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The general equilibrium effects of energy efficiency gains in developing countries with urban unemployment

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Abstract

This study is aimed at analyzing the effects of energy efficiency gains in the industrial sector of developing countries that feature urban unemployment. Such efficiency improvements will likely induce adjustment processes and structural change. Understanding the nature of such adjustments is straightforward in the (theoretical) case of economies that are free from distortions. However, in the presence of urban unemployment, the effects of energy efficiency gains are more subtle. Any change in factor productivity, be it autonomous or induced by policy measures such as technology transfer, programs to promote energy efficiency or regulations will be followed by production shifts, sectoral reallocation of labor, and internal migration. In this study, we develop a model of a dualistic economy in the spirit of Harris and Todaro (1970), and analyze the effects energy efficiency improvements.

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1 Introduction

Investments in energy efficiency are seen by many as a low-cost or even no-cost measure to curb greenhouse gas emissions, slow down growth in energy demand and increase energy security. Industrial sectors in developing countries, where frequently outdated and inefficient capital stocks prevail, are considered prime candidates for policies that aim at energy efficiency improvements. Consequently, many governments of developing countries are implementing programs that promote energy efficiency, frequently with support from international financial institutions and bilateral and multilateral donors.

Developing countries typically face a wide array of economic and social challenges, some of which might be exacerbated or attenuated by economy-wide effects of energy efficiency gains. In particular, if such efficiency gains are not brought about by autonomous technological progress, but rather constitute policy or investment options for governments, the private sector or donor agencies, the full effects of these decisions need to be understood and quantified. This allows decision makers to design optimal policies that fully reflect the objectives and priorities of the energy, economic, and social development policy agendas. For instance, if policies that are aimed at energy efficiency gains give rise to unemployment, a comprehensive development strategy needs to take this into account and implement social policy programs in parallel to minimize economic hardship of the affected population. Another example is internal migration that could be induced by energy policies; such movements can also affect social development and poverty reduction goals. Hence, energy efficiency policy options should not be analyzed and evaluated in isolation as they can have substantial effects beyond the sector where they occur.

This study takes a look at the general equilibrium effects of advances in energy efficiency in the industrial sectors of developing countries that feature urban unemployment. Urban unemployment, albeit important, is of course only one of the socio-economic issues that many developing countries face. Therefore, the main results presented in this paper could also be seen as an illustration of a more general message: whenever there are pre-existing distortions in the economy, energy efficiency gains in the industrial sector can have non-trivial and potentially unwanted effects in other parts of the economy that need to be carefully analyzed on a case-by-case basis.

In this paper we show that interaction effects between energy efficiency increases and a pre-existing labor market distortion induce a wide range of effects on wages, rental rates of capital, output, migration, employment and welfare. The direction of these effects is not always beneficial. Particularly, we show that social welfare can decrease, and unemployment can increase as a consequence of energy efficiency gains. We argue that these effects should be included in cost-benefit analyses of different policy choices.

The paper is structured as follows. In the following section, the model is developed. In section 3, the effects of energy efficiency gains on the general equilibrium of the economy are derived and interpreted. Finally, section 4 contains the conclusions.

2 The model

John Harris and Michael Todaro's (1970) influential paper on urban unemployment laid the ground for a broad literature on the interplay of migration, urbanization, unemployment and economic development. There have been numerous efforts to extend the original Harris-Todaro framework, *inter alia* to include more than two factors and more than two sectors in the economy. For instance, a number of authors have introduced pollution and environmental policy into the Harris-Todaro world (e.g. Yu and Ingene, 1982; Wang, 1990; Beladi and Rapp, 1993; Beladi and Frasca, 1999). But, to the best of our knowledge, energy efficiency has previously not been studied in a model of urban unemployment. In this section, we develop a version of the Harris-Todaro model that includes energy as an input in the industrial sector, and analyze the economy-wide effects of improved energy efficiency.

In our simple setup, the economy consists of two sectors, a rural sector (A, agriculture) and an urban sector[1] (M, manufacturing). There are three factors of production, labor (L), which is in fixed and inelastic supply, sector-specific capital stocks[2] ($K_i, i = A, M$) and energy (E). We further assume that energy is only used in the urban sector and that the country is a small open economy that imports all of its energy inputs.[3] Production takes place according to the functions $f_A(L_A, K_A) : R^2_+ \to R_+$ and $f_M(L_M, K_M, \rho E) : R^3_+ \to R_+$, which exhibit constant returns to scale, and are linearly homogeneous, strictly concave and twice continuously differentiable:

$$f^i_A > 0, f^{ii}_A < 0, f^{ij}_A > 0, f^i_M > 0, f^{ii}_M < 0, f^{ij}_M > 0 \tag{1}$$

$$|f^{ii}_A f^{jj}_A| = |f^{ij}_A f^{ji}_A|, |f^{ii}_M f^{jj}_M| > |f^{ij}_M f^{ji}_M| \tag{2}$$

Where the superscript denotes partial derivative, $i, j = \{L_A, K_A\}$ for the agricultural sector and $i, j = \{L_M, K_M, E\}$ for the manufacturing sector; and $i \neq j$. The parameter ρ is a measure of energy efficiency, thus ρE is the effective energy input. As the country is a small open economy, the goods prices p_A and p_M and the price of energy p_E are fixed. In the following we will normalize the price of the agricultural good so that $p_A = 1$.

Wage in the agricultural sector is competitively determined, and thus equals the value of the marginal product of labor in agricultural production:

$$w_A = \frac{\partial f_A(L_A, K_A)}{\partial L_A} \tag{3}$$

However, the wage rate in the urban sector is exogenously set by a minimum wage, which is higher than the market-clearing rate:

$$p_M \frac{\partial f_M(L_M, K_M, \rho E)}{\partial L_M} = \overline{w} \tag{4}$$

We will assume that the minimum wage is binding in the sense that firms do not want to hire more labor than is available at $\overline{w}$. Urban unemployment results as workers equate the wage rate in the agricultural sector with the expected wage rate in the urban areas:

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[1] To avoid excessive repetition of the term urban sector, we will interchangeably also refer to it as the industrial or manufacturing sector. All of these labels are illustrations only; what is really meant is the non-agricultural part of the economy.

[2] We assume that capital stocks are sectorally immobile, which implies that we take a more short-run perspective in our analysis. In the long run, it can be expected that unemployed industrial capital will flow towards the agricultural sector. However, assuming mobile capital does not affect our main results.

[3] We make these assumptions for simplicity only. Our central conclusions would survive the inclusion of energy as a production factor in the agricultural sector and a domestic energy sector.

$$w_A = \delta \overline{w} \tag{5}$$

where δ is the probability of being employed for urban workers.

Total labor force consists of rural employed, urban employed and urban unemployed:

$$L = L_A + L_M + L_U, \text{ thus } \delta = \frac{L_M}{L_M + L_U} \tag{6}$$

The rental rates of the sector-specific capital stocks are competitively determined and equal the value of their marginal productivities:

$$r_A = \frac{\partial f_A(L_A, K_A)}{\partial K_A}, \; r_M = p_M \frac{\partial f_M(L_M, K_M, \rho E)}{\partial K_M} \tag{7}$$

Finally, firms in the manufacturing sector use energy as an input up to the point where its price equals the value of the marginal productivity of energy:

$$p_E = p_M \frac{\partial f_M(L_M, K_M, \rho E)}{\partial E} \tag{8}$$

3 The effects of energy efficiency improvements

The key focus of our analysis is to determine the general equilibrium effects of changes in energy efficiency. Intuitively, the channel through which changes in ρ affect the endogenous variables is the input mix in industrial production. The optimal factor mix in the manufacturing sector depends on ρ; therefore, changes in that parameter will lead to a reallocation of input factors. As we assume that capital is specific, i.e. immobile between the sectors, adjustment to the new equilibrium will take place through changes in labor allocation and energy demand. Ultimately, all endogenous variables will readjust. Below, we characterize and interpret these changes.

In order to evaluate the general equilibrium effects of an increase in ρ, we condense equations (3)-(6) through substitution and arrive at

$$p_M \frac{\partial f_M(L_M, K_M, \rho E)}{\partial L_M} = \overline{w} \tag{9}$$

$$\frac{\partial f_A(L_A, K_A)}{\partial L_A} = \frac{L_M}{L - L_A} \overline{w} \tag{10}$$

The system of equations (7)-(10), consisting of 5 endogenous variables (L_M, L_A, r_M, r_A and E), and 7 exogenous parameters ($\overline{w}, \rho, p_M, L, K_M$ and K_A).

Totally differentiating the above system of equations and applying Cramer's rule to the comparative static system yields

$$\frac{dL_M}{d\rho} = E \frac{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial \rho} \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2} \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial \rho}}{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2} \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M} \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E}} \tag{11}$$

$$\begin{aligned}\frac{dL_A}{d\rho} = E & \frac{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial \rho}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial \rho}}{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2}} \\ & \times \frac{\frac{\partial f_A(L_A,K_A)}{\partial L_A}\frac{(L-L_A)}{L_M}}{\frac{\partial f_A(L_A,K_A)}{\partial L_A} + \frac{\partial^2 f_A(L_A,K_A)}{\partial L_A^2}(L_A - L)}\end{aligned} \tag{12}$$

$$\frac{dr_A}{d\rho} = \frac{dL_A}{d\rho}\frac{\partial^2 f_A(L_A,K_A)}{\partial K_A \partial L_A} \tag{13}$$

$$\begin{aligned}\frac{dr_M}{d\rho} = \Bigg[& \frac{\left(\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial K_M \partial L_M}\right)\left(\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial \rho} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial \rho}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E}\right)}{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2}} \\ & + \frac{\left(\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial K_M \partial E}\right)\left(\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial \rho}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial \rho}\right)}{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2}} \\ & + \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial K_M \partial \rho}\Bigg] \times E\, p_M\end{aligned} \tag{14}$$

$$\frac{dE}{d\rho} = \frac{E}{\rho}\frac{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial \rho}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial \rho}}{\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial L_M}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial E} - \frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E^2}\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M^2}} \tag{15}$$

Equations (11)-(15) show that the signs of the comparative static effects depend on the sign of the cross derivatives $\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial E \partial \rho}$, $\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial K_M \partial \rho}$ and $\frac{\partial^2 f_M(L_M,K_M,\rho E)}{\partial L_M \partial \rho}$. This reflects the fact that the main channels through which energy efficiency gains induce adjustment processes, and hence impact on the general equilibrium, are their effects on the marginal productivity of energy and the other input factors.

Therefore, in our analysis we need to distinguish between production technologies that are *fuel using*[4] and those that are *fuel conserving* in the sense of Saunders (2008). The former correspond to production functions where an increase in energy efficiency leads to an increase of the marginal productivity of energy at a given input level, while the latter correspond to the opposite case. We will further make the assumption that in case the production technology is fuel using (conserving), an increase in energy efficiency does not lead to a decrease (increase) in the marginal productivity

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[4] This property is featured e.g. by Cobb-Douglas production functions as well as by the greater part of the CES production function family.

of any other input factor.[5] Hence, fuel using production technologies are characterized by

$$\frac{\partial^2 f_M(L_M, K_M, \rho E)}{\partial E \partial \rho} > 0, \frac{\partial^2 f_M(L_M, K_M, \rho E)}{\partial L_M \partial \rho} \geq 0 \text{ and } \frac{\partial^2 f_M(L_M, K_M, \rho E)}{\partial L_M \partial \rho} \geq 0 \tag{16}$$

while for fuel conserving technologies the opposite inequalities hold.

In the following analysis we concentrate on the case of a fuel using technology. The analogously derived results for the case of a fuel conserving production function are presented in the propositions for completeness. Throughout the analysis we assume that the efficiency increase is not too big so that the urban minimum wage is still binding.

An increase in energy efficiency leads to migration from the rural to the urban areas due to the fact that the expected wage in the urban areas increases. While the effective wage rate in the industrial sector remains constant, employment increases and thus the unemployment rate goes down. Hence, the ratio of employed workers to total urban labor force increases and so does the expected urban wage rate, which induces rural-to-urban migration. Workers will continue to flow from the rural areas to the cities until the expected urban wage equals the agricultural wage.

Proposition 1. *If the production technology in the industrial sector is fuel using (conserving), an increase in energy efficiency leads to a migration flow from the rural (urban) to the urban (rural) areas.*[6]

Energy efficiency gains lead to an expansion of the industrial sector as an increase in energy efficiency leads to an increase in the marginal productivity of energy, which in turn increases energy input. The latter drags up the marginal productivity of labor so that more workers are employed. Hence, the output of the industrial sector increases. However, as the industrial expansion pulls workers from the rural areas to the cities, the agricultural sector contracts:

Proposition 2. *If the production technology in the industrial sector is fuel using (conserving), an increase in energy efficiency leads to an expansion of output in the industrial sector (rural sector) and to a contraction of agricultural output (industrial output).*

The urban minimum wage is still binding, and thus continues to be the effective wage rate in the industrial sector. However, due to the outflow of workers from the agricultural sector, the marginal productivity of labor increases there and pushes the wage rate upwards. Hence, the wage in the rural areas increases, while it remains constant in the urban areas, which means that the wage differential between employed workers in the cities and the rural areas decreases due to energy efficiency gains.[7]

Proposition 3. *If the production technology in the industrial sector is fuel using (conserving), an increase in energy efficiency leads to an increase (decrease) in the wage rate of the agricultural sector, and thus to a decrease (increase) of wage inequality.*

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[5] Indeed, it is difficult to imagine a technology where an increase in energy efficiency leads to an increase (decrease) in the marginal productivity of energy but at the same time causes a fall (rise) in the marginal productivity of labor or capital at the given input levels.

[6] The proofs of all propositions are given in the Appendix.

[7] Note that, formally, the unemployed earn zero income in this model; one could, however, also think of the urban unemployed as earning a (perhaps informal) subsistence income or receiving transfers, in which case the expected urban wage rate would need to be updated accordingly, but the main properties of the model would not change.

On the one hand, labor employment decreases in the agricultural sector, which leads to a decrease in the marginal productivity of capital, and hence, to a fall in the rental rate. On the other hand, the marginal productivity of capital in the manufacturing sector increases which pushes up the rental rate there. Hence, the owners of the industrial sector-specific capital are the winners of energy efficiency improvements, while the capital owners in the rural sector are the losers:

Proposition 4. *If the production technology in the industrial sector is fuel using (fuel conserving), an increase in energy efficiency leads to an increase (decrease) in the rental rate of capital in the urban sector, while the return to capital in the agricultural sector decreases (increases).*

Absolute employment in the urban sector increases due to the increase in the marginal productivity of labor, but employment in the rural sector decreases. Which one of these effects dominates, i.e. the sign of the net economy-wide employment effect of an increase in energy efficiency, is *a priori* ambiguous. Hence, it is possible that an increase in energy efficiency causes more unemployment:

Proposition 5. *An increase in energy efficiency can lead to an increase in the number of unemployed.*

We have established in Proposition 2 that, for fuel using technologies, energy efficiency gains lead to an expansion of the industrial sector and to a contraction of agricultural output. The former also means that imports of energy inputs, which are costly from a national perspective, will have to increase. As we are considering a small open economy, the prices of both the outputs and energy are unaffected as foreign producers adjust their production at constant marginal costs to ensure market clearing. Hence, there are three factors that affect national income. First, the increase in industrial production leads to a higher value of industrial output and thus to higher income. Second, *vice versa*, the decrease in agricultural output reduces national income. Third, also the higher energy import bill reduces income. As these three effects work in different directions, it is *a priori* ambiguous whether energy efficiency increases will also increase national income, or rather lead to a net reduction of welfare. This means that energy efficiency gains can cause a fall in the value of national production net of imports, as is shown by the following proposition.

Proposition 6. *An increase in energy efficiency can lead to a reduction in national income.*

From a technical point of view, an increase in energy efficiency is equivalent to factor-augmenting (or input-saving) technological change; with given energy input, a larger amount of output can be produced, or a given output level can be attained with lower energy input. Therefore, the result shown in Proposition 6 directly relates to the literature on immiserizing growth proposed by Bhagwati (1958, 1968) and Johnson (1967). As Bhagwati (1968) shows, whenever there is a distortion in the economy, be it domestic (e.g. a wage differential) or foreign (e.g. unexploited monopoly power in trade), factor accumulation or technological progress can lead to net welfare losses. This seemingly paradoxical result is essentially an application of the theory of the second best as the technological progress exacerbates the welfare loss due to the pre-existing distortion to an extent where it outweighs the positive income effect from higher factor productivity. An urban minimum wage, of course, is such a distortion. However, as Beladi and Naqvi (1988) and Yabuuchi (1998) demonstrate, in the standard two-factor Harris-Todaro model, immiserizing growth is not possible. This surprising property is due to the fact that, in the basic model, the urban minimum wage pins down the economy-wide rental rate of capital, which implies that also the agricultural wage rate remains constant in the face of technological progress. Beladi and Naqvi (1988) show that national income, i.e. total factor return does not depend on the urban-rural wage differential so that accumulation of either capital or labor necessarily leads to income growth. However, our model diverges in three important ways from the standard setting. First, there are three input factors in the industrial sector. Second, the energy bill has to be deducted from income so that, if the energy input in the industrial sector increases, the incremental energy imports reduce income. Third, we consider a model with sector-specific capital stocks. The key point is that the addition of energy as an input in industrial production means that the capital-to-labor ratio in the industrial sector is not fixed by the urban minimum wage through the linear homogeneity of the production function. Hence, the urban minimum wage pins down neither the rental rates of capital nor the agricultural wage rate.

Note that energy efficiency gains can be immiserizing even in the case of a domestic energy source (so imports would not reduce income), and in the case of sectorally mobile capital. Hence, the result in Proposition 6 is not a construct based on specific assumptions of the model, but rests on the very existence of energy as a third input factor, which breaks the link between urban minimum wage, on the one hand, and the agricultural wage rate and the rental rates of capital, on the other.

4 Concluding remarks

Energy efficiency improvements are frequently characterized as being a cheap or even free option to reap "low hanging fruits" in terms of greenhouse gas emission reductions and energy savings. This view has been challenged on the basis of the so-called rebound effect, i.e. it has been argued that an increase in energy efficiency might lead to an increase in energy consumption, partly offsetting the efficiency gains. In this paper we look at other collateral effects of energy efficiency gains focusing on unemployment.

In a 2-sector 3-factor model with urban unemployment we show that energy efficiency gains will lead to an expansion (contraction) of the industrial sector if the production technology is fuel using (fuel conserving). Similarly, the effects on wage, inequality, rental rate of capital and migration will have the opposite signs in the two cases. However, the net effect of energy efficiency gains on unemployment and welfare are ambiguous in both cases. Hence, no matter which technology prevails in the industrial sector, energy efficiency gains can have considerable and potentially unwanted consequences.

The described effects are not only relevant from an analytical point of view, but also carry normative implications for policy formulation and advice. If energy efficiency gains are the objective of a targeted policy measure, the social side-effects have to be quantified and taken into account in cost-benefit analysis, policy evaluation and policy design. These side-effects have to be analyzed case by case and could either reinforce or weaken the case for the policy.

Finally, we wish to emphasize that the case of urban unemployment considered in this paper should be seen as a highly stylized illustration for a more general point. Energy efficiency policies, particularly if they aim at large-scale transformations rather than isolated measures, are likely to bring about adjustment processes that spill over the borders of industrial sectors. Knowledge about the nature and magnitude of these processes is of key importance for the integration and alignment of energy efficiency policies within a broader development policy strategy.

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