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Energy intensity and directed fiscal policy

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ABSTRACT

This paper assesses the effects of fiscal policy on economy-wide energy intensity within an endogenous growth framework. To this end, we first develop a two-sector (investment good and consumption good) augmented AK model by integrating the Uzawa model with Rebelo's AK model, and assume that a non-renewable resource is one of the factors of production. Using this framework, we solve the model for the short and long run, identifying the sufficient parameter conditions that ensure higher energy intensity in the investment goods sector. We then introduce a balanced budget government, whose objective is to decrease the economy-wide energy intensity by levying tax on the energy-intensive investment goods sector and subsidizing the consumption goods sector. Contrary to our expectations, we find that this fiscal policy design increases economy-wide energy intensity as it leads to a decline in real GDP without changing total energy consumption. On the basis of this model, we propose the concept of a 'directed fiscal policy', which connotes a reduction of the economy-wide energy intensity by following a heterogeneous taxation policy across sectors.

1. Introduction

Due to concerns over the long-standing dependency on fossil fuels and the catastrophic consequences of climate change, particularly since the energy price crisis of the 1970s, global energy policies have two underlying principles: (1) increasing the utilization of renewable energy sources and (2) decreasing energy intensity. As a result, the global share of renewable energy sources in total primary energy consumption has increased by an average annual rate of 2 % since 1990, reaching 13.5 % in 2018, while there was a significant decline in global energy intensity from 0.173 in 1990 to 0.111 in 2018 (International Energy Agency, 2020),[2] largely due to developed economies' response to the oil price crises of the 1970s (see Greening et al., 1998; Liddle, 2012; Grossi and Mussini, 2017; among others). Various studies further attribute this decline in global energy intensity to two major drivers: the efficiency effect and the structural effect (Haas and Kempa, 2018). The former suggests that the decline is due to the

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2 The unit of energy intensity is tons of oil equivalent (toe) per thousand US$ in 2015 PPP; available at: https://www.iea.org/reports/energy-efficiency-indicators (Access Date: 31.10.2021).

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diffusion of energy saving technologies in the economy, and the latter attribute it to the change in sectoral composition in favor of less energy-intensive sectors.

Over recent decades, a vast amount of literature has emerged that empirically decomposes energy intensity into these two drivers (see, for instance, Metcalf, 2008; Löschel et al., 2015; Mulder, 2015; among others), seemingly with no consensus on which driver is dominating the decrease in global energy intensities. Sun (1998), for instance, suggests that the efficiency effect was responsible for more than 75 % and 90 % of the decline in intensity in the pre- and post-1980 periods, respectively. Mulder and de Groot (2012) analyze the energy intensity dynamics of 50 sectors in 18 OECD countries, and similarly find that, between 1970 and 2005, the efficiency effect dominated the decrease in energy intensity. On the other hand, Löschel et al. (2015) report variations in the results across EU countries in terms of drivers of the energy intensity decline. The apparent heterogeneity across countries cannot be totally attributed to economic development levels, however. Voigt et al. (2014), for instance, show that the efficiency effect is the main driver of energy intensity dynamics in most industrialized economies, but also that changes in the sectoral composition made a greater contribution in certain industrialized countries, including Japan, the US and Australia. Similar heterogeneity is also reported for India (Reddy and Ray, 2010) and China (Zeng et al., 2014).

Rather than aiming to determine which effect is more dominant in explaining the global energy intensity dynamics, in this article we mainly focus on the structural effect. Our objective is to assess the potential contribution of fiscal policy to decreasing the economy-wide energy intensity by directing the sectoral composition. To this end, we propose a stylized economy in which the government uses proportional income taxation and subsidies to reduce the economy's energy intensity. We call this approach "directed fiscal policy" following Acemoglu (1998, 2002). Our modeling approach includes two phases: First, we develop a two-sector endogenous growth model without government (Base Model) and provide the complete algebraic solution of the model in the short and long run. The base model is essentially a two-sector augmented AK model, following Uzawa (1961, 1963) and Rebelo (1991), in which a non-renewable resource is one of the factors of production. Then, we introduce the government, whose aim is to reduce energy intensity (Fiscal Policy Integrated Model), by applying heterogenous taxation policy. This framework illustrates how "directed fiscal policy" affects energy intensity dynamics via the structural effect.

The study has a three-fold contribution to the literature. Firstly, we take a different approach from standard two-sector endogenous growth models following Rebelo (1991), which are built upon the idea of heterogenous growth effects of different sectors. Generally, this stream of literature ensures endogenous growth by eliminating diminishing returns to a factor of production in one of the sectors. Our model, in contrast, proposes a more generalized modeling approach by defining production technologies symmetrically across sectors, which extends the approach of Acemoglu et al. (2012),[3] and hence contributes to that literature. Secondly, this approach has the ability to provide a complete algebraic solution of the model in the short and long run, which reveals the explicit parameter conditions ensuring that one sector has a higher energy intensity. Finally, by introducing government to the model, we show how fiscal policy affects economy-wide energy intensity via changing the sectoral composition of the economy, i.e., the structural effect. To our best knowledge, this approach has never been explicitly modeled in the literature and hence constitutes our largest contribution.

Using our two-sector stylized economy, and making the assumption, without loss of generality, that the first is the investment goods sector and the second the consumption goods sector, à la Uzawa (1961, 1963), we arrive at two important findings: (1) the base model proposes that the energy intensity of the investment sector will be higher as long as the output elasticity of energy input in the investment sector is "sufficiently" higher than in the consumption sector, and the ratio of consumption output to investment output is higher than the relative price of consumption goods in terms of investment goods; and (2), the fiscal policy integrated model shows that overall energy intensity is increased by imposing proportional income taxation on the more energy-intensive investment sector and subsidizing the less energy-intensive consumption sector. Although initially seeming counter-intuitive, the result is implied by the fact that the investment goods sector is a source of reproducible capital, and that taxation leads to a decline in aggregate output without changing total energy consumption. The literature so far seems to have overlooked the role of fiscal policy in directing economy-wide energy intensity.

This paper is structured as follows. In Section 2, the base model is described. Section 3 is dedicated to the fiscal policy integrated model. A comparison of economy-wide energy intensity with and without fiscal policy is presented in Section 4. Finally, Section 5 concludes with policy implications.

2. Base model

Consider an economy with two sectors, namely the investment goods (I) and consumption goods (C) sectors, following Uzawa (1961, 1963). We assume an augmented AK production function for both sectors:

$$Y_I = A_I \bullet K_I + R_I^{\alpha} \bullet L_I^{1-\alpha} \tag{1a}$$

$$Y_C = A_C \bullet K_C + R_C^{\beta} \bullet L_C^{1-\beta} \tag{1b}$$

where output Y_i is produced by inputs of physical capital K_i, non-renewable energy resource R_i, and labor L_i in sector i=I, C. In equation (1), $A_i > 0$ is a positive constant, $\alpha, \beta \in (0,1)$, and α/1-α and β/1-β represent the output elasticity of non-renewable energy

[3] In fact, our approach also deviates from Acemoglu et al. (2012) in that, although they also assume symmetric production technologies, only one sector uses (non-renewable) energy as an input, whereas in our setup both sectors employ energy as a factor of production.

resource relative to the output elasticity of labor in the investment and consumption sectors, respectively. Our motivation to assume an augmented AK form is that the non-renewable resource is required for production in the short run but inessential for long-run growth. The rationale for employing symmetrical augmented AK forms across sectors is to assess the role of the structural effect in energy intensity in an algebraically tractable way. If all factors of production were subject to diminishing returns, both their short-run solutions and the relative price would be a nonlinear function of the aggregate quantities of inputs. In addition to this, the model would then fail to show endogenous growth in the long run.

Under the full employment condition, factor market clearing constraints are as follows:

$$K_I + K_C = K \tag{2a}$$

$$R_I + R_C = R \tag{2b}$$

$$L_I + L_C = L \tag{2c}$$

where K, R and L are the aggregate quantities of capital, non-renewable energy and labor, respectively.

The first-order conditions derived from profit maximization under perfectly competitive market assumptions imply well-known factor-employment conditions. Defining $p = \frac{P_C}{P_I}$ as the relative price and assuming free movement of factors of production between sectors within the economy, these first-order conditions further imply:

$$A_I = p \bullet A_C \tag{3a}$$

$$\alpha \bullet R_I^{\alpha-1} \bullet L_I^{1-\alpha} = p \bullet \beta \bullet R_C^{\beta-1} \bullet L_C^{1-\beta} \tag{3b}$$

$$(1-\alpha) \bullet R_I^{\alpha} \bullet L_I^{-\alpha} = p \bullet (1-\beta) \bullet R_C^{\beta} \bullet L_C^{-\beta} \tag{3c}$$

Eq. (3a) directly implies $p = \frac{A_I}{A_C}$, which is constant both in the short and long run. This is a substantial deviation from Uzawa (1963), in which the relative price is a non-linear function of aggregate quantities of inputs in the short-run equilibrium. The solution of the system (3a) to (3c) leads to the short-run equilibrium values of L_I, L_C, R_I and R_C as follows:

$$L_I = \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\frac{R}{CR_1} - \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right) \bullet L \tag{4a}$$

$$L_C = \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) \bullet \left[L - \frac{R}{CR_1}\right] \tag{4b}$$

$$R_I = \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)[R - CR_2 \bullet L] \tag{5a}$$

$$R_C = \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) \bullet CR_2 \bullet L - \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right) \bullet R \tag{5b}$$

where $CR_1 = \left(\frac{A_I}{A_C}\right)^{\frac{1}{\alpha-\beta}} \bullet \left(\frac{\beta}{\alpha}\right)^{\frac{\beta}{\alpha-\beta}} \bullet \left(\frac{1-\beta}{1-\alpha}\right)^{\frac{1-\beta}{\alpha-\beta}}$, $CR_2 = \left(\frac{A_I}{A_C}\right)^{\frac{1}{\alpha-\beta}} \bullet \left(\frac{\beta}{\alpha}\right)^{\frac{\alpha}{\alpha-\beta}} \bullet \left(\frac{1-\beta}{1-\alpha}\right)^{\frac{1-\alpha}{\alpha-\beta}}$ and hence $\frac{CR_1}{CR_2} = \frac{\alpha(1-\beta)}{\beta(1-\alpha)}$.

Eqs. (4a), (4b), (5a) and (5b) suggest that the short-run equilibrium values of labor and non-renewable energy inputs across sectors are determined linearly by the aggregate quantities of non-renewable energy and labor inputs. Moreover, positivity conditions, namely $L_i > 0$ and $R_i > 0$ for $i = I, C$, must be satisfied in order to achieve an interior solution in the model. Otherwise, for instance if $L_i = 0$ or $R_i = 0$, one of the production functions in equation (1) will degenerate into a usual AK form. Note also that the positivity conditions ensure $L_i < L$ and $R_i < R$ along with the factor market clearing constraints, i.e., Eqs. (2a) to (2c). Consequently, these conditions together imply either $\alpha > \beta$ and hence $CR_2 < \frac{R}{L} < CR_1$ or $\alpha < \beta$ and hence $CR_1 < \frac{R}{L} < CR_2$ in equations (4) and (5).[4]

Without loss of generality and following the literature (see for instance, Chang et al., 2019, and references therein), we assume that the output elasticity of non-renewable energy input in the investment goods sector (I) is greater than that in the consumption goods sector (C):

Assumption 1. Output elasticity of non-renewable energy input in sector I is greater than that in sector C, that is, $\alpha > \beta$.

The solution of the model at short-run equilibrium follows with defining the real GDP in terms of the price of the investment good sector as:

$$Y = Y_I + p \bullet Y_C \tag{6}$$

Following Solow (1956) for one-sector models and Uzawa (1963) for two-sector models, we assume that the exogenous saving rate determines the (short-run) demands for alternative uses of income. Accordingly:

$$s \bullet Y = Y_I, \tag{7}$$

where s is the exogenous saving rate. Thus, $(1-s) \bullet Y$ constitutes the demand for consumption goods. Eqs. (6) and (7) together imply:

[4] See Appendix I for details.

$$Y_I = \frac{s}{1-s} \bullet p \bullet Y_C \tag{8}$$

Eq. (8) along with the short-run equilibrium values of L_I, L_C, R_I and R_C—represented by Eqs. (4a), (4b), (5a) and (5b)—would lead to short-run equilibrium values of K_I and K_C:

$$K_I = s \bullet K + \{\bullet\}_L \bullet L - \{\bullet\}_R \bullet R \tag{9a}$$

$$K_C = (1-s) \bullet K - \{\bullet\}_L \bullet L + \{\bullet\}_R \bullet R \tag{9b}$$

where $\{\bullet\}_L = \left\{\frac{s}{A_C}\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta} \bullet (CR_1)^{\beta} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) + \left(\frac{1-s}{A_I}\right)(CR_1)^{\alpha} \bullet \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right)\right\} > 0$ and $\{\bullet\}_R = \left\{\frac{s}{A_C}\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta} \bullet (CR_1)^{\beta-1} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) + \left(\frac{1-s}{A_I}\right)(CR_1)^{\alpha-1}\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\right\} > 0$, given Assumption 1. We observe that K_I and K_C are linear functions of aggregate quantities of capital, non-renewable energy, and labor.

Given the production functions defined by Eqs. (1a) and (1b), one can easily show the short-run equilibrium values of Y_I and Y_C:

$$Y_I = s \bullet [A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L] \tag{10a}$$

$$Y_C = (1-s) \bullet [A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L] \tag{10b}$$

where, given Assumption 1, $\bar{M}_1$, $\bar{M}_2$, $\bar{N}_1$ and $\bar{N}_2$ are all positive constants as follows:

$$\bar{M}_1 = \left\{(CR_1)^{\alpha-1}\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) - \frac{A_I}{A_C}\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta} \bullet (CR_1)^{\beta-1} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\right\}$$

$$\bar{N}_1 = \left\{\frac{A_I}{A_C}\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta} \bullet (CR_1)^{\beta} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) - (CR_1)^{\alpha} \bullet \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right)\right\}$$

$$\bar{M}_2 = \left\{\frac{A_C}{A_I}(CR_1)^{\alpha-1} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) - \left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta} \bullet (CR_1)^{\beta-1} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\right\}$$

$$\bar{N}_2 = \left\{\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta} \bullet (CR_1)^{\beta} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) - \frac{A_C}{A_I}(CR_1)^{\alpha} \bullet \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right)\right\}$$

The augmented AK form production functions proposed in our model lead to another important deviation from Uzawa (1963) type models; i.e., the short-run solution of Y_I and Y_C (and subsequently Y below) are additively separable linear functions of inputs, in contrast to standard Uzawa models.

Finally, the short-run energy intensities (EI) in both sectors can be determined. Using Eqs. (5a), (5b), (10a) and (10b), one can easily show:

$$EI_I = \frac{R_I}{Y_I} = \frac{\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)[R - CR_2 \bullet L]}{s \bullet [A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L]} \tag{11a}$$

$$EI_C = \frac{R_C}{Y_C} = \frac{\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) \bullet CR_2 \bullet L - \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right) \bullet R}{(1-s) \bullet [A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L]} \tag{11b}$$

One implication of Assumption 1 is that the investment sector could be assumed to be more energy intensive than the consumption sector. Using Eqs. (11a) and (11b), we can identify two sufficient conditions that ensure $EI_I > EI_C$:

Condition 1: $\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)[R - CR_2 \bullet L] > \left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) \bullet CR_2 \bullet L - \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right) \bullet R$.

which simplifies to $\left[1 + \frac{\alpha(1-\beta)}{\beta(1-\alpha)}\right]\frac{R}{L} > 2 \bullet CR_1$, recalling that $\frac{CR_1}{CR_2} = \frac{\alpha(1-\beta)}{\beta(1-\alpha)}$. Given Assumption 1, one can find $\frac{\alpha(1-\beta)}{\beta(1-\alpha)} > 1$. Moreover, since $\frac{R}{L} < CR_1$, this condition will hold if and only if α is "sufficiently" greater than β.[5]

Condition 2: $s \bullet [A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L] < (1-s) \bullet [A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L]$.

Given Assumption 1, this condition will hold if and only if $\frac{1-s}{s} > \frac{A_I}{A_C}$.

In summary, the energy intensity of the investment goods sector will be higher if α is "sufficiently" greater than β and $\frac{1-s}{s} > \frac{A_I}{A_C}$, that is, the ratio of consumption output to investment output is higher than the relative price of consumption goods in terms of investment goods.

[5] Please note that $\frac{\partial\left[\frac{\alpha(1-\beta)}{\beta(1-\alpha)}\right]}{\partial\alpha} > 0$, $\frac{\partial\left[\frac{\alpha(1-\beta)}{\beta(1-\alpha)}\right]}{\partial\beta} < 0$, $\frac{\partial CR_1}{\partial\alpha} < 0$, and $\frac{\partial CR_1}{\partial\beta} > 0$. Hence, increasing α and decreasing β increases the left-hand side of the condition and decreases the right-hand side.

As a last step, using (10a) and (10b) in (6), the short-run equilibrium real GDP can be found as follows.[6].

$$Y = s\bullet[A_I\bullet K + \bar{M}_1\bullet R + \bar{N}_1\bullet L] + \frac{A_I}{A_C}.(1-s)\bullet[A_C\bullet K + \bar{M}_2\bullet R + \bar{N}_2\bullet L] \tag{12}$$

Eq. (12) will further be used for the analyses in Section 4.

3. Fiscal policy integrated model

Now suppose that we introduce into the model the government, whose main objective is to reduce the economy's energy intensity; to achieve this, the most immediate approach is to change the composition of total output in favor of less energy-intensive sector(s). In our stylized two-sector base model, without loss of generalization, we presumed that under the two conditions defined above, that is, **Condition 1** and **Condition 2**, the investment sector is more energy-intensive. In this section, we introduce proportional income taxation, τ, to the investment sector and subsidy σ to the consumption sector. Under perfectly competitive market and free movement of factors of production between sectors within the economy assumptions, the first-order conditions derived from profit maximization will lead:

$$(1-\tau)\bullet P_I'\bullet A_I = (1+\sigma)\bullet P_C'\bullet A_C \tag{13a}$$

$$(1-\tau)\bullet P_I'\bullet\alpha\bullet R_I^{\alpha-1}\bullet L_I^{1-\alpha} = (1+\sigma)\bullet P_C'\bullet\beta\bullet R_C^{\beta-1}\bullet L_C^{1-\beta} \tag{13b}$$

$$(1-\tau)\bullet P_I'\bullet(1-\alpha)\bullet R_I^{\alpha}\bullet L_I^{-\alpha} = (1+\sigma)\bullet P_C'\bullet(1-\beta)\bullet R_C^{\beta}\bullet L_C^{-\beta} \tag{13c}$$

Note that Eq. (13a) now implies: $p' \equiv \frac{P_C'}{P_I'} = \frac{(1-\tau)\bullet A_I}{(1+\sigma)\bullet A_C}$, which is lower than the relative price in the base model. Compared to Eqs. (3a) to (3c), Eqs. (13a) to (13c) reveal that fiscal policy shifts leftward the supply curve of the investment good sector and rightward that of the consumption good.

The introduction of the government under a balanced budget assumption does not change the short-run equilibrium allocation of L_I, L_C, R_I and R_C. Hence, Eqs. (4a), (4b) and (5a) and (5b) still hold. Moreover, similar to the base model, defining the real GDP in terms of the price of the investment goods sector and continuing to assume that the exogenous saving rates determine the (short-run) demands for alternative uses of income as in (7), imply the demand for investment goods to be the same as formulated in (8). Subsequently, the short-run equilibrium values of K_I and K_C are determined as:

$$K_I' = s'\bullet K + \{\bullet\}_L'\bullet L - \{\bullet\}_R'\bullet R \tag{14a}$$

$$K_C' = K - K_I' = (1-s')\bullet K - \{\bullet\}_L'\bullet L + \{\bullet\}_R'\bullet R \tag{14b}$$

where $\{\bullet\}_L' = \left\{\frac{s'}{A_C}\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta}\bullet(CR_1)^{\beta}\bullet\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) + \left(\frac{1-s'}{A_I}\right)(CR_1)^{\alpha}\bullet\left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right)\right\}$ and $\{\bullet\}_R' = \left\{\frac{s'}{A_C}\left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)}\right)^{\beta}\bullet(CR_1)^{\beta-1}\bullet\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) + \left(\frac{1-s'}{A_I}\right)(CR_1)^{\alpha-1}\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\right\}$ for $s' = \frac{s(1-\tau)}{(1-s)(1+\sigma)+s(1-\tau)}$.

s' and $1-s'$ could be interpreted as tax weighted saving rates associated with the investment and consumption goods sectors, respectively. It is easy to show that $s > s'$ and $1-s < 1-s'$ and that $K_I' < K_I$ and $K_C' > K_C$ for a given K. We also note that a rise in the tax rate decreases the weighted saving rate in the investment sector ($\frac{\partial s'}{\partial\tau} < 0$), and a rise in the subsidy rate increases the weighted saving rate in the consumption sector ($\frac{\partial(1-s')}{\partial\sigma} > 0$).

Using the short-run values of all factors of production, we can calculate the short-run equilibrium values of Y_I' and Y_C':

$$Y_I' = s'\bullet[A_I\bullet K + \bar{M}_1\bullet R + \bar{N}_1\bullet L] \tag{15a}$$

$$Y_C' = (1-s')\bullet[A_C\bullet K + \bar{M}_2\bullet R + \bar{N}_2\bullet L] \tag{15b}$$

where, given Assumption 1, $\bar{M}_1$, $\bar{M}_2$, $\bar{N}_1$and $\bar{N}_2$ are all the same positive constants as before.

We assume that all of the tax revenue is directly used to subsidize the less energy-intensive sector. Hence, the balanced budget assumption $G = T$ implies:

$$\sigma\bullet p'\bullet Y_C' = \tau\bullet Y_I' \tag{16}$$

Using the short-run equilibrium values for Y_I' and Y_C' in Eq. (16) leads to:

$$\sigma = \left(\frac{A_C}{A_I}\right)\bullet\left(\frac{s}{1-s}\right)\bullet\tau\bullet\left[\frac{A_I\bullet K + \bar{M}_1\bullet R + \bar{N}_1\bullet L}{A_C\bullet K + \bar{M}_2\bullet R + \bar{N}_2\bullet L}\right] \tag{17}$$

Eq. (17) implies a fixed relationship between the subsidy rate and the tax rate imposed by the balanced budget assumption. One can easily show that the subsidy rate is increased by a higher tax rate on the investment sector, $\frac{d\sigma}{d\tau} > 0$, or a higher allocation of resources for investment goods, $\frac{d\sigma}{ds} > 0$.

[6] Since our paper aims to analyze the effects of fiscal policy in the short run, we refrain from providing the complete algebraic solution of the long-run equilibrium in the text. However, for the sake of completeness, Appendix II provides the long-run solution, which relies on the standard physical capital accumulation assumption and an unorthodox assumption of a constant depletion rate of non-renewable resources.

Using (5a), (5b), (16a) and (16b), we calculate the short-run energy intensities of both sectors as follows:

$$EI_I' = \frac{R_I}{Y_I'} = \frac{\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)[R - CR_2 \bullet L]}{s' \bullet [A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L]} \tag{18a}$$

$$EI_C' = \frac{R_C}{Y_C'} = \frac{\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right) \bullet CR_2 \bullet L - \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right) \bullet R}{(1-s') \bullet [A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L]} \tag{18b}$$

Eqs. (18a) and (18b) show in comparison with (11a) and (11b) that the fiscal policy has asymmetric effects on sectoral energy intensities; while the energy intensity of the investment sector is increasing, that of the consumption sector is decreasing in the aftermath of fiscal policy intervention. This contradictory result is because, although the symmetrical production functions across sectors imply no change in the short-run equilibrium allocation of labor and non-renewable resources, there is a change in the allocation of physical capital in favor of the consumption goods sector. Hence, the fiscal policy increases the supply of consumption goods and decreases the supply of investment goods, and subsequently lowers the relative price of the former in relation to the latter. We moreover observe that an increased intensity of fiscal policy via increasing tax or subsidy leads to an increase in the energy intensity of the investment goods sector ($\frac{\partial(EI_I')}{\partial\tau} > 0$, $\frac{\partial(EI_I')}{\partial\sigma} > 0$), and to a decrease in the energy intensity of the consumption good sector ($\frac{\partial(EI_C')}{\partial\tau} < 0$, $\frac{\partial(EI_C')}{\partial\sigma} < 0$).

Finally, recalling the balanced budget assumption in (16) and using Eqs. (15a) and (15b) in Eq. (6) along with the facts $p' = \frac{(1-\tau) \bullet A_I}{(1+\sigma) \bullet A_C}$ and $s' = \frac{s(1-\tau)}{(1-s)(1+\sigma)+s(1-\tau)}$, we can find the short-run equilibrium value of real GDP as follows:

$$Y' = \left[\frac{1-\tau}{(1-s) \bullet (1+\sigma) + s \bullet (1-\tau)}\right]\left\{s[A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L] + (1-s)\left(\frac{A_I}{A_C}\right)[A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L]\right\} \tag{19}$$

We will use all this information in the next section to demonstrate the impact of fiscal policy on energy intensity.

4. Energy intensity and directed fiscal policy

The overall success of the fiscal policy can be determined by examining the economy-wide energy intensity in our stylized economy. Firstly, in the base model the economy-wide energy intensity could be written using Eq. (12) as follows:

$$EI_b = \left(\frac{R}{Y}\right)_b = \frac{R}{s[A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L] + \frac{A_I}{A_C}.(1-s) \bullet [A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L]} \tag{20}$$

Secondly, noting that there is no change in non-renewable resource allocation in the short run in the aftermath of fiscal policy intervention, the economy-wide energy intensity in the fiscal policy integrated model could be written using Eq. (19) as follows:

$$EI_f = \left(\frac{R}{Y'}\right)_f = \frac{R}{\left[\frac{1-\tau}{(1-s) \bullet (1+\sigma)+s \bullet (1-\tau)}\right]\left\{s[A_I \bullet K + \bar{M}_1 \bullet R + \bar{N}_1 \bullet L] + \frac{A_I}{A_C}.(1-s) \bullet [A_C \bullet K + \bar{M}_2 \bullet R + \bar{N}_2 \bullet L]\right\}} \tag{21}$$

Proposition 1. Economy-wide energy intensity **increases** in the aftermath of fiscal policy intervention: $EI_f > EI_b$.

Proof.

Proof directly follows, since $1 - \tau < 1 + \sigma$ will always hold.∎

According to Proposition 1, economy-wide energy intensity increases with pursuing a directed fiscal policy, under the assumption that $\alpha > \beta$.

Proposition 2. Economy-wide energy intensity (EI_f) increases if the tax rate or the subsidy rate increases, i.e., $\frac{\partial EI_f}{\partial\tau} > 0$ and $\frac{\partial EI_f}{\partial\sigma} > 0$.

Proof.

Proof directly follows from Eq. (21). ∎.

The results depicted by Proposition 1 and Proposition 2 are initially quite counter-intuitive, since in our stylized model fiscal policy is particularly designed to decrease energy intensity by taxing the investment sector, assumed to be more energy-intensive, and by subsidizing the less energy-intensive consumption sector. Yet here we show that this fiscal policy design leads to a decrease in the real GDP for a given non-renewable energy, and hence to an increase in economy-wide energy intensity. This is because, in our model, the fiscal policy decreases the relative price and, in turn, the employment of physical capital and the production of investment goods. Our model highlights that success is not always guaranteed by fiscal policy aiming at lowering the overall energy intensity without considering the impact of a change in relative prices on production and the peculiarities of different sectors. In fact, as shown in Appendix III, in our modeling approach, taxing the less energy-intensive sector and subsidizing the more energy-intensive one would lead to a decrease in economy-wide energy intensity. Following the idea proposed by Acemoglu (1998, 2002) and Acemoglu et al. (2012), we call this approach “directed fiscal policy”.

5. Conclusions and policy implications

In this paper, we aimed to analyze the effects of fiscal policy on economy-wide energy intensity within an endogenous growth framework. To this end, we proposed a two-sector augmented AK model, by integrating Uzawa's two-sector model (Uzawa, 1961, 1963) with Rebelo's AK model (Rebelo, 1991). Following Uzawa (1961, 1963), we define two sectors, the investment and consumption sectors, both of which use non-renewable resources as a factor of production. In contrast to the general trend in the two-sector endogenous growth literature, we define symmetric production functions across sectors. Hence, we propose a more generalized modeling approach in which both sectors are a source of endogenous growth. We use this setup to study two stylized models: (1) the base model and (2) the fiscal policy integrated model. Using the base model, we present the complete algebraic solution both for the short and the long run and derive conditions under which the investment sector is more energy-intensive than the consumption sector. In the fiscal policy integrated model, we introduce a balanced budget government, whose main objective is to decrease economy-wide energy intensity via fiscal policy. We speculate that this could be facilitated by the government levying tax on the energy-intensive investment sector and subsidizing the less energy-intensive consumption sector, thus forcing a change in the sectoral composition of the economy.

Contrary to our expectations, we find that an increase, rather than a reduction, in the economy-wide energy intensity would result from this course of action. The reason is that the investment goods sector is the source of reproducible asset capital, and taxation leads to a decline in real GDP without changing total energy consumption. Hence, we propose that fiscal policy designs aiming to reduce economy-wide energy intensity should take into account these dynamics. Based on this conjecture, we develop the concept of a "directed fiscal policy", which recommends a comparison of each sector's relative energy intensity responsiveness to tax (or subsidy), and supporting those with a greater contribution to lowering the overall energy intensity.

The results achieved in this paper are mainly driven by the modeling choice of fiscal policy tools. A possible future research direction would be to employ a factor price taxation modeling approach that would change the allocation of non-renewable resource input across sectors. However, it is important to note that this approach would not necessarily lead to a closed form solution, particularly because a short-run equilibrium of factor inputs would then be a non-linear function of aggregated quantities of factors.

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Declarations of interest

None.

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Appendix I

For $L_I > 0$, using the short-run equilibrium in Eq. (4a), the following must hold:

$$\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\frac{R}{CR_1} > \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right)\bullet L$$

Noting that $\frac{CR_1}{CR_2} = \frac{\alpha(1-\beta)}{\beta(1-\alpha)}$, this leads to:

$$\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\frac{R}{L} > \left(\frac{\beta(1-\alpha)}{\alpha-\beta}\right)\bullet\frac{\alpha(1-\beta)}{\beta(1-\alpha)}\bullet CR_2$$

There are two possibilities for this condition to hold:

$\alpha > \beta$ and $\frac{R}{L} > CR_2$.

$\alpha < \beta$ and $\frac{R}{L} < CR_2$.

Similarly, for $L_C > 0$, using the short-run equilibrium in Eq. (4b), the following must hold:

$$\left(\frac{\alpha(1-\beta)}{\alpha-\beta}\right)\bullet\left[L-\frac{R}{CR_1}\right] > 0$$

There are two possibilities for this condition to hold:

$\alpha > \beta$ and $\frac{R}{L} < CR_1$.

$\alpha < \beta$ and $\frac{R}{L} > CR_1$.
If we collect these two results:
$\alpha > \beta$ and $CR_2 < \frac{R}{L} < CR_1$.
$\alpha < \beta$ and $CR_1 < \frac{R}{L} < CR_2$.
The same results would apply for $R_i > 0$, for $i = I, C$ using the short-run equilibrium values in Eqs. (5a) and (5b).

Appendix II

Long-run equilibrium in the base model.

Although for our purposes a short-run equilibrium will be enough, it is also possible to show the long-run equilibrium of our proposed model. Given the standard assumption that the production of the investment sector adds to the capital stock, the physical capital stock grows according to the following rule:

$$\dot{K} = Y_I - \delta \cdot K. \tag{II.1}$$

We also need to define the dynamics of the labor market and the non-renewable resource market. We assume that labor stock grows at a known rate n by the following rule: $L = L_0 \bullet e^{nt}$. Recall that $R_t = R_{It} + R_{Ct}$. We assume that the stock of the non-renewable resource is subject to the following depletion rule:

$$\dot{S}_t = -R_t \tag{II.2}$$

In this step, we make an unorthodox assumption and assume a constant depletion rate of the non-renewable resource for the sake of algebraic simplicity. In particular, we assume that the extraction rate is constant over time:

$$R_t = s_R \bullet S_t \tag{II.3}$$

Equations (II.2) and (II.3) imply that $S_t = S_0 \bullet e^{-s_R \bullet t}$, $R_t = s_R \bullet S_0 \bullet e^{-s_R \bullet t}$ (and hence $R_0 = s_R \bullet S_0$). Without a loss of generality, we assume that the extraction rate out of remaining stock is constant and identical for both sectors, that is, $s_{R1} = s_{R2} = s_R$.

We first write the fundamental equation of growth:

$$\dot{K} = s \bullet A_I \bullet K_t + \bar{M} \bullet R_t + \bar{N} \bullet L_t - \delta \cdot K_t$$

where

$$\bar{M} = \left\{ s \bullet (CR_1)^{\alpha-1} \left(\frac{\alpha(1-\beta)}{\alpha-\beta} \right) - \frac{s \bullet A_I}{A_C} \left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)} \right)^{\beta} \bullet (CR_1)^{\beta-1} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta} \right) \right\}$$

$$\bar{N} = \left\{ \frac{s \bullet A_I}{A_C} \left(\frac{\beta(1-\alpha)}{\alpha(1-\beta)} \right)^{\beta} \bullet (CR_1)^{\beta} \bullet \left(\frac{\alpha(1-\beta)}{\alpha-\beta} \right) - s \bullet (CR_1)^{\alpha} \bullet \left(\frac{\beta(1-\alpha)}{\alpha-\beta} \right) \right\}$$

Dividing both sides by L and imposing the time path of the non-renewable energy source defined by equations (II.2) and (II.3), we get:

$$\dot{k} = (s \bullet A_I - n - \delta) \cdot k_t + \bar{M} \bullet \left(\frac{s_R \bullet S_0}{L_0} \right) e^{-(s_R+n) \bullet t} + \bar{N} \tag{II.4}$$

We presume that $s \bullet A_I > n + \delta$. Define $A' = s \bullet A_I - n - \delta$ and $\bar{\bar{M}} = \bar{M} \bullet \left(\frac{s_R \bullet S_0}{L_0} \right)$. Then equation (II.4) can be expressed as

$$\dot{k} - A' \cdot k = \bar{\bar{M}} \bullet e^{-(s_R+n) \bullet t} + \bar{N} \tag{II.5}$$

Applying the formal solution to (II.5), one ends up with:

$$k = -\frac{\bar{\bar{M}}}{s_R + n + A'} \bullet e^{-(s_R+n) \bullet t} - \frac{\bar{N}}{A'} + \left[k_0 + \frac{\bar{\bar{M}}}{s_R + n + A'} + \frac{\bar{N}}{A'} \right] \bullet e^{A' \cdot t}$$

One can easily show that $\lim_{t \to \infty} k = \infty$ or $\lim_{t \to \infty} \frac{\dot{k}}{k} = A'$. Hence, we show that the model has endogenous growth and that the rate is A'.

Appendix III

Taxing less energy-intensive sector.

It is quite straightforward to show that taxing the consumption goods sector and subsidizing the investment goods sector would decrease economy-wide energy intensity by re-writing the first order conditions as follows:

$$(1 + \sigma) \bullet P_I' \bullet A_I = (1 - \tau) \bullet P_C' \bullet A_C \tag{III.a}$$

$$(1 + \sigma) \bullet P_I' \bullet \alpha \bullet R_I^{\alpha-1} \bullet L_I^{1-\alpha} = (1 - \tau) \bullet P_C' \bullet \beta \bullet R_C^{\beta-1} \bullet L_C^{1-\beta} \tag{III.b}$$

$$(1 + \sigma) \bullet P_I' \bullet (1 - \alpha) \bullet R_I^{\alpha} \bullet L_I^{-\alpha} = (1 - \tau) \bullet P_C' \bullet (1 - \beta) \bullet R_C^{\beta} \bullet L_C^{-\beta} \tag{III.c}$$

The remaining part of the solution follows directly, and one can show that under these sets of equations, economy-wide energy intensity will fall after this fiscal policy intervention, i.e., $EI^f < EI^b$.

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