Inter-fuel substitution and dynamic adjustment in input demand: Implications for deforestation and carbon emission in Malawi

BENJAMIN M BANDA[*]

Economics Department, Chancellor College, University of Malawi, Zomba

RASHID M HASSAN

Centre for Environmental Economics and Policy in Africa (CEEPA), University of Pretoria

This study estimates inter-fuel substitution elasticities and long-run substitution elasticities between energy and non-energy aggregate inputs used by production sectors in Malawi. All fuels are Morishima substitutes but there are significant sectoral variations in the magnitude of the elasticities. This indicates that economic instruments should be considered for energy policy but such policies should take into account not only differences in technology used across sectors but also the systematic distribution of costs when the relative prices of fuels change. Estimates of long-run elasticities for aggregate input demands indicate that energy-capital input ratios adjust faster than labor-capital input ratios. This suggests that investment policy should take into consideration tradeoffs between environmental gains and employment implicit in the production structure of the Malawian economy, as both capital and labor demands have dynamic interactions with energy in the long run, with potential significant cumulative impacts on the environment.

Keywords: inter-fuel substitution; energy aggregation; deforestation; carbon emissions

Cette étude évalue les élasticités de la substitution entre combustibles et les élasticités de substitution de longue durée entre les principaux intrants énergétiques et non énergétiques qu'utilisent les secteurs de la production au Malawi. Tous les combustibles sont des substituts Morishima mais on note d'importantes variations sectorielles dans la magnitude des élasticités. Ceci indique un besoin de considérer les instruments économiques lorsqu'il s'agit de politiques énergétiques, mais ces politiques ne devraient pas tenir compte uniquement des différentes technologies qu'utilisent les secteurs mais également de la distribution systématique des coûts lors de la fluctuation des prix relatifs des combustibles. Les évaluations des élasticités de longue durée pour les demandes d'intrants agrégées indiquent que les rapports intrants d'énergie / intrants de capital s'ajustent plus rapidement que les rapports intrants de main-d'oeuvre / intrants de capital. Ceci indique que la politique en matière d'investissement devrait tenir compte des compromis entre les bénéfices environnementaux et l'emploi implicites dans la structure de la production de l'économie Malawienne, puisque les demandes en capital et en main-d'œuvre sont dynamiquement liées à l'énergie, sur le long terme, avec un cumul d'impacts possibles et significatifs sur l'environnement.

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[*] Corresponding author: mattondo@gmail.com

Mots-clés : *substitution entre combustibles ; agrégation de l'énergie ; déforestation ; émissions de carbone*

1. Introduction

The energy demand structure in Malawi has serious consequences not only for greenhouse gas (GHG) emissions but also for sustainable development of the country. The economy's energy demand is putting tangible pressure on forest reserves and protected areas and threatens to raise carbon emissions above the average levels for low income countries. Currently, wood demand exceeds supply by one third, with about 50,000 hectares of forests cleared every year. Fuelwood deficit is also expected to reach 10 million cubic meters by 2010 (GoM, 2001).

It is therefore imperative to study the effect of shifting the energy mix of industries from biomass and fossil fuels to less environmentally damaging energy sources such as hydroelectricity and biogas. Although GHG emissions reductions are not at this stage obligatory for low income countries under the Kyoto Protocol, Malawi could take advantage of the opportunity to reduce emissions to correct distortions in its domestic energy markets. Towards this particular objective, estimating the structure of fuel demand in Malawi provides an opportunity for exploring energy efficiency potential at microeconomic level. In addition, reducing energy related GHG emissions now may be equivalent to averting long-term impacts on the environment (Biesiot & Noorman, 1999). A policy that supports alternatives to biomass and fossil fuels may also benefit the environment by arresting the rampant deforestation that is threatening natural forests in Malawi. However, such a policy will only be relevant if, in addition to regular price considerations, other factors that determine industrial fuel choices are identified.

Inter-fuel elasticities of substitution are important when considering energy conservation and energy related emission policies. Energy conservation policy will be inefficient or may be misguided if it does not recognize the nature of the relationship between energy and non-energy inputs in production functions, as well as between the fuel components themselves in the energy input aggregate. In particular, if energy-efficient capital is pursued when capital and energy are net complements in production, energy conservation might be a costly policy, as both capital and energy would have to be reduced. The view that energy conservation might lead to lower investment was particularly pervasive during the oil shock of the 1970s (Berndt & Wood, 1975; Thompson & Taylor, 1995; Thompson, 1997). However, when capital and energy inputs are substitutes, energy efficient capital investment should be encouraged since rising energy prices would stimulate demand for capital. The elasticity of substitution between labor and capital and between labor and energy should also be taken into account, especially if employment effects are important for welfare outcomes.

This paper estimates the elasticity of substitution between energy and non-energy factors of production in Malawi using a micropanel model of 59 sectors of the Malawi economy between 1998 and 2004. The paper also estimates the rate of dynamic adjustment in energy consumption by industrial energy users in response to price changes. These estimates are used to inform policy options that could be used to reduce energy related carbon emissions and deforestation. In particular, the existence of strong substitution elasticities between hydroelectricity and fossil fuels and between hydroelectricity and fuelwood would be a prerequisite for using economic instruments to induce production sectors in Malawi to reduce their use of fossil fuels and fuelwood, respectively, and thus reduce carbon emissions.

The rest of the paper is organized as follows. Section 2 discusses approaches to modeling inter-fuel substitution and aggregate input demand, Section 3 describes the data and main variables used in the estimation, Sections 4 and 5 discuss the econometric estimates of inter-fuel demand and aggregate inputs, and the paper concludes with some policy suggestions.

2. Modeling inter-fuel substitution and energy aggregation

Following the work of Fuss (1977), we adopted the assumption of homothetic weak separability between energy and other inputs (labor and capital) in production, which allows us to write the firms' technology constraint as:

$$Y = f\left(K, L, E\left(E_i\right)\right) \tag{1}$$

where Y is output, K and L are capital and labor, respectively, and E is the aggregator function of the energy sub-model. Duality theory implies that the corresponding cost function, C, under cost minimization will also be weakly separable:

$$C = G\left(P_E\left(P_{E_i}\right), P_K, P_L, Y\right) \tag{2}$$

where P_E is the energy price aggregator index and P_{E_i}, P_K, and P_L refer to prices of individual energy components, capital and labor inputs, respectively. Under the assumption of homothetic separability we can apply the two-stage aggregation model, which assumes that firms first decide their optimal fuel mix before considering quantities of non-energy inputs. Once the energy aggregate is composed, firms then vary their optimal energy aggregate in response to changes in demand for non-energy factor inputs (Mountain & Hsiao, 1989; Kemfert & Welsch, 2000; Klepper & Peterson, 2006). Applying Shephard's lemma (Diewert, 1971), we derive from equation (2) the system of cost-minimizing input demands:

$$Z_i = \frac{\partial C}{\partial P_i} \tag{3}$$

We used the unrestricted quadratic quasi-Cobb-Douglas system of equations based on relative fuel demands in the energy aggregate. This is a parsimonious system that extends the multi-input log-ratio formulations of the translog and linear logit models and is consistent with

Pindyck's (1979) two-stage aggregation model. The main energy sources used by firms in Malawi are hydroelectricity, oil, fuelwood and coal. Ignoring sector specific identifiers and time subscripts, the unrestricted quadratic log-ratio demand system for four fuels is specified as

$$\ln\left(\frac{X_i}{X_1}\right) = \ln\left[\frac{(\partial C/\partial p_i)}{(\partial C/\partial p_1)}\right] = \alpha_i + \sum_{j=2}^{4}\alpha_{ij}\ln\left(\frac{p_i}{p_1}\right) + \frac{1}{2}\sum_{j=2}^{4}\sum_{m=2}^{4}\alpha_{ijm}\ln\left(\frac{p_j}{p_1}\right)\ln\left(\frac{p_m}{p_1}\right) + \beta_i^X d_i^X + \iota(t) + \varepsilon_i \tag{4}$$

where $X_i, i = 2,3,4,$ is fuel $i's$ demand in real quantities, p_i is the corresponding unit price, α, β and ι are unknown parameters, t is a time trend variable and ε_i is a white noise error term. To account for differences in energy mix technologies in estimating equation (4), a set of dummy variables are defined in order to incorporate all observations for which the variables $\ln\left(\frac{X_i}{X_1}\right)$ and $\ln\left(\frac{p_j}{p_1}\right)$ are undefined or zero. This method was suggested by Battese (1997) and has been applied in energy studies (Brannlund & Lundgren, 2004). In particular, let

$$d_i^X = \begin{cases} 1 \quad if \quad \ln\left(\frac{X_i}{X_1}\right) \text{is undefined} \Rightarrow \text{set } \ln\left(\frac{X_i}{X_1}\right) = 0 \\ 0 \text{ otherwise} \end{cases} \tag{5}$$

The hypothesis that the rate of dynamic adjustment influences energy use intensities and vice versa cannot provide meaningful policy insights if tested on a relative demand system of fuel inputs only (Jones, 1996; Brannlund & Lundgren, 2004). Instead, a relative demand system that includes the energy aggregate, labor and capital is preferred with a view to accounting for cross-elasticities of substitution between energy and labor and between energy and capital, in addition to accounting for dynamic adjustments. Since technological change could also be influenced by the rate of dynamic adjustment, an interactive term for share neutral technological change is included in specifying factor demands. Accordingly, the relative factor demand system under the assumption of non-neutral technical progress with dynamic costs is specified as

$$\ln\left(\frac{Z_i}{Z_n}\right) = \beta_i + \sum_j \beta_j \ln\left(\frac{w_i}{w_n}\right) + \frac{1}{2}\sum_j\sum_m \beta_{ijm}\ln\left(\frac{w_j}{w_n}\right)\ln\left(\frac{w_m}{w_n}\right) + \beta_t t + \beta_y \ln Y + \lambda \ln\left(\frac{Z_i}{Z_n}\right)_{t-1} + \mu_t$$

(6)

for i, j, m referring to (K, L, E) and $\beta_{ijm} = \beta_{imj}$. Z_n is a quantity of a quasi-fixed input chosen from among capital (*K*), labor (*L*) and energy aggregate (*E*) and $w's$ are input prices.

Maximum likelihood estimates of a cost shares system are invariant to the selection of the base input (Considine & Mount, 1984). However, only capital is considered quasi-fixed over the relevant time frame in estimating equation (6). This allows the estimation of the dynamic adjustment rate, λ as labor and energy inputs vary. Also, equation (6) is estimated using generalized least squares, assuming an uncorrelated but autoregressive structure of the residuals within panels.

3. Data and variable definitions

Equation (6) was estimated using data from the Annual Economic Survey (AES). AES data are collected annually by the Malawi National Statistical Office (NSO). However, reports are only compiled every four years and are presented as summaries of industrial sectors at the 3-digit ISIC level. The AES itself is by design a panel of companies selected to reflect the current economic situation in the industrial sector. The variables in AES include sale of goods, stocks, purchases of intermediate materials and supplies used in production, employment, capital investment in fixed assets and profit. Other variables obtained from the AES are production, employment of labor, capital investment and profitability of enterprises. The main variables used in the analysis are summarized in Table 1.

Table 1: Definitions of variables

Variable	Description	Mean	Std dev.
X_1	Quantity of hydroelectricity purchased in megawatts	15,568.03	38,345.32
X_2	Quantity of oil purchased in megawatts	7,222.40	10,944.96
X_3	Quantity of fuelwood purchased in megawatts	12.31	39.13
X_4	Quantity of coal purchased in megawatts	114.86	101.50
p_1	Price of 3,413,000 Btu of electricity = price of 1000 kilowatts of energy	993.23	405.91
p_2	Price of 3,413,000 Btu of oil = price of 1000 kilowatts of energy	4,738.83	2,736.75
p_3	Price of 3,413,000 Btu of fuelwood = price of 1000 kilowatts of energy	693.68	218.32
p_4	Price of 3,413,000 Btu of coal = price of 1000 kilowatts of energy	346.30	203.41
L	Number of workers	17,865.45	102,127.40

	employed		
K	Gross investment minus depreciation plus changes in stocks in million Malawi kwacha	30,300.00	180,000.00
E	Energy aggregate in megawatts	185,467,330.79	295,927,336.65
w_L	Remuneration per worker in kwacha	538.99	1,189.65
w_K	User cost of capital (kwacha)	14.33	8.32
w_E	The weighted average price of 1000 kilowatts of energy	511.89	223.55
Y	Output value measured by net sales in million Malawi kwacha	207.48	842.34

The estimation covers two survey periods from 1998 to 2005. Since the NSO only reports aggregate use and supply figures, micro level energy demand data were obtained by the authors from archives of AES questionnaire responses. The data were then aggregated according to sector classifications used by the NSO. Energy data were classified by fuel type, i.e. hydroelectricity, coal, fuelwood and oil (ethanol, diesel, petrol). All fuels were measured in both physical quantities and monetary values. For uniformity, all energy inputs were converted into British thermal units (Btu) using standard conversion factors from the US Energy Information Administration (EIA, 2003) expressed at Lower Heating Value (LHV).[1] For lack of unit price data for the fuels, the study uses average prices obtained by dividing total energy expenditures per fuel by corresponding Btu quantities. Bjørner et al. (2001) argue that this is acceptable if the average price is not a function of sales and thus reflects marginal price. In the case of Malawi, virtually all firms are net buyers of fuels and are thus price takers in the energy market.

4. Estimates of relative fuel demands and inter-fuel elasticities

Regression results of the relative fuel demand functions are reported in Table 2. Since equation (6) is an unrestricted model of fuel demand, a set of linear restrictions is tested to verify the underlying structure of energy aggregation. Except for coal, demand functions for oil and fuelwood (models 1 and 2) are flexible as they satisfy the following set of restrictions:

a) Test if $\beta_j^X = 0$. Failing to reject the hypothesis that Battese (1997) dummies are equal to zero implies that production technologies at firm level are so different that it is not possible for some firms to use all fuels. Thus, equation (6) would be a misspecification since it is not feasible to substitute any of the fuels that a firm currently uses for another that the firm does not use.

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[1] Comparable conversion factors can be obtained from the US National Institute of Standards and Technology website. www.nist.gov/index.html

b) Test if $\alpha_{ij} = \alpha_{ijm} = 0, \forall i, j, m$. If this condition holds, it means that the energy aggregate used by a firm is composed of fixed proportions of oil, fuelwood, coal and hydroelectricity. Thus, the ratio of quantities of any pair of fuels is constant (Leontief function case) (Mountain, 1989; Mountain & Hsiao, 1989).

c) Unit elasticity of substitution (Mountain, 1989; Mountain & Hsiao, 1989): $\alpha_{ii} = \alpha_{jj} = -1, \forall i, j; \alpha_{ij} = 0, i \neq j; \alpha_{ijm} = 0, \forall i, j, m$. These conditions mean that elasticities of the fuels are restricted to unity and cross-price terms are zero. When these restrictions hold, the unrestricted function reduces to a regular Cobb-Douglas function.

Reading diagonally for the first three variables in Table 2, all demand equations have the expected signs for own price elasticities. For both oil and fuelwood, demand will increase if the price of any other fuel rises. For coal, demand rises with increases in relative price of fuelwood, implying that coal and fuelwood are substitutes, but the negative sign on the price of oil suggests a complementary relationship between coal and oil. However, the linear restriction tests show that coal has a slightly different structure as it follows a Cobb-Douglas specification.

Table 2: Fuel-mix regression results

	Model 1: Oil	***Model 2: Fuelwood***	***Model 3: Coal***
Variable	$\ln\left(\frac{X_2}{X_1}\right)$	$\ln\left(\frac{X_3}{X_1}\right)$	$\ln\left(\frac{X_4}{X_1}\right)$
$\ln\left(\frac{p_2}{p_1}\right)$	-1.96 (0.19)*	0.03 (0.12)	-0.07 (0.09)
$\ln\left(\frac{p_3}{p_1}\right)$	2.83 (0.85)*	-2.49 (0.50)*	0.25 (0.36)
$\ln\left(\frac{p_4}{p_1}\right)$	0.03 (0.48)	3.88 (0.45)*	-0.85 (0.29)*
$[\ln(p_2/p_1)]^2$	0.62 (0.07)*	0.00 (0.06)	0.02 (0.04)
$[\ln(p_3/p_1)]^2$	-0.22 (1.24)	-2.61 (0.77)*	0.34 (0.55)
$[\ln(p_4/p_1)]^2$	-0.24 (0.29)	2.50 (0.34)*	0.61 (0.23)*
$\ln(p_2/p_1) \times \ln(p_3/p_1)$	-1.14 (0.33)*	0.55 (0.23)**	-0.11 (0.17)
$\ln(p_2/p_1) \times \ln(p_4/p_1)$	-0.22 (0.18)	-1.30 (0.17)*	0.27 (0.11)*
$\ln(p_3/p_1) \times \ln(p_4/p_1)$	0.53 (0.50)	-2.14 (0.43)*	-0.97 (0.26)*
t	0.10 (0.03)*	-0.03 (0.02)***	0.02 (0.02)
β_j^X	-0.93 (0.31)*	1.58 (0.23)*	1.06 (0.20)*
Constant	0.62 (0.17)*	-1.63 (0.27)*	-1.04 (0.22)*
Linear constraints (chi-squared tests)			
Test for $\beta_j^X = 0$	8.92*	38.61*	19.56*
Test for Leontief restrictions	204.14*	153.27*	52.99*
Unit elasticity (Cobb-Douglas case)	26.57*	7.23*	1.60
Cobb-Douglas linear restrictions	12.28*	19.98*	0.72

Test for $t = 0$	9.03*	6.84*	1.22

* Significant at 1% level ** Significant at 5% level *** Significant at 10% level

The relative demand for coal also fails to satisfy the assumption of neutral technical change. However, demand for coal is still influenced by prices of other fuels through interactive price terms. This implies that cross-price effects strongly determine demand for coal and that some fuel prices may fall over time as firms switch to coal. Thus, the time trend in the demand function for coal reflects only expansion in coal production due to new investments in mining and/or increased use of coal due to lower prices but not necessarily technological change. Hence firms that use coal are less likely to change their fuel mix because of technological constraints but would shift demand from coal to another fuel only because of price effects.

Allen cross-price elasticities between hydroelectricity and other fuels are reported in Table 3. Oil and coal are Allen-Uzawa complements to hydroelectricity while fuelwood is a substitute. However, the Allen partial elasticity of substitution is inappropriate in energy studies since it lacks economic meaning. In addition, the estimated demand functions are not symmetric in sign and size of coefficients, hence rendering pairs of cross-price elasticities inconsistent. With three or more inputs, the percentage change in the relative input of factor *i* due to a change in the relative price of factor *j* is a meaningless statistic that holds all other inputs constant, when in fact all inputs adjust to any change in factor prices (Thompson, 2006).

Morishima substitution elasticities are instead estimated for all fuels and reported in Table 3. The Morishima elasticity of substitution (MES) measures the percentage change in the input quantity ratio $\left(\frac{X_j}{X_1}\right)$ with respect to a percentage change in the corresponding price ratio $\left(\frac{p_j}{p_1}\right)$. Oil, fuelwood and coal are all Morishima substitutes for hydroelectricity. This implies that it would be possible to switch energy demand from carbon intensive fuels such as coal and oil to cleaner fuels. It also means that it would be possible to substitute some biomass energy demand for other fuels and hence avert deforestation. The MES between oil and hydroelectricity is comparable to that between fuelwood and hydroelectricity although the MES between fuelwood and hydroelectricity is larger. The MES between fuelwood and hydroelectricity however is almost three times the MES between coal and hydroelectricity. This implies that in all cases relatively more electricity would be used when the other fuel becomes expensive, with the greatest response when the price of fuelwood is raised.

Table 3: Allen-Uzawa cross-price and Morishima substitution elasticities

Allen-Uzawa cross-price elasticities

	Oil	***Fuelwood***	***Coal***
Hydro	-0.65	0.91	-0.39
Oil		0.29	-0.05
Fuelwood	3.79		1.25

Coal	-0.85	3.51	
Morishima elasticities of substitution			
	Oil	***Fuelwood***	***Coal***
Hydro	1.11	1.42	0.52
Oil		0.49	0.32
Fuelwood	2.67		1.41
Coal	0.36	2.54	

Although oil and coal are Allen-Uzawa complements for hydroelectricity, the Morishima substitution elasticity unequivocally classifies all fuels as substitutes. This is consistent with the observation in several studies, including Stiroh (1999), Shankar et al. (2003) and Frondel (2004), that Allen-Uzawa complements might be Morishima substitutes. This is because the Allen-Uzawa elasticity considers the percentage change in an input as a result of a change in any one price, whereas the Morishima elasticity measures a change in input ratio resulting from the change in the price of interest. Since the price change affects both inputs in the ratio, it is conceivable that the Morishima elasticity may be positive when the Allen-Uzawa elasticity is negative.

There are sectoral differences in the size of Morishima substitution elasticities for oil, fuelwood and coal each paired with hydroelectricity (Table 4). Sectors such as manufacturing of fertilizer and plastics, pharmaceuticals, mining of hard coal and quarrying, and bakeries and confectionaries have the greatest potential for switching from oil to hydroelectricity. Thus, these sectors are expected to substantially curb emissions from oil combustion as the price of hydroelectricity falls relative to the price of oil. Manufacturing of sugar and of soaps, detergents and toiletries have the lowest MES between hydroelectricity and oil, implying that these sectors would not substantially reduce their carbon emissions from oil combustion even if a revenue neutral environmental tax was levied on oil offset by subsidies on hydroelectricity. Only the fabricated metal and metal stamping sector uses oil as a complement to hydroelectricity, implying that a revenue neutral environmental tax on oil would almost certainly not change this sector’s demand for oil.

Similarly, there would be substantial environmental gains from raising the price of fuelwood relative to the price of hydroelectricity for the sectors involved in mining of hard coal and quarrying, bakeries and confectionaries, and fertilizer and plastic products (Table 4). However, tobacco and sugar growing, and manufacturing of sugar, have the lowest potential for substituting fuelwood for hydroelectricity, although between them they use 87% of all fuelwood demanded by production sectors (NSO, 2001). Thus, these sectors would bear the highest burden of a tax levied on fuelwood proportional to the weight of fuelwood used or, alternatively, according to the equivalent forest area that must be cleared to obtain that amount of fuelwood. The fabricated metal and metal stamping sector would reduce demand for hydroelectricity by more than 3% if the price of fuelwood was raised by 1% since hydroelectricity and fuelwood are complements in that sector’s production. There is also strong complementarity between fuelwood and hydroelectricity in the manufacturing of soaps, detergents and toiletries, whereas for distilling spirits and manufacturing of malt liquor and soft drinks the complementarity is weak.

For coal, only the sector involved in distilling spirits and manufacturing malt liquor and soft drinks has elastic Morishima substitution for hydroelectricity. This is important for environmental policy because this sector's demand for coal accounts for 34% of all coal use by production sectors (NSO, 2001). Thus, a fuel switch from coal to hydroelectricity is possible for at most 34% of the coal in the sector. However, the demand for coal by the soaps, detergents and toiletries manufacturing sector is inelastic to a change in the price of hydroelectricity although this sector uses 63% of the coal used by all production sectors (NSO, 2001). This means that a carbon tax on coal offset by subsidies on hydroelectricity would disproportionately affect the cost of producing soaps, detergents and toiletries compared to the emissions that may be reduced.

Table 4: Sectoral Morishima elasticity of substitution for hydroelectricity calculated for 1% increase in price of oil, fuelwood or coal.

Sector name	***Oil***	***Fuelwood***	***Coal***
Tobacco & sugar growing	0.82	0.91	0.18
Tea, coffee & macadamia growing	0.95	1.25	0.31
Mining of hard coal and quarrying	1.51	2.09	0.65
Grain milling	1.17	1.79	0.51
Bakeries and confectionaries	1.43	2.03	0.62
Sugar	0.20	0.58	-0.02
Manufacturing of tea and other food products	0.95	1.25	0.31
Printing (books, music)	1.44	2.03	0.63
Pharmaceuticals	1.58	2.15	0.69
Soaps, detergents and toiletries	0.05	-1.52	0.68
Cement, lime & plaster	1.22	1.84	0.53
Construction	1.23	1.85	0.53
Sale of motor vehicles	1.36	1.96	0.59
Retail of auto fuel	0.89	1.55	0.38
Hardware, paints, and vanish	1.31	1.92	0.57
Other retail sale in specialized stores	1.23	1.85	0.53
Hotels	1.34	1.94	0.58
Restaurants, bars	1.23	1.85	0.53
Horticulture, fishing & forestry	1.19	1.81	0.51
Cattle, dairy & poultry	0.98	1.17	0.29
Meat and dairy products	1.20	1.82	0.52
Textiles and wearing apparel	1.19	1.81	0.52
Publishing	1.22	1.27	0.36
Fertilizer & plastics	1.61	2.18	0.70
Rubber tires & plastic products	1.15	1.78	0.50
Ceramics and structural metals	1.33	1.94	0.58
Fabricated metal and stamping of metal	-0.25	-3.07	0.62
Batteries & motor vehicle trailers	0.96	1.61	0.41
Maintenance of motor vehicles and sale of spare parts	1.44	2.03	0.63
W/sale on fee and agric raw mate	1.27	1.88	0.55
Retail in non-specialized stores, pharmacies and textiles	1.38	1.98	0.60
Distilling spirits/Malt liquor/Soft drinks	0.95	-0.45	1.16

Average	*1.11*	*1.41*	*0.52*
Standard deviation	*0.42*	*1.12*	*0.20*

The discussion above suggests that both carbon emissions and forest resource depletion due to industrial fuelwood use could be significantly reduced by changing the relative price of fossil and biomass fuels. This could be achieved for instance by imposing a tax on oil, coal and fuelwood while subsidizing hydroelectricity. In particular, since coal and oil are carbon intensive but have strong substitution possibilities with hydroelectricity in some sectors, raising the price of these fuels relative to hydroelectricity would significantly reduce carbon emissions. However, some key sectors of the economy such as manufacturing of sugar and of soaps, detergents and toiletries have inelastic demand for hydroelectricity relative to oil, implying that a fossil fuel tax could significantly raise costs for these sectors.

Similarly, fuelwood demand responds strongly to relative price changes of hydroelectricity in almost all sectors except for the main users of fuelwood, namely tobacco and sugar growing, and manufacturing of sugar. Thus, if price effects alone are not enough to reduce fuelwood use by production sectors, it would be prudent to focus on sectors that have inelastic demand to find alternative policies that could ensure sustainable use of fuelwood for industrial purposes. Coal has a substantial substitution potential for fuelwood. However, it would be inappropriate to support a switch from fuelwood to coal without the corresponding carbon tradeoffs.

5. Estimates of aggregate energy and labor demand functions

Following the theoretical framework outlined in Section 2, firms are assumed to combine their least cost fuel mix (the energy aggregate) with other least cost factor inputs. At this input aggregation stage, firms are assumed to combine energy, labor and capital with the same technology with which energy input is aggregated. This assumption is consistent with the assertion that the energy mix varies with the technology. We thus tested the hypothesis that the rate of dynamic fuel cost adjustment varies across industries, and this indirectly tests the proposition by Brannlund and Lundgren (2004) that the rate of dynamic adjustment varies with individual fuel mix.

Estimates of the unrestricted quasi-Cobb-Douglas demand functions for labor and energy are reported in Table 5. Both equations were estimated assuming panel specific first order autocorrelation in the residuals. The results show that the relative demand both for labor and for energy satisfies regularity conditions and is consistent with theoretical expectations. An increase in the price of energy may lead to a fall in labor demand, as indicated by the large negative coefficient for the price of energy. However, there could be some rather weak substitutability between labor and energy in some sectors, indicated by small but positive coefficients for the squared price of energy and energy-labor cross-price terms in the labor demand function. Also, an increase in a sector's output will lead to more employment of labor while the positive sign on the Hicks-neutral technical term may be interpreted as indicating that industrial employment of labor has expanded over time and that technical progress has favored intensive use of labor.

For aggregate energy demand, however, an increase in the price of labor could lead to an increase in demand for energy, which might be offset if the energy-capital price ratio in the cross-price term is large. Also, as in the case of labor, the positive sign on the Hicks-neutral technical term indicates that energy use by industrial sectors is expanding over time and that energy and capital demands adjust in the same direction. However, the negative sign on output implies that output growth does not necessarily lead to an increase in energy demand but rather that firms may be using energy inefficiently at low levels of output. Thus, a growth in demand for a firm's output may lead to considerable energy savings over time.

In the demand equations both for labor and for energy, the dynamic adjustment parameter (λ) is positive and significant, which is consistent with the Le Chatelier principle that short-run elasticities can never be greater than long-run elasticities in absolute value (Urga & Walters, 2003). The rate of adjustment for labor-capital ratio to its desired level is 88% $(1-\lambda)$ annually whereas energy-capital ratio adjusts by 98%.[2] The high adjustment speed has important implications for the effectiveness of policies aimed at curtailing energy use in the economy. In particular, energy conservation policies may be costly if the introduction of energy-efficient capital is pursued while capital and energy are net complements in production or when the rate of dynamic adjustment is slow. Since we found substitution among fuels within the energy aggregate, energy conservation can be pursued with little or no labor effects in the short run. However, the results show that production sectors adjust energy inputs faster than labour, implying that production sectors always match actual energy-capital ratios at their desired levels but can tolerate labour projection errors. The cumulative impact of projection errors on labor employment could be significant in the long run if energy tax policies are unpredictable.

Table 5: Estimates of aggregate energy and labor demand regressions

Relative demand for labor					**Relative demand for energy**				
Variables	Coef.	Std err.	Z	P>|Z|	Variables	Coef.	Std err.	Z	P>|Z|
$\ln(w_L/w_K)$	-0.19	0.05	-3.45	0.00	$\ln(w_L/w_K)$	0.12	0.04	3.17	0.00
$\ln(w_E/w_K)$	-0.74	0.13	-5.52	0.00	$\ln(w_E/w_K)$	-0.93	0.08	-12.20	0.00
$[\ln(w_L/w_K)]^2$	-0.04	0.02	-2.79	0.01	$[\ln(w_L/w_K)]^2$	0.02	0.01	2.53	0.01
$[\ln(w_L/w_K)]\times[\ln(w_E/w_K)]$	0.07	0.03	2.63	0.01	$[\ln(w_L/w_K)]\times[\ln(w_E/w_K)]$	-0.04	0.02	-2.38	0.02
$[\ln(w_E/w_K)]^2$	0.06	0.10	0.61	0.54	$[\ln(w_E/w_K)]^2$	0.34	0.07	4.97	0.00
$\ln Y$	0.08	0.05	1.70	0.09	$\ln Y$	-0.88	0.05	-16.88	0.00
t	0.26	0.09	2.74	0.01	t	0.07	0.07	1.08	0.28
$\ln(L/K)_{t-1}$	0.12	0.04	2.82	0.01	$\ln(E/K)_{t-1}$	0.02	0.01	2.30	0.02
β_2	-2.88	0.42	-6.85	0.00	β_3	18.11	0.36	50.26	0.00

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[2] For comparison, a labor-energy regression was estimated on the assumption that energy is quasi-fixed while capital is variable. Firms adjust their labor at the rate of 87% annually to the desired labor-energy ratio. This is very similar to the rate at which firms adjust labor to the desired labor-capital ratio.

To test the hypothesis that adjustment speed varies across industries, the rate of dynamic adjustment (λ) was multiplied by the observed lagged values for labor-capital and energy-capital ratios in log form (Table 6). The resulting values were compared across industries using a one-way analysis of variance. For labor, the test statistic $(F(5,216)=2.23)$ is barely significant at the 5% level, while for energy the test statistic $(F(5,216)=3.09)$ is significant at the 1% level. In both cases, however, the null hypothesis of equal variances cannot be rejected by the Bartlett's test. Further exploration of the adjustment structure revealed that for labor demand, services, mining and manufacturing have the highest long-run adjustment speeds with respect to labor-capital changes while agriculture and services have the highest long-run adjustment speeds with respect to energy-capital changes.

Table 6: Relative input adjustment speeds across industry

	Labor-capital adjustment speed			**Energy-capital adjustment speed**			**Labor-energy adjustment speed***		
Industry	Mean	Std dev.	Freq.	Mean	Std dev.	Freq.	Mean	Std dev.	Freq.
Agriculture	-0.21	0.22	28	0.15	0.12	28	-2.36	1.95	28
Manufacturing	-0.15	0.26	117	0.07	0.12	117	-1.89	2.10	117
Services	-0.1	0.18	14	0.14	0.17	14	-2.12	2.21	14
Mining	-0.14	0.25	7	0.06	0.12	7	-2.06	1.95	7
Distribution	-0.26	0.32	49	0.09	0.12	49	-2.24	2.18	49
All	-0.18	0.27	215	0.09	0.13	215	-2.13	2.10	215

* Labor-energy adjustment is presented here for comparison only since it was calculated from regression of labor normalized by energy aggregate.

6. Summary and conclusions

Inter-fuel substitution elasticities in the energy aggregate and substitution elasticities between capital, labor and energy aggregate inputs have been estimated in this paper for Malawian production sectors. The rates of dynamic adjustment in demand for labor and energy are presented as well as their environmental implications. The main finding of the inter-fuel substitution sub-model is that there is a strong case for an environmental tax or subsidy to help decrease energy-related carbon emissions and also for controlling deforestation associated with energy demand by producers. In addition, investment policy should take into consideration environmental concerns, since both capital and labor have dynamic interactions with energy demand in both the short and long term, with significant cumulative impacts on the environment.

Inter-fuel substitution results suggest that oil and fuelwood users have high potential for substituting other fuels under energy policy constraints since the structure of relative demand for oil and fuelwood is relatively flexible. Coal users on the other hand have limited substitution possibilities although fuelwood emerged as a key substitute. Thus, coal users are unlikely to change their energy mix over time but would respond to relative fuel price changes. This implies that the potential for reducing emissions from coal is limited first by technology and second by the environmental tradeoffs of increasing fuelwood use and the consequent deforestation. Hence, coal users would have the highest tax incidence when the thrust of environmental policy is to maintain biomass in standing forests. Coal and fuelwood users would also face the highest tax rates when environmental policy focuses on abating total energy related carbon emissions.

The finding that Morishima inter-fuel elasticities and dynamic demand adjustment rates vary considerably across sectors has important implications for policy efficacy in that the sectors with high dynamic adjustment rates face lower transition costs (high benefits) as environmental taxes (subsidies) are imposed on various fuels. In addition, the employment impacts of environmental taxation would be lower for sectors with high adjustment rates. Therefore, to minimize the distributional impacts of energy taxes, the best option would be to reduce fuelwood use in industry by levying taxes on coal while subsidizing hydroelectricity. Subsidizing hydroelectricity would be consistent with the ongoing rural electrification efforts (GoM, 2003).

The aggregate inputs demand model results suggest that policies that reduce labor intensity and increase capital intensity will lower energy use. However, since labor and energy are Morishima complements while capital and labor are substitutes, investing in energy saving capital equipment may increase unemployment over time. The dynamic adjustment parameters also show that energy-capital ratios adjust at a faster rate than labor-capital ratios, implying a trade-off between employment and environmental gains. As a consequence, the long-run environmental gains from energy saving investments in capital could be lower than the economic welfare losses resulting from unemployment.

It is therefore necessary to quantify the total economic costs of policies that aim to shift the energy mix from carbon intensive fuels and biomass sources to hydroelectricity. This would also require knowing the cost of different environmental aspects associated with the energy demand profile of the economy. For instance, the environmental costs of deforestation may be higher than the costs of additional carbon emissions or of investing in additional hydro generating capacity, in which case it would be pointless to tax carbon emissions more than fuelwood use. According to the Government of Malawi (GoM, 1994), the social cost of deforestation is estimated at US$55 million (2.7% of GDP) annually, on the basis of the replacement values of wood harvested above the sustainable yield and the reduced crop yield as a result of the increased incidence of soil erosion. This estimate is rather conservative as other costs such as sedimentation of main rivers and increased incidence of flooding are not included.

To evaluate the net effect of shifting demand from fuelwood and fossil fuels (oil and coal) to hydroelectricity, there is a need to evaluate multiple objectives using either multi-criteria programming or computable general equilibrium modeling to evaluate policies that give double or triple dividends in terms of smaller reductions in economic growth, lower emissions and less deforestation. One objective could be to invest in energy-efficient capital as a strategy for improving both energy efficiency and environmental quality in the Malawi industrial sector. Although the econometric results suggest negative impacts on employment from capital-labor and energy-labor substitutions, it is conceivable that labor employment impacts may be dampened by growth elsewhere in the economy, especially in agriculture and mining. This proposition could be evaluated using a computable general equilibrium model.

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