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Estimation of substitution elasticities in three-factor production functions: Identifying the role of energy

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Abstract

Existing estimation methods for multi-factor CES functions require limiting assumptions about the nature of technical change. We demonstrate how a system of equations and a fixed elasticity in the nested process can provide identification for more flexible specifications and for small data samples. We evaluate the role of energy inputs in an aggregate production function using data for Germany. The use of a Cobb-Douglas process for capital and labor by other studies biases elasticity estimates upwards. The estimated low elasticity means that energy availability is a potentially limiting factor for growth and that productivity gains for capital and labor are energy-using.

JEL classification: C30, E23, O41, O47, Q43
Keywords: technical change, multifactor production, energy demand, aggregate production

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1 Introduction

Energy consumption is integral to generating wealth within an economy. All transformative processes utilize energy of one form or another to effect value-adding changes. The utilization of new forms of energy has spurred many significant advances in economic output, productivity, and technology. Additionally, rising energy consumption as a function of economic activity and growth is one of the key issues which societies have to face, not only in their energy conservation efforts, but also in terms of environmental problems and geopolitical concerns about energy sourcing from politically unstable countries. Many dynamics at the macroeconomic level depend on the elasticity of substitution. For example, just like the impact of monetary policy and labor market policies, or the distribution of factor incomes, the role of energy can only be understood by examining the elasticity of substitution between production factors. In this paper, we develop a practical approach to estimating energy use in an aggregated three-factor nested constant elasticity of substitution (CES) production function and expand on existing methods of estimating this type of function. In doing so, we rely neither on a Cobb-Douglas nesting of capital and labor (Hassler et al., 2012) nor on strong neutrality assumptions[1] regarding technical change. We use this to examine the role of energy inputs as a third production factor, along with capital and labor, in an aggregate production function, using data for Germany. We demonstrate that holding the elasticity of the nested process fixed at an empirically motivated value enables us to estimate the parameters of a nested CES function with a minimum of limiting assumptions.

Our method extends and adapts the system approach formulated by León-Ledesma et al. (2010) for use with a nested CES production function. The application of the system approach is attractive, since direct estimations and linear approximations are either biased in their results or severely constrained in how they can model technical change — a consequence of the impossibility theorem formulated by Diamond et al. (1978). However, the unmodified system approach, when applied to a nested function, can produce severely biased results due to the identification problems within the nested CES process and the optimization behavior in nonlinear estimation algorithms. Nevertheless, starting from the results of a two-factor model and the implicit assumptions of the Cobb-Douglas nesting for capital and labor suggested by Acemoglu et al. (2012), Hassler et al. (2012), and Kander and Stern (2014) we find that treating the elasticity of the nested capital-labor CES process as a known constant during estimation gives the best results for simultaneously identifying the nesting (interprocess) elasticity and the technical change parameters. This marks a large increase in flexibility for empirically analyzing complex production functions.

The improved modeling of aggregate energy consumption enables us to better understand

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[1] Meaning that technical change is assumed to be zero for certain factors (Harrod-neutral with only labor productivity growth or Solow-neutral with only capital productivity growth) or not factor-specific (Hicks-neutral).

how factor use will develop, but also, importantly, the possible effects of energy constraints on growth. This underscores the fact that energy use is not only an environmental issue, but also a crucial economic one. The potential effect of energy constraints on economic output has been explored before: Jevons describes in 1865 how the possibility of exhausting its coal reserves was a threat for a rapidly industrializing and growing British economy. The topic resurfaced 40 years ago in the wake of the oil crisis, where the possible implications for growth were discussed by, among others, Dasgupta and Heal (1974), Solow (1974) and Stiglitz (1974). Saunders (1992) describes the importance of energy use and how it is substituted for other factors in an aggregated growth model. Ayres (2007) outlines the physical reasons for why energy as a production factor is likely to have a very low elasticity of substitution with respect to other production factors. Stern and Kander (2012) seek to further explore the topic of endogenous growth with the explicit inclusion of energy as a production factor. Generally, most studies that use an aggregated CES production function in order to explain long-term growth developments adopt a Cobb-Douglas process for capital and labor, which, due to its constraints, avoids the problems of identification in the nested CES process.

The CES model has been a powerful tool for research ever since its functional form for two factors was implied by Solow (1957) and formulated by Arrow et al. (1961). It is commonly used as a production function for analyzing the relationship between input factors, not only on a macroeconomic level as an aggregated production function, but also on a sectoral level and in panel data. Chirinko (2008) shows that the overwhelming empirical evidence points to substitution elasticities of less than unity between capital and labor. The fact that the CES function can model these different elasticities while still allowing for a precise economic interpretation of the parameters makes it an attractive choice compared to other approaches, such as Cobb-Douglas, which allows only a unitary elasticity of substitution. The attractiveness of n-input CES production functions for modeling complex interactions between inputs is in stark contrast with the difficulties of estimating them. This becomes more pressing when factor-biased technical change is included. A key insight of de la Grandville (1997) is the importance of considering the implicit technological impact of the elasticity of substitution. Solow (1956) already shows the dependence of growth on the interaction between elasticities and productivity: Under certain circumstances, a very high elasticity can allow for endogenous growth of per capita output even when there are no productivity gains. The standard way to estimate a CES production function uses the linear Kmenta approximation. The linear approximation is easy to estimate but has a number of drawbacks: (i) it only works when technical change is subjected to strong neutrality assumptions, (ii) its elasticity estimates are biased towards unity, and (iii) it does not work for nested models that include additional production factors.[2] Hoff (2004) demonstrates that the Kmenta approximation cannot be applied to more than two factors

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[2] An extensive treatment of other CES production function estimation approaches can be found in Henningsen and Henningsen (2011).

without further restrictions on parameter values. However, the alternative n-factor linear approximation proposed by Hoff still substantially biases the estimated elasticities towards unity, and lacks flexibility with respect to technical change specifications. Other studies of three-factor production models also including energy, such as Kemfert (1998) and Kemfert and Welsch (2000), either have not identified technical change, or, like Hassler et al. (2012) and Kander and Stern (2014), confine themselves to modeling capital and labor as a Cobb-Douglas process.

For many policy measures and distributional questions, the results are critically dependent on the elasticity of substitution between capital and labor (or the other factors used). King and Rebelo (1993), for example, analyze the rate of return on capital and its relationship with the elasticity of substitution. Klump and de la Grandville (2000) show how the elasticity can determine the level of per capita income. Engen et al. (1997) demonstrate that the impact of policy decisions, such as taxation schemes, varies substantially depending on the elasticity of substitution. Acemoglu et al. (2012) illustrate that the policy schemes necessary to combat climate change depend on the elasticity of substitution between production that utilizes clean or dirty energy inputs. More recently, Rognlie (2016) shows how the elasticity of substitution and technical change can explain a declining labor share. Chambers (1988) gives a comprehensive overview of how the addition ofinput factors further changes the interpretation of an elasticity of substitution in the case of more than two factors. We therefore expand on the importance of how substitution elasticities can be interpreted in a three-factor production function, and outline why Morishima elasticities, as defined by Blackorby and Russell (1981), best reflect the adaptive behavior resulting from price changes in a production process with three factors.

Since a direct estimation or use of the Kmenta approximation for three-factor CES models does not provide reliable results for models with a general definition of factor-specific technical change, we demonstrate how the León-Ledesma et al. (2010) system approach can be adapted for the three-factor case. For cross-sectional analysis, pioneering work on estimating a system of identifying equations was done by Marschak and Andrews (1944), who highlighted the empirical difficulties of correctly identifying the parameters of production functions from observed data. Moreover, they explicitly predicted the difficulties of making inferences from aggregate data. The system approach for two factors allows the estimation of elasticity, even without neutrality assumptions about technical change, which means that it circumvents the impossibility theorem of Diamond et al. (1978). A first necessary step is to normalize the production function (Klump et al., 2007) in order to produce parameter estimates that are independent of measurement choices. This means that the production functions of the same family can be identified correctly, regardless of the point on the production function or the measurement units used. The normalized function and its first-order conditions are then simultaneously estimated as a system. However, we find that the unrestrained system estimation does not provide robust results for three factors. One reason is that the nested process makes it impossible to isolate the productivity parameters in the first order conditions, which effectively removes the cross-equation constraints on technical change and elasticity in the nested process. We therefore hold the elasticity of the nested process constant during the estimation, mirroring the rigidity of the unitary elasticity in a Cobb-Douglas nesting. Another reason lies in the nature of nonlinear estimation: The numerical optimization for a nested production function has a tendency to get stuck near corner solutions, as a result of the close relation between elasticity and productivity, the discontinuity of the CES function around elasticities close to unity, and the relatively flat objective functions. Treating the nested elasticity as constant substantially improves the performance of the system approach, since the identification problem can be bypassed. This allows us to estimate the nested CES functions without a need for neutrality assumptions about technical change. Our estimation results imply that energy as a production factor has a very low elasticity of substitution, around 0.17, with regard to the capital-labor process. It follows from this result that productivity gains for capital and labor are energy-using, an important consideration for the evaluation of policies aimed at energy conservation. The elasticity estimate is between the much higher (and more long-term) estimation result of 0.65 obtained by Kander and Stern (2014) for Sweden and the result of a near zero elasticity obtained by Hassler et al. (2012) for the US. Given our observations about the behavior of nested CES functions and the modeling choices in these studies, we explain why the results differ, beyond the different data sets employed.

The remainder of this paper is structured as follows: We provide an outline of the development of the CES production function and its analysis, and describe the model in detail, in Section 2. In Section 3, we outline the data and its sources, and summarize its main features. We then compare the different specifications and identify the best approach to estimating a nested CES function in Section 4, where we also discuss the specific implications of the results on the role of energy as a production factor. We discuss the economic and methodological conclusions in Section 5.

2 Theoretical approach

2.1 The production function

In order to explain the use of energy and how it can be substituted for by other production factors we use the framework of an aggregated three-factor CES production function. A CES production function $F(x_1, x_2)$ relates the endogenous variable[3] Y (output) to the exogenous variables x_i (input factors), and is defined as

$$Y = A(\gamma {x_1^-}^\rho + (1-\gamma){x_2^-}^\rho)^{-\frac{1}{\rho}}. \tag{1}$$

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[3] The CES functional form can be applied to a number of economic topics, e.g. as a utility function, but it is most often used as a production function.

Factor A is a (Hicks-neutral) measure of productivity, $\gamma \in (0,1)$ is the equilibrium factor share of inputs, and $\rho \in (-1,0) \cup (0,\infty)$ determines the elasticity of substitution $\sigma = 1/(1+\rho)$. An advantage is that the CES formulation contains as its limits the Leontief production function when $\sigma \to 0$ ($\rho \to \infty$) and Cobb-Douglas functions when $\sigma \to 1$ ($\rho \to 0$).

One key problem with the CES production function, however, is that it is not easily linearizable for a reliable estimation of its coefficients. Kmenta (1967) proposed a Taylor expansion around $\sigma = 1$ as an approximation in order to estimate the function, but the technique works only when technical change is specified to follow some neutrality assumption. This approach also has the drawback that the Taylor series is expanded around a unitary elasticity of substitution, which can cause substantial biases towards unity, as shown by León-Ledesma et al. (2010). For non-neutral technical change, Diamond et al. (1978) posited an impossibility theorem, stating that biased or generalized technical change and the elasticity of substitution are not simultaneously identifiable.

Another issue is that of generalizability. It is not immediately clear how a CES formulation can be applied to the n-input case. As a generalized form, the following definition is discussed by (among others) Blackorby and Russell (1989):

$$Y = A(\sum_{i=1}^{n} \gamma_i x_i^{-\rho})^{-\frac{1}{\rho}}, \tag{2}$$
$$\text{with} \sum_{i=1}^{n} \gamma_i = 1.$$

This formulation, however, only allows for identical substitution elasticities between the input factors, a restriction that is often too limiting for real-world analyses. Sato (1967) suggests nesting multiple CES processes in a CES production function. This means that two inputs are combined in a CES production function, which is then nested in a further CES production function, either of a single input for a three-factor formulation or with another aggregate for four or more inputs. The nested formulation then looks like this:

for three factors:

$$Y = A\left(\gamma V_1^{\frac{\rho}{\rho_1}} + (1-\gamma)x_3^{-\rho}\right)^{-\frac{1}{\rho}} \tag{3}$$

for four factors:

$$Y = A\left(\gamma V_1^{\frac{\rho}{\rho_1}} + (1-\gamma)V_2^{\frac{\rho}{\rho_2}}\right)^{-\frac{1}{\rho}} \tag{4}$$
$$V_1 = \gamma_1 x_1^{-\rho_1} + (1-\gamma_1)x_2^{-\rho_1}$$
$$V_2 = \gamma_2 x_3^{-\rho_2} + (1-\gamma_2)x_4^{-\rho_2}.$$

Here, the ρ_i determine the elasticity of substitution within the factors of process V_i.

The model used is based on eqs. (1) and (3) but incorporates technology parameters that allow the incorporation of non-neutral (or biased) technical change. Expanding eq. (1) to allow for factor-biased technical change gives us the following production function:

$$Y_t = C\left[\gamma_L \left(A_{Lt}L_t\right)^{\frac{\nu-1}{\nu}} + \left(1-\gamma_L\right)\left(A_{Kt}K_t\right)^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}} . \tag{5}$$

Likewise, we define the nested three-factor model incorporating energy, biased technical change, and an energy quality index based on (3). Similar formulations have been proposed by Kemfert (1998), Hassler et al. (2012), Stern and Kander (2012) and Kander and Stern (2014). However, in both studies by Stern and Kander and the study by Hassler et al., capital and labor were nested in a more restrictive Cobb-Douglas process.

$$\begin{aligned} Y_t &= C\left(\gamma_V V^{\frac{(\sigma-1)\nu}{(\nu-1)\sigma}} + \gamma_E \left(A_{Et}Q_E E_t\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \\ \text{with } V &= \left[\gamma_L \left(A_{Lt}L_t\right)^{\frac{\nu-1}{\nu}} + \left(1-\gamma_L\right)\left(A_{Kt}K_t\right)^{\frac{\nu-1}{\nu}}\right] . \end{aligned} \tag{6}$$

Eq. (6) consists of a CES process (V) of capital (K) and labor (L) nested within a CES function with energy (E). Y denotes the produced output, C is a productivity parameter, σ is the elasticity of substitution between energy and the capital/labor aggregate, and ν is the elasticity of substitution between capital and labor. The parameters γ_V, γ_L, and γ_E are constants and denote the normalized within-process factor shares with $\gamma_V + \gamma_E = 1$. γ_L is the cost share of labor in the nested CES process. The productivity parameters, A_i, allow for factor-biased technical change. They are assumed to follow a constant time trend such that $A_{it} = A_{i0}e^{\alpha_i t}$. The choice of nesting a three-factor production function as (KL)E instead of (LE)K or (KE)L has been examined by Kemfert (1998), and is widely accepted as the standard way of separating the production factors (Saunders, 2008; Hassler et al., 2012; Stern and Kander, 2012).

Following Klump et al. (2007) we normalize eq. (6) before the estimation. Normalization means that the behavior of the production function is divorced from units and factors of measurements. As a consequence, production functions that are identical except for differing elasticities of substitution are tangent. More importantly, it also improves the estimates of the elasticity of substitution in the presence of biased technical change.

Normalizing eq. (6) with $A_{i0} = C = 1$, and dropping the time subscript for convenience, gives

$$
\begin{aligned}
Y &= \psi Y_0 \left(\gamma_V V^{\frac{(\sigma-1)\nu}{(\nu-1)\sigma}} + \gamma_E \left(e^{\alpha_E (t-t_0)} Q_E \frac{E}{E_0} \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \qquad (7) \\
\text{with } V &= \left[\gamma_L \left(e^{\alpha_L (t-t_0)} \frac{L}{L_0} \right)^{\frac{\nu-1}{\nu}} + (1-\gamma_L) \left(e^{\alpha_K (t-t_0)} \frac{K}{K_0} \right)^{\frac{\nu-1}{\nu}} \right].
\end{aligned}
$$

We choose the geometric sample average of our output, labor, capital, and energy measures as the normalization constants. For time and the factor share parameters, the sample mean is used[4]. Due to the stochastic nature of the data and the nonlinearity of the production function, an additional factor ψ has to be introduced with $E[\psi] = 1$.

2.2 Substitution elasticities

The concept of the elasticity of substitution is straightforward when looking at two production factors in a production function, but it becomes more complex when more than two factors are involved, which leads to multiple possible definitions of the elasticity . Stern (2011) provides a useful taxonomy of the different approaches that have been employed, and also establishes under what circumstances they differ from each other. The original Hicks-McFadden elasticity holds output constant and examines the ease of substitution between two specific input factors, while ignoring substitution possibilities with other production factors (de la Grandville, 1997). It was the basis for developing the CES production function. The Allen-Uzawa elasticity, formulated by Uzawa (1962), generalizes the concept to an n-factor case and explicitly allows other factors to adjust. Chambers (1988) points out that this makes the Hicks-McFadden elasticity a short-term elasticity in practice, since optimizing behavior would lead to adjustment over time for all factors when a factor price changes.

While Allen-Uzawa elasticities see widespread use due to a number of practical properties such as constancy and symmetry, Blackorby and Russell (1981, 1989) propose the Morishima definition of elasticity of substitution as an alternative that better reflects the behavior in the presence of price changes. In the two-factor case, the three definitions of elasticity are identical. In a nested CES formulation, however, the Morishima elasticities can be variable and asymmetric, depending on the cost shares in the different processes. This is because the nesting separates the relation between different levels of the nested production function. The top-level nesting elasticity σ in eq. (6), for example, does not account for substitution possibilities within the nested capital-labor process. In contrast, the Morishima elasticity accounts for all substitution possibilities and can be understood as the slope of the isoquants of the production function. It therefore more accurately reflects the ease with which factors can be substituted for one another. One caveat, however, is

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[4] The quality index Q_E is calculated using t_0 as a base year and is therefore already normalized.

that elasticities are not necessarily symmetrical due to this characteristic, if the factors are not within the same nest, meaning that the Morishima elasticity $\sigma_{ij} \neq \sigma_{ji}$ for i, j.

Blackorby and Russell (1989) define the Morishima elasticity σ_{ij} as $\sigma_{ij} = \eta_{ji} - \eta_{ii}$, where η_{ji} is the cross-price elasticity and η_{ii} the own-price elasticities of demand at constant output. Anderson and Moroney (1993) show that in the case of a nested CES function, this means that for goods i, j in the CES processes m, n, the Morishima elasticities can be defined using three factors: (i) σ_N, the constant nesting elasticity between processes, or interprocess elasticity; (ii) $\sigma_m(\sigma_n)$, the constant elasticity defining process $m(n)$ (the intraprocess elasticity); and (iii) γ_i^m, the cost share of the factor i in process m:

$$\sigma_{ij} = \sigma_{ji} = \sigma_{m(n)} \qquad \text{if} \quad i, j \in m(n) \tag{8a}$$

$$\sigma_{ij} = \gamma_i^m \sigma_N + (1 - \gamma_i^m)\sigma_m \qquad \text{if} \quad i \in m \quad \text{and} \quad j \in n \tag{8b}$$

$$\sigma_{ji} = \gamma_j^n \sigma_N + (1 - \gamma_j^n)\sigma_n \qquad \text{if} \quad i \in m \quad \text{and} \quad j \in n, \tag{8c}$$

where σ_{ij} is the Morishima elasticity between goods i and j, corresponding to a change in the price for good i. The equilibrium (average) Morishima elasticities for this three-factor nested CES function based on stable factor shares are then calculated using eq. (8):

$$\sigma_{KL} = \sigma_{LK} = \nu \tag{9a}$$

$$\sigma_{EL} = \sigma_{EK} = \sigma \tag{9b}$$

$$\sigma_{LE} = \gamma_L \sigma + (1 - \gamma_L)\nu \tag{9c}$$

$$\sigma_{KE} = (1 - \gamma_L)\sigma + \gamma_L \nu. \tag{9d}$$

While the Hicks-McFadden and Allen-Uzawa elasticities are always symmetric, i.e. $\sigma_{ij} = \sigma_{ji}$, this is not generally the case for Morishima elasticities. The reason is intuitively clear and underlines why Morishima elasticities are a better measure for the substitution possibilities in an n-good production function: When the price for good i changes the price relation p_i/p_j, it also changes the relative price of all other goods in relation to p_i. The difference between σ_{EL} and σ_{LE} is therefore due to the fact that a change in the price of energy does not change the relative prices of capital and labor. However, a change in the labor price that results in the same relative price movement for labor and energy simultaneously also changes the relative prices for capital and labor, therefore leading to a substitution within the capital-labor aggregate. Anderson and Moroney (1993) also formally show that in a nested CES formulation, σ_{LE} and σ_{KE} are not constant, but rather dependent on the factor share of L or K. In our results, we report the Morishima elasticities with respect to the average factor shares based on eq. (9).

In order to circumvent Diamond et al.'s impossibility theorem when estimating the elasticity of substitution as well as biased technical change, the methodology of Klump et al.

(2007) and León-Ledesma et al. (2010) is followed, and we construct a system of equations that permits us to jointly estimate the factors using normalized values in the production function. In doing so, we do not impose any limits on the values of α_i, which also means that we do not impose the condition that the output data have to be on a balanced-growth path (Uzawa, 1961). This allows the macroeconomic variables and key ratios, such as the capital-output ratio and factor income shares, to vary. While a balanced-growth path scenario is attractive for the tractability of the models, Acemoglu (2007) argues that transitional periods could lead to incentives favoring directed technical change for different production factors, even though technological progress seems to be asymptotically labor-augmenting. This argument is further strengthened in Acemoglu et al. (2012).

2.3 First-order conditions (FOCs)

In accordance with neoclassical economic theory and the existing literature, we expect production factors to be paid according to their marginal productivity in equilibrium. The relationship between real user costs and output is assumed to correspond to the accounting identity $Y \equiv wL + rK$ in the two-factor case and $Y \equiv wL + rK + pE$ in the three-factor case. w and r are the real wage and the real user cost of capital, respectively, whereas p represents the equivalent real energy price derived from the total real expenditure on all primary energy sources divided by the sum of heat units.

This gives us the following first-order conditions for a two-factor production function:

$$w = \left(\psi e^{\alpha_L(t-t_0)}\right)^{\frac{\nu-1}{\nu}} \cdot \left(\frac{Y_t/Y_0}{L_t/L_0}\right)^{\frac{1}{\nu}} \cdot \frac{\gamma_L Y_0}{L_0} \tag{10}$$

$$r = \left(\psi e^{\alpha_K(t-t_0)}\right)^{\frac{\nu-1}{\nu}} \cdot \left(\frac{Y_t/Y_0}{K_t/K_0}\right)^{\frac{1}{\nu}} \cdot \frac{(1-\gamma_L) Y_0}{K_0}, \tag{11}$$

and for the three-factor case:

$$p = \left(\psi e^{\alpha_E(t-t_0)}\right)^{\frac{\sigma-1}{\sigma}} \cdot \left(\frac{Y_t/Y_0}{Q_E \cdot E_t/E_0}\right)^{\frac{1}{\sigma}} \cdot \frac{\gamma_E Q_E Y_0}{E_0} \tag{12}$$

$$w = \left(\frac{Y_t}{Y_0}\right)^{\frac{1}{\sigma}} \cdot \left(\frac{L_t}{L_0}\right)^{\frac{-1}{\nu}} \cdot V^{\frac{\sigma-\nu}{\sigma(\nu-1)}} \cdot \left(e^{\alpha_L(t-t_0)}\right)^{\frac{\nu-1}{\nu}} \cdot \psi^{\frac{\sigma-1}{\sigma}} \frac{Y_0 \gamma_V \gamma_L}{L_0} \tag{13}$$

$$r = \left(\frac{Y_t}{Y_0}\right)^{\frac{1}{\sigma}} \cdot \left(\frac{K_t}{K_0}\right)^{\frac{-1}{\nu}} \cdot V^{\frac{\sigma-\nu}{\sigma(\nu-1)}} \cdot \left(e^{\alpha_K(t-t_0)}\right)^{\frac{\nu-1}{\nu}} \cdot \psi^{\frac{\sigma-1}{\sigma}} \frac{Y_0 \gamma_V (1-\gamma_L)}{K_0}. \tag{14}$$

For the estimation of the parameters, a system of equations consisting of the logs of the FOCs and the production function is used. Taking the logs helps to reduce the heteroskedasticity within the data. The simultaneous estimation increases the degrees of freedom[5] and allows us to utilize the cross-equation restrictions implicit in the system for

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[5] This is particularly helpful for small sample sizes.

a better identification. This, in combination with normalizing the variables of the production function to make them unitless, is the key to circumventing Diamond's impossibility theorem.

In order to evaluate the system approach for nested CES functions, we first construct a standard two-factor system of equations:

$$\ln\frac{Y}{Y_0} = \ln\psi + \frac{\nu}{(\nu-1)}\ln\left(\gamma_L\left(A_{Lt}L_t\right)^{\frac{\nu-1}{\nu}} + (1-\gamma_L)\left(A_{Kt}K_t\right)^{\frac{\nu-1}{\nu}}\right) \tag{15a}$$

$$\ln w = \frac{\nu-1}{\nu}\left(\ln\psi + \alpha_L\left(t-t_0\right)\right) + \frac{1}{\nu}\ln\left(\frac{Y_t/Y_0}{L_t/L_0}\right) + \ln\frac{\gamma_L Y_0}{L_0} \tag{15b}$$

$$\ln r = \frac{\nu-1}{\nu}\left(\ln\psi + \alpha_K\left(t-t_0\right)\right) + \frac{1}{\nu}\ln\left(\frac{Y_t/Y_0}{K_t/K_0}\right) + \ln\frac{(1-\gamma_L)Y_0}{K_0}. \tag{15c}$$

Analogously, we estimate the three-factor model using the following system of equations:

$$\ln\frac{Y}{Y_0} = \ln\psi + \frac{\sigma}{(\sigma-1)}\ln\left(\gamma_V V^{\frac{(\sigma-1)\nu}{(\nu-1)\sigma}} + \gamma_E\left(e^{\alpha_E(t-t_0)}Q_E\frac{E}{E_0}\right)^{\frac{\sigma-1}{\sigma}}\right) \tag{16a}$$

$$\begin{aligned}\ln w = {} & \frac{1}{\sigma}\ln\left(\frac{Y_t}{Y_0}\right) - \frac{1}{\nu}\ln\left(\frac{L_t}{L_0}\right) + \frac{\nu-1}{\nu}\left(\alpha_L\left(t-t_0\right)\right) + \frac{\sigma-1}{\sigma}\ln\psi \\ & + \frac{\sigma-\nu}{\sigma(\nu-1)}\ln V + \ln\frac{Y_0\gamma_V\gamma_L}{L_0}\end{aligned} \tag{16b}$$

$$\begin{aligned}\ln r = {} & \frac{1}{\sigma}\ln\left(\frac{Y_t}{Y_0}\right) - \frac{1}{\nu}\ln\left(\frac{K_t}{K_0}\right) + \frac{\nu-1}{\nu}\left(\alpha_K\left(t-t_0\right)\right) + \frac{\sigma-1}{\sigma}\ln\psi \\ & + \frac{\sigma-\nu}{\sigma(\nu-1)}\ln V + \ln\frac{Y_0\gamma_V(1-\gamma_L)}{K_0}.\end{aligned} \tag{16c}$$

$$\ln p = \frac{\sigma-1}{\sigma}\left(\ln\psi + \alpha_E\left(t-t_0\right)\right) + \frac{1}{\sigma}\ln\left(\frac{Y_t/Y_0}{Q_E\cdot E_t/E_0}\right) + \ln\frac{\gamma_E Q_E Y_0}{E_0} \tag{16d}$$

The system approach with cross-equation restrictions effectively triples our degrees of freedom in eqs. (15) and quadruples them in eqs. (16). However, in a three-factor production model, two more variables have to be estimated, which increases the number of estimated parameters from four in eqs. (15) to six in eqs. (16). More importantly, the nesting means that the productivity parameters for capital and labor are not restrained by additional cross-equation restrictions, since they are always explicitly included in V, thus reintroducing the identification problem identified by Diamond et al. (1978). This is why we systematically test the different specifications of the system approach and evaluate the robustness of the results to gauge how problematic this identification problem is for estimation.

3 Data

We use annual output, capital, and labor data from the German Statistical Office (Destatis) for the years 1991 – 2013[6] and energy data from the yearly energy accounts ("Energiebilanzen"), also provided by Destatis.

For the output measure, we use gross value added at factor costs for the private, non-residential sector, which means excluding indirect taxes, taxes on imports, and production taxes less subsidies. Housing, government services, and non-profit organizations are excluded from this measure. Notice that, in contrast to Stern and Kander (2012), we do not add the energy expenditures to this output measure. In order to compare the differences from estimating a two-factor and a three-factor model, using the same output measure seems advisable. It also allows us a better interpretation of the different elasticities for the capital-labor aggregate in the three-factor case. Output and factor prices are converted to real terms using the appropriate deflators as reported by Destatis.

Labor statistics are constructed analogously to the output data from Destatis. We use the number of private non-residential employees, of self-employed persons, and the total employee compensation in these sectors as our employment measures[7]. We do not use the reported gross wages, because they do not include payments into social services and retirement insurance made directly by the employers. Since we are interested in the factor cost of labor, total compensation more adequately reflects this cost. Additionally, self-employed people are obligated to pay all social insurance premia themselves. In order to disentangle capital and labor income for self-employed people, the labor compensation is a useful measure of the shadow price of labor. We therefore multiply the wage per employee in the private sector by the total number of people active in the labor force in order to more accurately reflect the split between capital and labor income (Klump et al., 2007).

Private non-residential net capital stock is also published in the yearly accounts. It is compiled using the perpetual inventory method and evaluated at repurchasing costs. Real user cost is then derived from the accounting identity. This is preferable to the error-prone derivation of real user costs of capital[8]. It means that the implied real user cost in the two-factor case is slightly higher than in the three-factor model. The economic interpretation is that the energy needed to utilize the capital is included in the real user costs of capital in the two-factor case. Another issue that has to be acknowledged is that letting the capital returns be identified by the accounting identity makes the Cambridge capital controversy relevant, since the rate of return depends on the measurement of the capital stock (Schefold, 2008).

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[6] Before 1991, the available energy data are limited, and one would also have to account for the structural break incurred by German reunification in 1990.

[7] Note that we call the labor compensation, as a factor cost for labor, wages as a more natural shorthand.

[8] This reduces the number of estimated parameters and is in line with empirical results from other studies, cf. Clarida et al. (1999); León-Ledesma et al. (2015). Other sources, such as Piketty and Zucman (2014), have similar values for capital costs.

Energy data is compiled using data on the sum of the heat contents of the primary energy sources (hard coal, lignite, gas, oil) and primary electricity[9] (such as from nuclear energy, hydro power, photovoltaics, and wind energy). Primary electricity, in this case, is electricity which is not produced from other primary energy sources which are quantifiable by volumes and meaningful prices. For mostly imported energy sources, such as oil, gas, and hard coal, we use the price at the border without tariffs and taxes. Primary electricity is valued at the gross weighted electricity price[10]. For lignite we assume a weighted average of the dust and brick lignite prices reported by the German statistics for the coal industry. All prices are converted to €/PJ in order to relate them to the heat content of the energy sources. The energy price p in the accounting identity and eq. (16d) is derived from actual energy expenditures on all the primary energy sources divided by the total sum of heat units, and therefore represents the average price per Joule in the production process.

The prices are then used to create a quality index which relates the simple sum of heat units to the different prices of energy sources. We follow the rationale of Kander and Stern (2014), who argue that the different productivity of energy sources is reflected in their relative prices. The heat content of different energy sources does not result in the same amount of useful energy[11] available in the production process for the different primary energy sources. A comparison of the relative prices of the different energy sources confirms this intuition: Primary electricity, as the most versatile energy source, has the highest price, followed by oil and natural gas. Hard coal and lignite have lower prices with the latter, where the process of extracting useful energy is laborious, being the cheapest primary energy source. In order to better model the aggregate development of energy use, we construct the quality index to reflect that the sum of heat contents is only an approximate measure of the actually available useful energy in the production process. The quality index is constructed from a Fisher-chained quantity index, which is divided by an index of the sum of heat units. This means that the productivity measure for energy is actually split: We have the estimated factor productivity parameter α_E and the energy quality index Q_E. Productivity improvements stemming from the substitution of less versatile energy sources for energy sources that are easier to use are therefore captured in Q_E.

The data shows that output growth in the observed periods has been modest, with only 1.01% annual growth on average. Table 1 also shows that primary energy consumption (as defined above) actually shrunk at the same time, from 13,415 PJ in 1991 to 12,010 PJ in

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[9] Electricity is normally considered secondary energy, or an energy carrier, since it is the product of an energy conversion process. However, we want to distinguish electricity which is not produced from fuel sources with meaningful market prices and directly used as a factor input, and which we therefore call "primary electricity", from electricity which is generated in a conversion process from other primary energy sources in the productive sector. In order to model the implications of the shift towards renewable energy, we therefore follow Kander and Stern (2014) and explicitly account for primary electricity.

[10] Weighting is necessary, because electricity prices can vary depending on how much is consumed as well as when it is consumed.

[11] The term "useful energy" should not be confused with the useful output of an energy conversion process at the end-use energy stage in the fuel chain, such as the light of a light bulb. We use it in a wider sense as a natural shorthand to mean energy in any form that is used as an input in the production process.

Table 1: Data overview 1991-2013

	1991	2013	mean	yearly change
Output (Bill. €)	1,340.32	1,688.86	1,496.83	1.01%
Labor input (1000 people)	32,303.00	34,693.00	32,497.61	0.31%
Capital stock (Bill. €)	2,112.19	2,914.66	2,599.89	1.40%
Primary energy (PJ)	13,415.18	12,010.35	12,651.37	-0.48%
Wages (€)	28,939.46	33,052.05	31,582.75	0.58%
Real user cost of capital	16.09%	14.18%	15.06%	-0.55%
Energy price (€/GJ)	4,897.47	10,740.75	6,268.43	3.41%
Quality index of energy	0.91	1.05	1.00	0.65%
Labor share	69.75%	67.90%	68.76%	-0.12%
Capital share	25.35%	24.47%	26.10%	-0.15%
Energy share	4.90%	7.64%	5.13%	1.93%

2013. In contrast, the price per Joule and the quality of the energy increased markedly, which results in an increase of the energy share of output from 4.90% to 7.64%. The data conforms with our expectations about the developments over time. The factor shares are relatively stable, the recent reduction in interest rates following the financial crisis is reflected in the user cost of capital, and, whether through policy measures that mandate a switch to renewable energies or an increase in fossil fuel prices since 1991, energy prices have risen substantially.

We also see the effects of the 2008 crisis reflected in the data: from 2008 to 2009 output shrunk by more than 8%, with a corresponding 7% drop in energy demand. The real user cost of capital dropped from 17.6% in 2007 to 13.2% in 2009, leading to a drop in the capital share from a high of 30.1% to only 24.9% in 2009. The developments of the quality index confirm the intuition that the energy mix shifts away from low-cost, low-quality primary sources like lignite to primary sources like natural gas or renewable energy. This trend is observable despite the phasing out of nuclear energy, which provides electricity at low market costs[12]. The increased use of primary electricity more than outweighs the reduction in nuclear energy output in the dataset.

4 Estimation results

4.1 Two-factor model

Due to the importance of the estimation method for the identification of substitution elasticities demonstrated by Chirinko (2008) we want to first compare the relative performance of the system approach to other methods. In order to show the strength of the system

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[12] The question of whether the true costs of nuclear energy are sufficiently internalized notwithstanding.

approach in estimating biased productivity changes and elasticities in a CES production function, we therefore initially perform the analysis for two factors. This also allows us to compare the results with existing studies and provides additional validation of the data and the methodology. We used the following three distinct specifications:

1. A direct estimation of the two-factor production function with total factor productivity;
2. A model with identical factor productivities[13];
3. A model with biased factor productivity gains as defined in eqs. (15).

The estimation results for the three models, shown in Table 2, exhibit a stark difference in performance between a direct estimation (model 1) and the system approach (models 2 and 3). The results of models 2 and 3 mirror the results of other empirical studies of σ in a two-factor case[14]. They have a good performance in all estimation techniques applied (NLSUR, 2SLS, 3SLS, FIML and GMM estimation)[15]. When comparing model 1 with models 2 and 3, it becomes clear that the system approach markedly improves the elasticity estimation results. We also see that identifying a biased productivity change can give more insight into how factor use develops, since factor productivity changes and elasticity estimates are linked.

Table 2: Estimation results for two-factor CES functions

	Model 1	Model 2	Model 3
	Coeff. (Std. Error)	Coeff. (Std. Error)	Coeff. (Std. Error)
ψ	0.9997^{***}	0.9790^{***}	0.9783^{***}
	(0.0040)	(0.0024)	(0.0024)
ν	1.5670	0.6577^{***}	0.5598^{***}
	(7.3683)	(0.0044)	(0.0036)
α	0.0047^{***}	0.0025^{***}	
	(0.0007)	(0.0004)	
α_L			0.0038^{***}
			(0.0010)
α_K			-0.0012
			(0.0019)
Res. cov.		$1.54E{-}11$	$1.54E{-}11$
R^2	0.9490	0.8470	0.8413
Adj. R^2	0.9439	0.8317	0.8162

All systems were estimated using EViews 8. Std. errors in parentheses. R^2 and adj. R^2 are reported w.r.t. (15a)

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[13] The results for a total productivity parameter are not reported, as they are identical to this formulation.

[14] For an overview of the estimation techniques that are used and the range of results, see Chirinko (2008).

[15] We use Eviews 8 and its system estimation capabilities to estimate the equation systems

León-Ledesma et al. (2015) show that assuming Hicks-neutral technical change leads to estimates of ν that are biased towards Cobb-Douglas. If, instead, Harrod-neutrality is assumed, the elasticity is also biased upwards when the true value is below unity. This is because the estimator tries to correct for trends in the observed data that are contrary to the imposed neutrality restrictions. This can also be seen in the estimation results, where the estimates for Hicks-neutral technical change lead to higher elasticity estimates. We also see a slight factor productivity decrease for capital over time, of around 0.1%. However, the fact that the null hypothesis for α_K cannot be rejected at even the 10% level implies that the Harrod-neutrality assumption might be fitting. Labor productivity, on the other hand, is increasing at 0.38% per year in the time examined. The connection between elasticity estimates and the estimated technical change, as established by Diamond et al. (1978), is not severed by using a system approach to circumventing the impossibility theorem. In the different results for models 2 and 3, we see how the specification of technical change can have a striking effect on the estimated elasticity of substitution. This effect is exacerbated when the model is expanded to three factors, which further underlines the need for estimation methods able to cope with biased technical change specifications.

4.2 Three-factor system estimation

4.2.1 Fixed elasticity identification

After the initial validation of the estimation technique and data in section 4.1, we estimate different specifications of eqs. (16) using multiple estimation techniques to showcase how the identification problem in the nested CES function influences estimation results. From section 4.1 we also have a benchmark value $\nu = 0.56$, which is in line with the literature. Since we saw in section 2.3 that the introduction of a third factor in a nested process means that cross-equation restrictions cease to restrict the estimates of the productivity parameters, we expect that it is necessary to hold the elasticity in the nested process fixed when estimating the function with generalized productivity specifications. We therefore estimate the system using different values for ν to show the performance of the system estimation under a number of different specifications.

We choose ν based on the two-factor estimation results of 0.56 and 0.66 and two additional values of 0.5 and 0.75 to validate the model's behavior around the estimated values. Furthermore, we compare the results when setting ν to more extreme values of 0.1 and 0.99. This gives us an effective grid around the estimated values and two extreme values, one with very low capital-labor substitution (which would also violate the nesting assumptions of separability of input factors) and one near the Cobb-Douglas limit of the CES process. We estimate the systems using a GMM estimator with heteroskedasticity and autocorrelation consistent errors and using the lag of the endogenous variables and output as instruments. This is necessary due to the autocorrelation in the data. Estimation using

SUR estimators can often lead to very low Durbin-Watson scores for the residuals of the individual equations. The results are reported in Table 3.

Table 3: Estimation results for different values of ν

	$\nu = 0.1$	$\nu = 0.5$	$\nu = 0.56$	$\nu = 0.66$	$\nu = 0.75$	$\nu = 0.99$
ψ	0.9923***	1.0028***	1.0029***	1.0029***	1.0030***	1.0058***
	(0.0013)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
σ	0.0028***	0.1704***	0.1713***	0.1723***	0.1727***	0.1535***
	(0.0001)	(0.0011)	(0.0010)	(0.0008)	(0.0006)	(0.0004)
ν	0.1	0.5	0.56	0.66	0.75	0.99
	fixed	fixed	fixed	fixed	fixed	fixed
α_L	0.0078***	0.0076***	0.0079***	0.0085***	0.0097***	0.1040***
	(0.0003)	(0.0000)	(0.0000)	(0.0001)	(0.0001)	(0.0019)
α_K	−0.0033***	−0.0034***	−0.0039***	−0.0054***	−0.0079***	−0.2553***
	(0.0002)	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0051)
α_E	0.0098***	0.0047***	0.0047***	0.0046***	0.0046***	0.0055***
	(0.0005)	(0.0001)	(0.0001)	(0.0000)	(0.0000)	(0.0001)
σ_{LE}	0.0332	0.2734	0.2927	0.3247	0.3531	0.4148
σ_{KE}	0.0696	0.3970	0.4386	0.5077	0.5697	0.7287
Res. Cov.	0.0116	$1.11E{-}11$	$7.96E{-}12$	$4.43E{-}12$	$2.44E{-}12$	$6.97E{-}13$
J-Statistic	0.4862	0.0606	0.0589	0.0567	0.0557	0.0924
R^2	0.8858	0.9461	0.9464	0.9456	0.9470	0.9516
Adj. R^2	0.8590	0.9334	0.9338	0.9345	0.9352	0.9403
DW Eq. (16a)	0.7107	1.4572	1.4421	1.4233	1.4712	1.6061
DW Eq. (16b)	1.2632	1.3098	1.3184	1.3298	1.3391	1.5197
DW Eq. (16c)	1.2737	1.3090	1.3520	1.4073	1.4441	1.3888
DW Eq. (16d)	0.9456	1.6589	1.6563	1.6536	1.6532	1.7921

All systems were estimated using GMM in EViews 8. Std. errors in parentheses.
R^2 and adj. R^2 are reported w.r.t.(16a)

When we fix ν[16], we see that our estimates of the respective factor productivity changes are generally in line with other empirical results, albeit with the surprising result of a diminishing α_K[17]. Likewise, we have remarkably consistent estimates of σ around 0.17, which is in line with theoretical considerations about the substitutability of energy (Ayres, 2007). When setting $\nu = 0.99$, we can observe pronounced fluctuations in the estimated α's, which is explained by the fact that α_K and α_L can not be separated and capital and labor are near perfect substitutes. In fact, the closer to unity one sets ν, the more extreme the values of the α's become. However, the weighted average productivity of the capital-labor aggregate is only about 0.49%. Similarly, when setting $\nu = 0.1$, the results change dramatically, with a near zero estimate for σ. Note that this can be explained by the nesting structure of a CES function, which should be motivated by the separability of

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[16] Sato (1967) already proposed a stepwise estimation procedure for nested CES functions as a potential method.

[17] This could be an artifact of the financial crisis and the impact of the German reunification.

input factors: $\nu = 0.1$ implies that σ should be even smaller, given the nesting structure we use. This is in contradiction to the empirical results between 0.15 and 0.17 we see with other specifications. It is, however, not an unexpected result, since $\nu \leq \sigma$ would imply that the *inter*process elasticity is larger than the *intra*process elasticity.

As the results for $\nu \in \{0.5, 0.56, 0.66, 0.75\}$ show, a reliable estimate of a nested production function with generalized productivity parameters is indeed feasible. In the band of probable ν-values we see that regardless of the chosen value, our estimates for σ remain stable at 0.17. This provides further confirmation that our estimate of σ is robust, and that the true value is in this area. It suggests that energy and capital/labor are gross complements, at least in the medium-term observed in our sample. The outcome of our analyses offers further evidence that the chosen nesting structure appropriately reflects substitution possibilities between the three factors.

The robustness of the result of σ means that the Morishima elasticities (reported in Table 3 using the average factor shares) of labor and energy σ_{LE}, and capital and energy σ_{KE} depend crucially on the value of ν. The Morishima elasticity of capital and energy in particular is more sensitive to different values of ν, since the smaller factor share of capital mean that σ play a larger role for the substitution behavior of capital. The results also show that changes in the user cost of capital lead to a stronger adjustment of energy demand than changes in the wages.

Analysis of the residuals shows that for $\nu \in \{0.5, 0.56, 0.66, 0.75, 0.99\}$, the null hypothesis that residuals are multivariate normal cannot be rejected. Despite using Newey-West HAC errors, autocorrelation can also still be observed in the residuals. However, the heteroskedasticity and autocorrelation are mainly to be found in the residuals of the output and wage series, normality of the residuals cannot be rejected for the user cost of capital and energy price series. The residuals display a break for 2009, the year with the sharpest downturn in German output owing to the financial crisis and the following recession. We see a negative residual for $\log Y/Y_0$ and upticks in the residuals for $\log w$ and $\log r$. This squares up well with the notion of sticky factor prices. However, it has to be mentioned that our data cannot account for unused capital stock. Accounting for real in-use capital as opposed to just capital stock in place could give even better results in tumultuous periods. The results of our estimation show a remarkable internal consistency between specifications and when placing them in context with other studies (Chirinko, 2008). Despite the short and tumultuous period under consideration (1991–2013), we see that the system approach gives robust results. Not only does the period encompass the immediate aftermath of German reunification in 1990, and with it a restructuring of productive capital stock, but it also includes the financial crisis in 2008 with its impact on output and capital utilization. At the same time, the German government launched efforts to change the mix of energy sources used in the economy in an attempt to limit the consumption of relatively cheap fossil fuels. Overall, average annual growth in the observed time-period is only a modest

1.01%, which, in the presence of elasticities below unity, limits the size of the expected technical change. The estimated values that we see for the technical change parameters in Table 3 reflect this. They also conform with an intuitive sanity check on the signs, with energy and labor costs increasing over the observed period in contrast to capital costs, which declined. Labor and energy inputs, however, decreased or stagnated relative to output growth, whereas the average yearly increase of capital stock outpaced output growth.

4.2.2 Standard system estimation

The results in table 3 show a good performance of the estimator and allow us to identify the plausible values for ν and evaluate them based on analysis of the residuals. The comparison with the results from unrestricted systems can establish what happens when the limitation of a fixed value for ν is relaxed. We estimated the following six models which highlight the potential issues that can arise when ν is freely estimated or when non-HAC errors are used for estimation. The models employ the following specifications:

1. Using total factor productivity and estimated ν;
2. Using generalized technical change and estimated ν with a GMM estimator;
3. Using generalized technical change and estimated ν with a SUR estimator;
4. Using a Cobb-Douglas process for labor and capital;
5. Using a fixed value for σ;
6. Using generalized technical change and $\nu = 0.66$ with a SUR estimator.

The models progress from a simple specification using of Hicks-neutrality for model 1 to a generalized specification using different estimating procedures in models 2 and 3. We then estimate a common three-factor specification with a Cobb-Douglas process for capital and labor (model 4). Afterwards we show that fixing the interprocess elasticity σ is insufficient (model 5), and compare the results of the model $\nu = 0.66$ using GMM to ones using SUR in model 6. The results are reported in Table 4. The intuition that the system estimation alone is not enough to allow a completely unrestrained estimation of the nested process is confirmed in the first three models where ν is freely estimated.

Introducing biased productivity change into the model highlights the difficulty of a robust identification for the inner processes of a nested CES function. In model 2, with all α_i as well as ν and σ freely estimated, we see an estimated productivity drop of 17% p.a. for capital combined with a 7% yearly gain in labor productivity. The estimate for ν is very close to unity, and thus close to the discontinuity of the production function. We see a similar result in model 3, but there are three key differences: (i) a higher estimate of σ, (ii) a reversal of the signs of α_L and α_K, and (iii) substantially worse Durbin-Watson

Table 4: Estimation results for three-factor production function

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ψ	1.0029***	1.0051***	1.0071***	1.0103***	1.0033***	1.0067***
	(0.0001)	(0.0001)	(0.0033)	(0.0006)	(0.0005)	(0.0024)
σ	0.1781***	0.1914***	0.3008***	0.5021***	0.2	0.3145***
	(0.0006)	(0.0005)	(0.0295)	(0.0002)	fixed	(0.0708)
ν	5.1763***	0.9863***	0.9623***	1	1.7244***	0.66
	(0.0636)	(0.0013)	(0.0230)	fixed	(0.0229)	fixed
$\alpha_{(L)}$	0.0043***	0.0733***	-0.0436	0.0055***	0.0057***	-0.0057^{***}
	(0.0000)	(0.0050)	(0.0299)	(0.0001)	(0.0001)	(0.0014)
α_K		-0.1738^{***}	0.1545*		0.0064***	0.0306***
		(0.0131)	(0.0793)		(0.0001)	(0.0015)
α_E		0.0036***	0.0043	-0.0230^{***}	0.0032***	-0.0082
		(0.0001)	(0.0026)	(0.0001)	(0.0001)	(0.0063)
σ_{LE}	1.7395	0.4397	0.5075	0.6576	0.6762	0.4224
σ_{KE}	3.6150	0.7380	0.7557	0.8445	1.2482	0.5521
Res. Cov.	$6.85E{-}12$	$9.73E{-}12$	$1.62E{-}10$	$6.24E{-}14$	$9.73E{-}12$	$2.31E{-}10$
J-Statistic	0.0665	0.1083		0.3616	0.1083	
R^2	0.9436	0.9456	0.7733	0.9294	0.9456	0.9401
Adj. R^2	0.9342	0.9328	0.7066	0.9176	0.9328	0.9268
DW Eq. (16a)	1.3670	1.4233	0.3343	1.0959	1.4233	1.2005
DW Eq. (16b)	1.3661	1.3071	1.1733	0.8439	1.3071	0.1855
DW Eq. (16c)	1.6455	1.5270	1.4974	0.8564	1.5270	0.2922
DW Eq. (16d)	1.6275	1.5398	0.9272	0.4641	1.5398	0.7854

All systems were estimated using GMM in EViews 8. Std. errors in parentheses.
R^2 and adj. R^2 are reported w.r.t.(16a)

statistics for the residuals, in particular for the output series (16a). When we examine the factor productivity increase for the capital-labor process as the average of the two extreme productivity estimates weighted by their factor shares, we find an average yearly productivity increase of 0.53% for model 2 and 1.01% for model 3. When the production function is explicitly specified as Cobb-Douglas, as in model 4, estimation yields a combined 0.55% yearly productivity gain for the capital-labor process as well as a significantly higher value for σ of 0.5, which is similar to the results of Stern (2012) and Kander and Stern (2014) of around 0.65, who also use a Cobb-Douglas nesting for capital and labor. The ν estimate so close to 1 exacerbates rounding errors and other difficulties with the numerical estimation procedure, as noted by Henningsen and Henningsen (2012). In model 5 we see that a reversed strategy is unsuccessful: Fixing $0.15 > \sigma > 0.2$ produces results which are similar to those of Models 1 and 2 with very high values for ν. Regardless of the choice of σ, ν is estimated as being close to, or larger than unity. When σ is set very far from the estimated value with $0.3 > \sigma > 0.9$ the values for α_E become negative and very large, in order to compensate for the imposed structure implied by the elasticity parameter. This result is mirrored in model 4, where we also see a high estimated σ combined with a strongly decreasing energy productivity of -2.3% per annum.

We see from the results for all six models that ψ is always suitably close to one, which is what we expected from our formal normalization. It is also apparent that the correct identification of technical change can be problematic when other approaches are used. Whereas the results with an empirically motivated fixed value for ν in 4.2.1 show robust results for the sign of the α's and the value of σ across specifications, using less flexible specifications or estimators without HAC-errors can reverse the signs of the estimated productivity changes or reduce the statistical significance. It also implies a much higher value of σ then we found before.

The two-factor analysis in Section 4.1 shows an elasticity of substitution around of 0.56 and 0.66 between capital and labor, depending on how technical change is specified, which is in line with the majority of other empirical results (Chirinko, 2008). In the expansion to three factors, however, the elasticity of substitution between capital and labor estimated in models 1, 2, and 3 is biased upwards. Despite the fact that the expansion to four equations increases the degrees of freedom of the system, identification becomes significantly worse for the parameters, especially for the nested production process (see 2.3). The results is an extension of the results of León-Ledesma et al. (2015), who show for two factors, that the elasticity estimates can pick up dynamics arising from a misspecification of the technical change parameters. This is exacerbated in the presence of nesting, and with the small absolute variations in the data of the sample. Furthermore, not accounting for the autocorrelation in the data has a tremendous impact on the results, which is highlighted in models 3 and 6: In both cases the estimates for ν are significantly higher than when using a GMM estimator. From the Durbin-Watson statistics we can infer that the estimates obtained from the SUR estimator still show significant autocorrelation in the residuals.

4.2.3 Interpretation of the results

One notable result is that the estimated two-factor elasticity of 0.56 is lower than the best fitting values of $\nu \in \{0.66, 0.75\}$, which have the best relative performance in the analysis of the residuals and also respond to empirical results of other studies. A possible explanation is the conceptual change from the two-factor model to the three-factor model: in the two-factor model, the energy expenditures are part of the capital income share, since labor compensation and output are identical for the two-factor model and the three-factor model. This means that the possibilities of substituting energy and labor are part of the substitution possibilities between capital and labor inputs. Once the low-elasticity energy inputs into production are explicitly accounted for, the elasticity of substitution between labor inputs and capital inputs increases. The result is in line with the conclusions of Sato (1967) regarding the practical concerns with separating the different levels of the CES production function: He assumed that interprocess elasticities can be expected to be smaller than intraprocess elasticities, thus accounting for their relative technological and economic similarity and differences. The results thus further validate the choice of a (KL)E nesting of production factors.

In addition to the inherent identification problem, estimating the nested CES function presents non-trivial technical challenges: Due to the nature of the objective function with its local extrema and wide flat areas, evaluating different specifications while holding certain parameters fixed can lead to much better performance, as shown by Henningsen and Henningsen (2011). As ν and σ approach 0 or 1, the objective function for the numerical estimation becomes ill-behaved. This is due to the discontinuities of the function when $\nu \in \{0, 1\} \vee \sigma \in \{0, 1\}$. Around these values the numerical solver can get stuck, since slight variations can lead to very large swings. In particular, the results for the elasticity and technical change of the nested factors have to be put under scrutiny. The performance of the numerical estimation procedure and the strength of the identification of the specification are linked: the specifications in 4.2.2 are sensitive to initial conditions and convergence of the unrestrained systems could be problematic. In contrast, the results in 4.2.1 were robust to a wide range of initial values, and converged reliably.

Compared to other studies, our results show that medium-run substitution elasticity is low, but not zero, which was the result of Hassler et al. (2012). One reason might be in the estimation method and identification strategy. We employed a system approach rather than a maximum likelihood estimator to identify the elasticity, because of the limits of a direct estimation and the bias of the available approximation methods. The maximum likelihood estimator introduces bias in the estimation, especially when it is used to identify the technical change parameter simultaneously. Another reason could lie with the data used: Since the elasticity of substitution is not entirely exogenous, but also dependent on the type of capital stock in play, the expected developments of factor prices, and the time horizon under consideration, it is possible that the private sector in Germany has higher incentives to increase the substitutability of energy inputs. Since primary energy costs in Germany are higher than in the US, this might explain the near-Leontieff conditions found by Hassler et al. (2012). We also include more energy sources into the analysis, since the energy demand of Germany is more diversified than that of the US. The other authors only included oil as an energy input and suggested a more nuanced energy view as a promising extension of their model. Nevertheless, the fundamental implications of our results are similar, since our low estimation result highlights the complementarity of energy inputs with capital and labor. Energy-augmenting technology will become more and more valuable, which means that private R&D efforts can complement efficiency increasing policies and regulatory mandates. Given the allocational pressures and upwards-trending energy price, it is even likely that the resulting technical change will outstrip governmental standards, where there is a chance that political motives lead to a focus on ineffective avenues for affecting energy-augmenting technical change.

5 Discussion and conclusions

The introduction of a third input factor into a CES function introduces a number of additional complexities, which means that the naïve application of a system approach to nested CES functions can lead to biased and spurious results. In this paper we demonstrate that the performance of the system approach to estimating a CES function with nested parameters can be substantially improved by holding the elasticity of the nested process fixed. With this approach we find that energy has a very low elasticity of substitution of 0.17 to the nested capital-labor composite.

The implications of the results are of both economic and methodological relevance. From an economic perspective, they indicate that production factors are gross complements, not only in the classic two-factor case, but also when extended to other production factors, such as energy. Energy in particular has a low elasticity of substitution to the other production factors, at least in the medium run. Our estimated elasticity of around 0.17 is substantially lower than the previous estimates of Stern and Kander (2012) and Kander and Stern (2014), who estimate the elasticity of energy with respect to the capital-labor composite to be around 0.65. This might be because energy inputs in modern economies are even harder to replace than during the period examined in Kander and Stern (2014) (1850–1950), where labor inputs were more likely to be used for their energy content. It might also be because long-run behavior provides more time for directed technical change to respond to shifts in energy availability. The capital stock responds to the changing opportunities provided by new energy uses, and incorporates these new possibilities of using energy.

Our results are higher than those of Hassler et al. (2012). One reason could be the identification strategy: Hassler et al. use a maximum likelihood estimator to directly estimate the CES function, they use a Cobb-Douglas capital/labor aggregate, and there is no normalization. An important implication of our results is that productivity increases for labor or capital are energy-using: for gross complements, factor productivity gains for a given factor lead to increased demand for the other factors. Despite the difficulties in identifying technical change for capital and labor, it is clear that their aggregate productivity increases more than that of energy in the observed time frame. This also holds when we do not account for changes in the energy mix, and instead treat energy as a simple sum of Joules. Another reason that we find a higher elasticity in Germany could be a result of higher energy prices. This means that incentives to increase substitution possibilities and improve the productivity of energy are higher.

The results underpin considerations by Ayres (2007), who posit a low elasticity of substitution for energy on the basis of physical limits to the use and transformation of energy. A consequence of the low elasticity would be the strong complementarity between energy and other production factors, and therefore a strong constraint of minimum energy consumption on growth. Stern and Kander (2012) highlight this issue, and propose that the low elasticity of substitution of energy and other production factors makes productivity gains for energy a key component of long-term development and growth potential. The implication is that without substantially increasing the amount of effectively usable renewable energies, economic growth necessitates an inexorable expansion of primary energy consumption in the form of fossil fuels.

From a methodological perspective, this analysis shows the complexities in the study of multiple production factors in the presence of biased technical change. Even when utilizing the system approach in order to analyze a three-factor production model, the results can be unreliable. The nesting structure is not sufficiently constrained by the system to ensure a good convergence, in particular when the model features generalized technical change. Instead, we see that a reliable performance is only possible when the intraprocess elasticity of substitution is fixed during the estimation. Additionally, the analysis demands the use of carefully gathered data with a sufficiently large sample size, a frequent problem for macroeconomic studies. The effective increase of the degrees of freedom achieved by the system approach makes it therefore particularly attractive for analyzing aggregate production functions. Despite our relatively small sample size, any problems with estimating the production function were owed to the fundamental features and behavior of the CES function, rather than a lack of data. The relatively flat objective functions make identification of the optimum and convergence for nonlinear estimators difficult (Henningsen and Henningsen, 2012). Similarly to the purely numerical search grid suggested by Henningsen and Henningsen (2012), we impose an empirically motivated fixed value on ν. We see that our procedure not only circumvents the identification problem in the nested CES process, for sensible values of ν the added constraint also dramatically improves convergence.

As a consequence, we suggest that an empirically motivated fixed value for the elasticity in nested CES processes can be effectively combined with a system estimation approach in order to provide better empirical results for multi-factor production analysis. This is especially true when the assumptions of a balanced growth path and some form of productivity neutrality are likely to be violated. Using energy as a third production factor, we show the strength of the methodology. Our results highlight the vital role that energy plays in the production process, which renders it so difficult to substitute.

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