.86  | 0.62     | 1.21  | 0.82  | 0.77 |
| Finland         | 1978–2005   | 0.66  | 0.37     | 1.47  | 1.07  | 0.74 |
| United Kingdom  | 1978–2005   | 0.95  | 0.70     | 0.97  | 1.06  | 0.77 |
| Austria         | 1980–2005   | 0.33  | 0.32     | 2.06  | 0.55  | 0.63 |
| Czech Republic  | 1996–2005   | 0.47  | 0.63     | 0.64  | 0.43  | 0.69 |
| Netherlands     | 1987–2005   | 0.54  | 0.83     | 1.05  | 0.79  | 0.91 |
| Portugal        | 1996–2005   | 0.76  | 0.55     | 0.94  | 0.59  | 0.45 |

(b) Service sector

| Country          | Period      | $a_k$ | $a_\ell$ | $a_e$ | $t_0$ | 2005 |
|------------------|-------------|-------|----------|-------|-------|------|
| Netherlands      | 1987–2005   | 0.42  | 1.09     | 5.93  | 0.47  | 0.90 |
| Denmark          | 1980–2005   | 0.29  | 0.86     | 1.62  | 0.51  | 1.10 |
| Italy            | 1978–2005   | 0.83  | 0.92     | 0.81  | 1.28  | 1.10 |
| Germany          | 1992–2005   | 0.33  | 0.92     | 0.81  | 0.39  | 0.92 |
| Japan            | 1978–2005   | 0.74  | 0.33     | 2.86  | 0.48  | 0.47 |
| United Kingdom   | 1978–2005   | 0.63  | 0.62     | 1.34  | 0.84  | 0.71 |
| Sweden           | 1994–2005   | 0.84  | 0.79     | 0.44  | 0.77  | 0.69 |
| Portugal         | 1996–2005   | 0.60  | 1.10     | 0.35  | 0.33  | 0.68 |
| Austria          | 1980–2005   | 0.42  | 0.64     | 1.54  | 0.45  | 0.66 |
| Czech Republic   | 1996–2005   | 0.21  | 0.90     | 0.31  | 0.25  | 0.78 |
| Finland          | 1978–2005   | 0.80  | 0.72     | 0.35  | 0.70  | 0.61 |

Notes: Countries are arranged in descending order of energy-saving technology in the year 2005 by sector. This table reports the levels of capital-, labor-, and energy-augmenting technologies relative to the United States ($a_k, a_\ell, a_e$) in the first and last years of observations.

6.2.2 International differences

The levels of factor-augmenting technologies differ substantially across countries. Table 3 reports the levels of capital-, labor-, and energy-augmenting technologies relative to the United States in the first and last years of observations for each country and sector. The level of capital-augmenting technology...
relative to the United States in the year 2005 ranges from 0.35 (0.25) to 1.07 (1.28) in the goods (service) sector. The level of labor-augmenting technology relative to the United States in the year 2005 ranges from 0.40 (0.47) to 1.26 (1.10) in the goods (service) sector. Although the levels of capital- and labor-augmenting technologies were higher in the United States than in most other countries for each sector and year, the level of energy-saving technology was lower in the United States than many other countries especially in the 1970s and 1980s. Looking at the first year of observations, eight (five) countries had a higher level of energy-saving technology than the United States in the goods (service) sector. The United States achieved progress in energy-saving technology after the mid-1980s, as shown above. Looking at the year 2005, the United States was placed fifth behind Japan, Italy, Denmark, and Sweden in the goods sector, and fifth behind the Netherlands, Denmark, Italy, and Germany in the service sector. The level of energy-saving technology relative to the United States in the year 2005 ranges from 0.34 (0.13) to 2.83 (3.71) in the goods (service) sector.

There was greater variation across countries in the level of energy-saving technology than in the levels of capital- and labor-augmenting technologies for each sector and year. In the year 2005, the ratios of the maximum of energy-saving technology to the minimum were 8.4 and 29.0 in the goods and service sectors, respectively, while the ratios of the maximum of capital- (labor-) augmenting technology to the minimum were 3.1 (3.1) in the goods sector and 5.0 (2.3) in the service sector. One reason for this may be that the cross-country differences in energy-saving technology were more persistent than those in capital- and labor-augmenting technologies.

Figure 3 illustrates the convergence of factor-augmenting technologies by plotting the annual rates of growth in factor-augmenting technologies against their initial levels for each sector. Capital- and labor-augmenting technologies were more likely to grow faster in countries where they were initially low. Thus, they had a tendency to converge among countries for each sector. Moreover, the rate of convergence was faster in the service sector, where more capital and labor were used in the process of production, than in the goods sector. However, energy-saving technology did not converge among countries in the goods sector, where more energy was used in the process of production. In the year 2005, energy was used on average 2.4 times more in the goods sector than in the service sector, while capital and labor were used on average 3.2 and 2.6 times more in the service sector than in the goods sector.

The differences in the tendency to converge among factor-augmenting technologies may be related to difficulties in technology adoption. Energy-saving technology tends to be specific to the country for at least three reasons. First, there is a difference in the availability of fossil fuels across countries. Second, there is a difference in available renewable energy sources across countries. The type of renewable energy available depends on the climate and geography of the country. Finally, there is a difference in public attitudes across countries toward energy sources such as nuclear power. Consequently, if new technologies that can save capital, labor, and energy are developed in one country, the energy-saving technology is presumably less likely to be adopted in other countries than the capital- and labor-saving
technologies. Nonetheless, more research may be needed to determine the cause and mechanism of the slower rate of convergence in energy-saving technology.

Figure 3: Convergence of factor-augmenting technologies

(a) Goods sector

(b) Service sector

Notes: The vertical axis indicates the annual rates of growth in factor-augmenting technologies ($a_k$, $a_l$, or $a_e$) from the first year of observation ($t_0$) to 2005 (e.g., $100 \times (\ln a_{k,2005} - \ln a_{k,t_0})/(2005 - t_0)$). The horizontal axis indicates the logs of factor-augmenting technologies in the first year of observation (e.g., $\ln a_{k,t_0}$). The estimated coefficients in the regressions of the annual rates of growth in factor-augmenting technologies on the initial levels of factor-augmenting technologies are reported at the lower left of each figure. The heteroscedasticity-robust standard errors are also reported in parentheses at the lower left of each figure.

6.2.3 R&D spending and patent counts

We correlate our measure of energy-saving technological change with conventional measures of energy-saving technological change. The first row of Table 4 reports the correlation coefficients between our measure and conventional measures of energy-saving technological change for each sector. Our measure of energy-saving technology is positively and significantly correlated with energy-related R&D spending by the government and the number of energy-related patents in logs (odd-numbered columns). The correlation coefficients are greater than 0.3 for both R&D spending and patent counts. Meanwhile, our
measure of energy-saving technology is not significantly correlated with energy-related R&D spending or energy-related patent counts in 10-year growth rates (even-numbered columns). The correlation may be obscured by some common factors in factor-augmenting technological change. The second and third rows report the correlation coefficients calculated using the ratio of energy- to labor- or capital-augmenting technology \( \frac{a_e}{a_\ell} \) and \( \frac{a_e}{a_k} \). These ratios represent the direction of technological change and are not subject to the influence of any common factors. The relative energy-saving technology is positively and significantly correlated in 10-year growth rates with energy-related R&D spending but not with energy-related patent counts (even-numbered columns). The former result indicates that technological change tends to be directed toward energy as government spending on energy-related R&D increases. The size of the correlation is greater in the goods sector than in the service sector, reflecting the fact that more energy is used in the goods sector than in the service sector. The latter result suggests that our measure of energy-saving technological change contains complementary information on unpatented innovation and/or no unnecessary information on useless patents.

Table 4: Correlations with alternative measures

|                  | Goods sector | Service sector |
|------------------|--------------|---------------|
|                  | R&D          | Patents       | R&D            | Patents       |
|                  | log change   | log change    | log            | log change    |
| \( a_e \)        | 0.328        | 0.376         | 0.304          | 0.380         |
| \( a_e/a_\ell \) | 0.196        | 0.255         | 0.364          | 0.439         |
| \( a_e/a_k \)    | 0.098        | 0.194         | 0.048          | 0.213         |

Notes: Correlation coefficients are reported. All variables are taken in logs. The numbers in square brackets are \( p \)-values under the null hypothesis of no correlation.

6.3 Growth accounting

We measure the contribution of factor inputs and factor-augmenting technologies to economic growth for each country and sector. The first column of Table 5 reports the rate of growth in gross output. We allow for the presence of markup in the growth decomposition. The second column reports the rate of growth in markup based on the results of De Loecker and Eeckhout (2020). When countries are arranged in descending order of growth rate of gross output by sector, Italy and Portugal are placed quite differently depending on whether changes in markup are taken into account. Most of the countries are, however, placed roughly the same irrespective of the presence or absence of markup. The third to fifth columns report the portions attributable to the pairs of factor inputs and factor-augmenting technologies \( (a_k k, a_\ell \ell, \text{ and } a_e e) \). The sixth to eleventh columns report the portions attributable to each factor input \( (k, \ell, \text{ and } e) \) and each factor-augmenting technology \( (a_k, a_\ell, \text{ and } a_e) \). The last column reports the portions attributable to TFP, calculated as the sum of the portions attributable to factor-augmenting technologies.
for each country. Given the results above, the decomposition results are calculated based on the one-level CES production function in which the elasticity of substitution is set to 0.444.

All the pairs of factor inputs and factor-augmenting technologies contribute to economic growth in the goods and service sectors of almost all countries. The contribution of factor inputs and factor-augmenting technologies to the gross output growth is proportional to the factor share of income and the rate of increase in factor inputs and factor-augmenting technologies, as can be readily shown. The average capital, labor, and energy shares of income in the year 2005 are, respectively, 22 (24), 49 (69), and 29 (7) percent in the goods (service) sector. Since the labor share of income is much greater than the capital share of income and the energy share of income, the pair of labor input and labor-augmenting technology contributes most to economic growth. Since the energy share of income is greater in the goods sector than in the service sector, the pair of energy input and energy-saving technology tends to contribute to economic growth more in the goods sector than in the service sector. Consequently, the pair of energy input and energy-saving technology contributes to economic growth more than the pair of capital input and capital-augmenting technology in the goods sector of half of the countries but less than the pair of capital input and capital-augmenting technology in the service sector of almost all countries.

Capital input contributes to economic growth in the goods and service sectors of all countries. The contribution of capital input is greater than that of capital-augmenting technology in the goods sector of most countries and in the service sector of all countries. Labor input does not contribute to economic growth in the goods sector but contributes to economic growth in the service sector, reflecting the fact that labor input decreased in the goods sector but increased in the service sector. In contrast, the contribution of labor-augmenting technology is greater in the goods sector than in the service sector for most of the countries. Among the six elements of factor inputs and factor-augmenting technologies, labor-augmenting technology contributes the most to economic growth in the goods and service sectors of most countries. Energy input contributes to economic growth in the goods and service sectors of almost all countries, while energy-saving technology contributes to economic growth in the goods or service sector of the majority of the countries, including Denmark, Finland, Germany, Italy, Japan, Sweden, the United Kingdom, and the United States. This result holds even when material inputs are taken into account (see Table A1 in Appendix A.5). The contribution of energy-saving technology is greater than that of energy input in the goods and service sectors of several countries. The TFP has a great deal of contribution to economic growth or stagnation in all countries. The rate of increase in the TFP is greater in the goods sector than in the service sector for almost all countries, which is consistent with existing studies of value-added growth accounting (Herrendorf et al., 2014).

Table 6 presents the quantitative contribution of factor inputs and factor-augmenting technologies to international differences in economic growth compared to the United States. The results in Table 6 are based on those in Table 5 and obtained by subtracting each value in the United States from the corresponding values in other countries for the same period. The differences in the rates of growth in gross output compared to the United States are attributed mainly to the pair of labor input and labor-augmenting technology in the goods sector. The differences are calculated based on the one-level CES production function in which the elasticity of substitution is set to 0.444.
Table 5: Sources of economic growth

(a) Goods sector

| Country          | Period     | $y$  | $\omega$ | $a_k$ | $a_\ell$ | $a_e$ | $k$  | $\ell$ | $e$  | $a_k$ | $a_\ell$ | $a_e$ | $a$  |
|------------------|------------|------|----------|-------|----------|-------|------|-------|------|-------|----------|-------|------|
| Sweden           | 1994–2005  | 5.47 | −0.07    | 1.36  | 3.42     | 0.70  | 0.96 | 0.08  | 0.43 | 0.40  | 3.34     | 0.27  | 4.01 |
| Italy            | 1978–2005  | 4.76 | 3.22     | 0.85  | 2.73     | 1.18  | 0.58 | −0.70 | 0.54 | 0.27  | 3.43     | 0.64  | 4.34 |
| Japan            | 1978–2005  | 3.98 | 0.89     | 0.83  | 2.59     | 0.56  | 0.93 | −0.83 | 0.29 | −0.10 | 3.41     | 0.27  | 3.58 |
| Finland          | 1978–2005  | 3.78 | 1.02     | 0.72  | 1.99     | 1.07  | 0.34 | −0.72 | 0.70 | 0.38  | 2.71     | 0.37  | 3.46 |
| Czech Republic   | 1996–2005  | 2.87 | 1.16     | 0.84  | 0.98     | 1.05  | 0.98 | −0.63 | 1.47 | −0.14 | 1.61     | −0.42 | 1.05 |
| United States    | 1978–2005  | 2.74 | 1.26     | 0.37  | 1.47     | 0.90  | 0.32 | −0.01 | 0.01 | 0.05  | 1.47     | 0.89  | 2.42 |
| Denmark          | 1980–2005  | 2.70 | 2.07     | 0.49  | 1.47     | 0.74  | 0.49 | −0.66 | 0.50 | 0.00  | 2.12     | 0.24  | 2.37 |
| Austria          | 1980–2005  | 2.66 | 1.06     | 0.60  | 1.45     | 0.61  | 0.17 | −0.74 | 1.28 | 0.43  | 2.19     | −0.67 | 1.95 |
| Netherlands      | 1987–2005  | 2.40 | 0.30     | 0.80  | 1.39     | 0.21  | 0.26 | 0.00  | 1.10 | 0.54  | 1.38     | −0.89 | 1.04 |
| United Kingdom   | 1978–2005  | 1.77 | 1.72     | 0.29  | 0.46     | 1.03  | 0.17 | −0.91 | 0.48 | 0.11  | 1.37     | 0.55  | 2.03 |
| Germany          | 1992–2005  | 0.95 | 0.90     | 0.19  | 0.82     | −0.07 | 0.19 | −1.46 | −0.39 | 0.01  | 2.28     | 0.32  | 2.61 |
| Portugal         | 1996–2005  | 0.06 | −2.71    | 0.27  | 0.39     | −0.73 | 0.81 | −0.14 | 2.48 | −0.54 | 0.54     | −3.21 | −3.21 |

(b) Service sector

| Country          | Period     | $y$  | $\omega$ | $a_k$ | $a_\ell$ | $a_e$ | $k$  | $\ell$ | $e$  | $a_k$ | $a_\ell$ | $a_e$ | $a$  |
|------------------|------------|------|----------|-------|----------|-------|------|-------|------|-------|----------|-------|------|
| Italy            | 1978–2005  | 4.68 | 3.22     | 0.95  | 3.23     | 0.50  | 0.62 | 1.25  | 0.10 | 0.33  | 1.98     | 0.40  | 2.71 |
| United Kingdom   | 1978–2005  | 4.69 | 1.72     | 1.08  | 3.14     | 0.47  | 0.88 | 1.27  | 0.41 | 0.20  | 1.87     | 0.06  | 2.13 |
| United States    | 1978–2005  | 4.37 | 1.26     | 0.83  | 3.21     | 0.33  | 0.85 | 1.58  | 0.13 | −0.02 | 1.63     | 0.20  | 1.81 |
| Japan            | 1978–2005  | 4.05 | 0.89     | 0.84  | 3.02     | 0.19  | 1.27 | 0.57  | 0.24 | −0.43 | 2.45     | −0.05 | 1.97 |
| Denmark          | 1980–2005  | 3.84 | 2.07     | 1.12  | 2.38     | 0.35  | 0.61 | 0.53  | 0.13 | 0.51  | 1.85     | 0.22  | 2.57 |
| Austria          | 1980–2005  | 3.27 | 1.06     | 0.73  | 2.29     | 0.25  | 0.77 | 0.98  | 0.66 | −0.04 | 1.31     | −0.41 | 0.87 |
| Finland          | 1978–2005  | 3.08 | 1.02     | 0.53  | 2.06     | 0.49  | 0.65 | 0.96  | 0.57 | −0.12 | 1.10     | −0.09 | 0.89 |
| Netherlands      | 1987–2005  | 3.04 | 0.30     | 0.75  | 2.24     | 0.05  | 0.87 | 1.54  | 0.10 | −0.12 | 0.71     | −0.05 | 0.54 |
| Czech Republic   | 1996–2005  | 2.92 | 1.16     | 1.38  | 1.11     | 0.43  | 1.31 | 0.36  | 0.58 | 0.07  | 0.76     | −0.15 | 0.68 |
| Germany          | 1992–2005  | 2.69 | 0.90     | 0.68  | 1.88     | 0.13  | 0.88 | 0.51  | 0.01 | −0.21 | 1.37     | 0.12  | 1.28 |
| Sweden           | 1994–2005  | 2.41 | −0.07    | 0.41  | 1.89     | 0.11  | 0.95 | 0.81  | 0.05 | −0.54 | 1.08     | 0.06  | 0.60 |
| Portugal         | 1996–2005  | −0.16| −2.71    | −0.29 | −0.03    | 0.16  | 2.02 | 1.30  | 0.47 | −2.31 | −1.34    | −0.32 | −3.96|

Notes: The first and second columns report the annual rates of growth in gross output ($y$) and markup ($\omega$) from the first year of observation ($t_0$) to 2005 (i.e., $100 \times (\ln y_{2005} - \ln y_{t_0})/(2005 - t_0)$). The sixth to eleventh columns report the results of the Shapley decomposition. The third, fourth, and fifth columns report the sum of the numbers in the sixth and ninth columns, the seventh and tenth columns, and eighth and eleventh columns, respectively. The last column reports the sum of the numbers from the ninth to eleventh columns. Countries are arranged in descending order of growth rate of gross output by sector.
Table 6: Differences in economic growth compared to the United States

(a) Goods sector

| Country      | Period   | Gross Output Growth | Markup Growth | a | b | c | k | l | e | A | a |
|--------------|----------|---------------------|---------------|---|---|---|---|---|---|---|---|
| Sweden       | 1994–2005| 2.54                | -0.89         | 0.81 | 1.50 | 0.24 | 0.53 | 0.22 | 0.63 | 0.28 | 1.28 | -0.39 | 1.17 |
| Italy        | 1978–2005| 2.02                | 1.96          | 0.48 | 1.27 | 0.28 | 0.26 | -0.69 | 0.53 | 0.21 | 1.96 | -0.26 | 1.92 |
| Japan        | 1978–2005| 1.23                | -0.36         | 0.45 | 1.12 | -0.34 | 0.61 | -0.82 | 0.28 | -0.16 | 1.94 | -0.63 | 1.16 |
| Finland      | 1978–2005| 1.04                | -0.23         | 0.35 | 0.52 | 0.16 | 0.02 | -0.71 | 0.69 | 0.33 | 1.23 | -0.53 | 1.04 |
| Denmark      | 1980–2005| 0.30                | 0.83          | 0.23 | 0.55 | -0.47 | 0.20 | -0.65 | 0.54 | 0.02 | 1.19 | -1.01 | 0.20 |
| Austria      | 1980–2005| 0.27                | -0.18         | 0.34 | 0.53 | -0.60 | -0.12 | -0.73 | 1.32 | 0.45 | 1.26 | -1.93 | -0.21 |
| Czech Republic| 1996–2005| 0.11                | 0.36          | 0.32 | -0.75 | 0.55 | 0.56 | -0.29 | 1.78 | -0.24 | -0.45 | -1.24 | -1.93 |
| Netherlands  | 1987–2005| -0.09               | -0.61         | 0.37 | 0.04 | -0.50 | -0.08 | 0.01 | 1.11 | 0.45 | 0.03 | -1.60 | -1.13 |
| United Kingdom| 1978–2005| -0.97               | 0.46          | -0.09 | -1.01 | 0.12 | -0.14 | -0.90 | 0.47 | 0.06 | -0.11 | -0.35 | -0.40 |
| Germany      | 1992–2005| -1.55               | 0.34          | -0.29 | -0.65 | -0.60 | -0.23 | -1.53 | -0.21 | -0.06 | 0.88 | -0.39 | 0.42 |
| Portugal     | 1996–2005| -2.81               | -3.51         | -0.25 | -1.33 | -1.23 | 0.39 | 0.19 | 2.79 | -0.64 | -1.53 | -4.03 | -6.20 |

(b) Service sector

| Country      | Period   | Gross Output Growth | Markup Growth | a | b | c | k | l | e | A | a |
|--------------|----------|---------------------|---------------|---|---|---|---|---|---|---|---|
| Italy        | 1978–2005| 0.31                | 1.96          | 0.12 | 0.02 | 0.18 | -0.23 | -0.33 | -0.03 | 0.35 | 0.34 | 0.21 | 0.90 |
| United Kingdom| 1978–2005| 0.33                | 0.46          | 0.25 | -0.07 | 0.14 | 0.03 | -0.31 | 0.28 | 0.23 | 0.24 | -0.14 | 0.33 |
| Denmark      | 1980–2005| -0.18               | 0.83          | 0.35 | -0.50 | -0.04 | -0.24 | -1.01 | -0.04 | 0.59 | 0.51 | 0.00 | 1.10 |
| Japan        | 1978–2005| -0.32               | -0.36         | 0.01 | -0.19 | -0.14 | 0.42 | -1.01 | 0.11 | -0.41 | 0.82 | -0.25 | 0.17 |
| Netherlands  | 1987–2005| -0.74               | -0.61         | 0.09 | -0.72 | -0.11 | 0.00 | 0.13 | -0.04 | 0.09 | -0.85 | -0.07 | -0.83 |
| Austria      | 1980–2005| -0.75               | -0.18         | -0.03 | -0.59 | -0.13 | -0.08 | -0.56 | 0.49 | 0.05 | -0.03 | -0.63 | -0.61 |
| Germany      | 1992–2005| -0.99               | 0.34          | 0.12 | -1.13 | 0.02 | -0.04 | -0.95 | -0.09 | 0.16 | -0.19 | 0.11 | 0.08 |
| Finland      | 1978–2005| -1.29               | -0.23         | -0.30 | -1.15 | 0.16 | -0.21 | -0.61 | 0.45 | -0.09 | -0.53 | -0.29 | -0.91 |
| Czech Republic| 1996–2005| -1.50               | 0.36          | 0.73 | -2.53 | 0.30 | 0.31 | -0.87 | 0.50 | 0.42 | -1.66 | -0.20 | -1.44 |
| Sweden       | 1994–2005| -1.73               | -0.89         | -0.20 | -1.54 | 0.01 | -0.01 | -0.54 | -0.04 | -0.19 | -1.00 | 0.06 | -1.13 |
| Portugal     | 1996–2005| -4.59               | -3.51         | -0.94 | -3.68 | 0.04 | 1.02 | 0.08 | 0.40 | -1.96 | -3.75 | -0.37 | -6.09 |

Notes: The first and second columns report the annual rates of growth in gross output and markup of each country relative to the United States. The sixth to eleventh columns report the results of the Shapley decomposition. The third, fourth, and fifth columns report the sum of the numbers in the sixth and ninth columns, the seventh and tenth columns, and eighth and eleventh columns, respectively. The last column reports the sum of the numbers from the ninth to eleventh columns. Countries are arranged in descending order of growth rate of gross output by sector.
augmenting technology in the goods and service sectors of most countries. However, they are also attributed to the pair of capital input and capital-augmenting technology in the goods sector of most countries and in the service sector of half of the countries and to the pair of energy input and energy-saving technology in the goods and service sectors of several countries. The differences from the United States tend to be attributed to energy input more than energy-saving technology in the goods sector, but to energy-saving technology more than energy input in the service sector. A significant fraction of the differences from the United States can be attributed to the TFP in the goods and service sectors of most countries.

7 Extension

We end our analysis by discussing the interpretation of our results and testing the main implication of the model when factor-augmenting technologies are endogenous.

7.1 A model of technology choice

Following Caselli and Coleman (2006), we consider a model of technology choice, in which the representative firm chooses factor-augmenting technologies \((a_k, a_\ell, a_e)\) as well as the quantities of inputs \((k, \ell, e)\), so as to maximize its profits subject to production technology and a technology frontier. The technology frontier, from which the firm chooses the optimal mix of technologies, is given by:

\[
\left[ \left( \frac{a_k}{A_k} \right)^\eta + \left( \frac{a_\ell}{A_\ell} \right)^\eta + \left( \frac{a_e}{A_e} \right)^\eta \right]^{\frac{1}{\eta}} \leq B, \quad \text{for} \quad \eta > \frac{\sigma}{1 - \sigma} \tag{24}
\]

where \(A_k, A_\ell,\) and \(A_e\) govern the trade-offs between capital-, labor-, and energy-augmenting technologies, and \(B\) governs the technology frontier. We assume \(\eta > \sigma / (1 - \sigma)\) as well as \(\sigma < 1\) to satisfy the second-order condition of this problem. This assumption implies \(\eta > \sigma\) and \(\eta \sigma / (\eta - \sigma) < 1\).

Suppose that the production technology is represented by the one-level CES production function (3). For a given choice of input quantities \((k, \ell, e)\), the optimal choice of technologies can be written as:

\[
a_k = B \left[ (A_k k)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_\ell \ell)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_e e)^{\frac{\eta \sigma}{\eta - \sigma}} \right]^{-\frac{1}{\eta}} A_k^{\frac{\eta}{\eta - \sigma}} k^{\frac{\sigma}{\eta - \sigma}}, \tag{25}
\]

\[
a_\ell = B \left[ (A_k k)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_\ell \ell)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_e e)^{\frac{\eta \sigma}{\eta - \sigma}} \right]^{-\frac{1}{\eta}} A_\ell^{\frac{\eta}{\eta - \sigma}} \ell^{\frac{\sigma}{\eta - \sigma}}, \tag{26}
\]

\[
a_e = B \left[ (A_k k)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_\ell \ell)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_e e)^{\frac{\eta \sigma}{\eta - \sigma}} \right]^{-\frac{1}{\eta}} A_e^{\frac{\eta}{\eta - \sigma}} e^{\frac{\sigma}{\eta - \sigma}}. \tag{27}
\]

The production function (3) can then be rewritten as:

\[
y = \left[ (A_k B k)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_\ell B \ell)^{\frac{\eta \sigma}{\eta - \sigma}} + (A_e B e)^{\frac{\eta \sigma}{\eta - \sigma}} \right]^{\frac{\eta - \sigma}{\eta \sigma}} \quad \text{for} \quad \frac{\eta \sigma}{\eta - \sigma} < 1, \tag{28}
\]
where \( \eta \sigma / (\eta - \sigma) \) represents the degree of substitution among capital, labor, and energy inputs when the firm can adjust the mix of factor-augmenting technologies as well as the mix of factor inputs in response to changes in factor prices. In this case, the elasticity of substitution among capital, labor, and energy inputs is \( \epsilon_{\eta \sigma} \equiv (\eta - \sigma) / (\eta - \sigma - \eta \sigma) > 0 \). Therefore, the elasticity of substitution is greater when both factor inputs and factor-augmenting technologies are endogenous than when only factor inputs are endogenous (i.e., \( \epsilon_{\eta \sigma} > \epsilon_{\sigma} \)).

The first-order conditions with respect to \( \ell, l', \text{and} e \) imply that

\[
\frac{w}{r} = \left( \frac{A_{\ell}}{A_k} \right) \frac{\epsilon_{\eta \sigma} - 1}{\epsilon_{\eta \sigma}} \left( \frac{\ell}{k} \right)^{-1},
\]

\[
\frac{w}{v} = \left( \frac{A_{\ell}}{A_e} \right) \frac{\epsilon_{\eta \sigma} - 1}{\epsilon_{\eta \sigma}} \left( \frac{\ell}{e} \right)^{-1}.
\]

These equations are of the same form as equations (4) and (5) with a different parameter. Hence, the elasticity of substitution (\( \epsilon_{\eta \sigma} \) or \( \epsilon_{\sigma} \)) can be estimated using the same equations, irrespective of whether technologies are endogenous or exogenous. Whether we estimate the elasticity \( \epsilon_{\eta \sigma} \) (or \( \epsilon_{\sigma} \)) from equations (17) and (18) depends on whether we use differences over a long (or short) period during which technologies are endogenous (or exogenous) in the estimation.

The coefficients of capital, labor, and energy inputs in the production function (28) can be derived from equations (28)–(30) as follows:

\[
A_k B = \left( \frac{r \ell}{r k + w \ell + ve} \right) \frac{1}{\epsilon_{\eta \sigma}} \left( \frac{y}{k} \right),
\]

\[
A_{\ell} B = \left( \frac{w \ell}{r k + w \ell + ve} \right) \frac{1}{\epsilon_{\eta \sigma}} \left( \frac{y}{\ell} \right),
\]

\[
A_e B = \left( \frac{ve}{r k + w \ell + ve} \right) \frac{1}{\epsilon_{\eta \sigma}} \left( \frac{y}{e} \right).
\]

These equations are of the same form as equations (6)–(8), yet with a different parameter. Moreover, it can be readily shown that factor-augmenting technologies \( (a_k, a_{\ell}, a_e) \) retain the same form as equations (6)–(8) with the same parameter, irrespective of whether technologies are endogenous or exogenous. The same results apply to the case in which the production technology is represented by the two-level nested CES production function (10).

Whether we measure \( (A_k B, A_{\ell} B, A_e B) \) or \( (a_k, a_{\ell}, a_e) \) as a result of calculating the right-hand side of equations (31)–(33) depends on whether we use the elasticity \( \epsilon_{\eta \sigma} \) or \( \epsilon_{\sigma} \) in the calculation. We are concerned with the possibility that our estimates of the elasticities of substitution may be closer to those of \( \epsilon_{\eta \sigma} \) than those of \( \epsilon_{\sigma} \). However, we obtain similar estimates of the elasticities of substitution if we look at the differences over a shorter period. This result implies that our estimates would be closer to those of \( \epsilon_{\sigma} \), and a longer span of data would be needed to estimate \( \epsilon_{\eta \sigma} \).
Equations (4) and (5) imply that technological change is directed toward scarce (abundant) factors when the elasticity of substitution $\epsilon_{cr}$ is less (greater) than one; in other words, factor inputs are complementary (substitutable) to some extent (Acemoglu, 2002; Caselli and Coleman, 2006). Consequently, energy-saving technology tends to progress in countries with scarce (abundant) energy resources when the elasticity of substitution is less (greater) than one, as can be seen from equation (8). Our estimates of the elasticity of substitution imply that energy-saving technology should progress in countries or years in which energy resources are scarce.

7.2 Energy resources and development

We examine whether energy-saving technology tends to progress in countries or years in which energy resources are scarce. Figure 4 illustrates the relationship between energy-saving technological change and energy resource abundance for each sector. Energy-saving technological change is measured using the 10-year change in the log of energy-saving technology. The abundance of energy resources is measured using the self-sufficiency rate of energy supply. The Czech Republic and Portugal are not included in the figure due to an insufficient number of periods.

As of the year 1978, the self-sufficiency rates were low at 4.4 percent in Denmark, 10.9 percent in Japan, 16.6 percent in Italy, and 24.1 percent in Finland; medium at 35.8 percent in Austria and Sweden and 49.9 percent in Germany; and high at 78.1 percent in the United States, 81.1 percent in the United Kingdom, and 107.6 percent in the Netherlands. Looking at the goods sector, where more energy is used in the process of production, energy-saving technological change occurred in Denmark, Finland, Italy, and Japan, which were not endowed with fossil fuels. At the same time, energy-saving technological
change did not occur in the Netherlands, which was endowed with abundant natural gas. In the United Kingdom, the self-sufficiency rate used to be lower than 50 percent in the early 1970s but increased up to 100 percent in the early 1980s, in part due to the development of oil and natural gas in the North Sea. In the United States, the self-sufficiency rate gradually declined from 91 to 80 (70) percent between the years 1982 and 1995 (2005). In the two countries, energy-saving technological change occurred in the period during which energy resources were less abundant.

Overall, energy-saving technological change is negatively associated with the self-sufficiency rate at a correlation coefficient of −0.216 (−0.038) and a p-value of 0.011 (0.662) in the goods (service) sector. The non-parametric regression curves indicate that energy-saving technological change is negatively associated with the self-sufficiency rate in the range where the self-sufficiency rate is lower than 30 percent and higher than 80 percent for both sectors. The observed negative association between energy-saving technological change and energy resource abundance is consistent with the prediction of the model when energy and non-energy inputs are complementary to some extent.

We close this section by touching upon energy development and policies in countries, where energy-saving technology has made progress. The two oil crises in the 1970s were turning points in energy development and policies. Many countries subsequently promoted energy conservation and sought alternative energy sources. On the one hand, countries without fossil fuels advanced the use of renewable energy and nuclear energy. On the basis of climatic and geographical conditions, Denmark, Japan, and Finland achieved the development of wind, solar, and woody biomass energy, respectively. In addition, Japan and Finland achieved the development of nuclear energy. Italy did not win public support for nuclear power but managed to import electricity generated by nuclear power and hydro power from France and Switzerland. On the other hand, countries with fossil fuels advanced the expansion of indigenous production. Against a backdrop of stable energy supply, the United Kingdom and the United States deregulated the energy market from the 1980s to the 1990s. Therefore, energy-saving technological change might be associated with the development of alternative energy and the deregulation of energy markets. We leave it for future research to determine the impact of specific energy policies and regulations.

8 Conclusion

This study aims to provide an understanding of the trends and differences in energy-saving technological change among OECD countries. When we measure the level and growth rate of energy-saving technology for each country and sector, we use the theoretical result that technological change can be measured using data on output per factor input and factor income shares for a given value of the elasticity of substitution in production. The main challenge that arises here is to estimate the elasticity of substitution between energy and non-energy inputs after taking into account the cross-sectional and time variation in the unobserved components of factor-augmenting technologies. We address this issue by using cross-
country and cross-industry panel data and shift–share instruments. Our results indicate that capital, labor, and energy inputs are complementary to some extent in production.

Our study is the first to measure and compare the levels and growth rates of energy-saving technology across countries and sectors. This makes it possible to conduct two kinds of analysis. First, we examine the nature of energy-saving technological change and its differences across countries. Second, we evaluate the quantitative contribution of energy-saving technology to economic growth.

Our analysis yields the following findings. First, the levels and growth rates of energy-saving technology vary substantially across countries over time both in the goods and service sectors. Cross-country differences in energy-saving technology are more persistent than those in capital- and labor-augmenting technologies. Second, energy-saving technology has progressed in countries or years in which energy resources are scarce, as theory predicts when factor inputs are complementary to some extent in production. Energy-saving technology relative to other technologies has also progressed in countries in which government spending on energy-related R&D is large. Finally, energy-saving technological change has a positive contribution to economic growth in the goods or service sector of many countries, although not to the extent of labor-augmenting technological change.

Our findings suggest that global energy efficiency can be improved by developing general-purpose energy-saving technology and accelerating international transfers of such technology. Such efforts would subsequently lead to an increase in the national income for each country.
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A Appendix

A.1 Shapley decomposition

We describe the procedure to decompose the rate of growth in gross output into the contribution of specific factor inputs and factor-augmenting technologies. Let \( Y \) denote output and \( d_m \) for \( m \in \{1, 2, \ldots, M\} = M \) denote its determinant factors, including factor inputs \((k, \ell, \text{and } e)\) and factor-augmenting technologies \((a_k, a_{\ell}, \text{and } a_e)\). For a given country, sector, and year, the natural log of output is given by

\[
\ln Y = F(d_1, d_2, \ldots, d_M). \tag{A.1}
\]

To quantify the contribution of each factor, we consider counterfactual situations in which some or all of the factors are fixed at the initial level. Let \( \Gamma(G) \) denote the value that \( \ln Y \) takes if the factors \( d_m \) for \( m \notin G \subseteq M \) are fixed at the initial level, \( o = (o_1, o_2, \ldots, o_M) \in O \) denote the order in which the factors are fixed, and \( G(o_{\tau}, o) = \{ o_{\tau'} | \tau' > \tau \} \) denote the set of factors that remain unfixed after the \( \tau \)-th factor is fixed. The marginal contribution of the \( m \)-th factor to the log changes in output, \( \Delta \ln Y \), can be measured as:

\[
\Lambda_{d_m}^o = \Gamma(G(d_m, o) \cup \{d_m\}) - \Gamma(G(d_m, o)). \tag{A.2}
\]

The marginal contribution, \( \Lambda_{d_m}^o \), depends on the order in which the factors are fixed, but the average of the marginal contributions over all possible sequences, \( \Lambda_{d_m} \), does not. The Shapley decomposition is

\[
\Delta \ln Y = \sum_{m \in M} \Lambda_{d_m}, \tag{A.3}
\]

where

\[
\Lambda_{d_m} = \frac{1}{M!} \sum_{o \in O} \Lambda_{d_m}^o. \tag{A.4}
\]

This decomposition is not only path independent but also exact (Shorrocks, 2013). The results of the decomposition are expressed in terms of growth rates by dividing by the number of years between the first and last years.

A.2 Rental price of capital

We describe the procedure to calculate the rental price of capital. Capital is divided into capital equipment and structure. Capital equipment is composed of computing equipment, communications equipment, software, transport equipment, and other machinery and equipment, while capital structure is composed of non-residential structures and infrastructures, residential structures, and other assets. Let \( j \in \{ \text{equipment, structure} \} \) denote an index for the capital components. The rental price of capital \( (r_{ji}) \) is determined by the price of investment \( (q_{ji}) \), the depreciation rate \( (\delta_j) \), and the interest rate \( (\iota) \). The
price of investment is calculated by dividing the nominal value by the real value of investment for each component. The depreciation rate is the time average of those obtained from the law of motion of capital.

We calculate the rental price of capital in two ways. When we assume the absence of markup, we adopt the internal rate of return approach of O’Mahony and Timmer (2009), who calculate the rental price of capital as:

\[ r_{jt} = \delta_j q_{jt} + \left( t_t - \frac{q_{jt} - q_{j,t-1}}{q_{j,t-1}} \right) q_{j,t-1}, \]  

(A.5)

where the interest rate is the internal rate of return:

\[ t_t = \frac{\sum_j r_{jt} k_{jt} - \sum_j \delta_j q_{jt} k_{jt} + \sum_j (q_{jt} - q_{j,t-1}) k_{jt}}{\sum_j q_{j,t-1} k_{jt}}. \]  

(A.6)

The advantage of this approach is to maintain consistency between national income and production accounts. When we allow for the presence of markup, we adopt the external rate of return approach of Harper, Berndt and Wood (1989), who calculate the rental price of capital as:

\[ r_{jt} = \delta_j q_{jt} + \bar{i}_t q_{j,t-1}, \]  

(A.7)

where the real rate of return ($\bar{i}_t$) is set to a constant 3.5 percent. The advantage of this approach is not to require the assumption of competitive markets.

### A.3 Adjustment for input composition

We describe the procedure used to adjust for the variation in the composition of capital, labor, and energy inputs over time when calculating the prices and quantities of capital, labor, and energy inputs. The procedure is similar to that used by Autor, Katz and Kearney (2008), who adjust for the compositional changes in labor inputs when estimating the aggregate production function with two types of labor in the United States. In our case, capital is divided into capital equipment and structure; labor is divided into skilled and unskilled labor; and energy is divided into sulfur fuel oil, light fuel oil, natural gas, electricity, automotive diesel, steam coal, and coking coal. The procedure requires the assumption that the input components are perfect substitutes within each type of input.

Here, we denote the price of input by \( p \in \{ r, w, v \} \) and the quantity of input by \( x \in \{ k, \ell, e \} \) as \((\text{equipment, structure}), (\text{skilled, unskilled}), (\text{sulfur fuel oil, light fuel oil, natural gas, electricity, automotive diesel, steam coal, coking coal})\). We use squiggles to represent unadjusted prices and quantities. If there were no need to make adjustments to input prices and quantities, we could calculate the price of input in country \( c \), sector \( s \), and year \( t \) as \( \bar{p}_{cst} = \sum_j \theta_{jcs}^x \bar{p}_{jcs} \), where \( \theta_{jcs}^x \) is the share of component \( j \) in input \( x \) (i.e., \( \theta_{jcs}^x = \bar{x}_{jcs} / \sum_j \bar{x}_{jcs} \)), and the quantity of input in country \( c \), sector \( s \), and year \( t \) as \( \bar{x}_{cst} = \sum_j \bar{x}_{jcs} \).

We adjust for the variation in input composition over time by holding the shares of input components
constant when calculating input prices and by using time-invariant efficiency units as weights when calculating input quantities. Let $T_c$ denote the number of years observed for country $c$ and $J_x$ denote the number of components in input $x$. We can calculate the composition-adjusted price of input in country $c$, sector $s$, and year $t$ as $p_{cst} = \sum_j \theta_j^{x} \tilde{p}_{jcs}$, where $\theta_j^{x}$ is the country- and sector-specific mean of $\theta_{jcs}$ (i.e., $\theta_j^{x} = \frac{\sum_{t=1}^{T_c} \theta_{jcs}^x}{T_c}$), and the composition-adjusted quantity of input in country $c$, sector $s$, and year $t$ as $x_{cst} = \sum_j (\tilde{p}_{jcs}/\bar{p}_{cst}) \bar{x}_{jcs}$, where the weight is the country- and sector-specific mean of $\tilde{p}_{jcs}$ (i.e., $\bar{p}_{cst} = \sum_j \tilde{p}_{jcs}/J_s$) normalized by its mean across components (i.e., $\bar{x}_{jcs} = \frac{\sum_{t=1}^{T_c} \tilde{p}_{jcs}/T_c}{\bar{p}_{cst}}$).

We construct the data on the prices of input components $\tilde{r}_j$ and $\tilde{w}_j$, the shares of input components $\theta_j^k$ and $\theta_j^\ell$, and the quantities of inputs $\bar{k}$, $\bar{\ell}$, and $\bar{e}$ from the EU KLEMS database and obtain the data on the energy price $\tilde{v}_j$ and the share of energy components $\theta_j^e$ from the IEA database (World Energy Prices and World Energy Balances).

### A.4 Factor productivity and factor income shares

Figures A1 and A2 show the trends in output per factor input in the goods and service sectors of 12 OECD countries. Output per factor input is often used as the measure of factor productivity. Output per capital input does not exhibit a clear trend in many countries but exhibits a moderate increasing trend in the goods sector of several countries and a modest decreasing trend in the service sector of several countries. Output per labor input exhibits an increasing trend in the goods and service sectors of almost all countries. The rate of increase in output per labor input is greater in the goods sector than in the service sector for each country. Output per energy input exhibits different trends across countries over time both in the goods and service sectors. When these trends are compared, output per labor input tends to increase more or decrease less than output per capital (energy) input in the goods and service sectors of all (most) countries. However, the rate of increase in output per energy input is similar to that in output per labor input in the goods and service sectors of the United States and the service sector of Germany and Sweden, and greater than that in output per labor input in the service sector of Italy. The increase in output per energy input is noticeable in Italy and the United States.

Figures A3 and A4 show the trends in the capital, labor, and energy shares of income in the goods and service sectors of 12 OECD countries. The capital share of income tends to increase modestly in the goods sector of many countries, while the labor share of income tends to decrease modestly in the goods sector of many countries. The rates of change in the capital and labor shares of income tend to be smaller in the service sector than in the goods sector. The energy share of income decreased in the 1980s or 1990s and increased in the late 1990s or 2000s in the goods and service sectors of many countries. The rate of decrease is large especially in Denmark, Italy, the United Kingdom, and the United States.
Figure A1: Output per factor input in the goods sector

| Country       | y/k | y/l | y/e |
|---------------|-----|-----|-----|
| (a) Austria   |     |     |     |
| (b) Czech Republic |     |     |     |
| (c) Denmark   |     |     |     |
| (d) Finland   |     |     |     |
| (e) Germany   |     |     |     |
| (f) Italy     |     |     |     |
| (g) Japan     |     |     |     |
| (h) Netherlands|     |     |     |
| (i) Portugal  |     |     |     |
| (j) Sweden    |     |     |     |
| (k) United Kingdom |     |     |     |
| (l) United States |    |     |     |

Notes: The solid, dashed, and dotted lines represent output per capital input (y/k), output per labor input (y/l), and output per energy input (y/e), respectively. All series are expressed as log differences relative to the first year of observations.
Figure A2: Output per factor input in the service sector

Notes: The solid, dashed, and dotted lines represent output per capital input ($y/k$), output per labor input ($y/l$), and output per energy input ($y/e$), respectively. All series are expressed as log differences relative to the first year of observations.
Notes: The solid, dashed, and dotted lines represent the capital, labor, and energy shares of income (i.e., $r/k(k + w/l + v/e)$, $w/l(k + w/l + v/e)$, and $v/e(k + w/l + v/e)$), respectively.
Figure A4: Factor income shares in the service sector

(a) Austria  (b) Czech Republic  (c) Denmark  (d) Finland

(e) Germany  (f) Italy  (g) Japan  (h) Netherlands

(i) Portugal  (j) Sweden  (k) United Kingdom  (l) United States

Notes: The solid, dashed, and dotted lines represent the capital, labor, and energy shares of income (i.e., \( r(k/rk + w\ell + ve) \), \( w\ell/(r(k/rk + w\ell + ve)) \), and \( ve/(r(k/rk + w\ell + ve)) \), respectively. The left vertical axis indicates the capital and energy shares, while the right axis indicates the labor share.

A.5 Additional results

We present four additional sets of results. First, we show the extent to which energy-saving technological change can vary according to the value of the elasticity of substitution. We consider six values \{0.444, 0.02, 0.95, 1.25, 0.343, 0.580\}, the first of which is used to measure energy-saving technological change in Figures 1 and 2. The second and third values are close to the limit cases when the CES production function converges to Leontief and Cobb-Douglas, respectively. The second value is also Hassler et al.’s (2021) estimate of the elasticity of substitution between capital and fossil energy. Hassler et al. (2021) obtain the elasticity estimate using time-series data on the price and quantity of fossil energy in the
United States. The fourth value is Karabarbounis and Neiman’s (2014) estimate of the elasticity of substitution between capital and labor. Karabarbounis and Neiman (2014) obtain the elasticity estimate using long-term changes in the labor income of value added over 15 to 37 years in approximately 50 OECD and non-OECD countries. The second and fourth values are the lower and upper bounds of the existing estimates, respectively. The fifth and sixth values are the estimates obtained separately for the goods and service sectors using the specification in the second column of Table 2. Figures A5 and A6 show how energy-saving technological change varies according to the first four values in the goods and service sectors, respectively. Note that the scales of the right and left vertical axes are different. Energy-saving technological change grows tenfold when the elasticity of substitution increases from 0.444 to 0.95. Not only the magnitude but also the direction of energy-saving technological change can vary when the elasticity of substitution changes from 0.444 to 0.02 or 1.25. Figures A7 and A8 show that the results in Figures 1 and 2 remain almost unchanged regardless of whether we allow the elasticity of substitution to vary across sectors.

Second, we show the extent to which energy-saving technological change can vary according to the degree of returns to scale. We consider the CES production function extended to allow for increasing or decreasing returns to scale.

\[ y = \left[ (a_k k)^\sigma + (a_\ell \ell)^\sigma + (a_e e)^\sigma \right]^{\frac{\mu}{\sigma}} \quad \text{for} \quad \sigma < 1. \]  

(A.8)

The parameter \( \mu \) governs the degree of returns to scale. When the returns to scale are not constant, factor-augmenting technologies can be rewritten as:

\[
\begin{align*}
    a_k &= \left( \frac{r_k}{w_k + v + e} \right)^{\frac{\epsilon_k}{\sigma - 1}} \left( \frac{y}{k} \right)^{\frac{\mu}{\sigma - 1}}, \\
    a_\ell &= \left( \frac{w_\ell}{r_\ell + w_\ell + v + e} \right)^{\frac{\epsilon_\ell}{\sigma - 1}} \left( \frac{y}{\ell} \right)^{\frac{\mu}{\sigma - 1}}, \\
    a_e &= \left( \frac{v e}{r_k + w_\ell + v + e} \right)^{\frac{\epsilon_e}{\sigma - 1}} \left( \frac{y}{e} \right)^{\frac{\mu}{\sigma - 1}}.
\end{align*}
\]

(A.9) (A.10) (A.11)

where gross output is \( y = (r_k + w_\ell + v + e) (\omega/\mu) \). De Loecker, Eeckhout and Unger (2020) estimate the returns to scale in the United States from the year 1955 to 2016. They find that the estimates of the returns to scale vary over time and across specifications, ranging from 0.95 to 1.2. We consider a wider range of values for the returns-to-scale parameter \( \mu \) from 0.9 to 1.2. Figures A9 and A10 show how energy-saving technological change varies according to these values in the goods and service sectors, respectively. Energy-saving technological change varies only marginally according to the degree of returns to scale.

Third, we show the extent to which factor-augmenting technological change can vary after taking into account material inputs. Let \( m \) denote the material quantity, \( \tau \) the material price, and \( a_m \) material-
augmenting technology. We consider the CES production function with capital, labor, energy, and material inputs:

\[ y = \left[ (a_k k)^\sigma + (a_c \ell)^\sigma + (a_e e)^\sigma + (a_m m)^\sigma \right]^{\frac{1}{\sigma}} \quad \text{for} \quad \sigma < 1. \]  

(A.12)

Factor-augmenting technologies retain the same form as equations (6)–(8). In this case, gross output is \( y = (r k + w \ell + v e + \tau m)\omega \). Figures A11 and A12 show that both the magnitude and the direction of capital-, labor-, and energy-augmenting technological change remain essentially unchanged. In addition, there was not much change in material-augmenting technology in most of the countries.

Finally, we show the extent to which the results of growth accounting can change when material inputs are included. Table A1 reports the quantitative contribution of capital-, labor-, energy-, and material-augmenting technologies in addition to that of capital, labor, energy, and material inputs to economic growth for each country. Since the material share of income is large, the contribution of capital, labor, and energy inputs and of capital-, labor-, and energy-augmenting technologies to economic growth becomes smaller when material inputs are included than when they are not. However, the contribution of energy-saving technology is not negligible in many countries.
Figure A5: Energy-saving technological change for different values of the elasticity of substitution in the goods sector

Notes: Each line represents energy-saving technology \( \left( a_e \right) \) when the elasticity of substitution \( \left( \epsilon_s \right) \) is 0.444, 0.02, 0.95, or 1.25. The left and right vertical axes indicate the scale of \( a_e \) when \( \epsilon_s \) is 0.444 or 0.02 and when \( \epsilon_s \) is 0.95 or 1.25, respectively. All series are expressed as log differences relative to the first year of observations.
Figure A6: Energy-saving technological change for different values of the elasticity of substitution in the service sector

Notes: Each line represents energy-saving technology ($a_e$) when the elasticity of substitution ($\epsilon_r$) is 0.444, 0.02, 0.95, or 1.25. The left and right vertical axes indicate the scale of $a_e$ when $\epsilon_r$ is 0.444 or 0.02 and when $\epsilon_r$ is 0.95 or 1.25, respectively. All series are expressed as log differences relative to the first year of observations.
Figure A7: Energy-saving technological change in the goods sector when the elasticity of substitution varies across sectors

Notes: Each line represents energy-saving technology ($a_p$) when the elasticity of substitution ($\epsilon_{tr}$) is 0.343 or 0.444. The shaded area represents the 90 percent confidence interval. All series are expressed as log differences relative to the first year of observations.
Figure A8: Energy-saving technological change in the service sector when the elasticity of substitution varies across sectors

Notes: Each line represents energy-saving technology (\(a_e\)) when the elasticity of substitution (\(\epsilon_{ir}\)) is 0.580 or 0.444. The shaded area represents the 90 percent confidence interval. All series are expressed as log differences relative to the first year of observations.
Figure A9: Energy-saving technological change for different degrees of returns to scale in the goods sector

Notes: Each line represents energy-saving technology ($a_e$) when the scale parameter ($\mu$) is 1, 0.9, or 1.2. All series are expressed as log differences relative to the first year of observations.
Figure A10: Energy-saving technological change for different degrees of returns to scale in the service sector

Notes: Each line represents energy-saving technology \( a_e \) when the scale parameter \( \mu \) is 1, 0.9, or 1.2. All series are expressed as log differences relative to the first year of observations.
Figure A11: Capital-, labor-, energy-, and material-augmenting technological change in the goods sector

Notes: The solid, dashed, dotted, and dashed-dotted lines are capital-, labor-, energy-, and material-augmenting technologies \((a_k, a_l, a_e, a_m)\), respectively. The shaded area represents the 90 percent confidence interval for \(a_e\). All series are expressed as log differences relative to the first year of observations.
Figure A12: Capital-, labor-, energy-, and material-augmenting technological change in the service sector

Notes: The solid, dashed, dotted, and dashed-dotted lines are capital-, labor-, energy-, and material-augmenting technologies \((a_k, a_l, a_e, a_m)\), respectively. The shaded area represents the 90 percent confidence interval for \(a_e\). All series are expressed as log differences relative to the first year of observations.
Table A1: Sources of economic growth when material inputs are included

(a) Goods sector

| Country            | Period  | \( y \) | \( a_k k \) | \( a_\ell \ell \) | \( a_e e \) | \( a_{m+m} \) | \( k \) | \( \ell \) | \( e \) | \( m \) | \( a_k \) | \( a_\ell \) | \( a_e \) | \( a_{m+m} \) | \( a \) |
|--------------------|---------|---------|-----------|-------------|-------------|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| Sweden             | 1994–2005 | 5.27    | 0.57      | 1.47        | 0.27        | 2.96        | 0.43  | 0.03  | 0.19  | 1.90  | 0.14  | 1.43  | 0.08  | 1.06  | 2.72 |
| Italy              | 1978–2005 | 5.12    | 0.45      | 1.64        | 0.63        | 2.40        | 0.27  | -0.38 | 0.25  | 1.15  | 0.19  | 2.02  | 0.37  | 1.25  | 3.83 |
| Czech Republic     | 1996–2005 | 5.02    | 0.69      | 0.90        | 0.98        | 2.45        | 0.37  | -0.25 | 0.55  | 4.49  | 0.32  | 1.15  | 0.42  | -2.04 | -0.14|
| Finland            | 1978–2005 | 4.49    | 0.45      | 1.39        | 0.68        | 1.96        | 0.16  | -0.38 | 0.33  | 1.30  | 0.29  | 1.78  | 0.35  | 0.66  | 3.08 |
| Japan              | 1978–2005 | 3.55    | 0.25      | 0.95        | 0.17        | 2.19        | 0.37  | -0.37 | 0.11  | 0.90  | -0.12 | 1.31  | 0.06  | 1.29  | 2.54 |
| Austria            | 1980–2005 | 3.32    | 0.39      | 0.99        | 0.43        | 1.51        | 0.08  | -0.37 | 0.58  | 1.46  | 0.32  | 1.36  | -0.15 | 0.05  | 1.57 |
| Denmark            | 1980–2005 | 2.67    | 0.20      | 0.65        | 0.31        | 1.52        | 0.20  | -0.29 | 0.21  | 0.99  | 0.00  | 0.94  | 0.10  | 0.53  | 1.56 |
| United States      | 1978–2005 | 2.66    | 0.18      | 0.72        | 0.44        | 1.32        | 0.16  | 0.00  | 0.00  | 0.83  | 0.02  | 0.73  | 0.44  | 0.49  | 1.67 |
| Netherlands        | 1987–2005 | 2.06    | 0.28      | 0.46        | 0.02        | 1.30        | 0.11  | 0.00  | 0.48  | 1.10  | 0.17  | 0.46  | -0.46 | 0.20  | 0.37 |
| United Kingdom     | 1978–2005 | 1.99    | 0.17      | 0.34        | 0.59        | 0.89        | 0.09  | -0.47 | 0.24  | 0.40  | 0.09  | 0.82  | 0.35  | 0.49  | 1.74 |
| Germany            | 1992–2005 | 1.97    | 0.25      | 0.86        | 0.18        | 0.67        | 0.08  | -0.70 | -0.18 | 1.40  | 0.17  | 1.56  | 0.36  | -0.73 | 1.36 |
| Portugal           | 1996–2005 | -1.22   | -0.08     | -0.13       | -0.60       | -0.41       | 0.31  | -0.05 | 1.00  | 1.51  | -0.38 | -0.08 | 1.60  | -1.92 | -3.98|

Notes: The first column reports the annual rate of growth in gross output (\( y \)) from the first year of observation (\( t_0 \)) to 2005 (i.e., \( 100 \times (\ln y_{2005} - \ln y_{t_0}) / (2005 - t_0) \)). The sixth to thirteenth columns report the results of the Shapley decomposition based on the one-level CES production function. The second, third, fourth, and fifth columns report the sum of the numbers in the sixth and tenth columns, the seventh and eleventh columns, the eighth and twelfth columns, and the ninth and thirteenth columns, respectively. The last column reports the sum of the numbers from the tenth to thirteenth columns. Countries are arranged in descending order of growth rate of gross output by sector.