Economic Growth, Emission Reduction and the Choice of Energy Technology in a Dynamic-Game Framework

Jürgen Scheffran

Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg C4,
P.O. Box 601203, D-14412 Potsdam, Germany, scheffran@pik-potsdam.de

Abstract. To assess options in energy policy, the relationship between energy technology, economic output and emissions is analyzed in a dynamic-game framework which describes the interaction between players aiming at economic output and emission reduction. The players allocate investment to various energy technologies, differing in costs, economic output and emissions per energy unit. Control variables for each player are the amount of investment and its allocation. Game-theoretic analysis is used to discuss conditions under which players would change behavior and select energy technologies to pursue their objectives more cooperatively. Policy instruments are compared with regard to the different energy paths and the compatibility of economic and environmental objectives.

1 Introduction

In economic theory technical progress is a primary source of growth. Its endogenization is an active branch of current research (Barro and Sala-i-Martin 1995, Aghion and Howitt 1998). In neoclassical theory the production of output is a function of capital and labor as input factors while energy and other natural resources are neglected. The energy crises of the 1970s, demonstrated the "limits to growth" and induced an economic crisis, providing a concrete experience of how a rise in energy prices could adversely effect economic growth. The crisis has induced a number of studies on natural resources and energy in economic growth, some of which have early recognized the need for an interdisciplinary perspective (Kümmel 1980, Eichhorn et.al. 1982). Some studies focused on the productive power of energy and used it as a factor in the production function (Renshaw 1981, 36, Hudson and Jorgenson, 1974, 461). Empirical data justified the econometric estimation of the energy elasticity in the Cobb-Douglas production function for the US, Japan and Europe. Being about 0.5 it is roughly equal to the sum of the two other elasticities and ten times the share of the energy cost in total factor cost (Kümmel, Lindenberger and Eichhorn 2000).

The energy-economy debate was revived by the anthropogenic greenhouse effect and projected risks of climate change, analyzed in recent reports (IPCC 2001). As part of the Rio process the Framework Convention on Climate Change (FCCC) agreed on general principles and rules which were specified by the Kyoto Protocol to reduce emissions. Among the policy instruments for emission reduction are administrative concepts (emission taxes), market instruments (tradeable emission permits) and cooperative approaches such as Joint Implementation and the Clean Development Mechanism (CDM).

Economists have estimated the potential damage of rising global temperatures on society and economy and developed models to understand the impacts and costs of avoiding climate change. The Nordhaus model provided a first approach for an integrated assessment (Nordhaus 1994) which induced a number of models to overcome the simplifying assumptions. The macroeconomic perspective, optimizing a global welfare function, has been extended by game-theoretic models on emission reduction (Svirezhev et.al. 1999, Finus 2001, Kemfert 2001). This paper integrates the relationship between economic growth, emission reduction and energy technology into a dynamic-game framework, based on the VCX model developed by the author to analyze dynamic multi-player interaction (the model and some mathematics is explained in Scheffran 2001a; model applications with regard to energy and environment can be found in Scheffran 2000; Scheffran and Pickl 2000; Ipsen, Rösch and Scheffran 2001; Scheffran 2001b).

2 Technical Choice and Conflicting Demands

To model the interaction between energy, evironment and economy, basic variables are energy production E, greenhouse gas emissions G and economic output Q, each for a given time period (e.g. one year) and for particular acting units (players), which can be firms, consumers or nation states. For continuous time, these variables turn into flow variables. The usual measure of economic output is the Gross Domestic Product (GDP). Total emissions can be expressed as a product of the following factors (Edenhofer 2001):

$$G = g^e \times e^q \times q^n \times N$$

where N is the population, $g^e = G/E$ the emission intensity $e^q = E/Q$ the energy intensity and $q^n = Q/N$ the labor productivity. Another relevant ratio is the economic output per energy unit and time unit $q^e = Q/E = 1/e^q$. In general, the factors are not constant and can be functions of time, energy and other variables. For the following analysis they are assumed to be fixed for a particular time period and energy type. Emirical date on the ratios are available and show the decoupling between economic output and emission in industrialized countries.

An increase ΔE of installed power (e.g. more power plants) from one time period to the next requires financial investment $C = c^e \cdot \Delta E$, where c^e is the cost to install one power unit. For fixed g^e and q^e additional power increases both economic output and emissions

$$\Delta G = g^e \cdot \Delta E = g^c \cdot C > 0$$
$$\Delta Q = q^e \cdot \Delta E = q^c \cdot C > 0$$

where $g^c = g^e/c^e$ and $q^c = q^e/c^e$ are emissions and output per cost unit. To simplify notation, index e is ignored, i.e. $g = g^e, q = q^e, c = c^e$.

Each player is assumed to have the choice between different energy paths $k = 1, ..., m$, which correspond to different energy technologies (fossil, solar, nuclear). As a special case, $m = 2$ paths are analysed: the "old" path uses established energy technology ($k = 1$), the "new" path more advanced energy technology ($k = 2$) with less emissions per energy unit, $g_2 < g_1$. $0 \le p \le 1$ is the fraction of investment into new energy technology and c_k are the costs per unit of energy technology $k = 1, 2$. Installed power can be reduced by ΔE^-, by shut-down of existing power facilities.

The problem is to find a cost-effective allocation of investments C to energy production to satisfy both economic demands $\Delta Q = V^Q > 0$ (economic growth) and environmental demands $\Delta G = V^G < 0$ (agreed emission reduction), depending on the technical parameters g, q, c (V^Q and V^G are the respective target levels). This leads to two target lines:

$$C^G = \frac{V^G + g_1 \Delta E_1^-}{g_p^c}, \quad C^Q = \frac{V^Q + q_1 \Delta E_1^-}{q_p^c}.$$

where $g_p^c = (1-p)g_1/c_1 + p \cdot g_2/c_2$ is the emission-to-cost ratio for allocation p and $q_p^c = (1-p)q_1/c_1 + p\, q_2/c_2$ is the output-to-cost ratio for allocation p. Both target lines intersect in the point of satisfaction

$$\widehat{C} = \frac{g_1 V^Q - q_1 V^G}{D} \equiv y, \quad \widehat{\Delta E}_1^- = \frac{g_p^c V^Q - q_p^c V^G}{D} \equiv x$$

where $D = g_1 q_p^c - q_1 g_p^c$. Both targets are compatible if they are within the feasible set $(0, 0) \le (\hat{x}, \hat{y}) \le (x^+, y^+)$ where x^+, y^+ denote the upper limits of action space. If the targets are incompatible, the player can change the allocation p, influence the technical-economic parameters g, q, c or adapt the target levels V^G and V^Q.

With $g_1^q = g_1/q_1$, the equilibrium costs are $\hat{C} = (g_1^q V^Q - V^G)/\bar{D}$ where $\bar{D} = D/q_1$. Since the numerator is positive for emission reduction targets $V^G < 0$, satisfaction can be achieved for positive investments as long as $\bar{D} = q_2^c(g_1^q - g_2^q)\, p > 0$ which is the case for $p > 0$ and $g_1^q = g_1/q_1 > g_2/q_2 = g_2^q$ i.e. the new technology emits less per economic output. As a simple example we use the special case $g_2 = 0.5\, g_1, q_2 = 1.5\, q_1, c_2 = 2\, c_1$, i.e. new technologies are cheaper and more productive but cost twice as much per unit. Then $g_2^q = g_1^q/3 < g_1^q$, $D > 0$ and $\hat{C} > 0$.

Within this framework it is possible to analyze conditions for cooperation between an industrialized country (IC) and a developing country (DC) by shifting to reduced-emission technology in DC with financial support from IC. For the simple example in the previous paragraph, a cooperation channel exists which allows both to achieve their targets at reduced cost by shifting to new technology and joint activities (see Scheffran 2001b).

3 Optimization in Climate Games

3.1 Utility and Damage Associated with Energy

While in the previous analysis economic and environmental targets were treated separately, the usual approach is to integrate the impact of production Q_i and emissions G_i for $i = 1, ..., n$ players Pi into welfare functions $V_i(Q, G) = U_i(Q_i) - D_i(G)$ where $G = \sum_j G_j$ is the sum of emissions of all players Pj and $Q = (Q_1, ..., Q_n)$ is the output vector. Utility function U_i and damage function D_i are defined as $U_i = u_i \cdot Q_i^{\alpha_i}$ and $D_i = d_i \cdot G^{\beta_i}$ where α_i and β_i are the respective elasticities, u_i and d_i are proportionality factors. Various models use $0 < \alpha_i \leq 1$ and $\beta_i \geq 1$. If both production $Q_i = q_i \cdot E_i^{\nu_i}$ and emissions $G_i = g_i \cdot E_i$ depend on energy consumption E_i, welfare of player Pi is a function of energy consumption of all players:

$$V_i(E_1, ..., E_n) = u_i Q_i^{\alpha_i} - d_i G^{\beta_i} = u_i^e E_i^{\eta_i} - d_i (\sum_j g_j E_j)^{\beta_i}$$

where $u_i^e = u_i q_i^{\alpha_i}$ and $\eta_i = \nu_i \alpha_i$. The marginal impact of Pi's energy increase on its welfare $\partial V_i / \partial E_i$ is the difference between marginal utility and damage of energy. Setting this term to zero provides the optimal energy level for Pi, as a function of the energy consumption of all other players Pj.

As an example we treat the case of two players ($n = 2$), each with $\alpha_i = \nu_i = 0.5$ and $\beta_i = 1$ (linear damage function) such that $\eta_i = 1/4$. Then the condition $\partial V_i / \partial E_i = 0$ leads to $E_i^* = (u_i^e / 4 d_i g_i)^{4/3}$. Thus, an increase in u_i^e or a decline in d_i or g_i would increase the optimal energy level which is independent of other players' actions. For $\beta_i = 2$ other players come into the optimization game, and the optimal level can be determined implicitly as $E_j = (u_i^e / 8 d_i g_i g_j) \cdot E_i^{-3/4} - E_i / g_j$ which corresponds to a set of reaction curves in energy space. The special case that Pi is the only emitter ($E_j = 0$) leads to the optimum $E_i^* = (u_i^e / 8 d_i g_i)^{4/7}$.

3.2 Negotiations on Emission Reduction

Now consider $i = 1, ..., n$ players generating economic oputput Q_i, emissions G_i and emission reduction R_i. We assume a linear utility function $U_i = u_i Q_i$, a linear relationship between output and emissions $Q_i = g_i G_i (1 - R_i)$ and a quadratic damage function ($\beta_i = 2$). In addition, the costs are a quadratic function $C_i(R_i) = r_i R_i^2$ of emission reduction. Then as a net value function of utility, damage and costs we define (with $u_i^g = u_i g_i$)

$$V_i = U_i(Q_i) - D_i(G) - C_i(R_i) = u_i^g G_i (1 - R_i) - d_i (\sum_j G_j (1 - R_j))^2 - r_i R_i^2.$$

The optimality condition $\partial V_i / \partial R_i = 0$ yields optimal emission reductions

$$R_i^* = \frac{d_i (\sum_{j \neq i} G_j (1 - R_j)) - u_i^g G_i / 2}{d_i G_i + r_i}.$$

which defines a reaction curve for Pi in emission space. The optimal emission reductions are in the feasible range $0 \leq R_i^* \leq 1$ for

$$G_i^- = \frac{d_i(\sum_j G_j(1-R_j)) - r_i}{u_i^g/2 + d_i} \leq G_i \leq \frac{2d_i(\sum_{j\neq i} G_j(1-R_j))}{u_i^g} = G_i^+$$

If all countries would agree on the same emission reduction $R_i = R$ for $i = 1, ..., n$, then $\partial V_i/\partial R = 0$ gives the optimal emission reductions.

3.3 Position Change and Coalition Formation

If for a player Pi it is individually optimal not to reduce emissions, some incentives are required to change its position $x_i = R_i$ by Δx_i. This can be achieved by sanctions or cooperation and coalition formation which implies that a group of players achieves a "coalition gain". Players are willing to change their positions to jointly concentrate their power resources (critical mass) for achieving a coalition gain which they are unable to do alone. The following terms can influence a position change Δx_i:

1. Position change of player Pi leads to value change $\Delta V_{ii}(\Delta x_i)$.
2. Deviation from Pi's optimum by sharing coalition gain: $\Delta V^i(x)$
3. Impact of other players' power use (reward and punishment) ΔV_{ij}
4. Own costs fractions $\Delta C_{ij} = p_{ij} \cdot C_i$ to influence other players Pj.

Then a condition for a position change Δx_i of player Pi is total value change

$$\Delta V_i = \Delta V_{ii} + \Delta V^i(x) + \sum_j \Delta V_{ij} - \sum_j C_{ij} > 0.$$

4 Technology Choice of Competing Firms

4.1 The Cobb-Douglas Production Function

In the following the analysis is extended to a Cobb Douglas production function, with energy E, capital K and labor L as production factors:

$$Q = \beta \cdot K^{\alpha^K} L^{\alpha^L} E^{\alpha^E}.$$

β measures production efficiency and $\alpha^K, \alpha^L, \alpha^E$ elasticities. Labor $L = p^L C/c^L$ and energy $E = p^E C/c^E$ depend on fractions p^E, p^L of investment C, where c^L, c^E are labor and energy unit costs. Assume capital grows with

$$\dot{K} = p^K e^K C - \delta \cdot K.$$

where δ is the decay rate, e^K is the investment efficiency for capital and p^K the percentage of investment for capital. The steady-state condition $\dot{K} = 0$ leads to $K^* = p^K C/(\delta\, c^K)$ where $c^K = 1/e^K$ is the unit cost to maintain the capital stock K^*. Then produced output can be expressed as a function of costs $Q = \beta \cdot \Pi^\alpha \cdot C^\alpha$ where $\Pi = (p^K/c^K)^{\alpha^K} \cdot (p^L/c^L)^{\alpha^L} \cdot (p^E/c^E)^{\alpha^E}$ and $\alpha = \alpha^K + \alpha^E + \alpha^L$. According to Jensen's inequality, Π and thus Q is maximized for $p^E = \alpha^E/\alpha, p^L = \alpha^L/\alpha, p^K = \alpha^K/\alpha$.

4.2 The Impact of Emission Tax on Competing Firms

We now model firms Pi ($i = 1, ..., n$) with Cobb-Douglas production functions $Q_i = \beta_i K_i^{\alpha_i^K} L_i^{\alpha_i^L} E_i^{\alpha_i^E} = \beta_i \gamma_i \pi_i \cdot C_i$ where $\pi_i = (p_i^K)^{\alpha_i^K} (p_i^L)^{\alpha_i^L} (p_i^E)^{\alpha_i^E}$ is the allocation function and $\gamma_i = (c_i^K)^{-\alpha_i^K} (c_i^L)^{-\alpha_i^L} (c_i^E)^{-\alpha_i^E}$ inverse unit costs. Let $E_i^k = p_i^k C_i / c_i^k$ be energy of type k of firm Pi, where p_i^k and c_i^k are the respective allocation and unit costs. One way to convince firms to switch to more sustainable technologies with less emissions is an emission tax τ. Then the net value for firm Pi with product Q_i can be expressed in terms of costs

$$V_i = q \cdot Q_i - C_i - \tau \sum_k g_i^k E_i^k = (v_i - \sum_j v_{ij} C_j) C_i$$

where $q = a - b \cdot \sum_j Q_j$ is the demand-dependent market price for good Q and v_i, v_{ij} are appropriate factors. For $\partial V_i / \partial p_i > 0$ a change towards new energy technology provides individual value gains. This defines a *lower tax threshold* τ_i^* depending on the model parameters. For $\tau > \tau_i^*$ it would be rational for firm Pi to switch to new energy technologies, if the taxes are not too high to prevent positive value. The condition $V_i > 0$ leads to the *upper tax threshold* $\tau_i^0 > \tau_i$. As long as $\tau_i^0 < \tau_i^*$, environmental and economic demands are compatible. For $\tau_i^0 < \tau_i^*$ however, there is a conflict between both.

4.3 Dynamics and Computer Simulation

Partial derivatives $\partial V_i / \partial C_i = 0$ and $\partial V_i / \partial p_i = 0$ define optimality conditions for costs $\tilde{C}_i$ and allocation $\tilde{p}_i$ which correspond to reaction functions. The adaptation dynamics leads to a system of difference equations

$$\Delta C_i(t) = C_i(t+1) - C_i(t) = \alpha_i^c (\tilde{C}_i(t) - C_i(t))$$
$$\Delta p_i(t) = p_i(t+1) - p_i(t) = \alpha_i^p (\tilde{p}_i(t) - p_i(t))$$

which describe an evolution of firm's behavior over time (see Scheffran 2000a).

For numerical simulation, we assume two firms Pi ($i = 1, 2$) which produce goods Q_i with initial price $a = 1$ and elasticity $b = 0.01$ and two energy technologies E_i^k, where old technology ($k = 1$) initially costs half of new technology ($k = 2$) per energy unit, i.e. $c_i^1 = 1, c_i^2 = 2$, while emissions are twice as much ($g_i^1 = 1, g_i^2 = 0.5$). Capital and labour are assumed to cost the same ($c_i^K = c_i^L = 1$). Exponents and allocation priorities of the production function are highest for energy ($\alpha_i^E = p_i^E = 0.5$), while for capital and labor the estimates $\alpha_i^K = p_i^K = 0.3$ and $\alpha_i^L = p_i^L = 0.2$ are used. Half of initial investment stock $C_i^K = 10$ is used for investment flow C_i. Initially all investment is used for old energy technology $p_i^1 = 1$. The reaction parameters for the adaptation algorithms to approach target costs and allocation are set to $\alpha_i^c = \alpha_i^p = 0.5$. Both firms behave alike, with one exception: production efficiency is slightly higher for firm P1 compared to P2 ($\beta_1 = 5.5, \beta_2 = 4.5$).

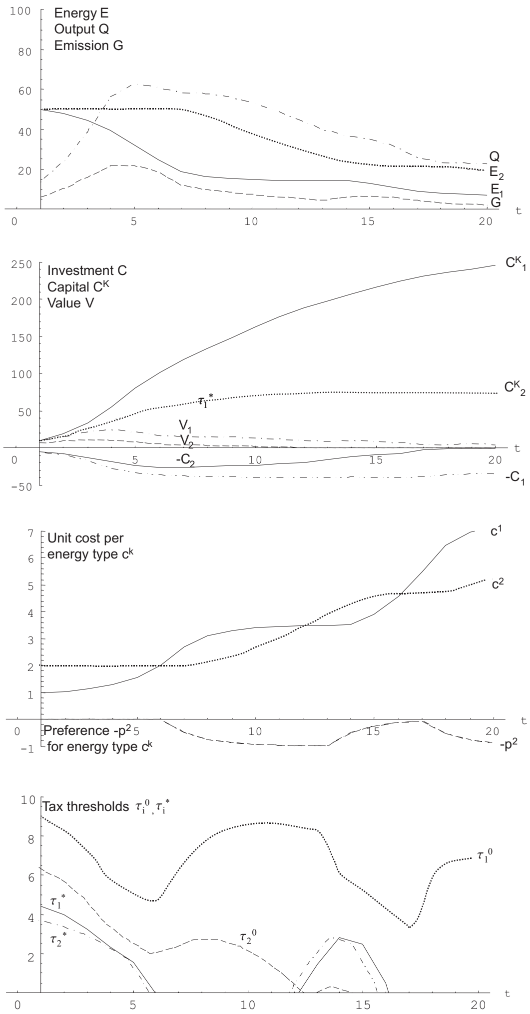

Fig. 1. Simulation of energy, economic output, emissions, investment, value and technology priority for two firms. Tax thresholds are depicted below.

With these initial conditions simulations for 20 iterations are depicted in Figure 1. They suggest that firm P1 with slightly higher production efficiency succeeds in competition with firm P2 by a factor of 5 after 20 time steps. The more energy is depleted, the more the density-dependent unit costs increase (by a factor 3 to 7). Each time when unit costs of one technology become higher than the other, a switch in allocation results. Emissions increase with production but show a decline after unit costs increase due to scarcity. The lower tax thresholds τ_i^* for technology change decline and reach zero after 5 iterations, corresponding to the actual allocation switch. Another peak occurs at around 15 time steps. The upper tax thresholds τ_i^0 reach zero for firm 2 after 13 time steps. Only firm P1 can then profitably exploit the remaining energy and accumulates capital.

References

1. Aghion, P., Howitt, P. (1998) Endogenous Growth Theory. MIT Press, Cambridge
2. Barro, R.J., Sala-i-Martin, X. (1995) Economic Growth. MIT Press, Cambridge
3. Edenhofer O. (2001) The Sustainability Transition and Technological Change. A Research Agenda. Working Paper. Potsdam, PIK
4. Eichhorn, W., Henn, R. et al. (eds.) (1982) Economic Theory of Natural Resources, Physica, Würzburg Wien
5. Finus, M. (2001) Game Theory and International Environmental Cooperation. Edward Elgar, Cheltenham
6. Hudson, E.A., Jorgenson, D.W. (1974) U.S. Energy Policy and Economic Growth, 1975-2000. Bell J. Econ. Managem. Science **5**, 461-514
7. IPCC (2001) Climate Change 2001. Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press
8. Ipsen, D., Rösch, R., Scheffran, J. (2001) Cooperation in Global Climate Policy. Potentialities and Limitations. Energy Policy **29/4**, 315-326
9. Kemfert, C., (2001) International Games of Climate Change Policies. The Economic Effectiveness of Partial Coalition Games. Working Paper. University of Oldenburg, Dept. of Economics 1, Febr.
10. Kümmel, R., (1980) Growth Dynamics of the Energy Dependent Economy. Oelgeschlager, Gunn and Hain, Cambridge, Mass.
11. Kümmel, R., Lindenberger, D., Eichhorn, W. (2000) The Productive Power of Energy and Economic Evolution. Indian J. Appl. Econ. **8**, 231-262
12. Nordhaus, W.D. (1994) Managing the global commons. The economics of climate change. The MIT Press
13. Renshaw, E.T. (1981) Energy Efficiency and the Slump in Labor Productivity in the USA. Energy Economies **3**, 36-42
14. Scheffran, J. (2000) The Dynamic Interaction Between Economy and Ecology. Mathematics and Computers in Simulation **53**, 371-380
15. Scheffran, J., Pickl, S. (2000) Control and Game-Theoretic Assessment of Climate Change. Options for Joint Implementation. Annals of Operations Research **97**, 203-212
16. Scheffran, J., (2001a) Stability and Optimal Control of a Multiplayer Dynamic Game, in: Fleischmann, B. et.al., Operations Research Proceedings 2000. Springer, Berlin, Heidelberg, 14-19
17. Scheffran, J., (2001b) Conflict and Cooperation in Energy and Climate Change. The Framework of a Dynamic Game of Power-Value Interaction, to appear in: M. Holler (ed.), Yearbook New Political Economy
18. Svirezhev, Y.M., von Bloh, W., Schellnhuber, H.J. (1999) “Emission game”: some applications of the theory of games to the problem of CO2 emission. Environmental Modelling and Assessment **4**, 235-242