Interplay of Policy Instruments in Climate Economics

Mathematical Methods in the Social Sciences

Elizabeth Tyger

Abstract

In this analysis, I use a common, two-period framework to compare three instruments often used in climate economic research. In particular, I compare the effects of funding research through consumer investment and taxation, taxing pollution and redistributing the revenues to the consumers, and using tax revenues to buy fossil fuel reserves to prevent future emissions. Total utility is calculated by subtracting a parabolic harm from emissions function from the benefit of consumption. A benevolent social planner chooses the optimal propensity to consume in each period; the remainder of total output is used to fund research. Under the parameters used in this analysis, I find that a pollution tax to fund research results in the largest drop in emissions, and the pollution tax to buy reserves results in the least reserves left to burn in future periods.

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1 Introduction

The impending threat of climate change is hard to escape. Even in our complex modern world, complete with nuclear weapons and artificial intelligence, it is often thought of as one of the most existential threats to our existence [Sengupta, 2018]. The economics of this problem are muddied with elements of political science, game theory, psychology, and environmental science, making a clear, feasible solution impossible. Though, theoretically, the simplest way to mitigate the problem is to include the adverse externalities of climate change into the market price for carbon, this approach has generally proven to be unfeasible due to political constraints and the game theoretical difficulties involved with such a complex global negotiation process. The negotiation processes of both major global agreements of the past several decades, the Kyoto Protocol signed in 1997 and the Paris Climate Agreement adopted in 2015, disregarded many basic economic principles. The perverse incentives involved in tying long-term emissions to a future emissions level and a large potential for free-rider effects made both unlikely to achieve their goals, regardless of how many nations officially signed the agreement. In addition, when one group of countries commits to a set of policies, the impacts of these policies can have unanticipated side effects that result in non-participants emitting more than they did previously. This concept of carbon leakage can render well-meaning policies ineffective [IPCC, 2007]. Overall, the complexities of global politics combined with local interests make large-scale negotiations near impossible, leaving space for economists to investigate alternatives to the traditional solutions.

Given these constraints, much of climate economics research has attempted to find ways to force the hand of the reluctant actors in the free market to limit the use of fossil fuels and migrate consumption towards the use of green alternatives. The motivation behind this analysis is to compare several of these methods along the metrics of both consumer utility and harm from pollution. Among the existing literature describing various policy or strategic options for mitigating climate change by moving away from fossil fuels, there is little comparison between methods. This is due in part to the complex nature of these models and the mathematical difficulty of incorporating multiple strategies into one cohesive model. Given these constraints, the model presented here does not attempt to abstract a generalized solution, but instead substitutes values into the equations and generates a solution numerically. These values were chosen carefully and changed periodically to
ensure that no single number has too much power over the result of the simulation.

2 Literature Review

One of the best theoretical alternatives to the current structure of negotiations is William Nordhaus’s suggestion of pricing the social cost of carbon into the market price, as described in his book *The Climate Casino* [Nordhaus, 2013]. This market driven approach requires all countries around the world to commit to an effective carbon tax (either through a literal tax or through cap and trade restrictions) that would increase gradually over time. By pricing the risk of impending climate change into everyday choices, this tax would allow consumers to make the efficient choice in the market without having to perform their own calculations. Nordhaus’ integrated assessment models, the DICE and RICE models, demonstrate the positive impact these policies would have on curbing global climate change. However, this method would be politically difficult to implement due to friction both at the international treaty level and at the individual country level. An alternative implementation plan that is less than global would be generally ineffective due to the universal nature of the problem.

The kind of tax Nordhaus suggests is more generally referred to as a Pigovian tax [Pigou, 1920]. Pigovian taxes incorporate externalities into the price of a given good with the goal of eliminating market inefficiencies. These taxes will be also be incorporated into the model described here.

Another principle to keep in mind when conducting analyses of the use of nonrenewable resources over multiple periods is Hotelling’s Rule. Hotelling’s rule states that a profit maximizing firm will set its percentage change in price for each unit of time equal to the discount rate, or $P'(t)/P(t) = \delta$ [Hotelling, 1931]. Hotelling shows that this will maximize the present value of extracting the resource to depletion.

An alternative approach to environmental issues that will also be incorporated in this model is using supply side theory. In particular, Bard Harstad presents this model by defining two sets of countries, $M$ and $N$ who collectively make up the world market [Harstad, 2012]. The countries in $M$ are actively concerned about the future harm caused by climate change, while those in $N$ are either not convinced of the need for action or are politically unable to implement policies to combat it. If $M$ simply implemented policies to reduce their own demand for fossil fuels, this would cause
the global carbon price to decline and countries in \( N \) would consume (pollute) more. Similarly, if \( M \) reduced their own supply, \( N \) would respond by increasing its supply to the global marketplace. These policies, as described by Harstad, would be second-best and inefficient. However, if a deposit market existed, where countries are able to purchase the right to exploit a deposit from other countries, \( M \) would be able to purchase deposits in \( N \), thereby reducing \( N \)’s supply directly. Harstad’s model finds that in a one-shot game, \( M \) will purchase the deposits with the lowest profit margin (as the owners are willing to sell at lower prices). This allows them to reduce their own supply by a marginal amount that will not result in \( N \) increasing their own supply. The result is more efficient levels of global consumption and pollution.

Harstad successfully expands his model to account for efficient investment by country \( M \) in green energy and to span over two periods, showing that leakages are prevented by a deposit market. However, he does not take into account the possibility for technological developments in the green energy sector. The work of Simone Valente models a world in which there is some backstop technology such as solar energy available, and a benevolent social planner must choose when to switch from nonrenewable fossil fuels to this green energy [Valente, 2011]. The switch is modeled as a discrete jump in which consumption falls immediately, but the growth rate increases substantially and causes output to rise quickly back to its previous state. This relates to the reluctance of policy makers to make the switch to renewable energy because of short term harm, despite the fact that there is more potential for growth in those areas.

The motivation for this analysis is to set up a framework that allows for an apples-to-apples comparison of the effectiveness of these instruments. The techniques to be compared are pricing carbon through Pigovian taxes, using supply side techniques to purchase fossil fuel reserves, and observing the effects of investment in research. I will consider a one market model (i.e. no outside trade) over two periods and determine how these various forms of taxation and uses of the tax revenues will affect the total emissions generated and overall consumption.
3 Framework

In this discussion, I present a two-period model of energy consumption. The two periods (referred to moving forward as period 0 and period 1) should be thought of as each taking place over several decades. The reason for this is the technological growth from one period to the next is significant, and the fossil fuels used over the course of the two periods should be thought of as nearly all fossil fuel used before complete transfer to the green alternative. Any remaining reserves are stranded in a third “ghost” period. The quantity of reserves remaining and available to consume will be a way of comparing the traditional taxes to the supply-side instrument described in the final section.

3.1 General Assumptions

In setting up this two-period model, I made a few baseline assumptions. First, the consumers are taken to be the general population and the producers are taken to be the producers of fossil fuels. Given that fossil fuel producers are a small percentage of the overall world, and all consumers use fuel to support their daily activities, this separation is reasonable.

The consumers have the potential to produce $Y$ units of goods. These $Y$ units can be divided in any way between consumption $C$ and investment $D$ in each period, so long as consumption makes up at least sixty percent of the total production. This restriction ensures that consumption does not drop low enough so as to be unable to sustain the population. Investment in this model can be thought of as an income tax used to fund research or as contributions to universities and other non-governmental institutions that contribute to the body of green energy research.

We define $C = c \cdot Y$ and $D = d \cdot Y$ such that $c + d = 1$. The proportions $c$ and $d$ are free and able to change over the two periods. Given that we are only considering two periods, the maximal value of $c$ in the second period will always be one, since there are no gains to future research if we do not consider further periods. This will not heavily restrict the analysis, so a value of $c_1 = 1$ will be assumed throughout.

3.2 Utility Calculation

The social planner’s maximization decision will be to choose $(c, d)$ in each period to maximize total utility. Utility here is defined as total consumption goods minus the harm incurred from climate
change due to fossil fuel emissions. In other words, total utility in period \( i \) is equal to:

\[
U_i = c_i \cdot Y_i - H_i = C_i - H_i
\]  

(1)

To calculate \( H_i \), we begin with the incremental harm function, \( h_i \). This function describes the marginal harm incurred from burning an additional unit of fossil fuels:

\[
h_i = \alpha \cdot q_i^\gamma
\]

(2)

The exponent parameter \( \gamma \) is greater than one to reflect the increasing marginal harm from every additional unit of fossil fuel emissions, and the coefficient parameter \( \alpha \) is in the interval \((0, 0.1)\) in order to slow the harm accumulation during early units of emission.

In order to calculate the total harm incurred in each period, \( H_i \), we integrate \( h_i \) over the appropriate interval. In period zero, this interval is from zero to \( q_{0\text{FF}} \), or the quantity of fossil fuels consumed in period zero. In period one, this interval is from \( q_{0\text{FF}} \) to \( q_{1\text{FF}} \). The results of this simple integration result in the following equation for \( H_i \):

\[
H_i(q_i) = \begin{cases} 
\frac{\alpha}{\gamma+1} \cdot q_i^{\gamma+1} & \text{if } i = 0 \\
\frac{\alpha}{\gamma+1} \cdot q_i^{\gamma+1} - H_{i-1}(q_{i-1}) & \text{if } i = 1 
\end{cases}
\]

(3)

For both pieces of utility, we discount each portion from period one at discount rate \( r \), and treat period zero as the present (no discounting), so that total utility over both periods is equal to the following:

\[
U = C_0 - H_0 + \frac{1}{(1 + r)}(C_1 - H_1)
\]

(4)

### 3.3 Fuel Demand

In order to show the results with more clarity, demand for fuel by the consumer is assumed to be perfectly price inelastic (i.e., takes the form of a vertical demand curve), but not income inelastic. This means that consumers do not change their quantity of fuel consumed in response to prices. However, an increase in prices could lead the social planner to choose a lower level of fuel
consumption in a period by lowering $c$, the propensity to consume.

### 3.4 Fossil Fuel Supply

The initial supply curve for fossil fuels is assumed to take the parabolic form

$$P_i = A \cdot Q_i^2 + B$$

where $A$ and $B$ are constants and $P_i$ and $Q_i$ are the price and quantity of fuel in period $i$, respectively. The coefficient $A$ is restricted to the interval $[0, 1]$ to allow for a fairly slow increase in marginal costs early on, as is realistic when producers are using already discovered, easy to access deposits. $B$ must be greater than zero so that there are no quantities with negative prices. This equation demonstrates the increasing marginal costs of extracting more fossil fuels.

An important point to note is that this supply curve carries over from one period to the next. In other words, the price axis effectively shifts out to $q_0$ after the first period so that consuming the first unit of fossil fuels in period one has the same marginal cost as consuming the additional $(q_0^{FF} + 1)$ unit in period zero. We will assume a fixed quantity $F$ of comparatively low-cost fossil fuel available to extract. After this quantity has run out, we will assume that prices will be high enough that a green alternative will be preferable to finding new deposits of fuel.

### 3.5 Green Energy Supply

Supply of green energy, on the other hand, takes the less traditional form of a two disjoint, horizontal supply curves. The supply of green energy is horizontal because the marginal costs of renewable energy are typically near constant, so are assumed to be as such in this simple model. This is due to the fact that in many manifestations of green energy, once the infrastructure is in place, the additional costs for procuring an additional unit are constant, not increasing.

The first piece of this supply is a non-infinite curve, which describes the fact that the low-cost supply is not large enough to meet total demand for any possible green alternative at a price comparable to the marginal cost of fossil fuel extraction. The second extends from the “end” of the fossil fuel supply curve (when quantity of fossil fuels is greater than $F$). For our purposes, this second piece is infinite, since a larger amount of green energy is available at a higher price point.
This infinite piece serves as a pure backstop; once fossil fuel runs out, we will use any form of green energy possible to continue fuel consumption.

Price (marginal cost) and quantity of the low-cost green energy in period zero are constants; we inherit these conditions from the past. From period zero to period one, both quantity and price change as a function of research, \( D_0 = d \cdot Y_0 \) (plus any tax revenues in the appropriate situations – see section 4 for details), as well as the initial price and quantity from period zero according the following equations:

\[
Q^G_1 = Q^G_0 + e \cdot D^f_0 \quad (6)
\]

\[
MC^G_1 = MC^G_0 - g \cdot D^h_0 \quad (7)
\]

The price and quantity are described separately due to the horizontal nature of the green supply curve. Here, \( e, f, g, h \) are all constants greater than 0. The exponents \( f \) and \( h \) are in the interval \((0, 1)\) in order to represent the decreasing marginal benefit of more investment in period zero, \( D_0 \). The coefficient \( e \) is also in the interval \((0, 1)\) in this model in order to keep quantity growth.
reasonable. The coefficient $g$ is assumed to be greater than one.

The higher cost, infinite supply curve follows the fossil fuel curve from period zero to period one and continues to serve its role as a pure backstop technology. No actions of the social planner or the consumer directly impact its placement.

As a notation clarification, the capital letter $Q_i^G$'s represent the hypothetical green quantities (i.e., the maximum amount of green energy available in a given period), whereas the lower case $q_i^G$'s represent the actual quantity used in period $i$.

### 3.6 Aggregate Supply

Before describing aggregate supply, I define the following quantities to simplify notation:

\[ Q_0^{MIN} = \sqrt{\frac{MC_0^G - B}{A}} \]  \hspace{1cm} (8)

\[ Q_0^{MAX} = \sqrt{\frac{MC_0^G - B}{A}} + Q_0^G \] \hspace{1cm} (9)

\[ Q_1^{MIN} = \max\{\sqrt{\frac{MC_1^G - B}{A}}, Q_0\} \] \hspace{1cm} (10)

\[ Q_1^{MAX} = \max\{\sqrt{\frac{MC_1^G - B}{A}}, Q_0\} + Q_1^G \] \hspace{1cm} (11)

$Q_i^{MIN}$ represents the quantity at which the low-cost green energy is as expensive as fossil fuels in period $i$, and is calculated from setting the equation for price of fossil fuel, equation 5, equal to the marginal cost of green energy and solving for quantity. $Q_i^{MAX}$ represents the quantity end of the low-cost green energy supply curve in period zero. These quantities are calculated in nearly the same way in each period, but given the effective shift in the $y$-axis for period 1, $Q_1^{MIN}$ either starts at $Q_0$ if marginal cost of fossil fuels is less than $MC_1^G$ or at $\sqrt{(MC_1^G - B)/A}$ if this is not the case.

The green alternative supply is combined with the fossil fuel demand as follows. In period zero, the basic fossil fuel supply curve (equation 5) is used until the quantity $Q_0^{MIN}$. Then, the horizontal line of the green alternative supply curve is inserted into the original parabola, for a length of $Q_0^G$, or until quantity is equal to $Q_0^{MAX}$. The parabola then continues as written from the end of the horizontal line until quantity equals $F + Q_0^G$, or when fossil fuels run out. From there,
the horizontal, infinite portion of the green alternative supply completes the curve.

As in the basic model described in section 3.3, the period one supply curve begins at \( q_0 \), or quantity of fuel demanded in period zero. If the marginal cost of the green alternative, \( MC^G_1 \), is less than or equal to the price at \( q_0 \), then the curve begins with the green alternative supply curve, and then continues with the fossil fuel parabola after a length of \( Q^G_1 \) until supply runs out as in period zero. If the marginal cost of the green alternative is greater than the price at \( q_0 \), then the period one supply curve beings with the fossil fuel supply parabola, and switches to the green alternative curve when price is equal to the green alternative marginal cost, as in period zero.

Two examples of this supply curve are displayed in figures 2 and 3, where the vertical line is the demand in period zero. Note how the aggregate supply begins at this demand line as if it were the adjusted price axis.

The mathematical description of the aggregate supply curves in each period are included below.

\[
P_0(q) = \begin{cases} 
A \cdot q^2 + B, & \text{if } q < Q^{MIN}_0 \\
MC^G_i & \text{if } Q^{MIN}_0 < q < Q^{MAX}_0 \\
A \cdot (q - Q^G_0)^2 + B & \text{if } Q^{MAX}_0 < q < F + Q_0 + q^G_0 \\
A \cdot F^2 + B & \text{if } q > F + Q^G_0
\end{cases}
\]  

(12)

\[
P_1(q) = \begin{cases} 
0 & \text{if } q < Q_0 \\
A \cdot q^2 + B, & \text{if } Q_0 < q < \sqrt{(MC^G_1 - B)/A} \\
MC^G_1 & \text{if } Q^{MIN}_1 < q < Q^{MAX}_1 \\
A(q - Q^G_1 - q^G_0)^2 + B & \text{if } Q^{MAX}_1 < q < F + Q^G_1 + q^G_0 \\
A \cdot F^2 + B & \text{if } q > F + Q^G_1 + q^G_0
\end{cases}
\]  

(13)

If no green energy is used in period zero, then it is appropriate to use \( q^G_0 \) in this equation and obtain the proper result.

In this analysis, set values were chosen for the parameters in order to compare alternative policy plans. The abstracted, theoretical model proved to be intractable for these purposes. A complete list of these parameters in included in the appendix in figure 9.
Figure 2: Aggregate Supply Curves: Green Energy Used in Period Zero

Figure 3: Aggregate Supply Curves: Green Energy not Used in Period Zero
4 Tax Scenarios

Given the previously described setups, there are several potential policy instruments that could impact overall utility. The traditional tax scenarios that I will discuss in this section are no tax, a pollution tax that is redistributed to the consumers, a consumption tax that is invested in green energy research, and a pollution tax that is invested in green energy research. Given that demand is price inelastic, none of these will have a direct effect on how much fuel is consumed. Some will, however, change the optimal value of \( c \) which would indirectly change the amount of fuel consumed in these two periods.

The numerical results for consumption, harm, and utility for each policy situation are included in the appendix in figure 9.

4.1 No tax

Under these circumstances, without any policy interventions, the threat of impending climate change causes the ideal consumption rate in period zero to be the minimum percentage of 0.6. Despite the fact that this proportion is quite low (perhaps unrealistically low), it gives a good baseline with which to compare other tax policies. This equilibrium is described graphically in figure 4.

4.2 Pollution tax: Redistributed

Given the assumption of inelastic demand, a pollution tax that is redistributed is not beneficial from an environmental standpoint. In fact, due to its impact on the maximum choice of \( c \) (\( c = 0.89 \) under this policy), it ends up increasing total emissions. Though it redistributes many of the profits of fossil fuel companies to the consumer, increasing consumer utility, more fossil fuels are consumed given the increased propensity to consume and the overarching emission problem is not solved. See figure 5 for graphical representation.

The reason this outcome incentivizes consumers to increase their propensity to consume, resulting in higher utility, is because this analysis separates the consumer and the producer into different actors. Additionally, we do not take into account how the higher prices effect the overall utility of the consumers. It is assumed these higher prices would be absorbed into inflation given that we
are viewing the entire economy as the consumer. With other combinations of input numbers, this result could vary. Regardless, the conclusion from a redistributed pollution tax is that it does more
harm than good from the environmental point of view.

4.3 Consumption tax: Research

A slightly more environmentally friendly outcome is taxing consumption and using the revenues to fund more green energy research. As in the no tax case, utility is maximized when $c = 0.6$. This policy under the current parameters does not increase total utility due to the fact that we are reducing the benefit from consumption with the tax by a larger amount than we are reducing the harm due to lower total emissions. However, we do get the benefit of slightly decreased fossil fuel consumed during these two periods, resulting in the smallest $H$ of any policy we have examined thus far. Additionally, the impacts of research gives high likelihood for mostly green energy to be consumed during the third “ghost” period. Though figure 6 does not show large improvement, with a different configuration of numbers this policy can have a larger impact. This downward impact on emissions is the overall important takeaway for this scenario.

![Figure 6: Equilibrium with a Consumption Tax used for Research Funding](image)

The third and final traditional tax-based instrument is to tax pollution and use the revenues to fund research. Given the possibility for substantial tax revenues here, this policy does help in reducing the amount of fuel consumed over these two periods. In the current setup, this research
pushes the marginal cost of green energy down to zero in the second period and increases the 
quantity available substantially (shown graphically in figure 7). This greatly decreases the amount 
of fossil fuels consumed, dropping $H$ to its lowest point in all scenarios examined thus far.

Figure 7: Equilibrium with a Pollution Tax used for Research Funding
5 Supply-side Policy Scenarios

An additional, non-traditional, policy instrument is to use tax revenues to buy the most costly fossil fuel reserves to prevent their extraction. This alternative proves to be one of the most effective methods of mitigating climate change under framework.

There are two ways to enact this policy: through a tax on consumption and through a tax on fossil fuel emissions. We will not examine the tax on consumption very closely because, under the numbers in this analysis, there is not a large enough amount of revenue generated to make such a policy very effective. The graphs and the emissions numbers closely resemble those when there is no policy, but with the downside of a very low consumption utility due to the consumption tax.

A tax on pollution, on the other hand, has a rather large impact on the amount of fossil fuels consumed and overall utility. The maximum proportion of $c$ here is 0.6, as in several of the other options. The revenue generated from taxes in this alternative is high enough to buy 6.3 percent of the initial stock of the usable fossil fuel after the first period, and 29.6 percent of the initial stock after the second period for a total of 31.6 percent of the total usable stock. Under this policy, there is no fossil fuel left after the revenues from period one are used to purchase any fossil fuel remaining. This is done while still contributing forty percent of output to research, ensuring that in the third “ghost” period, prices will not sky-rocket due to a lack of low-cost green energy to replace all of the fossil fuel previously consumed. This scenario is modeled graphically in figure 8.

Another potential upside to this policy, not modeled here, is the potential for green energy investment to come from the fossil fuel companies. The revenues they receive from the purchasing of the fuel they will never produced could go into converting their businesses into green energy companies. The potential for this kind of side effect on top of an already beneficial policy gives this alternative an additional advantage over the other tax policies.
6 Conclusion

After considering these various tax options, it is clear that the most environmentally effective alternatives are a pollution tax with revenues going towards research, or a pollution tax with revenues going towards buying fossil fuel reserves. These two instruments made the most impact on reducing harm without decimating the utility from consumption.

As a caveat to these conclusions, under a different parameter set, it could be the case that a consumption tax would be more effective. The limitations of this numerical model make it difficult to abstract a clear instrument of choice from among the alternatives presented. A possible area for further research would be to either develop a stronger methodology for choosing parameters (perhaps based on empirical data), or to complete this abstraction under this framework in order to better understand the interactions between variables.
The following tables are presented with the appropriately discounted values for $U_i$, $C_i$, and $H_i$ in each period and in calculating the total. The total column for fossil fuel consumed is not the total, but the fuel remaining for the third “ghost” period.

![Table](image)

**Figure 9: Values for all parameters**
Table 1: No policy

<table>
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<tr>
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<th>Period 0</th>
<th>Period 1</th>
<th>Total</th>
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<tr>
<td>$U_i$</td>
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<td>$H_i$</td>
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<td>Fossil fuel consumed</td>
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Table 2: Pollution: redistribution

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<td>$H_i$</td>
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<td>Fossil fuel consumed</td>
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Table 3: Consumption: research funding

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<td>Fossil fuel consumed</td>
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<td>32.00</td>
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Table 4: Pollution: research funding

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<th>Period 1</th>
<th>Total</th>
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<td>$H_i$</td>
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<td>Fossil fuel consumed</td>
<td>29.00</td>
<td>0.00</td>
<td>71.00</td>
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Table 5: Pollution: buy reserves

<table>
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<th>Period 0</th>
<th>Period 1</th>
<th>Total</th>
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<td>$U_i$</td>
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<td>$C_i$</td>
<td>60.00</td>
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<tr>
<td>$H_i$</td>
<td>77.76</td>
<td>445.57</td>
<td>523.33</td>
</tr>
<tr>
<td>Fossil fuel consumed</td>
<td>36.00</td>
<td>32.41</td>
<td>0</td>
</tr>
<tr>
<td>Fossil fuel purchased</td>
<td>6.30</td>
<td>29.60</td>
<td>31.59</td>
</tr>
</tbody>
</table>

Table 6: Pollution: buy reserves

<table>
<thead>
<tr>
<th></th>
<th>Period 0</th>
<th>Period 1</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_i$</td>
<td>-17.76</td>
<td>-350.25</td>
<td>-368.01</td>
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<td>$C_i$</td>
<td>60.00</td>
<td>95.33</td>
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<tr>
<td>$H_i$</td>
<td>77.76</td>
<td>445.57</td>
<td>523.33</td>
</tr>
<tr>
<td>Fossil fuel consumed</td>
<td>36.00</td>
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</tbody>
</table>
References


