

Nuclear Power Policy as a Differential Game*

Kenneth Backlund
Department of Economics,
University of Umeå,
SE - 901 87 Umeå, Sweden

Abstract

This paper examines nuclear energy output in a differential game framework involving two countries. The countries differ regarding nuclear technology with one being relatively safe and the other less safe. Simulation of a numerical model gives the following results. (i) A cooperative agreement will imply less use of nuclear energy compared with both a noncooperative Nash equilibrium and an uncontrolled market solution. (ii) The country with relatively safe nuclear energy technology benefits most from a cooperative solution. (iii) Starting from an uncontrolled market economy, an agreement between the countries to introduce taxation of nuclear energy will be beneficial for both countries. However, by starting from the noncooperative Nash equilibrium, an agreement to slightly increase the nuclear energy taxes will be most beneficial for the country with less safe nuclear energy technology.

*I would like to thank Thomas Aronsson, Karl-Gustaf Löfgren, Runar Brännlund, Magnus Wikström and Kurt Brännäs for valuable guidance, comments and suggestions. A research grant from The Swedish Council for Research in Humanities and Social Sciences (HSFR) is gratefully acknowledged. The usual disclaimer applies.

1 Introduction

The question of whether to increase or decrease the use of nuclear energy has been the subject of discussion for several decades. The background is that, following a number of nuclear accidents¹ and with mounting stocks of nuclear waste, policymakers and the general public have become more aware of the complexity of nuclear power as a source of energy. The decision to use or to abolish nuclear energy will not only affect public safety, it will also have environmental and economic effects. The low probability, high consequence accident that is typical for nuclear energy is connected both to the production of nuclear energy and to the process of storing the resulting waste. As long as the power stations work well and the storage process is satisfactory, the use of nuclear energy may have no or only negligible effects on the environment. However, if a serious accident occurs, and large amounts of radioactivity are spread outside the power station, the impact on the ecosystem is substantial.

The external effects from the use of nuclear energy are, therefore, closely related to the risk for a nuclear accident. Aronsson et al. (1998), analyze these externalities in a general equilibrium model. They derive the dynamic Pigouvian tax system that is required to make the decentralized market economy reach a socially optimal resource allocation. In their model, the producer of nuclear energy disregards the risks involved and produces more nuclear energy than is socially optimal. Hohmeyer (1990) studies the external effects from nuclear energy empirically and uses the accident in Chernobyl in 1986 to calculate the social cost of a nuclear accident. He argues that there may be considerable costs involved in the use of nuclear energy that are not reflected in the market prices.

¹Such as Three Mile Island in 1979 and Chernobyl in 1986.

The purpose of this paper is to extend the analysis conducted by Aronsson et al. (1998) to a global economy, where the risk for a nuclear accident caused by the production of nuclear energy and the storage of waste in one country affect the well-being of people in other countries. A recent example is that the accident in Chernobyl was (is) a catastrophe that affected not only the former Soviet Union, it also affected neighboring countries. Sweden and Norway were contaminated with radioactivity, and thirty per cent of the Norwegian cattle were contaminated between 1987-1989 (Faure and Skogh 1992). The accident also had a negative effect on international tourism (Hultkrantz and Olsson 1997).

One way of analyzing the global externalities arising from the use of nuclear energy is in the context of a differential game. Recent studies aiming to assess environmental policies as differential games have generated many useful insights. Mäler (1989) analyzes the acid rain problem in terms of a Nash-game. In Kaitala et. al. (1992), transboundary acid rain is analyzed as a dynamic game between the former Soviet Union and Finland. Both cooperative agreements and noncooperative games are analyzed and the results indicate that the cooperative solution is beneficial to Finland although not to the Soviet Union. Tahvonen (1994), analyzes the CO₂ problem as a differential game where the world is divided into five geopolitical areas. One of his major findings is that the cooperative agreement is found to be beneficial for the developing countries and costly for the industrialized countries.²

In order to address the nuclear policy question in a differential game framework, I develop a model where the costs and welfare effects from different nuclear energy policies are analyzed. The analysis is based on a numerical general equilibrium model, where the main focus is on the energy sector. The deterministic part of the model originates from the SEEP-model of Nordhaus

²For further references, see Cesar (1994), Mäler and de Zeeuw (1995) and Missfeldt (1996).

(1995). The SEEP-model is extended in various directions, where the main extensions are:

- to include the probability of an accident in the production phase of nuclear energy
- to include the probability of an accident in the process of storing the nuclear waste

Based on this model, I construct two fictive countries which are identical in all respects apart from nuclear technology. It is assumed that the first country has a relatively safe technology for producing nuclear energy and for storing nuclear waste, whereas the second has a less safe technology for producing nuclear energy and for storing nuclear waste. The nuclear energy market will be described as a competitive market with a capacity constraint. Once the companies have a licence from the government to produce nuclear energy, they are price takers on the market for electricity. For the sake of simplicity, I assume that the countries do not export or import energy.

I study three different types of interactions between the countries: (i) they act as uncontrolled market economies; (ii) a noncooperative Nash open loop equilibrium; and (iii) a cooperative equilibrium.

The uncontrolled market economy serves as a reference point. In this setting, the nuclear energy producer maximizes profit at each point of time, and does not take into account the risk he/she is imposing on the consumers. This approach is based on an idea by Aronsson and Löfgren (1999) and differs from most previous analyses of environmental issues in terms of differential games, where a noncooperative Nash equilibrium concept is typically used as a reference point. In the noncooperative Nash game each country acts as if the resource allocation is decided upon by a national social planner, who treats the outcome of choices made by other countries as exogenous.³ Under the open

³See Basar and Olsder (1982, Chapter 6).

loop strategy, each country chooses the values of its controls at the beginning of the planning period, and the country does not revise its decision during the game. Finally, I analyze the outcome of the cooperative solution, and compare it with the uncontrolled market solution and the noncooperative Nash solution.

The cooperative and the noncooperative Nash solution can be implemented in market economies being controlled by different "Pigouvian-related" taxes, levied on the producers of nuclear energy. These taxes involve very strong informational requirements, which make them complicated to implement in practise. An additional complication arising from the implementation of the cooperative solution is that it requires each country to adopt the globally preferable level of nuclear power. With reference to the uncontrolled market economy and the noncooperative Nash equilibrium, I shall examine the welfare effects of "small cooperative projects". Considering that a cooperative equilibrium may be particularly difficult to implement in practice, it seems reasonable to analyze situations where the taxes on nuclear energy are not optimally chosen from society's point of view. Therefore, I will address the welfare effects arising when the countries agree to uniformly increase their nuclear energy taxes.

The outline of the paper is as follows. Section 2 briefly presents the basic structure of the model and describes the difference between the uncontrolled market economy, the noncooperative Nash game and the cooperative equilibrium. I derive the Pigouvian tax and transfer system required to internalize the external effects from nuclear power, as well as analyze the welfare effects of uniform tax increases on nuclear energy when the initial taxes are suboptimal. In Section 3, the functional forms of the numerical model are presented. Section 4 describes and interprets the simulation experiments. Section 5 sets out the conclusions.

2 The basic structure of the model

The theoretical model comprises a two country economy and includes agents with preferences for consumption. To simplify the mathematical analysis, I neglect population growth and normalize the population in each country to equal one. The instantaneous utility function facing the consumer in country i , is assumed to be increasing, twice continuously differentiable and strictly concave in consumption. It is given by

$$u_i(t) = u_i(c_i(t)), \quad i = 1, 2 \quad (1)$$

where $c_i(t)$ is consumption in country i at time t .

Let me then turn to the stochastic part of the model. Here uncertainty is related to the risk of a nuclear accident where large amounts of radioactivity leak out in to the environment. One way to endogenize the probability of an accident is to use the hazard function, which is defined

$$\delta(g_1^n(t), g_2^n(t), x_1(t), x_2(t)) = \frac{\phi(t)dt}{1 - \Phi(t)} \quad (2)$$

where $g_1^n(t)$ and $g_2^n(t)$ are the production of nuclear energy in countries 1 and 2, respectively, and $x_1(t)$ and $x_2(t)$ are the resulting stocks of radioactive waste from countries 1 and 2. The function $\phi(t)$ is the probability density function and $\Phi(t)$ is the cumulative distribution function. We can interpret $1 - \Phi(t)$ as the probability that no accident has occurred up to time t . Provided that no accident has occurred up to time t , the hazard function is the probability of an accident in the small interval $(t, t + dt)$. This conditional probability depends both on the amount of nuclear energy produced at time t and the stock of radioactive waste fuel at time t , i.e. on the present and previous actions of energy producers. I assume that $\partial\delta/\partial g_1^n > 0$, $\partial\delta/\partial g_2^n > 0$, $\partial\delta/\partial x_1 > 0$ and $\partial\delta/\partial x_2 > 0$. From equation (2), I obtain

$$1 - \Phi(t) = e^{-\int_0^t \delta(g_1^n(s), g_2^n(s), x_1(s), x_2(s)) ds} = e^{-\Delta(t)} \quad (3)$$

Before turning to the formal description of the objective function, let me present some of the intuition upon which the model is based. First, at each point in time, there is a probability of a nuclear related accident. Therefore, in order to calculate the expected utility, the sum of the utilities from consumption is weighed with the probability of "survival" at each point in time from zero to infinity. Second, if a nuclear accident occurs, social welfare is reduced. Let W_i represent the post-accident value function, where W_i for simplicity is assumed to be constant, and define $\delta(t) = \delta(g_1^n(t), g_2^n(t), x_1(t), x_2(t))$ to be used as a short notation for the hazard function at time t . Then, if T denotes the stochastic time of the accident, it follows that the pre-accident objective function takes the form

$$E(U_i(0)) = \int_0^\infty \delta(T) e^{-\Delta(T)} \left[\int_0^T u_i(c_i(t)) e^{-\theta t} dt + W_i e^{-\theta T} \right] dT \quad (4)$$

By using the rules of partial integration, equation (4) can be written⁴

$$E(U_i(0)) = \int_0^\infty (u_i(c_i(t))) e^{-(\theta t + \Delta(t))} dt + \omega_i \quad (5)$$

where $\omega_i = \frac{\delta(0)}{\theta + \delta(0)} W_i$. This means that uncertainty with respect to the probability of a nuclear accident affects the objective function in terms of an additional utility discount rate, i.e. the utility discount rate of country i at time t is given by $\theta + \delta(t)$.⁵

Turning to the production side of the economy, output is produced by labor (normalized to one), physical capital, $k_i(t)$, and energy, which is divided into nuclear energy, g_i^n and an alternative risk free energy source, g_i^a . Net output

⁴See e.g. Reed and Heras (1992).

⁵Similar optimization problems involving uncertainty have also been discussed by Cropper (1976), Reed and Heras (1992), Clark and Reed (1994) and Tsur and Zemel (1998).

in country i is determined by

$$y_i(t) = f_i(1, k_i(t), g_i^n(t), g_i^a(t)) \quad (6)$$

where $f_i(\cdot)$ is assumed to be twice continuously differentiable, strictly concave as well as nondecreasing in g_i^n and g_i^a . Since $y_i(t)$ is measuring net output, depreciation of physical capital can make the marginal product of capital negative, provided the capital stock is sufficiently large. Net investments in physical capital are determined by

$$\dot{k}_i(t) = y_i(t) - c_i(t) - I_i(g_i^n(t), g_i^a(t)) \quad (7)$$

where $I_i(\cdot)$ is an increasing, twice continuously differentiable and strictly convex cost function. Typical for the production of nuclear energy is that it leads to an accumulation of radioactive nuclear waste. Following Aronsson et al. (1998), one simple way to model this accumulation process is to assume that the stock of waste fuel accumulates by

$$\dot{x}_i(t) = h_i(g_i^n(t)) - \gamma x_i(t) \quad (8)$$

where γ is its rate of decay. The depreciation term is used to capture that the radioactive content of a given stock of nuclear waste declines over time. The function $h_i(\cdot)$ is increasing in nuclear energy, g_i^n .

2.1 The uncontrolled market economy

This section briefly describes the structure of the uncontrolled market economy. The economy consists of three different agent types: a consumer, a producer of energy and a producer of final goods. First we have a representative consumer in country i with the following utility maximization problem

$$\max_{c_i(t)} E(U_i(0)) = \int_0^{\infty} u_i(c_i(t)) e^{-(\theta t + \Delta(t))} dt + \omega_i \quad (9)$$

s.t

$$\dot{k}_i(t) = \pi_{1i}(t) + \pi_{2i}(t) + r_i(t)k_i(t) + w_i(t) - c_i(t) \quad \text{and} \quad k_i(0) = k_{0i} \quad (10)$$

where $\pi_{1i}(t)$ is the pure profit from the production of final goods, $\pi_{2i}(t)$ the pure profit from the production of energy, $r_i(t)$ the interest rate and $w_i(t)$ labor income. I also require that the consumer obeys the No Ponzi Game (NPG) condition, meaning that the present value of the capital stock is non-negative at the terminal point.⁶ Without this condition, the consumer would borrow enough to maintain the marginal utility from consumption equal to zero, resulting in an escalating debt.⁷ The necessary conditions are

$$\frac{\partial u_i(c_i(t))}{\partial c_i(t)} e^{-(\theta t + \Delta(t))} - \rho_i(t) = 0 \quad (11)$$

$$\dot{\rho}_i(t) = -\rho_i(t)r_i(t) \quad (12)$$

$$\lim_{t \rightarrow \infty} \rho_i(t) = 0 \quad (13)$$

where $\rho_i(t)$ reflects the consumer's valuation, in present value terms, of one more unit of capital.

The final goods producer acts competitively, and behaves as if he/she is choosing $g_i^n(t)$, $g_i^a(t)$ and $k_i(t)$ at each instant to maximize profits.⁸ The objective function may be written

$$\max_{g_i^n(t), g_i^a(t), k_i(t)} f_i(1, k_i(t), g_i^n(t), g_i^a(t)) - w_i(t) - r_i(t)k_i(t) - p_i^n(t)g_i^n(t) - p_i^a(t)g_i^a(t) \quad (14)$$

⁶The NPG condition imposes a restriction on the limit of $k(t)e^{-\int_0^t \tau(s)ds}$, not on the limit of $k(t)$, when t goes to infinity. Therefore, the transversality condition is written as corresponding to a free terminal k .

⁷See Blanchard and Fischer (1989)

⁸In the numerical section of the paper all other energy sources, like e.g. hydro power and biofuels, will be included in the risk free alternative. They also comprise different forms of risk in the production phase. However, in order to simplify the analyzes these risks will not be considered.

where $p_i^n(t)$ is the price of nuclear energy at time t and $p_i^a(t)$ the price of the alternative energy source at time t . The necessary conditions are⁹

$$\frac{\partial f_i(\cdot)}{\partial g_i^n(t)} - p_i^n(t) = 0 \quad (15)$$

$$\frac{\partial f_i(\cdot)}{\partial g_i^a(t)} - p_i^a(t) = 0 \quad (16)$$

$$\frac{\partial f_i(\cdot)}{\partial k_i(t)} - r_i(t) = 0 \quad (17)$$

Finally, I have to describe the behavior of the energy producer, who is assumed to act competitively. The representative energy producer will produce nuclear energy and/or a risk free alternative. The objective function can be written as

$$\max_{g_i^n(t), g_i^a(t)} p_i^n(t)g_i^n(t) + p_i^a(t)g_i^a(t) - I_i(g_i^n(t), g_i^a(t)) \quad (18)$$

where $I(g_i^n(t), g_i^a(t))$ represents the cost of the resources used in the production process. The necessary conditions are

$$p_i^n(t) - \frac{\partial I_i(\cdot)}{\partial g_i^n} = 0 \quad (19)$$

$$p_i^a(t) - \frac{\partial I_i(\cdot)}{\partial g_i^a} = 0 \quad (20)$$

These are standard efficiency conditions and will not be explained further.

2.2 Noncooperative Nash game with a open loop solution

The purpose of this section is to derive the noncooperative Nash solution, which will be compared with the uncontrolled market solution. The noncooperative Nash-game can be thought of as a game between national social planners. This means that part of the external effects that would otherwise arise from the use of

⁹Different energy sources are not perfect substitutes for each other, e.g. electricity for lighting is not easily substituted with other energy sources, whereas the energy needed for heating and industrial boilers can be produced by a variety of energy sources, e.g. electricity, oil gas, coal and biofuels.

nuclear power are internalized. The characteristics of the noncooperative Nash solution will be used in section 2.4 to construct a tax system that forces the agents in the market economy to replicate the noncooperative Nash solution.

Suppose the resource allocation in each country is decided upon by a social planner, who takes the nuclear policy of the other country as exogenously given. As pointed out by e.g. Kamien and Schwartz (1971), Clark and Reed (1994) and Aronsson et al. (1998), the optimization problem facing the social planner is not a standard optimal control problem, since part of the discount factor, $\Delta(t)$, is a function of the control variables, $g_i^n(t)$ and the state variables, $x_i(t)$. To transform this problem into the standard form, I introduce a new state variable, $\Delta(t)$ defined as

$$\Delta(t) = \int_0^t \delta(g_1^n(s), g_2^n(s), x_1(s), x_2(s)) ds \quad \text{and} \quad \Delta(0) = 0 \quad (21)$$

Differentiating with respect to t I obtain

$$\dot{\Delta}(t) = \delta(g_1^n(t), g_2^n(t), x_1(t), x_2(t)) \quad (22)$$

which describes how $\Delta(t)$ develops over time.

The optimization problem can now be written as a standard control problem with infinite time horizon. Writing the problem in its most general form, the social planner in country i , faces the following maximization problem

$$\max_{c_i, g_i^n, g_i^a} E(U_i(0)) = \int_0^{\infty} u_i(c_i(t)) e^{-(\theta t + \Delta(t))} dt + \omega_i \quad (23)$$

subject to the equations of motion for k_i , x_i and Δ , given by equations (7), (8) and (22), initial conditions $k_i(0) = k_{oi}$, $x_i(0) = x_{oi}$, and $\Delta(0) = 0$ and terminal conditions $\lim_{t \rightarrow \infty} k_i(t) \geq 0$, $\lim_{t \rightarrow \infty} x_i(t) \geq 0$, while $\Delta(t)$ has a "free" terminal state. The present value Hamiltonian for country i is written

$$H_i(t) = u_i(c_i(t)) e^{-(\theta t + \Delta(t))} + \lambda_i(t) \dot{k}_i(t) + \mu_i(t) \dot{x}_i(t) + \nu_i(t) \dot{\Delta}(t) \quad (24)$$

where $\lambda_i(t)$, $\mu_i(t)$, and $\nu_i(t)$ are present value costate variables in utility terms. In addition to Equations (7), (8) and (22), as well as to the initial and terminal conditions, the first-order conditions for country i , where $i = 1, 2$, can now be written

$$\frac{\partial H_i(t)}{\partial c_i(t)} = \frac{\partial u_i(c(t))}{\partial c_i(t)} e^{-(\theta t + \Delta(t))} - \lambda_i(t) = 0 \quad (25)$$

$$\frac{\partial H_i(t)}{\partial g_i^n(t)} = \lambda_i(t) \left[\frac{\partial f_i(\cdot)}{\partial g_i^n(t)} - \frac{\partial I_i(\cdot)}{\partial g_i^n(t)} \right] + \mu_i(t) \frac{\partial h_i(\cdot)}{\partial g_i^n(t)} + \nu_i(t) \frac{\partial \delta(\cdot)}{\partial g_i^n(t)} = 0 \quad (26)$$

$$\frac{\partial H_i(t)}{\partial g_i^a(t)} = \lambda_i(t) \left[\frac{\partial f_i(\cdot)}{\partial g_i^a(t)} - \frac{\partial I_i(\cdot)}{\partial g_i^a(t)} \right] = 0 \quad (27)$$

$$\dot{\lambda}_i(t) = -\frac{\partial H_i(t)}{\partial k_i(t)} = -\lambda_i(t) \frac{\partial f_i(\cdot)}{\partial k_i(t)} \quad (28)$$

$$\dot{\mu}_i(t) = -\frac{\partial H_i(t)}{\partial x_i(t)} = \mu_i(t)\gamma - \nu_i(t) \frac{\partial \delta(\cdot)}{\partial x_i(t)} \quad (29)$$

$$\dot{\nu}_i(t) = -\frac{\partial H_i(t)}{\partial \Delta(t)} = u_i(c_i(t)) e^{-(\theta t + \Delta(t))} \quad (30)$$

$$\lim_{t \rightarrow \infty} \lambda_i(t) \geq 0 \quad (= 0 \text{ if } \lim_{t \rightarrow \infty} k_i(t) > 0), \quad (31)$$

$$\lim_{t \rightarrow \infty} \mu_i(t) \geq 0 \quad (= 0 \text{ if } \lim_{t \rightarrow \infty} x_i(t) > 0), \quad (32)$$

$$\lim_{t \rightarrow \infty} \nu_i(t) = 0 \quad (33)$$

Let

$$\Psi_i^*(t) = (c_i^*(t), g_i^{a*}(t), g_i^{n*}(t)), \quad \forall t$$

solve country i 's optimization problem. The solution $(\Psi_1^*(t), \Psi_2^*(t))$ for $t \in (0, \infty)$ is a Nash equilibrium, if

(i) $\{\Psi_1^*(t)\}_0^\infty$ solves the decision problem of country 1 conditional on $\Psi_2(t) = \Psi_2^*(t)$ for all t and

(ii) $\{\Psi_2^*(t)\}_0^\infty$ solves the decision problem of country 2 conditional on $\Psi_1(t) = \Psi_1^*(t)$ for all t .

The superindex "*" will be used throughout the paper to denote the noncooperative Nash equilibrium in open loop form.

Equation (26) will be important in later analyses. The first term on the right side is the difference between the marginal product of nuclear energy and the marginal cost of producing nuclear energy. The second part of the equation is related to the fact that nuclear energy production gives rise to nuclear waste, where $\mu_i (< 0)$ is the present value of an additional unit of waste. The third part reflects the direct effect of the daily production of nuclear energy on the conditional probability of an accident in the time interval $(t, t + dt)$. Comparing this condition with the necessary conditions in the uncontrolled market economy, it is clear that they do not coincide. According to (15)¹⁰, the energy producer in the uncontrolled market economy maximizes his/her private profit and does not take into account how the production of nuclear energy affects the consumer's objective function.

Note that the noncooperative open loop solution only internalizes the domestic welfare effects arising from the use of nuclear energy. The external effect that hampers welfare for the consumers in the other country is uninternalized. This solution may be referred to as a "local or national command optimum" where each country solves a social optimization problem, conditional on the actions taken by the other country.

2.3 Cooperative agreement

In this section the cooperative solution is derived. This implies that the external effects of nuclear energy from the respective country are completely internalized at a global level. The characteristics of this "global first best" solution will also be used in section 2.4 to construct a tax system that forces the agents in the market economy to replicate the behavior of the cooperative solution.

For the sake of simplicity, suppose a global planner maximizes the sum of

¹⁰By substituting (19) into (15), the first order condition for the firm can be compared with (26).

utilities¹¹

$$\max_{c_i, g_i^n, g_i^a} \sum_{i=1}^2 \left[\int_0^{\infty} u_i(c_i(t)) e^{-(\theta t + \Delta(t))} dt + \omega_i \right] \quad (34)$$

subject to the equations of motion for k_1 , k_2 , x_1 , x_2 , and Δ , as well as to the initial and terminal conditions. The present value Hamiltonian can be written

$$H(t) = \sum_{i=1}^2 \left[u_i(c_i(t)) e^{-(\theta t + \Delta(t))} + \lambda_i(t) \dot{k}_i(t) + \mu_i(t) \dot{x}_i(t) \right] + \nu(t) \dot{\Delta}(t) \quad (35)$$

The first-order conditions for an optimal solution for country i can now be written

$$\frac{\partial H(t)}{\partial c_i(t)} = \frac{\partial u_i(c(t))}{\partial c_i(t)} e^{-(\theta t + \Delta(t))} - \lambda_i(t) = 0 \quad (36)$$

$$\frac{\partial H(t)}{\partial g_i^n(t)} = \lambda_i(t) \left[\frac{\partial f_i(\cdot)}{\partial g_i^n(t)} - \frac{\partial I_i(\cdot)}{\partial g_i^n(t)} \right] + \mu_i(t) \frac{\partial h_i(\cdot)}{\partial g_i^n(t)} + \nu(t) \frac{\partial \delta(\cdot)}{\partial g_i^n(t)} = 0 \quad (37)$$

$$\frac{\partial H(t)}{\partial g_i^a(t)} = \lambda_i(t) \left[\frac{\partial f_i(\cdot)}{\partial g_i^a(t)} - \frac{\partial I_i(\cdot)}{\partial g_i^a(t)} \right] = 0 \quad (38)$$

$$\dot{\lambda}_i(t) = -\frac{\partial H(t)}{\partial k_i(t)} = -\lambda_i(t) \frac{\partial f_i(\cdot)}{\partial k_i(t)} \quad (39)$$

$$\dot{\mu}_i(t) = -\frac{\partial H(t)}{\partial x_i(t)} = \mu_i(t) \gamma - \nu(t) \frac{\partial \delta(\cdot)}{\partial x_i(t)} \quad (40)$$

$$\dot{\nu}(t) = -\frac{\partial H(t)}{\partial \Delta(t)} = \sum_{i=1}^2 u_i(c_i(t)) e^{-(\theta t + \Delta(t))} \quad (41)$$

for $i = 1, 2$. In what follows, I will use the superindex "***" to denote the cooperative solution.

Comparing equation (41) with equation (30), it is clear that the cooperative agreement leads to a different kind of behavior than in the noncooperative game. Contrary to the shadow price of the accumulated hazard function in the

¹¹This assumption is made to preserve simplicity. See e.g. Aronsson and Löfgren (1999), Aronsson et al. (2000), Tahvonen (1994) and Kaitala et al. (1992).

noncooperative Nash solution, the shadow price in equation (41) reflects all direct effects of country i 's use of nuclear energy. This implies that the global planner will take into account how the choice of nuclear energy policy in country i affects the welfare of consumers in both countries. In other words, contrary to the noncooperative Nash equilibrium, the cooperative solution implies that the external effects have become fully internalized at the global level.

2.4 The corrected market economy

Consider a controlled market economy, where the policy maker imposes a tax, $\tau_i(t)$, on the producer of nuclear energy in country i in the following way

$$\max p_i^n(t)g_i^n(t) + p_i^a(t)g_i^a(t) - I_i(g_i^n(t), g_i^a(t)) - \tau_i(t)g_i^n(t) \quad (42)$$

The tax revenues are returned to the consumers in a lump sum fashion. As suggested by e.g. van der Ploeg and de Zeeuw (1992) and Aronsson and Löfgren (1999) in other contexts, it is possible to choose this tax such that the market economies replicate either the noncooperative Nash equilibrium in open loop form or the cooperative equilibrium.

Observation 1 If the tax on nuclear energy is chosen such that

$$\tau_i^*(t) = -(\mu_i^*(t) \frac{\partial h_i^*(\cdot)}{\partial g_i^{n*}(t)} + \nu_i^*(t) \frac{\partial \delta^*(\cdot)}{\partial g_i^{n*}(t)}) / \lambda_i^*(t)$$

for $i = 1, 2$, and all t , the controlled market economies will reproduce the noncooperative Nash open loop solution.

This corrective dynamic tax will be referred to as the "noncooperative Pigouvian tax". It consists of two parts. The first term on the right side of the expression for $\tau_i^*(t)$ captures the disutility of waste fuel in country i , and the second term captures the effect on the probability of accident arising from the daily production of nuclear energy in country i .

Observation 2 If the tax on nuclear energy is chosen such that

$$\tau_i^{**}(t) = -(\mu_i^{**}(t) \frac{\partial h_i^{**}(\cdot)}{\partial g_i^{n**}(t)} + \nu_i^{**}(t) \frac{\partial \delta^{**}(\cdot)}{\partial g_i^{n**}(t)}) / \lambda_i^{**}(t)$$

for $i = 1, 2$, and all t , where all entities are determined from the cooperative solution, the controlled market economies will reproduce the cooperative solution.

Clearly, the tax policy required to internalize all external effects must take into account all welfare consequences arising from the use of nuclear power. The tax $\tau_i^{**}(t)$, will be referred to as the "cooperative Pigouvian tax". This tax formula looks similar to that required for the decentralized economy to reproduce the noncooperative Nash open loop solution. However, contrary to the shadow price $\nu_i^*(t)$ in the noncooperative Nash equilibrium, the shadow price $\nu^{**}(t)$ captures all welfare effects of country i 's contribution to the hazard function.

To derive the "cooperative Pigouvian tax" discussed above, knowledge of the cooperative solution is required. This means that, although there is a tax system that makes the decentralized economy support the cooperative solution, the informational requirements are enormous (to say the least). It also requires that the countries follow the agreement. A similar argument can be given as to the complication of implementing the "noncooperative Pigouvian tax" in the decentralized economy.

It is possibly more realistic to consider a case where the initial level of nuclear energy is suboptimal, and assume that the countries agree upon smaller projects, e.g. "small tax reforms". Aronsson et al. (1998) analyze in a "one country" economy with external effects from nuclear power, the welfare effects arising from higher taxation on nuclear energy. An interesting result is that an introduction of a small nuclear energy tax is always welfare improving in the market economy. Turning to the multi-country framework the picture is more complicated, and the results from the "one-country" economy do not in general carry over to situations where several countries are involved, see Aronsson et

al. (2000). Therefore, as a complement to the analyses of noncooperative and cooperative equilibria, I will use the numerical model to evaluate the welfare effects that will arise, if the countries agree to slightly increase their (possibly suboptimal) taxes on nuclear energy.

3 The functional forms¹²

In this section, I present important features of the numerical model¹³. The assumption that social welfare will fall to a constant base level W_i , made in previous section, implies that the size of W_i , will not affect the optimization problem. To simplify the analysis, I assume that the social welfare reduces to zero in case an accident occurs. The instantaneous utility function takes the form

$$u_i(c(t)) = (\alpha_{1_i} + \alpha_{2_i}(c_i(t))^{\alpha_{3_i}})$$

where α_{1_i} , α_{2_i} , α_{3_i} , are constants.

Turning to the functional form of the hazard function, I assume that the probability of a nuclear accident depends on the production of nuclear energy, g_1^n and g_2^n , and the stock of radioactive waste, x_1 and x_2 , where these events are assumed to be independent although not mutually exclusive. The additive law of probability can then be used to compute the probability of these four events by

$$\begin{aligned} \dot{\Delta}(t) = & \alpha_4^1 g_1^n(t) + \alpha_6^1 x_1(t) + \alpha_5^2 g_2^n(t) + \alpha_7^2 x_2(t) - \alpha_4^1 g_1^n(t) \alpha_6^1 x_1(t) - \\ & \alpha_4^1 g_1^n(t) \alpha_7^2 x_2(t) - \alpha_4^1 g_1^n(t) \alpha_5^2 g_2(t) - \alpha_6^1 x_1(t) \alpha_5^2 g_2^n(t) - \\ & \alpha_6^1 x_1(t) \alpha_7^2 x_2(t) - \alpha_5^2 g_2^n(t) \alpha_7^2 x_2(t) + \alpha_4^1 g_1^n(t) \alpha_6^1 x_1(t) \alpha_5^2 g_2^n(t) + \end{aligned}$$

¹²An appendix, available from the author on request, documents in detail the structure of the model, and its solution methods.

¹³The numerical model is solved in the dynamic optimization program, GAMS (General Algebraic Modeling System).

$$\alpha_4^1 g_1^n(t) \alpha_6^1 x_1(t) \alpha_7^2 x_2(t) + \alpha_6^1 x_1(t) \alpha_5^2 g_2^n(t) \alpha_7^2 x_2(t) + \\ \alpha_4^1 g_1^n(t) \alpha_5^2 g_2^n(t) \alpha_7^2 x_2(t) + (\alpha_4^1 g_1^n(t) \alpha_5^2 g_2^n(t) \alpha_6^1 x_1(t) \alpha_7^2 x_2(t))$$

where α_4^1 , α_5^2 , α_6^1 and α_7^2 are constants. The risk scenario for the less safe country implies that, on average, a nuclear energy related accident occurs once in every 10000 reactor years, and for the safe country once in every 100000 reactor years. These probabilities are controversial. The theoretical probabilities discussed in the literature are frequently smaller, assuming one accident in one million reactor years or one accident in 100 million reactor years. Historical data, on the other hand, informs us that we have had two (Three Mile Island 1979 and Chernobyl 1986) severe accidents of which the latter was most severe¹⁴, implying an accident in 6500 reactor years¹⁵. The safety target for the nuclear industry in Sweden is set to be no more than one accident in 100000 reactor years. However, recent reports from one of the reactors (Oskarshamn 2) estimate the probability to be in the interval, one in 1000 to one in 10000 reactor years, or ten to one hundred times more dangerous than the safety target.¹⁶ Considering the complexity of the systems involved and the relatively short time interval the reactors have been working, it is extremely difficult to calculate the proper probability for a nuclear accident.

The choice of probabilities in this paper can be interpreted as a compromise between the most optimistic and the most pessimistic views about the risk involved. By assuming that one country has relatively safe nuclear technology and the other a less safe technology, I can analyze how different risk levels affect the resource allocation. The probability of an accident is also a function

¹⁴250 persons died directly in the accident and three years later 600 000 persons were complaining of health problems related to the accident, see Faure and Skogh (1992).

¹⁵For further discussion of the proper probabilities for nuclear accidents, see e.g. U.S. Nuclear Regulatory Commission (1975).

¹⁶These results originate from a preliminary safety study, performed by Oskarshamns Kraftgrupp (OKG), presented in a press release from the Swedish Nuclear Power Inspectorate (SKI), 980429.

of the amount of radioactive nuclear waste generated. Because we have no historical experience of long-term storage, it is difficult to estimate the proper probabilities of a severe accident. Despite that, it seems reasonable to assume that these probabilities are substantially lower than for the daily production of nuclear energy and in the reference case, the risk is assumed to be one hundredth of the risk from the daily production of nuclear energy.

I assume a linear relationship between the use of nuclear energy and the stock of radioactive waste fuel

$$\frac{dx_i(t)}{dt} = \beta_5 g_i^n(t) - \beta_6 x_i(t)$$

where β_5 is based on an approximation of the relation between nuclear energy and nuclear waste.¹⁷ The constant β_6 is set so that the radioactive waste fuel generates one per cent of the initial radiation after one thousand years.¹⁸

The remaining parts of the model are close to the SEEP model of Nordhaus (1995). The output of final goods is given by

$$f_i(\cdot) = \beta_{1_i} Al_i(t) \left(\frac{El_i(t)}{El_{0_i}} \right)^{\beta_{2_i}} \left(\frac{Ot_i(t)}{Ot_{0_i}} \right)^{\beta_{3_i}} \left(\frac{Tr_i(t)}{Tr_{0_i}} \right)^{\beta_{4_i}}$$

where the economy is divided into a non-energy sector and an energy sector, and β_{1_i} is interpreted to represent the influence of production factors other than energy. Following the SEEP-model, the investment decision is exogenous where $Al_i(t)$ is measuring the total factor productivity. The energy sector is divided into; specific electricity uses, other energy uses and transportation, where

¹⁷By producing 70 Tw/h per year, approximately 200 tons of nuclear waste is generated. Assuming a linear relationship gives, $\beta_5 = 2.849$.

¹⁸Nuclear waste consists of different subjects with different half-lives and my formulation of the process is obviously a simplification. However, that will be of little importance for the results in this paper.

$El_i(t)$	=	Electricity in the electricity sector in country i
El_{0_i}	=	Initial energy consumption from the electricity sector in country i
$Ot_i(t)$	=	Non electricity energy consumption in country i
Ot_{0_i}	=	Initial energy consumption in the non electricity sector in country i
$Tr_i(t)$	=	Energy consumption in the transport sector in country i
Tr_{0_i}	=	Initial energy consumption in the transport sector in country i

These three sectors are combined in a loglinear production function, where the shares equal the expenditures in the base year 1994. Most important for the analysis is the electricity sector and this sector is divided into, specific electricity uses, where electricity is assumed to be the only reasonable energy source (e.g. for lightning) and general electricity uses where the energy can be produced by a variety of techniques. See Nordhaus (1995, App-4) for the exact form of the substitution function. The cost function for energy has the form

$$I_i(g_i^n(t), g_i^a(t)) = g_i^n(t)mc_i^n + g_i^h(t)mc_i^h + g_i^{eo}(t)mc_i^{eo} + g_i^o(t)mc_i^o + g_i^c(t)mc_i^c + g_i^g(t)mc_i^g + g_i^{bf}(t)mc_i^{bf}$$

where

mc_i^n	=	Marginal cost for nuclear energy in country i ¹⁹
mc_i^h	=	Marginal cost for hydro energy in country i
mc_i^{eo}	=	Marginal cost for other electricity in country i
mc_i^o	=	Marginal cost for energy produced by oil in country i
mc_i^c	=	Marginal cost for energy produced by coal in country i
mc_i^g	=	Marginal cost for energy produced by gas in country i
mc_i^{bf}	=	Marginal cost for energy produced with biofuels in country i

The distribution costs are included in the marginal cost, and the different energy producing techniques are also divided into old, (existing) and new, with higher marginal cost.²⁰

4 Simulation results

4.1 The uncontrolled market economy

To analyze different equilibrium concepts and risk scenarios, I first perform a reference case simulation for the uncontrolled market economy. This simulation is then compared with the outcome of the noncooperative and cooperative solutions. The rate of time preference is set to equal to 5 per cent/year and the model is simulated for 27 periods.

As indicated in Table 1, the average yearly use of nuclear in the coun-

¹⁹The marginal cost for nuclear energy includes certain taxes and fees that are assumed to cover storage and waste treatment costs. According to Swedish law, cost of waste disposal shall be the responsibility of the nuclear energy producers. Therefore, the producers have established the Swedish Nuclear Fuel and Waste Management Company (SKB), see e.g. Nordhaus (1995).

²⁰The marginal cost for new energy producing techniques is higher because the building costs for new power stations are included.

try with relatively safe nuclear production and storing technology will be 134 Twh/year with a capacity constraint on existing nuclear power stations at 140.4 Twh/year. The value function, equal to 24465.7 (displayed in Table 1), measures the discounted value of the objective function.²¹ The value function will be used to measure welfare and to evaluate the effects from different nuclear energy policies.

Table 1: The uncontrolled market economies.

	Safe	Less Safe
Nuclear output	134.0	134.1
Value function	24465.7	24466.3
\sum Value functions	48932.0	

For the country with less safe production technology, the average yearly use of nuclear energy will be approximately the same (134.1 Twh/year) as for the safe country (134.0 Twh/year), and the same follows for the welfare generated (24466.3) and (24465.7). With the assumption that the energy producer only maximizes profit at each point in time, the behavior of the producers and the magnitude of the value function will be the same in both countries. The reason why the solutions are not exactly the same, is that I solve this market model in an iterative manner and the solutions are therefore approximations.²²

²¹Note that the objective function is discounted with both θt and $\Delta(t)$.

²²The uncontrolled market economy is solved by forcing the countries to play the non-cooperative game not taking into account the negative effects from nuclear power.

4.2 Noncooperative Nash game and cooperative agreement

This subsection concerns the simulation results corresponding to the noncooperative Nash and the cooperative solutions. The result of the noncooperative Nash solution is presented in Table 2.

Table 2: The noncooperative Nash open loop solution.

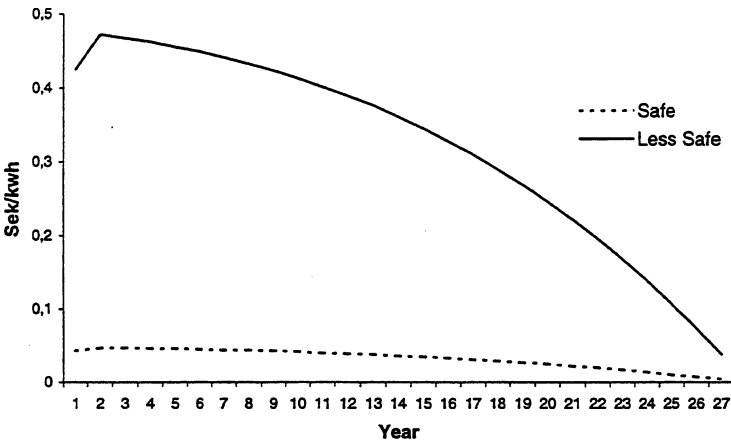
	Safe	Less Safe
Nuclear output	118.9	21.8
Value function	25146.2	24951.6
Σ Value functions	50097.8	

Note first that the noncooperative Nash equilibrium implies that both countries will use less nuclear energy, and that their value functions will be higher, compared with the uncontrolled market solution. The difference between the noncooperative Nash solution and the uncontrolled market economy is that both countries now recognize that the use of nuclear energy will affect the probability of an accident. Consequently, each country uses less nuclear energy in the noncooperative Nash equilibrium than in the uncontrolled market economy. However, note that the external effects from nuclear energy are only partly internalized. The reason is that the "noncooperative Pigouvian tax" in country i only takes into account that the use of nuclear energy will affect the consumer in country i (a consequence of the noncooperative Nash concept).

By comparing the country with relatively safe nuclear energy production with the country with relatively less safe nuclear energy production technology, it is clear that the safer country will use more nuclear energy and also

generate more welfare. By solving the noncooperative Nash game it is possible to estimate the "noncooperative Pigouvian tax" on nuclear energy implicit in the noncooperative Nash equilibrium.

Figure1: The "noncooperative Pigouvian taxes"



Comparing the countries, it is apparent that the tax in the less safe country is higher than in the safe country. The time profiles of the taxes, with high taxes in the beginning and low taxes in the final years, are explained by the fact that I use a positive discount factor and an accident in the present time is therefore more "costly" than an accident in the future.

Let me continue by examining how nuclear energy policy and welfare differ between the cooperative and the noncooperative solutions. The result of the cooperative solution is presented in Table 3.

First, by comparing the different solutions it is clear that the cooperative solution implies less use of nuclear energy. This is so, because the planner takes into account how the use of energy will adversely affect the utility of both countries. Despite using less energy, welfare is increased, since the neighbor country also uses less nuclear energy. The explanation is that, when country 1

decreases its use of nuclear energy, the probability for an accident is decreased also for the consumers in country 2. This will exogenously decrease the utility discount rate in country 2, enforcing the consumers in country 2 to be more patient. In order to avoid an increase in the endogenous part of the utility discount rate, less nuclear energy is produced in country 2 (which is positive for the consumers in country 1).²³

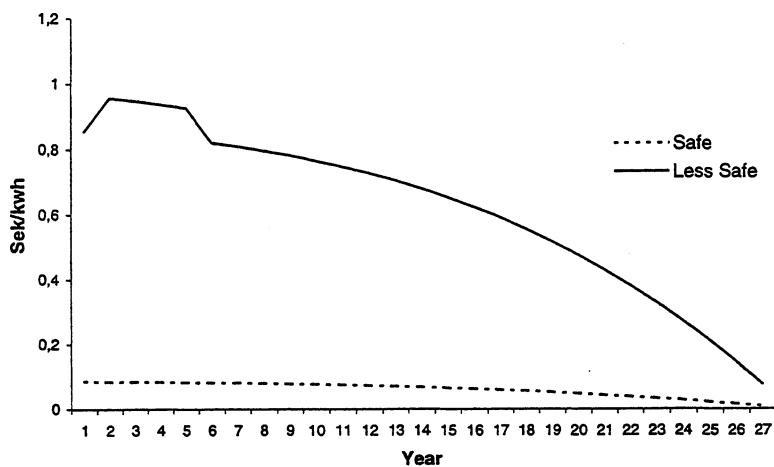
Table 3: The cooperative solution.

	Safe	Less Safe
Nuclear output	101.1	5.2
Value function	25154.0	24958.3
\sum Value functions	50112.4	

This result suggests that both countries will benefit from cooperation, even though more welfare is generated in the safer country. The "cooperative Pigouvian taxes" implicit in the cooperative solution are shown in Figure 2.

²³For a thorough discussion of "patience" and "impatience" effects, see Aronsson et al. (1998).

Figure 2: The "cooperative Pigouvian taxes"



It is clear that the development over time of the "cooperative Pigouvian tax" follows that of the "noncooperative Pigouvian tax" presented in Figure 1, although the tax levels are higher in the case of cooperation.

4.3 Small steps towards cooperation

In practice, cooperation is not likely to mean implementation of a first best cooperative equilibrium. It is, instead, more realistic to argue that countries agree upon "smaller projects", the purpose of which is to improve the resource allocation in comparison with the initial, prereform equilibrium. I will consider the welfare effects of a sequence of agreements between the countries to increase their taxes on nuclear energy. The initial structure is the uncontrolled market economies. Each country increases its nuclear energy tax by adding a small time independent tax to the initial rate, and the additional tax revenues are returned to the consumers in the form of a lump sum subsidy. The results of the experiments are presented in Table 4.

Table 4: The market solution with different uniform tax levels on nuclear energy in both countries.

	Safe	Less Safe
Uncontrolled Market Economy		
Nuclear output	134.0	134.1
Value function	24465.7	24466.3
Σ Value functions	48932.0	
Nuc tax: 0.005 SEK/kWh		
Nuclear output	132.6	132.6
Value function	24479.8	24480.5
Σ Value functions	48960.3	
Nuc tax: 0.01 SEK/kWh		
Nuclear output	131.1	131.1
Value function	24494.6	24495.2
Σ Value functions	48989.9	
Nuc tax: 0.05 SEK/kWh		
Nuclear output	115.7	115.1
Value function	24619.2	24619.4
Σ Value functions	49238.6	
Nuc tax: 0.1 SEK/kWh		
Nuclear output	90.9	89.8
Value function	24749.2	24749.3
Σ Value functions	49498.4	
Nuc tax: 0.2 SEK/kWh		
Nuclear output	0	0
Value function	24998.1	24998.1
Σ Value functions	49996.2	

Table 4 indicates that, compared with the uncontrolled market economy, both countries are better off when the use of nuclear energy are taxed in both countries. The tax induces them to reduce their use of nuclear power, and thereby the risk for a nuclear accident. In both countries the positive welfare effect is relatively large. For the relatively less safe country, and given that the uniform tax rate is sufficiently high, this policy generates a higher welfare level than both the noncooperative and the cooperative solutions. The reason is that the relatively less safe country benefits from the large decrease in the nuclear energy use in the relatively safe country. As expected, the sum of the post reform value functions is greater than in the uncontrolled market solution. Note that when the tax is relatively large (0.20 SEK/kWh), there will be no use of nuclear energy, whereas the sum of the value functions is higher than in the uncontrolled market economy. This implies that, compared with an uncontrolled market solution, the countries are better off if nuclear energy is not used at all.

What happens if the prereform equilibrium is given by the noncooperative Nash equilibrium in open loop form? This question is interesting because previous studies on environmental policies in global economies are often based on a comparison between the outcome of a cooperative agreement and the outcome of a noncooperative Nash game between the countries. Therefore, consider the case where the initial tax structure is the "noncooperative Pigouvian tax" and that the countries agree to uniformly increase their nuclear energy taxes.²⁴

²⁴The additional tax revenues are returned to the consumers in the form of a lump sum subsidy

Table 5: Uniform tax increases on nuclear energy in both countries in the noncooperative Nash open loop equilibrium.

	Safe	Less Safe
Noncooperative Nash solution		
Nuclear output	118.9	21.8
Value function	25146.2	24951.6
Σ Value functions	50097.8	
Nuc tax: 0.005 SEK/kWh		
Nuclear output	116.9	21.4
Value function	25146.5	24953.1
Σ Value functions	50099.6	
Nuc tax: 0.01 SEK/kWh		
Nuclear output	115.0	18.3
Value function	25150.9	24954.4
Σ Value functions	50105.3	
Nuc tax: 0.05 SEK/kWh		
Nuclear output	98.0	13.0
Value function	25147.8	24964.5
Σ Value functions	50112.3	
Nuc tax: 0.1 SEK/kWh		
Nuclear output	75.5	7.5
Value function	25123.8	24975.2
Σ Value functions	50099.0	
Nuc tax: 0.2 SEK/kWh		
Nuclear output	0	0
Value function	24998.1	24998.1
Σ Value functions	49996.2	

Starting from the noncooperative Nash solution, the relatively less safe country is better off with an additional tax on nuclear energy. For the relatively safe country, the welfare effect is positive with a low additional tax and then becomes negative as the tax scale continues to rise. Compared with the situation when the uncontrolled market economy constitutes the reference case, the global welfare effect of the reform is smaller. One reason is that the external effects from the use of nuclear power are partly internalized initially. Accordingly, the room to improve welfare is smaller.

5 Conclusions

This paper examines how the uncertainty involved in the use of nuclear power will affect consumers' welfare in an economy involving two countries. Different types of interactions between the countries are analyzed and, given the complexity of the tax and transfer system required to implement both the noncooperative Nash open loop and the cooperative solutions, the uncontrolled market economy seems to be a more reasonable reference point. I would like to summarize the main results as follows:

- The uncontrolled market economy implies a substantial overuse of nuclear energy and each of the different tax schedules on nuclear energy examined in this paper generates more welfare than the uncontrolled market economy.
- The noncooperative Nash solution only internalizes part of the external effects, and implies a too intensive use of nuclear energy and thereby too much nuclear waste.
- Compared to the uncontrolled market equilibrium, the cooperative solution is beneficial for both countries. The decrease in the use of nuclear energy in the less safe country will have a large positive effect on welfare also for the consumers in the safe country (due to the reduced risk for a nuclear accident).

However, the safe country only decreases its use of nuclear energy marginally, thus the positive effect for the less safe country is smaller.

•I have also examined the welfare effects of "small" cooperative agreements to introduce or raise the taxes on nuclear energy in both countries. If the uncontrolled market economy is used as a reference case, welfare is increased in both countries. If, on the other hand, the starting point is the noncooperative Nash equilibrium, a tax increase on nuclear energy will affect the countries differently. For the safe country there is a positive welfare effect when the additional tax is relatively small and a negative welfare effect when the additional tax becomes larger. For the less safe country, the welfare effects of all these reforms are positive.

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