Theoretical Economics Letters, 2024, 14, 869-877
https://www.scirp.org/journal/tel
ISSN Online: 2162-2086
ISSN Print: 2162-2078

Investment, Green Transformation and Growth

Edward B. Barbier

Department of Economics, Colorado State University, Fort Collins, CO, USA
Email: edward.barbier@colostate.edu

How to cite this paper: Barbier, E. B. (2024). Investment, Green Transformation and Growth. *Theoretical Economics Letters, 14,* 869-877.
https://doi.org/10.4236/tel.2024.143045

Received: February 19, 2024
Accepted: June 14, 2024
Published: June 17, 2024

Abstract

The aim of this paper is to develop a two-sector model to explore green economic transformation. The clean energy sector includes a novel technology subject to learning by doing and knowledge spillovers across firms. The dirty sector generates pollution, global warming and other environmental damage from energy used for production. Comparing investment and growth under decentralized, or private, decision-making with socially optimal investment and growth helps to identify the policies required to promote a green transition of the economy. In the decentralized economy, infinitely lived households maximize (indirect) utility and individual firms in the two sectors maximize profits, so that both externalities are ignored. In contrast, a social planner accounts for the externalities. The result is that investment and thus growth of the clean energy sector under decentralized decision-making are too low, whereas growth of the dirty energy sector is too high, compared to the socially optimal growth rates of these sectors. The implications are that policies that boost green R&D and innovation and impose carbon pricing are necessary. These results are in line with policy strategies that advocate economy-wide support for green innovation, carbon pricing and infrastructure investments for clean energy adoption.

Keywords

Carbon Pricing, Clean Energy, Economic Growth, Green Economy, Green Innovation

1. Introduction

Transition to a low-carbon or "green" economy requires considerable structural change. As Fankhauser et al. (2013: p. 903) note: "The creation of a green economy will therefore affect not just a few sectors but the product mix and production processes of virtually the whole economy". However, it is not always clear what policies might be required to support green structural transformation. In the following paper, this problem is explored through developing a model of investment and growth for a two-sector economy.

Theoretical treatments of green economic transformation often portray it as reducing dependence on a "dirty" (i.e. high-carbon and more polluting) energy source while increasing use of a "clean" (low-carbon and less polluting) source. Or more succinctly, a two-sector economy becomes less reliant on a "dirty energy" as opposed to a "clean energy" sector (Acemoglu et al., 2012; Greaker et al., 2018; Hart, 2019; Mattauch et al., 2015). However, the various modeling approaches to this problem often differ in their policy conclusions. For example, directed technical change models, such as by Acemoglu et al. (2012) and Greaker et al. (2018), generally conclude that policies to direct research and development (R&D) away from "dirty" energy towards "clean" sectors are more important compared to carbon and pollution pricing. In contrast, general equilibrium-inspired models, such as Hart (2019) and Mattauch et al. (2015), suggest that both policies are necessary for green transformation.

The following simple two-sector model of investment and growth explores green economic transition under decentralized versus socially optimal decision-making. Both sectors display unique externalities. As the clean energy sector includes a novel technology, there is learning by doing and a positive knowledge spillover across firms. The dirty sector generates pollution, global warming and other environmental damage from energy used for production. In the decentralized economy, infinitely lived households maximize (indirect) utility and individual firms in the two sectors maximize profits, so that both externalities are ignored. In contrast, a social planner accounts for the externalities. The result is that investment and thus growth of the clean energy sector under decentralized decision-making are too low, whereas growth of the dirty energy sector is too high, compared to the socially optimal growth rates of these sectors. As suggested by Hart (2019) and Mattauch et al. (2015), the socially optimal policy response consists of both carbon pricing and public support for clean energy innovation.

2. Model

The economy comprises two sectors, one which uses a "clean" (low-carbon and less polluting) energy source and the other employs a "dirty" (high-carbon and more polluting) source. A representative individual consumes products from both sectors, which is modeled here as contributing to the consumer's indirect utility. The aim of this section is to provide the key assumptions underlying these two production sectors and consumer behavior, which are then used to explore green economic transition under decentralized versus socially optimal decision-making in Section 3.

2.1. Clean Energy (Sector 1)

The clean energy sector is also denoted as Sector 1. Each firm i in this sector exhibits neoclassical production, with positive and diminishing marginal product of each input and constant returns to scale. Technology is assumed to be labor augmenting. Workers in each firm must become familiar with the new technology required for clean energy, and as their knowledge of the new technology increases, it augments the effectiveness of labor in production.

Let Y_{1i} be the output of firm *i*, then:

$$Y_{1i} = Y_1\left(K_{1i}, A_{1i}L_{1i}, X_{1i}\right), \tag{1}$$

where K_{1i} is capital, L_{1i} is labor and A_{1i} is the index of knowledge employed by firm *i*, and X_{1i} is the amount of clean (low carbon) energy used by the firm.

The clean energy technology employed by each firm in Sector 1 is novel and thus subject to learning by doing and knowledge spillovers across all firms in the sector. As pointed out by Rodrik (2014: p. 470), these characteristics may "exist in general for all kinds of new technologies, whether they are of the green or dirty kind", but they are especially relevant to green technologies due to "their novelty, their highly experimental nature, and the substantial risks involved for pioneer entrepreneurs". Learning by doing is the result of a firm's investment so that an increase in each firm's capital stock leads to a parallel increase in its stock of knowledge. Knowledge spillover occurs, because each firm's knowledge is a public good that any other firm in Sector 1 can access at zero costs. The implications of these two assumptions is that the change in each firm's technology $\mathrm{d}A_{1i}/\mathrm{d}t$ corresponds to the overall learning occurring in the sector and is therefore proportional to the change in aggregate capital stock of the sector $\mathrm{d}K_1/\mathrm{d}t$. It follows that $A_{1i} = K_1$.

Although each firm uses clean energy in production, following Frankel (1962), it is assumed that overall use of this energy source by each firm *i* depends on the capital-intensity (capital-labor ratio) of the firm. That is, letting $\Phi_1\left(K_{1i}/L_{1i}\right), \Phi_1' > 0$ be the contribution of clean energy to production of Y_{1i}, then (1) can be rewritten as:

$$Y_{1i} = F_1\left(K_{1i}, K_1L_{1i}\right) + \Phi_1\left(K_{1i}/L_{1i}\right). \tag{2}$$

Note that an important assumption is that each firm in the clean energy sector is small enough to neglect its own contribution to the aggregate capital stock of the sector and therefore treats K_1 as given in Equation (2).

In equilibrium, all firms make the same choices (all firms are identical) so that $y_{1i} = Y_{1i}/L_{1i} = Y_1/L_1 = y_1$ and $k_{1i} = K_{1i}/L_{1i} = K_1/L_1 = k_1$. It follows from (2) that output per worker is:

$$y_{1i} = y_1 = f_1\left(k_1, K_1\right) + \phi_1\left(k_1\right) \tag{3}$$

Average product of capital is therefore $y_1/k_1 = f_1\left(K_1/k_1\right) + \phi_1\left(k_1\right)/k_1$, and using $f_1\left(k_1, K_1\right) = f_1\left(K_1/k_1\right)k_1$, marginal product of capital is $\partial y_1/\partial k_1 = f_1\left(L_1\right) - L_1 f_1'\left(L_1\right) + \phi_1'\left(k_1\right)$.

2.2. Dirty Energy (Sector 2)

Sector 2 comprises all firms t using dirty (i.e. high-carbon and polluting) technology. As in Sector 1, each firm *i* exhibits neoclassical production, and its energy use also depends on the capital-intensity (capital-labor ratio) of the firm. Technology is labor augmenting, so that effective labor input is $A_{2i}L_{2i}$. However, this is old technology that is familiar to all workers and firms in Sector 2. Consequently, the index of knowledge for this technology is the same and unchanging for each firm and can thus be normalized to one, i.e. $A_{2i} = A_2 = 1$.

Production for each firm *i* in Sector 2 is therefore defined by:

$$Y_{2i} = Y_2\left(K_{2i}, L_{2i}, X_{2i}\right) = F_2\left(K_{2i}, L_{2i}\right) + \Phi_2\left(K_{2i}/L_{2i}\right), \tag{4}$$

where K_{2i} is capital, L_{2i} is labor, X_{2i} is the amount of dirty (high carbon) energy used by the firm and $\Phi_2' > 0$. All firms in Sector 2 are identical, so that $y_{2i} = Y_{2i}/L_{2i} = Y_2/L_2 = y_2$ and $k_{2i} = K_{2i}/L_{2i} = K_2/L_2 = k_2$. It follows from (4) that output per worker is:

$$y_{2i} = y_2 = f_2\left(k_2\right) + \phi_2\left(k_2\right),\ \partial y_2/\partial k_2 = f_2'\left(k_2\right) + \phi_2'\left(k_2\right). \tag{5}$$

2.3. Utility

Let per capita consumption of goods and services produced by Sector 1 be c_1, and per capita consumption of Sector 2 be c_2. Total per capita consumption is therefore $c = c_1 + c_2$ and utility is defined as $u(c) = u(c_1 + c_2)$. Denoting I as total income in the economy and N as population, per capita income is I/N. If p_1 and p_2 are the vectors of prices associated with c_1 and c_2 respectively, then the indirect utility of a representative consumer is:

$$v\left(p_1, p_2, I/N\right) = v\left(\left(I/N\right)/P\right) = v\left(y\right), \tag{6}$$

where P is the price index that transforms income into utility, and real per capita income is defined as $\left(I/N\right)/P = y$. The latter variable is real GDP, or the per capita production of all goods and services in the economy. For example, if utility is expressed as CES preferences for c_1 and c_2 such that $u(c) = \left[c_1^\rho + c_2^\rho\right]^{1/\rho}$, then the indirect utility function of Equation (6) will take the explicit form $v(y) = \left(I/N\right)\Big/\left(p_1^{\rho/\rho-1} + p_2^{\rho/\rho-1}\right)^{(\rho-1)/\rho}$.

3. Decentralized versus Optimal Decision-Making

The above assumptions from Section 2 concerning production in the clean and dirty energy sectors as well as consumer behavior enable exploration of how green economic transformation might differ under decentralized as opposed to socially optimal decision-making. Such a comparison helps, in turn, to identify the policies required to promote a green transition of the economy.

3.1. Decentralized Economy

In the decentralized economy, infinitely lived households maximize (indirect) utility and individual firms in Sectors 1 and 2 maximize profits so that all externalities are ignored. These externalities include the spillover of knowledge across firms in Sector 1 and the disutility from pollution, global warming and other environmental damages from energy used for production in Sector 2.

Let real GDP, or the per capita production of all goods and services in the economy, be $y = y_1 + y_2$, where from (3) $y_1 = f_1(k_1, K_1) + \phi_1(k_1)$ and from (5) $y_2 = f_2(k_2) + \phi_2(k_2)$. If η is the rate of discount, n is population growth and δ_1, δ_2 is the rate of capital depreciation in Sectors 1 and 2 respectively, then the maximization problem of the representative consumer is:

$$J = \max_{y_1, y_2} \int_0^\infty e^{-(\eta+n)t} v(y_1 + y_2) dt \tag{7}$$

subject to $\dot{k}_1 = f_1(k_1, K_1) + \phi_1(k_1) - (\delta_1 + n)k_1 - c_1$, $k_1(0) = k_{10}$ and $\dot{k}_2 = f_2(k_2) + \phi_2(k_2) - (\delta_2 + n)k_2 - c_2$, $k_2(0) = k_{20}$.

The problem yields the following first-order conditions:

$$v' = \lambda_1 = \lambda_2,$$

$$\dot{\lambda}_1 - \lambda_1(\eta + n) = \lambda_1\left[n + \delta_1 - \left(f_1(L_1)L_1 - f_1'(L_1) + \phi_1'(k_1)\right)\right],$$

$$\dot{\lambda}_2 - \lambda_2(\eta + n) = \lambda_2\left[n + \delta_2 - \left(f_2'(k_2) + \phi_2'(k_2)\right)\right].$$

The latter two expressions become:
$\dot{\lambda}_1 = \lambda_1\left[\eta + \delta_1 - \left(f_1(L_1)L_1 - f_1'(L_1) + \phi_1'(k_1)\right)\right]$ and
$\dot{\lambda}_2 = \lambda_2\left[\eta + \delta_2 - \left(f_2'(k_2) + \phi_2'(k_2)\right)\right]$.

Using $v''\dot{y}_1 = \dot{\lambda}_1$ and $v''\dot{y}_2 = \dot{\lambda}_2$, the decentralized growth rates for Sectors 1 and 2 are, respectively:

$$\gamma_1^D = \dot{y}_1/y_1 = (1/\sigma_1)\left[f_1(L_1)L_1 - f_1'(L_1) + \phi_1'(k_1) - (\eta + \delta_1)\right],\ \sigma_1 = -v''y_1/v', \tag{8}$$

$$\gamma_2^D = \dot{y}_2/y_2 = (1/\sigma_2)\left[f_2'(k_2) + \phi_2'(k_2) - (\eta + \delta_2)\right],\ \sigma_2 = -v''y_2/v'. \tag{9}$$

3.2. Social Planner

The social planner includes the two externalities, which are the spillovers of knowledge across firms in Sector 1 and the disutility from pollution, global warming and other environmental damages from energy used for production in Sector 2. Denoting the latter disutility (in absolute value terms) to the representative consumer as $z(\phi_2(k_2))$, $z' > 0$, $z'' < 0$, the maximization problem of the social planner is:

$$J = \max_{y_1, y_2} \int_0^\infty e^{-(\eta+n)t}\left[v(y_1 + y_2) - z(\phi_2(k_2))\right] dt \tag{10}$$

subject to $\dot{k}_1 = f_1(L_1)k_1 + \phi_1(k_1) - (\delta_1 + n)k_1 - c_1$, $k_1(0) = k_{10}$ and $\dot{k}_2 = f_2(k_2) + \phi_2(k_2) - (\delta_2 + n)k_2 - c_2$, $k_2(0) = k_{20}$.

The social planner's problem yields the following first-order conditions:

$$v' = \lambda_1 = \lambda_2,$$

$$\dot{\lambda}_1 = \lambda_1\left[\eta + \delta_1 - \left(f_1(L_1) + \phi_1'(k_1)\right)\right]\ v' = \lambda_1 = \lambda_2,$$

$$\dot{\lambda}_2 = \lambda_2\left[\eta + \delta_2 - \left(f_2'(k_2) + \phi_2'(k_2)\right)\right] + z'(\phi_2(k_2))\phi_2'(k_2).$$

Using $v''\dot{y}_1 = \dot{\lambda}_1$ and $v''\dot{y}_2 = \dot{\lambda}_2$, the socially optimal growth rates for Sectors 1 and 2 respectively are:

$$\gamma_1^S = \dot{y}_1/y_1 = (1/\sigma_1)\left[f_1(L_1) + \phi_1'(k_1) - (\eta + \delta_1)\right],\ \sigma_1 = -v''y_1/v' \quad (11)$$

$$\gamma_2^D = \dot{y}_2/y_2 = (1/\sigma_2)\left[f_2'(k_2) + \left(1 - \left(z'\left(\phi_2(k_2)\right)/v'\right)\right)\phi_2'(k_2) - (\eta + \delta_2)\right], \\ \sigma_2 = -v''y_2/v' \quad (12)$$

3.3. Results and Findings

It is clear from the above results that green economic transformation will differ in the decentralized as opposed to the socially planned economy. That is, investment and thus growth of the clean energy sector under decentralized decision-making is too low, whereas growth of the dirty energy sector is too high, compared to the socially optimal growth rates of these sectors.

Comparing (8) and (11), $\gamma_1^S > \gamma_1^D$. Growth in Sector 1 under decentralized decision-making is too low compared to the socially optimal growth rate. Unlike individual producers in Sector 1, the planner recognizes that each firm's increase in its capital stock adds to the aggregate capital stock of the sector and thus contributes to the productivity of all clean energy firms. The social planner therefore sets the growth rate of the sector in accordance with the average product of capital of the sector $f_1(L_1)$, whereas each firm in sector 1 relates the growth rate to the marginal product of capital $f_1(L_1)L_1 - f_1'(L_1)$. As the average product of capital exceeds the marginal product, the socially optimal growth rate for Sector 1 is higher than its growth in the decentralized economy.

Comparing (9) and (12), $\gamma_2^S < \gamma_2^D$. Growth in Sector 2 under decentralized decision-making is too high compared to the socially optimal growth rate. Whereas decentralized decision-making ignores the disutility from pollution, global warming and other environmental damages from energy used for production in Sector 2, the social planner does consider such adverse impacts. Compared to the decentralized growth rate, the socially optimal growth rate for Sector 2 is lowered by the impact of this disutility $-\left(z'\left(\phi_2(k_2)\right)/v'\right)\phi_2'(k_2)$.

4. Policy Implications

Overall, the results of this two-sector model of investment and growth tend to support the conclusions of Hart (2019) and Mattauch et al. (2015). Green structural transformation requires policies to induce greater spillover of knowledge across firms in Sector 1 and to curb the disutility from pollution, global warming and other environmental damages from energy used for production in Sector 2. Two broad policies could be adopted to correct each of the externalities and thus ensure a faster green transition, i.e. higher socially optimal growth of Sector 1 and lower growth of Sector 2.

To spur more knowledge creation and thus greater spillover across firms in Sector 1, the government could subsidize clean energy research and development (R&D) by all clean energy firms or provide an investment tax credit for their purchases of capital goods, or some combination of these policies. Aghion et al. (2019) outline an even broader range of policies to encourage economy-wide innovation to transition to clean energy.

To internalize the pollution externality, the government could tax the carbon and other polluting emissions generated by fossil fuel energy use in Sector 2, or equivalently, administer a tradeable permit system for these emissions by producers in the sector. It is possible that the tax revenues raised by the pollution pricing schemes could finance the subsidies to create more clean energy R&D or capital investment in Sector 1. If not, lump sum taxes on consumers should make up the difference. Alternatively, if tax revenues exceed revenues, the balance could be rebated as dividends to consumers or to recycle revenues to lessen payroll taxes, pay annual dividends to households, raise the minimum wage, provide payments or retraining for displaced workers, and reduce burdens for vulnerable households affected by the green transition (Barbier, 2020, 2023; Goulder et al., 2019; Klenert et al., 2018).

Carbon pricing and other emission taxes could also promote innovation, which then also reduces the disutility from pollution. For example, Fried (2018) finds that a carbon tax induces significant innovation in green technologies. This innovation response in turn increases the effectiveness of the policy in reducing greenhouse gas emissions. As a result of the boost to innovation, the size of the carbon tax required to reduce emissions by 30% over 20 years is 19.2% lower.

To foster greater adoption of clean energy, green transition strategies often propose a combination of policies for low-carbon innovations and emissions taxes, as well as complementary infrastructure investments. For example, during the COVID-19 pandemic, several proposals called for widespread fossil fuel and carbon pricing policy reforms, public support for green R&D, smart grids, electrical vehicle charging networks, and other long-term investments to "green" economic recovery and speed up a low-carbontransition (Barbier, 2020, 2023; Hepburn et al., 2020; O'Callaghan et al., 2022).

To summarize, the main implication to emerge from the model developed here is that a strategy to promote green economic transformation should include both policies to direct research and development (R&D) away from "dirty" energy towards "clean" sectors and policies to impose carbon and pollution pricing. This is supported by theoretical and empirical research suggesting that carbon pricing and green R&D support are the right tools for a low-carbon transition (Blanchard et al., 2023). Complementary infrastructure investments to speed up economy-wide adoption of clean energy and compensation to vulnerable households adversely impacted by green transformation may also be necessary.

5. Conclusion

A simple two-sector model of investment and growth under decentralized compared to socially optimal decision-making enables exploration of the conditions that lead to a green economic transformation. This transition is characterized by less reliance of the economy on a "dirty" (i.e. high-carbon and more polluting) energy sector as opposed to a "clean" (low-carbon and less polluting) energy sector.

The main result of the model indicates that, left to private decision-making, growth will be too low in the clean energy sector and too high in the dirty energy sector. The socially optimal policy response consists of permanent carbon and other environmental taxes as well as an R&D subsidy and other support for clean energy innovation. This accords with findings from general equilibrium-inspired models of green structural transformation (Hart, 2019; Mattauch et al., 2015) and also with post-pandemic strategies for green economic recovery (Barbier, 2020, 2023; Hepburn et al., 2020; O'Callaghan et al., 2022).

Acknowledgements

E.B.B. thanks Amit Batyabal for the invitation to submit to this journal.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The Environment and Directed Technical Change. *American Economic Review*, *102*, 131-166. https://doi.org/10.1257/aer.102.1.131

Aghion, P., Hepburn, C., Teytelboym, A., & Zenghelis, D. (2019). Path Dependence, Innovation and the Economics of Climate Change. In R. Fouquet (Ed.), *Handbook on Green Growth* (pp. 67-83). Edward Elgar. https://doi.org/10.4337/9781788110686.00011

Barbier, E. B. (2020). Greening the Post-Pandemic Recovery in the G20. *Environmental and Resource Economics*, *76*, 685-703. https://doi.org/10.1007/s10640-020-00437-w

Barbier, E. B. (2023). Greening the G7 Economies. *Oxford Review of Economic Policy*, *39*, 731-751. https://doi.org/10.1093/oxrep/grad039

Blanchard, O., Gollier, C., & Tirole, J. (2023). The Portfolio of Economic Policies Needed to Fight Climate Change. *Annual Review of Economics*, *15*, 689-722. https://doi.org/10.1146/annurev-economics-051520-015113

Fankhauser, S., Bowen, A., Calel, R., Dechezleprêtre, A., Grover, D., Rydge, J., & Sato, M. (2013). Who Will Win the Green Race? In Search of Environmental Competitiveness and Innovation. *Global Environmental Change*, *23*, 902-913. https://doi.org/10.1016/j.gloenvcha.2013.05.007

Frankel, M. (1962). The Production Function in Allocation and Growth: A Synthesis. *The American Economic Review*, *52*, 996-1022.

Fried, S. (2018). Climate Policy and Innovation: A Quantitative Macroeconomic Analysis. *American Economic Journal: Macroeconomics*, *10*, 90-118. https://doi.org/10.1257/mac.20150289

Goulder, L.H., Hafstead, M.A., Kim, G., & Long, X. (2019). Impacts of a Carbon Tax across US Household Income Groups: What Are the Equity-Efficiency tRade-Offs? *Journal of Public Economics, 175,* 44-64. https://doi.org/10.1016/j.jpubeco.2019.04.002

Greaker, M., Heggedal, T. R., & Rosendahl, K. E. (2018). Environmental Policy and the Direction of Technical Change. *The Scandinavian Journal of Economics*, *120*, 1100-1138. https://doi.org/10.1111/sjoe.12254

Hart, R. (2019). To Everything There Is a Season: Carbon Pricing, Research Subsidies, and the Transition to Fossil-Free Energy. *Journal of the Association of Environmental and Resource Economists*, *6*, 349-389. https://doi.org/10.1086/701805

Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will COVID-19 Fiscal Recovery Packages Accelerate or Retard Progress on Climate Change? *Oxford Review of Economic Policy*, *36*, S359-S381. https://doi.org/10.1093/oxrep/graa015

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., & Stern, N. (2018). Making Carbon Pricing Work for Citizens. *Nature Climate Change, 8,* 69-677. https://doi.org/10.1038/s41558-018-0201-2

Mattauch, L., Creutzig, F., & Edenhofer, O. (2015). Avoiding Carbon Lock-In: Policy Options for Advancing Structural Change. *Economic Modelling*, *50*, 49-63. https://doi.org/10.1016/j.econmod.2015.06.002

O'Callaghan, B., Yau, N., & Hepburn, C. (2022). How Stimulating Is a Green Stimulus? The Economic Attributes of Green Fiscal Spending. *Annual Review of Environment and Resources*, *47*, 697-723. https://doi.org/10.1146/annurev-environ-112420-020640

Rodrik, D. (2014). Green Industrial Policy. *Oxford Review of Economic Policy*, *30*, 469-491. https://doi.org/10.1093/oxrep/gru025