Transition From Fossil Fuels To Renewable Energy Sources By The North And The South

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Abstract: A model is developed for projecting the transition from non-renewable to renewable energy sources over the next 25 decades by the North and the South. Supply and demand for energy is equilibrated in each decade by the world price of energy. Demand as a function of price increases through time in line with projected growth in per capita income and population. The marginal cost of renewable energy declines at a constant rate. Carbon dioxide emissions are treated as a global stock pollutant. An insight into how the transition to renewable energy resources may develop over the next 250 years, and the associated changes in the present value of net returns to the North and the South, is gained by examining the transition paths for three alternative behavioural scenarios. In the first, the North and the South burn fossil fuels disregarding the costs of concomitant global pollution to the North and the South. In the second, the North and the South combine to maximize the total net present values of returns. In the third, the North and the South are players in a game in which each determines its optimal transition path, taking account only of its net returns, and taking the transition path of the other player as given.

Keywords: *Global warming; Backstop technology; Fossil fuel; Dynamic game; Modelling*

1. INTRODUCTION

Game theory is particularly suited to examine the incentive structure of international environmental agreements. In our model, the North and the South are taken as players, roughly grouped as the Annex 1 and non-Annex 1 countries under the Kyoto protocol. The *interactions* between the North and the South in burning fossil fuels are depicted as a dynamic environmental gam*e* affecting their atmospheric *common stock* of carbon dioxide and the consequent global damage costs far into the future.

A number of studies have investigated the gains or losses of welfare of interacting countries from reducing emissions for the *cooperative* and *non-cooperative* solution to determine whether side payments are required in order to sustain the cooperative solution (see for example, Fankhauser and Kverndokk, 1996; and Xepapadeas and Yiannaka 1997).

Our paper differs from previous studies by analyzing the incentives for cooperation in reducing emissions of fossil fuels allowing for solar power as a backstop technology.

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2. THE NORTH AND SOUTH AS PLAYERS

2.1 Functions in the dynamic models

The North and the South decide simultaneously fossil fuel consumptions, $Q_{N,t}$ and $Q_{S,t}$ respectively, at the beginning of each year t $(t = 1, 2, \ldots, T)$. In section 3 the decision problem is extended to allow for the North and the South also deciding the supply of substitute energy from backstop technology. Fossil fuel consumption is measured as a price weighted conglomerate of coal, oil and gas in terms of energy. The resulting carbon emissions are:

$$E_t = \gamma_N * Q_{N,t} + \gamma_S * Q_{S,t} \tag{1}$$

where γ_N and γ_S are the carbon emission coefficients for aggregate fossil fuel, based on the emission coefficients for coal, oil and gas, weighted by the energy contribution of each fuel component The emissions are assumed to mix perfectly globally and add to the previous year's stock of carbon dioxide in the atmosphere S_{t-1}, which slowly decays over the years. The stock of atmospheric carbon at the beginning of year t is written:

$$S_t = f\{S_{t-1}, E_t\} \qquad (2)$$

Increases in the stock of atmospheric carbon lead to global warming and associated damage costs $DC_t\{S_t\}$, borne in fixed proportions α_N and α_S by the North and the South.

However, emissions also lead to consumption benefits. For each player the benefit of consumption of fossil fuel in year t, Q_t', is given by consumers' willingness to pay, measured by the area under the inverse demand schedule, $D_t^{-1}\{Q_t\}$, from $Q_t = 0$ to Q_t'. The resulting price of fossil fuel in the end-use sector is $p_e\{Q_t\} = D_t^{-1}\{Q_t\}$. Different end-use prices may hold in the North and the South, implying, as a simplification, that trade in fossil fuel is perfect within the North and the South, but imperfect between the blocs.

The cost of supplying Q_t' is accumulated over two stages: an extraction stage (stage 1) and a processing and distribution stage (stage 2). It is assumed that stage-2 processes are competitive or contestable. Stage-2 constant marginal costs, c_2, are just covered by the mark up in price from mine-mouth or oil-head price p_1 to end-use price p_e.

The stage-1 extraction costs, c_1, are also constant marginal costs, but may be lower than $p_1 = p_e - c_2$ to allow for differences in unit extraction rents $(p_1 - c_1)$ in the North and the South. The North and the South are modelled as supplying unprocessed fuel to both their own market and the other bloc's market, in fixed proportions.

The net benefit of bloc X, where X equals N for the North and S for the South, over a consumption planning horizon of T years is the present value of annual net returns given by:

$$\begin{aligned} &NB_X\{Q_N, Q_S, S_0\} = \\ &\sum_{t=1}^{T} (1+r)^{-y} [\int_0^{Q_{X,t}} D_{X,t}^{-1}\{\theta_X\} d\theta_X - p_{e,X} * Q_{X,t} \\ &+\beta_{N,X} * (p_{1,X} - c_{1,X}) * Q_{N,t} \\ &+\beta_{S,X} * (p_{1,X} - c_{1,X}) * Q_{S,t} \\ &-\alpha_X * DC_t\{S_t\} \quad \text{for } X = N, S \end{aligned} \qquad (3)$$

where Q_N and Q_S are the vectors of annual consumption of fossil fuel over the planning horizon, r is the annual rate of discount, $\beta_{N,X}$ is the proportion of $Q_{N,t}$ supplied by bloc X, and $\beta_{S,X}$ is the proportion of $Q_{S,t}$ supplied by bloc X. The constraints $\beta_{X,N} + \beta_{X,S} = 1$ for $X = N$ and S apply.

2.2 Cooperative outcome: joint maximization

An efficient global outcome arises if both blocs set Q_N and Q_S cooperatively to maximize joint net benefits. The joint maximization problem is:

$$\max_{Q_N, Q_S} \sum_{X=N,S} NB_X\{Q_N, Q_S, S_0\} \qquad (4)$$

subject to initial carbon stock, non-negativity constraints $Q_N, Q_S \geq 0$, and the carbon stock dynamics equation (2).

2.3 Non-cooperative outcome: dynamic Nash equilibrium

In the absence of any international cooperative agreement, the North may decide on Q_N and the South on Q_S independently at the beginning of each year t. In a non-cooperative scenario, each bloc sets its consumption of fossil fuel to maximize its own interest, accepting the other bloc's decision on fossil fuel consumption as given or not open to negotiation. The outcome is the yearly profiles of fossil fuel consumption by the North and the South given by:

$$Q_N^* = \arg\max_{Q_N} [NB_N\{Q_N, Q_S^*, S_0\}] \qquad (5)$$

$$Q_S^* = \arg\max_{Q_S} [NB_S\{Q_N^*, Q_S, S_0\}] \qquad (6)$$

referred to as a dynamic Nash equilibrium.

3. BENEFIT AND COST FUNCTIONS

3.1 Fossil fuel demand functions for the North and the South

Linear demand schedules for aggregate fossil fuel for the North and the South are specified, with parameters consistent with estimated consumption, price, and price elasticity of demand for the base year, 1996. An extensive survey was conducted of empirically estimated long-run elasticities of demand for energy[1] in developed and developing countries. Our estimates of own-price elasticities are –0.8 and –0.6 for the North and the South respectively, which are very close to the estimates of Barker et al. (1995 p. 60, Table 3.1). The income elasticities are empirically about unity for both blocs.

The price of aggregate fossil fuel was calculated as the weighted average of the observed end-use prices of the component fossil fuels (IEA, 1998a), using consumption shares for weighting (IEA, 1998b). The stage-1 price p_1 was derived from the mine-mouth/oil-head prices for coal, oil and gas published in IEA (1998c), using the same weighting procedure. Consumption of aggregate fossil fuel was calculated as the sum of consumption of each component fuel in British thermal units (Btu) using standard conversion factors. Parameters calculated for the base year 1966 are shown in Table 1. The linear demand equations for end-use fossil fuel in the North and the South consistent with these parameters are:

$$p_{e,N} = 22.84 - 0.08 Q_N \quad (7)$$

$$p_{e,S} = 13.79 - 0.08 Q_S \quad (8)$$

where, $p_{e,N}$ and $p_{e,S}$ are in 1996 US$/million Btu, and Q_N and Q_S are in 10^{15} Btu. Demand as a function of price increases through time as population and per capita income rise. This is achieved in the model by making the slope of each demand schedule inversely proportional to projected GDP. For the initial year in model runs, 1996, the North's GDP grows at an annual rate of 2.70 per cent. The rate of growth declines at 0.988 per cent annually. Corresponding rates for the South are 3.75 and 0.487 (adapted from OECD, 1993; Table 59, p.145).

3.2 Marginal cost of aggregate fossil fuel production

The extraction cost of coal is published by the IEA (1998c). Extraction costs of oil and gas are derived from previous studies (IEA, 1995). Multiplying the extraction costs of coal, oil and gas by relative shares in total production a weighted stage-1 cost for fossil fuel, c_1 is derived (see Table 1).

The differential marginal rents, $p_1 - c_1$, that are estimated for extraction in the North and the South, may fall over time. It is assumed that rents remain constant during the planning period of 250 years.

Table 1. Economic parameters for aggregate fossil fuel for the base year, 1996.

	North	South
Q	153.59	113.92
p_e	10.15	5.17
p_1	2.18	2.81
c_1	1.41	0.88
Price elasticity of demand	-0.80	-0.60

Note: All prices and costs are in 1996 US $/million Btu. Consumption (Q) is in 10^{15} Btu.

3.3 Cost functions for backstop technology

The backstop technology is assumed to be solar energy, obtained from photovoltaic technology, in which significant advances have been made in the last 20 years (Dennis, 1997).

Ahmed (1994) conducts perhaps the most comprehensive projection of the future cost of renewable energy technologies. She expects the costs to continue to decrease and stabilize eventually at 2 cents per kWh ($5.86/million Btu). We adopt Ahmed's (1994) projection and set a lower bound for the cost of producing electricity from solar power at 2 cents per kWh and further assume that the lower bound will be reached in 2100. The 1996 base year cost is set at 25 cents per kWh. Thus the annual rate of decline is 2.49 per cent. We assume identical time profiles of the costs of backstop technologies for the North and the South.

[1] Fossil fuels were the predominant energy sources in the studies surveyed. Aggregate fossil fuel consumption is taken to be the same as total energy consumption for 1996 as a reasonable approximation.

With each bloc able to choose the level of backstop technology as an alternative supply of energy to that provided from fossil fuel, the net benefit functions are augmented as follows:

$$NB_X\{Q_N, B_N, Q_S, B_{S,} S_0\} =$$
$$\sum_{t=1}^{T}(1+r)^{-y}[\int_0^{Q_{X,t}+B_{X,t}} D^{-1}_{X,t}\{\theta_X\}d\theta_X$$
$$-c_{B,t} * B_{X,t} - p_{e,X} * Q_{X,t} \tag{9}$$
$$+\beta_{N,X} * (p_{1,X} - c_{1,X}) * Q_{N,t}$$
$$+\beta_{S,X} * (p_{1,X} - c_{1,X}) * Q_{S,t}$$
$$-\alpha_X * DC_t\{S_t\}] \text{ for } X = N, S$$

where $B_{X,t}$ is the fossil-fuel equivalent of energy supplied from backstop technology in bloc X in year *t*, and $c_{B,t}$ is the marginal cost of backstop technology in year *t*, $NB_X\{Q_N, B_{N,} Q_S, B_{S,} S_0\}$ is substituted for $NB_X\{Q_N, Q_S, S_0\}$ in formulating the joint maximization and dynamic Nash equilibrium problems allowing for the decisions on use of backstop technology.

3.4 Annual damage cost function

To estimate the damage cost of global warming, a complex chain of uncertain relationships has to be analyzed, from emissions to carbon stocks, to radiative forcing, to changes in temperature of the atmosphere and the deep oceans, to resulting material damage, to the value of the material damage. The stock dynamics function (equation 2) relates the change in stock of atmospheric carbon to fossil fuel burning. The first segment of the chain is obtained by following the relationship used by Nordhaus (1994) in the DICE model:

Carbon stock dynamics equation:

$$S_t - 590 = 0.64E_t + 0.99167(S_{t-1} - 590) \tag{10}$$

where S_t is carbon stock and E_t are emissions, both are in billion tonnes.

Radiative forcing equation of carbon stock:

$$F_t = 4.1(\log\left[S_t / 590\right] / \log(2)) \tag{11}$$

where F_t is in watts per square meter (W/m^2).

Change in mean temperature (^{0}C) in the atmosphere relative to pre-industrial period:

$$T_t = T_{t-1} + 0.226(F_t - 1.41T_{t-1} - 0.44[T_{t-1} - T^*_{t-1}]) \tag{12}$$

Change in mean temperature (^{0}C) in the deep ocean relative to pre-industrial period:

$$T^*_t = T^*_{t-1} + 0.226 \ \ (0.44[T_{t-1} - T^*_{t-1}]) \tag{13}$$

Most research on global warming damage has focused on the benchmark scenario of a doubling of the pre-industrial CO_2-equivalent concentration of all greenhouse gases ($2xCO_2$) with an associated temperature increase of 2.5 to 3^{0}C (IPCC, 1996). The resulting costs of global warming damage are estimated for a future world economy with income and population equal to current levels.

To generalize from this particular scenario, Fankhauser (1995) suggests a damage function of the form:

$$D_t = k_t \left[\frac{T_t}{\Lambda}\right]^\theta * (1+\phi)^{(t^* - \bar{t})} * (1+\eta_t) \tag{14}$$

where D_t is the annual damage in billion 1996 US dollars from global warming due to the change in atmospheric temperature T_t, and η_t is the annual growth rate of GDP. In the IPCC Report (1996) all studies assume that the doubling of carbon dioxide will occur in the middle of the 21st century when the mean atmospheric temperature of the earth will have increased by 2.5^{0}C. In equation (14) Fankhauser sets $\Lambda = 2.5\,^0$C and $t^* = 2050$. When $T_t = \Lambda$ and $t^* = \bar{t}$, annual damage in period t becomes $D_t = k_t$. Therefore, k_t represents the benchmark damage costs of $2xCO_2$, which is estimated by Fankhauser et al. (1997) as 405.2 billion 1988 US dollars after making an adjustment for inequality. We take the damage to be 486.52 billion in 1996 US dollars allowing for inflation. Of this cost, 56 per cent occurs in the North and 44 per cent in the South. Other parameter settings are θ = 1.3 and ϕ = 0.006 following Nordhaus (1993).

In the model, the year $\bar{t}$ in which a rise in mean temperature of 2.5^0 C occurs is endogenously determined by an iterative process.

3.5 The planning horizon and decision stage interval

The burning of fossil fuels has an impact on global warming far into the future because the decay of the carbon stock is slow. Equation (10) implies a half-life of carbon stock of about 83 years. Solutions are obtained for a planning horizon of T = 250 years. Estimated terminal values at the end of 250 years are incorporated in the objective functions. Further details can be obtained from the authors.

To reduce computation, decisions on fossil fuel consumption and backstop technology apply across a decade rather than annually. The same annual energy levels apply for each year of the decade.

4. MODEL RESULTS

The global and game-theoretic welfare maximization problems are solved assuming the stock of fossil fuels is unlimited. A discount rate of 2 per cent is used for calculating the present value of net returns. The results for three runs are reported in Table 2 and Figure 1. Run A is referred to as *blinkered joint maximization*, where both players jointly maximize the present value of their net returns disregarding the damage costs. Run B is referred to as *global joint maximization*, where both blocs act cooperatively to jointly maximize the present value of total net returns less the damage costs. Run C is the non-cooperative Nash equilibrium outcome. The reported net benefits for each run are all in terms of net returns less damage costs.

Table 2. Net benefits to the North, the South, and globally, for alternative objective functions.

	Present Value of net benefits from 1996 to 2246 (US$b, 1996 prices)		
Run	North	South	Global
A *Blinkered JM*	148,651	73,677	222,328
B *Global JM*	171,105	213,534	384,639
C *Nash*	171,086	213,492	384,578

In run A, the North switches to backstop at the beginning of 2086 but the South never switches to backstop over the planning period (not shown here). Net benefits are much lower because damage costs are ignored, leading to greater consumption of fossil fuels and higher damage costs. In run B, the North switches to backstop in 2066 while the South switches to backstop in 2086 (Figure 1). Thus internalizing the damage costs induces the North to switch 2 decades earlier and the South to switch 15 decades earlier.

Under global joint maximization welfare can be increased by about 42 per cent compared to under blinkered joint maximization. This increase in welfare is obtained through transition to less expensive solar power, and reduced damage costs in burning fossil fuels. The consumption of fossil fuels by the North and the South together is less than 80 per cent of the world's commercially exploitable reserves estimated by Rogner (1997). The maximum increase in the mean temperature is 2.26^0 C, which would occur in 2106. These results are significantly lower than those predicted by the IPCC (1996).

A striking result from Table 2 is that there is no significant difference between the welfare under global joint maximization in run B and that under the Nash outcome in run C. This implies that cooperation between the North and the South to maximize joint benefits is hardly superior to the North and the South maximizing their own benefits in isolation.

Examination of the derivative of equation (11) in the equation system (10) to (13) used by Nordhaus and others gives:

$$\frac{\partial F_t}{\partial S_t} = \frac{4.1}{\log(2)} * \frac{1}{S_t} \qquad (15)$$

For S_t large relative to emissions $\gamma_x Q_{xt}$, F_t and hence rise in temperature T_t (equation 12) and damage cost (equation 14) are relatively insensitive to emissions (equation 1). The result is that numerically the optimal values of Q_{xt} are little different for the cooperative and non-cooperative problems

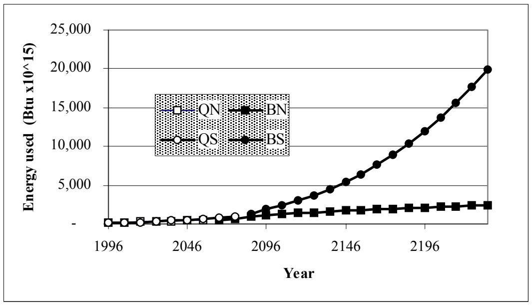

Figure 1. Energy used from fossil fuel (Q) and backstop technology (B) by the North and the South under global joint maximization.

5. CONCLUSION

Although the global joint maximization outcome is Pareto superior, the gain in welfare over that from maximizing strategic self-interest is insignificant. Contrary to most people's expectations, our results indicate that it is quite possible for use of the standard global warming equation system (used for example in Nordhaus' DICE model) to not support the case for cooperative decision making between players. It follows that either there is not a strong case for international cooperation if the equation system is valid, or that the equation system should be subjected to more scrutiny by physicists and economists.

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