On the Economics of Recycling and Small Open Circular Economies

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1 Introduction

Significant improvements in social welfare have recently been linked to large scale recycling programs across the world, projects that have been termed as *circular economies*[1]. Among the gains claimed to be associated with material re-purification and re-manufacturing the most appealing dividends that call to the attention of local and regional authorities - especially in the European Union, China and Japan - include job creation, economic growth, increased competitiveness, reduced dependence on foreign raw material, pollution control and environmental sustainability (e.g. European Commission 2015; State Council of the People's Republic of China, 2013). From an academic and non-academic perspective, the discussion on circular economies and their expected impacts has been relatively rich and controversial, ranging from concepts and definitions (e.g. EMF 2015a, 2015b; Hollander et al., 2017; Blomsma and Brennan, 2017), metrics (e.g. EMF, 2015c.; Liender et. al., 2017; Tisserant et al., 2017; Haupt et al., 2017; Lebre et al., 2017) to more critical postures (e.g. Fellner et al.,

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[1]Moreau (2017) cites EMF's definition of the circular economy: "A circular economy is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times. The concept (....) is a continuous positive development cycle that preserves and enhances natural capital, optimizes resource yields, and minimizes system risks by managing finite stocks and renewable flows. It works effectively at every scale".

2017; Zinc and Geyer, 2017; Richa and Gaustad, 2017). Despite this *momentum*, the environmental and resource economics literature has shed limited) light on the topic, a formal input that is expected to play an important role in the comprehension of key circular mechanisms strongly determined by market forces (Liender et al., 2017).
With the objective of contributing to a better understanding of the economics of circular economies, we derive conditions on an economy's fundamentals in a fully integrated environment that explain *why* small open economies lacking of direct ownership of raw material rationally activate or deactivate the main recycling loops of the circular economy, that is re-purification and re-manufacturing. Throughout this document we understand *small open* as the condition in which the local open economy cannot affect neither the global consumption (depletion rate) of raw material nor the relative international price at which it is traded and where spatial heterogeneity plays no tangible role in the characterization of major externalities. We focus on the particular class of economies that experience an inevitable shortage of landfill capacity, toxic and potentially lethal pollution released from economic activity and endogenous population growth. In order to connect our investigation with ongoing research in circular economies, we assume that technologies - including capital accumulation - are constrained by material balance restrictions, the impossibility of dematerialization, thermodynamic efficiency and entropic costs. Our model provides an explanation as to why small open economies behave in a linear (no input coming from recycling), fully circular (all material inputs come from recycled material) or mixed linear-circular manner. As an interesting result, we formally show that the circular economy is typically not consistent with the so called hierarchy of waste management, confirming non-mathematical insights of authors as Richa and Gaustad (2017). Finally, we proceed to optimally price the circular economy, illustrating the basic type of information that would be required in order to restore optimality for the circular economy market in the presence of typical externalities associated to it.

Although, to the best of our knowledge, the economics literature has not formally tackled the circular economy model in its full dimension, our model fits in the general equilibrium dynamic recycling literature, whose seminal works were provided by Plourde (1972) and Smith (1972). Plourde (1972) introduced the problem of control of pollution by transforming hazardous waste into a nonhazardous component. Smith (1972), building on Plourde (1972), allowed for the reintroduction of waste into the consumption chain under material balance restrictions, introducing a more familiar form of material reuse into the modelling. A rich exposition of mathematical methods for the classic study of the economics of dynamic recycling is exposed in Smith (1977). In the same spirit, Lusky (1975, 1975b, 1976) and Hoel (1978) study the introduction of material scarcity and its role in optimal re-purification and re-manufacturing, emphasizing the effect of material depletion costs and environmental services on consumer's welfare. Stylized recycling dynamic models have been enriched with land-filling costs (Dinan, 1993; Huntala 1999) and renewable resources (Huntala, 1999). A second wave of recycling dynamic models treats the introduction of capital accumulation, relaxing short-term substitution of material and energy considered in the previous literature. Introduction of physical capital and growth in dynamic recycling is initially explored by DiVita (2001), although violating material balance re-

strictions. Pittel et al. (2010) and Akao and Managi (2007) reconsider DiVita's setup, restricting capital formation explicitly introducing linear material balancing, although assuming extreme (asymptotic) substitution between capital and energy and without considering the environmental dimension. The lack of thermodynamic considerations in the recycling growth literature is reported by Fagnart and Germain (2011).
Building on this literature, we contribute to the economics of recycling in two directions. First, we formally introduce the study of small open circular economies in a dynamic set-up by developing a fully integrated model capable of analyzing circularities in the presence of environmental, technological and material constraints keeping full thermodynamic consistency and therefore allowing for realistic tracking of materials. Second, we show how, under absence of asymptotic de-materialization, (nested) Leontief technologies offer a natural, flexible and tractable way of studying circular phenomena for both long and very short run scenarios, overcoming the lack of steady state introduced in presence of entropic costs.

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