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A Hotelling model for the circular economy including recycling, substitution and waste accumulation

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ABSTRACT

Non-renewable resources include a large variety of deposits that have been formed by geological processes over millions of years. Although extraction of such resources provides benefits as employment and economic revenues, it also contributes to negative environmental externalities and it increases resource scarcity. An important policy question is how to optimally extract non-renewable resource stocks over time while taking possible substitutes and recycling into account. The present paper adds to the literature by developing a generic numerical optimisation model that can be used to simulate non-renewable resource management regimes and the effects of different policy instruments deployed at different stages of the resource's life cycle. By including recycling and substitution, the model extends the seminal cake-eating Hotelling model that dominates the non-renewable resource economics literature. In addition to being generically designed, the model can accommodate for non-competitive market settings, interacting policy instruments and environmental externalities at different stages of the material's life cycle. The model's possibilities are illustrated by means of a numerical simulation example for the extraction of sand.

1. Introduction

Non-renewable resources include a large variety of mineral deposits from which metals, fossil fuels and other processed minerals can be obtained. Although the extraction of these resources provides local employment and revenues, it is usually accompanied by negative environmental externalities. For example, quarrying sand and gravel can be noisy and dusty and traffic to the mining pit can create disamenities for neighbours. Furthermore, the natural environment can be damaged by biodiversity loss, run-off water, waste generation and visual pollution (Eckermann et al., 2012). Along with these negative aspects is often a problem of scarcity. As the crude forms of these non-renewable resources were created by long-term geological processes, their rate of formation is so slow – in timescales relevant to humans – that they should be labelled as non-renewable (Perman et al., 2011). In addition, the intensive use of these resources that formed the basis of economic prosperity in many developed countries, and strict demarcations of mining areas, causes remaining reserves to be limited and scarce (European Commission, 2011a). The European Union has recognised that the current rate of extraction of non-renewable resources is not sustainable and it has identified resource efficiency as one of seven flagship projects to pursue in its Europe 2020 strategy (European Commission, 2011b). This flagship initiative, which has the aim of creating frameworks for policies to support the shift towards a more resource-efficient and low-carbon economy, raises the key policy question: what is the optimal extraction path over time of a non-renewable resource in a circular economy[1] setting?

There is no straightforward answer to this question because non-renewable resources are heterogeneous and it is often unclear what policies should be undertaken in order to facilitate the transition towards a resource-efficient economy. The prevailing view is that increasing scarcity of non-renewable resources will be accompanied by a steady price increase that signals scarcity to consumers and provides incentives for eco-innovations for substituting or limiting the use of scarce materials. However, the incentives given by the price mechanism are often fundamentally flawed when it comes to the reaction of private sectors. Private resource owners are often more impatient than society as a whole, which leads to excessively fast exploitation (Jagannathan et al., 2016). In addition, market prices often reflect insufficiently environmental externality costs in the absence of proper government

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[1] See for example Ellen MacArthur Foundation (2015), Stahel (2016) or Van Acker et al. (2016) for attempts to define the concepts of circular economy and resource efficiency in more detail.

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regulation (Dubois and Eyckmans, 2014; Söderholm and Tilton, 2012). Based on these observations, implementing policy instruments to foster more sustainable resource use is justified. Moreover, this is in accordance with the calls for 'true pricing' by internalising external costs and with the green tax shift debate. At present, many European Member States have not made a substantial shift from labour towards environmental taxation, even though environmental taxes can be a step towards reflecting the full external and social costs of resource extraction, utilisation and end-of-life practices (Bringezu, 2002; Wilts et al., 2014). Along with steering behaviour, these taxes would help to reorientate public finances away from labour taxation, which could benefit job creation and economic growth.

The discussion so far highlights the difficulty of identifying policies that trigger the transition towards a resource-efficient, circular economy. The challenge is exacerbated by the lack of appropriate methodologies that combine phenomena such as resource extraction, environmental externalities, waste accumulation, recycling and substitution in a unified framework. This paper intends to add to the existing literature by developing a generic optimisation model that can be used to simulate non-renewable resource regimes and the effects that different policy instruments can have within the material flow of a particular substance. The generic optimisation model provides a tool for designing policies that foster the transition towards a more resource-efficient economy, which can boost economic performance while reducing resource use and negative environmental externalities.

Section two describes in detail the modelling framework. In the third section, numerical simulations are presented, illustrating the capabilities of the modelling framework. A discussion of the model's capabilities and limitations and of interesting future research topics is presented in section four. Section five concludes the article with an overview of the most important findings.

2. Hotelling model with recycling

Numerical models often serve as a bridge between theoretical models and analyses of real-world policy questions. In addition, numerical optimisation problems are often used to quantify the net effects of counteracting forces that theoretical models are unable to sign unambiguously (Conrad, 1999; Epple and Londregan, 1993; Flakowski, 2004). Although such optimisation problems are actually simplified representations of reality, they can provide generally applicable and policy-relevant insights into how to foster resource efficiency by implementing an appropriate mix of policy instruments. The basis of the model developed in this chapter lies with the well-known Hotelling model (Hotelling, 1931). According to the Hotelling rule, the shadow price of a non-renewable resource should increase at the rate of discount along the socially optimal extraction path. This rising shadow price reflects the increasing opportunity cost as remaining non-renewable resource reserves are consumed. Private profit maximising resource owners interacting on a competitive commodity market will choose an extraction path that coincides with the socially optimal one provided the private and social discount rates are equal (Chermak and Patrick, 2002; Perloff, 2011).

Already in the 1970s, several theoretical models on resource extraction and recycling were developed. In a study by Smith (1972) for example, a rudimentary model was used that emphasises only those elements essential to the recycling problem. Later, Lusky (1975) developed an integrated model of conservation and recycling in a framework of a natural resource cycle, and Hoel (1978) studied the optimal path of extraction and recycling under various assumptions about the environmental effects of recycling and the assimilative capacity of the environment. In addition to these theoretical models, also numerical simulation models in the same spirit were published. In the study by Weikard and Seyhan (2009) for example, a resource extraction model was built for a competitive fertilizer market including different recycling options. Seyhan et al. (2012) also focused on the extraction and recycling of Phosphorus, and developed a resource-specific model. Compared to these studies, this paper develops a comprehensive generic optimisation model that can be used to simulate non-renewable resource regimes and effects of different policy instruments within the material flow of a particular resource. Our model includes recycling, substitution and waste accumulation in a unified framework, and is able to simulate different scenarios like non-competitive market settings, first-best welfare maximisation scenarios, interacting policy instruments and environmental externalities linked to different stages of the material flow.

2.1. Economic actors in decentralised market model

The model involves four different types of economic actors: (i) consumers, (ii) resource owners, (iii) suppliers of substitute material and (iv) recyclers.

2.1.1. Consumers

We assume a large number of identical consumers. The representative consumer chooses to consume an amount of non-renewable resources, Q_t, to maximise its utility while taking into account its budget constraints. In the model, preferences for consumption are represented by an increasing and strictly concave utility function $U(Q_t)$, so that $U' \geq 0$ and $U'' \geq 0$. Furthermore, there is a numéraire good, v_t, the price of which is normalised to unity. Making use of this numéraire good facilitates comparisons as all relative prices in the model can be expressed in terms of this numéraire as a tradable economic commodity. It is further assumed that the income of the consumers is exogenous and that no intertemporal savings or borrowing take place. In the model, the exogenous income is denoted by $\overline{y}_t$ and is strictly larger than zero. The price of the good is denoted by p_t, and can be supplemented with a consumption excise tax t_t^q. We assume there is a waste market where recycling companies try to acquire discarded consumption products for recycling the embedded material. In order to introduce this waste market we foresee the possibility that consumers are paid a price p_t^w for their end of life consumption products w_t. Note however that in the waste market equilibrium, this waste price can be negative meaning that the consumer would be charged a price for disposing waste instead of receiving money for handing over end of life products to the recyclers. In the section on recyclers we will discuss in detail the determinants of this equilibrium waste price. Combining all these elements provides the following constrained utility optimisation problem in period t:

$$max_{v_t,Q_t} v_t + U(Q_t) s.\ t.\ v_t + [p_t + t_t^q]Q_t - p_t^w w_t \leq \overline{y}_t \tag{1}$$

Assuming that consumption goods only lasts for one period,[2] we can replace w_t by Q_t and the corresponding Lagrangian function of this consumer problem is given by:

$$L(v_t, Q_t, \lambda_t) = v_t + U(Q_t) + \lambda_t[\overline{y}_t - v_t - [p_t + t_t^q - p_t^w]Q_t] \tag{2}$$

In Eq. (2), parameter λ_t represents the Lagrange multiplier of the consumer's budget constraint or marginal utility of extra income. Taking the derivative of the Lagrangian with respect to the numéraire good v_t, it follows directly that $\lambda_t = 1$. The relevant Karush-Kuhn-Tucker first-order conditions for a utility maximum, taking into account the non-negativity constraint in consumption Q_t, can be written as:

$$U'(Q_t) - p_t - t_t^q + p_t^w \leq 0,\ Q_t \geq 0,\ [U'(Q_t) - p_t - t_t^q + p_t^w]Q_t = 0 \tag{3}$$

Basically, Eq. (3) says that in case of an interior solution $Q_t > 0$, consumers will buy consumption goods up to the point at which their marginal utility of consumption equals the full consumer price of the

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[2] More sophisticated ways of modelling the intertemporal link between consumption and ensuing waste are discussed in Section 2.2.