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NATURAL RESOURCES AND ECONOMIC GROWTH
THE CIRCULAR ECONOMY CONTRIBUTION

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To Tübingen.

Because it and its inhabitants inspired the idea of this thesis.

Because of what I learned in this University.

Because here I understood more about the world.

Because here I understood much more about myself.

Because of the people I met here and the ones who shared this experience with me, in all of its aspects.

Auf Wiedersehen.

ABSTRACT

The main aim of this work is to link the concept of Circular Economy to the context of Economic Growth formal modeling. In particular, the recycling process and the material balance principle, two fundamental and concrete aspects of the circular economies, are introduced in a neoclassical framework model for which exhaustible natural resources are essential for the production. The outcomes in terms of level of output, of consumption, and of prices for production's material inputs are distorted with respect to the optimum, when certain market failures arise or complete recycling is not possible for technical reasons. Consequently, the introduction of a market for waste and of a system of subsidies/taxes on virgin and recycled resources compensates the externalities due to the market failures. The importance of technological progress, both to improve resources efficiency of the production process and to enhance the reflux of materials from waste to production, is highlighted.

L' obiettivo principale di questo lavoro è di collegare il concetto di Economia Circolare ai modelli teorici di crescita economica. L'economia circolare si propone come alternativa agli attuali sistemi economici, basati su flussi lineari di risorse naturali: dall'ambiente, alla produzione, al consumo, all'ambiente nuovamente, ma in forma di rifiuto. In particolare, il processo di riciclaggio e il principio di bilancia materiale, due aspetti fondamentali e concreti dell'economia circolare, sono introdotti in un modello di tipo neoclassico, nel quale le risorse naturali esauribili sono un fattore di produzione essenziale. I risultati in termini di livello di produzione, di consumo e di prezzi per i fattori di produzione materiali (cioè risorse vergini o riciclate) sono distorti rispetto a quelli ottimali, quando sono presenti alcuni fallimenti del mercato o il riciclaggio completo non è possibile per ragioni tecniche. Di conseguenza, l'introduzione di un mercato per i rifiuti e di un sistema di sussidi/tasse sulle risorse riciclate e vergini compensa le esternalità dovute ai fallimenti del mercato. Inoltre, viene sottolineata l'importanza del progresso tecnico, non solo per rendere il processo di produzione più efficiente in termini di uso di risorse, ma anche per l'introduzione di innovazioni in grado di rendere sempre più circolare il flusso di risorse.

Economics:

from Ancient Greek οἶκος (oîkos, “house”) and νέμω (némō, “manage”)

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LIST OF SYMBOLS AND ABBREVIATIONS

p_R	Price of recycled resources
p_V	Price of virgin resources
ψ_1	Capital shadow price
ψ_2	Virgin resources shadow price
ψ_3	Recycled resources shadow price
A	Technological progress parameter
C	Aggregate consumption
D	Household wealth, stock of government bonds
E	Renewable resources input
$F(.)$	Production technology
J	Capital – resource ratio
K	Capital input
L	Labor input
R	Recycled resources input
S	Stock of non-renewable resources
$U(.)$	Utility function
V	Virgin natural resources input
W	Stock of recyclable waste
Y	Aggregate output
r	Net interest rate

$\alpha, \beta, \varepsilon, \gamma$	Marginal output elasticity of capital, virgin resources, renewable resources, recycled resources.
θ	Elasticity of substitution between inputs
ρ	Utility discount rate
σ	Parameter for elasticity of marginal utility
x	Material loss, i.e. share of materials which cannot be recycled after consumption for technical reasons

RER	Rental element of consumption
RVC	Potential marginal recycling value as a byproduct of consumption
RVP	Potential marginal recycling value of inputs in production

MATHEMATICAL NOTATION:

- First-order derivatives (of variable X w.r.t. Z):

$$\frac{dX}{dZ} = \frac{\partial X}{\partial Z} = X'(Z) = X_Z$$

- Second-order derivatives:

$$\frac{\partial^2 X}{\partial Z} = X''(Z)$$

- Time variations:

$$\frac{dX}{dt} = \frac{dX_t}{dt} = \dot{X}$$

- Growth rates:

$$\frac{\dot{X}}{X} = g_X$$

CHAPTER 1: INTRODUCTION

The sustainability of current economic systems is threatened by two facts of environmental character: the exhaustibility of the natural resources, which are essential for our production processes, and the limited capacity of nature to absorb the wastes of human activities.

Starting with Malthus and Ricardo debate in the nineteenth century and Hotelling 1931 fundamental paper, economic literature considered constraints to growth imposed by the scarcity of natural resources. The long-run forecasts for the survival and prosperity of economies are either catastrophic or optimistic. In this last case, they are usually based on solutions to the sustainability issue which do not make it necessary to reframe the linear fashion characterizing current economic flows.

On the other side, Environmental Economics research focused on the limits to growth arising from limited ability of nature to act as a sink for human wastes.

In particular this work is focused on solid waste.
Waste, defined by European Commission's Waste Framework Directive of 2008 as any substance or object which the holder discards or intends to discard, potentially represents an enormous loss of resources in the form of both materials and energy.
Today, it represents a problem for local administrations in terms of treatment costs and in terms of volumes to be managed. The more consumption levels has grown, the more the amount of waste generated has increased. According to Eurostat data for the European Union aggregate, the total quantity of waste generated in 2014 reached 2 503 million tons: almost 5 tons per capita. In the last twenty years, the mass of municipal waste generated grew by eight per cent.

Furthermore waste represents a threat for the environment, per se or because of byproducts of its treatment. In particular waste landfill or incineration generate substances, or transform waste in substances, which are dangerous to human health or to the natural environment.

Economies are nowadays characterized by linear economic, material and energetic flows: resources are extracted from the environment, employed in the production sector or in the energy one, consumed and eventually discarded. Such a linear model inevitably encounters limits.

In 2012, in the European Union 5 billion tones of materials were consumed, 80% of which coming from virgin resources and only 20% coming from secondary raw materials (European Parliament 2017, p.16).

A theoretical answer to both mentioned problems is constituted by the circular economy concept. The ultimate aim of circular economy is to minimize virgin resources extraction and to limit human activities byproducts, maximizing material and energy efficiency of economic processes. Within a circular economy context, material resources are employed again in production after their first use. The fundamental idea is to move from the perception of waste as a problem to the perception of waste as a valuable input. The advantage would be twofold:

- Possibility to substitute a semi-renewable secondary raw materials flow to the virgin one, alleviating the scarcity of exhaustible resources.
- Possibility to reduce environmental burden generated by human consumption and production processes, since waste accumulation would not represent an optimal use of resources.

The circular economy concept found in the literature is quite ideal, as it will be shown. Thus, in this work I will only consider the effects of the introduction of two concrete aspects of it, recycling and the material balance principle, in an economic model formerly relying on exhaustible resources (and capital) inputs only. The material balance principle states that all the materials employed in production flow into a “waste pile” after consumption; in this way, it ensures that the natural system is closed and that the evolution of the stock of waste accumulating in the environment must be taken into account when seeking to maximize the welfare of the economy. On the other side, recycling allows a circular flux of materials from the waste pile to production again.

The major part of the research on economic growth and resources scarcity does not distinguish between use of exhaustible virgin resources and recycled ones, however a literature discussing the effects of recycling on sustainability also exists. This literature can be roughly divided in two branches: the first one considers recycling as a way to extend availability of non-renewable resources; the second one introduces recycling in the analysis of pollution abatement activities, i.e. the alleviation of waste disposal problems. Only recently waste production and/or reuse has been considered from a formal macroeconomic point of view.

Pittel et al. 2010, for example, consider man-made capital, virgin and recycled resources as input factors in a neoclassical growth framework. Complete circulation of matter, via a material balance constraint, is imposed. Indeed, material inputs are either bound in physical capital stock or recycled after consumption. Complete recycling is considered in this study and technological progress is exogenous. Pittel et al. 2005 modifies the former model adding endogenous growth features à la Romer 1990 and adding a human capital sector like in Lucas 1988. Both papers provide formal solutions to achieve long-run sustainability.

Di Vita 2001 present a model in which exhaustible natural resource, recyclable and non-recyclable waste are taken into account. The first type of waste is used to produce secondary raw materials and its degree of recyclability is an increasing function of R&D activity. The second kind of waste is discharged into the environment. Circulation of matter is also considered in this paper. One of the main findings is that the policy maker is able to increase economy growth rate by promoting research activities. Di Vita 2002 extends the results introducing renewable resources; a tax and a subsidy on natural resources and on recycled materials respectively are also introduced. Finally, Di Vita 2007 considers the case in which virgin resources and reused ones are not perfect substitutes.

Lafforgue, Rouge 2017 consider an endogenous growth model where the use of a non-renewable resource generates waste which can be recycled. The recycling activity can start only after the quality of the secondary raw material has reached a minimum threshold and, therefore, investment in a specific R&D sector is required to improve recycled materials quality.

Nevertheless none of this introduces the concept of circular economy. Although this concept was developed already a few decades ago, it only became popular in the last years, also promoted by the European Union, by several national governments and businesses. However, the research content of this concept is currently superficial and constituted by separate ideas from several fields.

I chose the model presented in Pittel et al. 2010 as a workhorse model because it is suitable to explain the circular economy idea. The main aim of this work is to link this concept to the context of Economic Growth formal modeling and to verify if this can be a way to achieve sustainable development. More specifically, I will try: to investigate if a growth model with neoclassical characteristics in which the traditional linear extraction-production-consumption-dump flow of materials is replaced by a (more or less) circular one can reach sustainable long run growth, and, secondly, to examine the level of economic activity and the implications for resources use. The

effects of two realistic market failures will also be taken into account, leading to a decentralized solution of the model which differs from the socially optimal one.
The main deviation from the workhorse model is represented by the introduction of incomplete recycling due to technical reasons, in order to abandon the idealistic assumption of complete recycling.

To complete this work, the conclusions that ensue from the theoretical model are compared to actual data and policies carried out by the European Union in order to support the implementation of circular economies.

The work proceeds as follow. In Chapter 2 the issue of depletion of natural resources will be analyzed from a theoretical point of view and the formal solutions to it, presented within the neoclassical framework, are summarized. In Chapter 3, after introducing the concept of circular economy, a neoclassical framework model characterized by the mentioned circular economy features is presented; the consequences of incomplete recycling and of certain market failures are analyzed by comparing the socially optimal (section 3.2) and the market solution of the model (section 3.3); eventually some policy implications conclusions are drawn (section 3.4). Chapter 4 differs from the others, since an empirical approach is adopted; the analysis follows three steps: first, the positive correlation between recycling level, a proxy for economy circularity, and income level is checked by exploiting econometric techniques (section 4.1); secondly (section 4.2), the efficiency and the environmental sustainability of the waste management system at a European level are analyzed and the European Union policies to support circular economy are also examined; at last (section 4.3), the current level of circularity of the European Union economies is inspected and some critical considerations on the effectiveness of the contribution of recycling for sustainability are drawn. To conclude, Chapter 5 summarizes the main findings of the thesis and reports some personal remarks.

My personal contributions to the existing literature consist mainly in: linking the (sometimes abstract) concept of circular economy to theoretical Economic Growth models; providing a modification to the model presented in Pittel et al. 2010, in order to make its assumptions more realistic and to formally show the effects of the impossibility of complete recycling due to technical reasons; investigating empirically some of the model findings, comparing its policy implications to actual EU policies to support the transition from linear to circular economic systems, and examining the features of European countries' waste management systems.

CHAPTER 2: THE PROBLEM OF NATURAL SCARCE RESOURCES

During the nineteenth century Thomas Robert Malthus and David Ricardo were among the firsts to consider the possible effects of resources scarcity on the economic system and on standards of living. In their views exhaustible natural resources are responsible of diminishing marginal returns of capital and labor inputs and thus their scarcity leads to long run economic stagnation. A non-renewable resource is a natural resource the amount of which on earth is finite and which has no natural regeneration, at least in a relevant time scale (Groth 2007). These two classical economists had primarily land in mind, but, with the Industrial Revolutions and with production processes getting always more technological, other non-renewable resources became increasingly primary.

Since the 1970s, under growing concerns for depletion and pollution of the environment due to human activities, attention was devoted to the question whether it is possible and appropriate to continue present patterns of economic growth. That was the decade of the first two oil crises, which turned on the interest in research on natural resources.
In 1972 the "Limits to growth" report for the Club of Rome depicted a "sudden and uncontrollable decline in both population and industrial capacity" when no "conditions for ecological and economic stability that is sustainable far into the future" are put in place (Meadows et al. 1972). This report exploited data for the period 1900-1970 to develop a model to forecast the evolution of certain measures and variables on the period 1970-2100. This is summarized in Figure 1. The depletion of natural resources in few decades would have lead to production collapse, pushing humanity in a Malthusian trap.

Formal macroeconomic modeling considering non-renewable resources lead off with Solow's, Stiglitz's, Dasgupta and Heal's contributions, published in a symposium issues of Review of Economic Studies in 1974.

I summarize now the most important insights coming from this symposium in a single model, despite the authors had partly different approaches or focused on partly different aspects of the non-renewable resources issue. This "Dasgupta-Heal-Solow-Stiglitz" (D-H-S-S) model will represent our pessimistic benchmark as for its conclusions and it will serve as a workhorse model late on.

The final section of this chapter is devoted to the formal mechanisms indicated within the neoclassical framework to achieve long-run sustainability of economies.

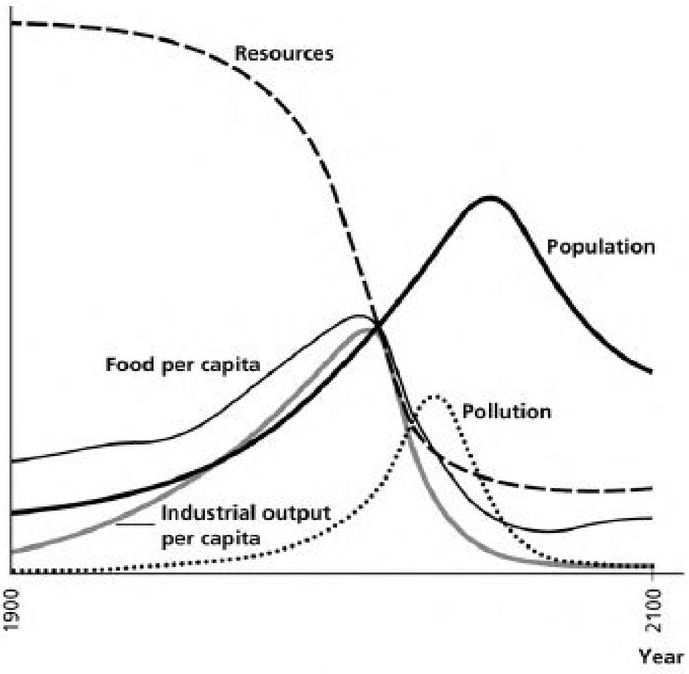

Fig. 1 Growth forecasts from “Limits to growth”. Source: Meadows et al., 1972.

2.1 THE PESSIMISTIC BENCHMARK: “DASGUPTA-HEAL-SOLOW-STIGLITZ” MODEL

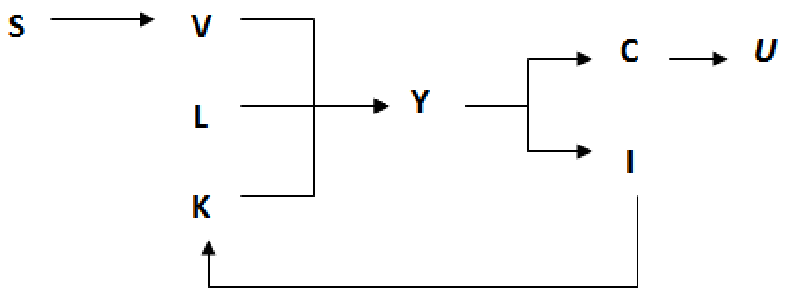

Fig. 2 Stylized economic flows in D-H-S-S model. Own illustration.

- STRUCTURE OF THE MODEL

The D-H-S-S model is characterized by linear material and economic flows.

Aggregate output Y is produced employing capital K, labor L and exhaustible, virgin natural resources V. The public sector is neglected as well as renewable natural resources.

$$Y_t = F(K_t, L_t, V_t) \tag{1}$$

This production function has typical neoclassical features[1]: constant returns to scale; positive, but decreasing marginal returns for all inputs; satisfies the Inada conditions.

Man-made capital accumulates according to:

$$\dot{K}_t = Y_t - C_t - \delta K_t \tag{2}$$

where, in general, $\dot{X}$ represents the variation of variable X in time dX/dt (as in the rest of the paper), C_t represents aggregate consumption at time t, $\delta \geq 0$ represents capital depreciation rate. The difference $Y_t - C_t$ represents gross investment, as a closed economy is considered.

The flow of virgin, natural resources V_t employed in production is extracted at each t from a given stock of non-renewing resources S:

$$\dot{S}_t = -V_t \tag{3}$$

Since it must be that $S_t \geq 0$ for all t, there is a finite upper bound on cumulative resources extraction:

$$\int_0^\infty V_t \, dt \leq S_0 \, .$$

Costs of extraction of the natural resource are neglected.

Aggregate output is allocated either on consumption, determining household's well-being, or on investment, contributing to capital accumulation.

Also note that the production and consumption processes do not generate any form of pollution or byproducts: environmental consequences of this processes are not considered. Furthermore material flows are accounted only in input/output/consumption units terms and not in mass terms.

The household derives utility from consumption solely. The household's future utility depends on every descendant's utility. The utility function $U(C_t)$ exhibits positive but diminishing marginal returns[2]. Finally, future consumption contributes always less to the household's welfare the more it is far in time; future utility is discounted at rate $\rho > 0$.

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[1] Formally, for a generic production function having X_i inputs: $F(bX_i) = bF(X_i)$ for constant returns to scale; $\partial F(X_i)/\partial X_i > 0$, $\partial^2 F(X_i)/\partial X_i < 0$ for monotonically increasing and concave production function; $\lim_{X_i \to 0} \partial F(X_i)/\partial X_i = \infty$ and $\lim_{X_i \to \infty} \partial F(X_i)/\partial X_i = 0$ to satisfy Inada conditions.

[2] Formally: $U'(C_t) > 0$, $U''(C_t) < 0$.

- THE STARVATION OF MANKIND

In order to obtain the greatest possible social welfare, the present value of utility is maximized subject to the evolution of man-made capital stock $\dot{K}_t$ and the constraints imposed by the finiteness of the resource stock $\dot{S}_t$ and to boundaries and non-negativity constraints for capital and resource stock[3]:

$$\max\ (C,V)\int_0^\infty e^{-\rho t}U(C_t)dt \qquad \text{s.t. } (2),(3)$$

To solve the problem, the dynamic optimization technique is exploited. Setting up the present value Hamiltonian (where ψ_1 and ψ_2 represent capital and exhaustible resources shadow prices respectively):

$$\mathrm{H} = e^{-\rho t}U(C_t) + \ \psi_1\left[\dot{K}_t\right] + \psi_2\left[\dot{S}_t\right], \tag{4}$$

taking first order conditions (derivation in Appendix A) and combining them it is possible to derive a Keynes-Ramsey rule and a Hotelling rule.

The Keynes-Ramsey rule, giving the optimality condition for consumption growth rate, is :

$$\dot{C} = -(F_K - \rho)\frac{U'(C)}{U''(C)} \tag{5}$$

It states that Household's optimal consumption path depends on capital marginal productivity F_K (please note that F_X denotes the first-order derivative of the production function with respect to input X), on the discount rate and, of course, on utility function specification.

The Hotelling rule is:

$$\frac{\dot{F}_V}{F_V} = F_K - \delta \tag{6}$$

It describes the optimal natural resource extraction path. Resource owners when choosing not to extract it from the environment are effectively transferring wealth to the future, while the alternative option would be investing in the capital market (note marginal productivity of capital minus its depreciation gives net return on capital): in the equilibrium both options must be

---

[3] $K_0 = K(0),\ K(t) \geq 0;\ S_0 = S(0),\ S(t) \geq 0.$

equivalent and natural resources bound in the environment must yield the net capital market return (Pfeiffer 2017, p.9).

Some specifications for the model assumptions can be adopted in order to draw further conclusions. I adopt the same specifications as in Merz 2017.
Consider a Cobb-Douglas specification for the production function and assume $L = 1$ and constant:

$$Y_t = F(K_t, L_t, V_t) = K^{\alpha} V^{1-\alpha} \qquad 0 < \alpha < 1 \,.$$

Assume capital rate of decay is negligible: $\delta = 0$.
Adopt constant inter-temporal elasticity of substitution (CIES) specification for the utility function[4]:

$$U(C) = \frac{C^{1-\sigma} - 1}{1 - \sigma} \qquad \sigma > 0, \sigma \neq 1$$

For this type of utility function the inter-temporal elasticity of substitution is a constant equal to $1/\sigma$; the parameter σ measures the elasticity of marginal utility with respect to consumption: it increases with household's willingness to avoid consumption fluctuations.

It's straightforward that the Keynes-Ramsey rule (5) can be rewritten as:

$$\sigma\, g_C = (F_K - \rho) \tag{7}$$

where g_C denotes consumption growth rate (in the following $g_X = \dot{X}/X$ stands for variable X growth rate).

The Cobb-Douglas production function is homogeneous of degree one, so it is possible to write, defining capital–resource ratio as $J \equiv K/V$:

$$F(K, V) = K^{\alpha} V^{1-\alpha} = J^{\alpha} V$$

Consequently:

$$F_K = \alpha\, J^{\alpha-1}\, V \frac{1}{V} = \alpha\, J^{1-\alpha}$$

$$F_V = J^{\alpha} + \alpha\, J^{1-\alpha} \left(-\tfrac{K}{V}\right) V = (1 - \alpha)\, J^{\alpha}$$

Inserting these in the Hotelling rule (6), it can be written in this way:

---

[4] In case $\sigma = 1$ the CIES utility function assumes the logarithmic form. This specific calibration is adopted in Merz 2017, but I deviate from this in order to deal with the more general case of a non-fixed elasticity parameter.

$$\frac{(1-\alpha)\,\alpha\,J^{\alpha-1}\,\dot{J}}{(1-\alpha)\,J^{\alpha}} = \mathrm{\alpha}\,J^{\alpha-1} \rightarrow \dot{J} = J^{\alpha} \tag{8}$$

Equation (8) is a non-linear Bernoulli differential equation having solution:

$$J(t) = (J_0^{1-\alpha} + (1-\alpha)t)^{\left(\frac{1}{1-\alpha}\right)} \tag{9}$$

Rearranging the Hotelling rule and inserting this result, one can derive the growth rate of the capital–resource ratio:

$$\frac{\dot{J}}{J} = J^{-(1-\alpha)}$$

$$\frac{\dot{J}}{J} = (J_0^{1-\alpha} + (1-\alpha)t)^{\left(\frac{1}{1-\alpha}\right)(\alpha-1)} = (J_0^{1-\alpha} + (1-\alpha)t)^{-1}$$

This leads to a very Ricardian conclusion. Indeed, since $0 < \alpha < 1$ and $J_0 > 0$, the capital–resource ratio is monotonically increasing over time, because the man-made input is gradually substituted to the natural resource while this become scarce: $\dot{J}/J > 0$. This means that the marginal product of capital is decreasing over time.

Furthermore it can be shown that the growth rate of the capital–resource ratio is declining over time:

$$\frac{\partial(\dot{J}/J)}{\partial\, t} = \frac{\partial[1/(J_0^{1-\alpha} + (1-\alpha)t)]}{\partial\, t} = \frac{1}{[J_0^{1-\alpha} + (1-\alpha)t]^2}\,(1-\alpha) \quad < 0$$

This is due to the fact that the substitution of man-made input to the natural one becomes increasingly impossible.

Eventually it is possible to attest that consumption unambiguously converges to zero in the very long-run. Consider Keynes-Ramsey rule (7) and insert the expression for F_K and $\dot{J} = J^{\alpha}$:

$$\sigma\, g_C = \alpha\,\frac{\dot{J}}{J} - \rho$$

$$\sigma\,\frac{d\ln(C)}{d\,t} = \alpha\,\frac{d\ln(J)}{d\,t} - \rho$$

Integrating both sides of this equation from $t = 0$ to $t = t$:

$$\int_0^t \sigma \, \frac{d \ln(C)}{d\, t} \, d\, t = \int_0^t \left[\alpha \, \frac{d \ln(J)}{d\, t} - \rho\right] d\, t$$

$$\sigma[\ln(C_t) - \ln(C_0)] = \alpha[\ln(J_t) - \ln(J_0)] - \rho t$$

$$\frac{C_t^\sigma}{C_0^\sigma} = J_0^{-\alpha} \, (J_t)^{\alpha/(1-\alpha)} \, e^{-\rho t}$$

Inserting (9):

$$\frac{C_t^\sigma}{C_0^\sigma} = J_0^{-\alpha} \, (J_0^{1-\alpha} + (1-\alpha)t)^{\alpha/(1-\alpha)} \, e^{-\rho t}$$

$$C_t = \left[C_0^\sigma \, J_0^{-\alpha} (J_0^{1-\alpha} + (1-\alpha)t)^{\alpha/(1-\alpha)} \; e^{-\rho t}\right]^{\frac{1}{\sigma}}$$

Considering now $\lim_{t\to\infty} C_t$, one can see it converges to zero.

The dynamics predicted by this model for consumption, capital input and production levels are even more drastic than Meadows et al. 1972 ones: they all converge to zero in the very long run and depict a complete "starvation of mankind".

This ill-fated result is due to a positive time preference rate for consumption, $\rho > 0$ - which is absolutely realistic -, to a constant efficiency of the production process, to the fact that the natural resource does not regenerate at all and to the fact that this is essential for production.

2.2 SOLUTIONS TO THE STARVATION OF MANKIND WITHIN THE NEOCLASSICAL FRAMEWORK

The aim of Dasgupta, Heal, Solow and Stiglitz was also to investigate the ways to avoid the starvation of mankind in spite of the inevitable decline in resources use. Following Groth 2007, three main mechanisms are illustrated in the neoclassical framework.

- SUBSTITUTABILITY

In this case man-made inputs or renewable resources are gradually substituted to the exhausting, non-renewable one.

Consider the general case of a constant elasticity of substitution production function (CES):

$$Y = \left(\alpha K^\phi + \beta L^\phi + \varepsilon E^\phi + \gamma V^\phi\right)^{\frac{1}{\phi}}; \;\; \alpha, \beta, \varepsilon, \gamma \geq 0; \;\; \alpha + \beta + \varepsilon + \gamma = 1; \; \phi < 1; \; \phi \neq 0 \quad (10)$$

where K, L, V input factors are defined as before, E denotes renewable natural resources and ϕ is the parameter which determines the elasticity of substitution.

Whether increasing employment of alternative inputs is enough to avoid production collapse depends critically on the degree of substitutability between non-renewable resource and other inputs.

The elasticity of substitution between any two production inputs, here represented by variables X and Z, is defined as:

$$\theta \ \in [0, \infty] = \frac{d(X/Z)}{(X/Z)} * \frac{(Y_Z/Y_X\ )}{d(Y_Z/Y_X)}$$

It expresses the percentage increase of the X/Z ratio that a cost-minimizing firm will adopt in response to a one per cent rise in the factors' price ratio Y_Z/Y_X . In the case of the CES production function this elasticity is a constant: $\theta = 1/(1-\phi)$.

Three cases can show up.
First, when $\theta > 1$ (i.e. $0 < \phi < 1$), then:

$$\lim_{V\to 0} Y = \left(\alpha K^{\phi} + \beta L^{\phi} + \varepsilon E^{\phi}\right)^{\frac{1}{\phi}} \ > 0$$

Here non-renewable resources are not essential: they are not necessary for a positive output.
This implies that firms would simply turn to other inputs the more exhaustible resources get scarce and their price rises. This would happen automatically and only depends on optimizing behavior of firms.
Note that this solution is in many cases unrealistic, or at least not automatic, as switching to different inputs implies the use of different technologies and production processes.

Second, when $\theta < 1$ (i.e. $\phi < 0$), then:

$$\lim_{V\to 0}\ \frac{Y}{V} V = \left(\alpha\left(\frac{K}{V}\right)^{\phi} + \beta\left(\frac{L}{V}\right)^{\varphi} + \varepsilon\left(\frac{E}{V}\right)^{\phi} + \gamma\left(\frac{V}{V}\right)^{\phi}\right)^{\frac{1}{\phi}} V = \gamma^{\frac{1}{\phi}} V = 0$$

For $\phi < 0$, inputs are essential and output approaches zero when the finite natural resource is exhausted.

Third, when $\theta = 1$ (i.e. $\phi = 0$), although equation (10) is not defined, it can be shown (Arrow et al. 1961, p. 231) that:

$$\lim_{\psi\to 0} Y = \left(\alpha K^{\phi} + \beta L^{\phi} + \varepsilon E^{\phi} + \gamma V^{\phi}\right)^{\frac{1}{\phi}} \to \left(K^{\alpha}\, L^{\beta}\, E^{\varepsilon}\, V^{\gamma}\right)$$

implying:

$$\lim_{R \to 0} \left(K^{\alpha} L^{\beta} E^{\varepsilon} R^{\gamma}\right) \to 0$$

This case corresponds to the Cobb-Douglas one. Interestingly, although non-renewable resources are an essential input, output-resources ratio is not bound from above, i.e. $\lim_{R \to 0} Y/_R = \infty$. A debate around the question whether in this framework non-decreasing per capita consumption can be sustained arose (see Solow 1974; Hartwick 1977; Perman et al. 2003, Chapter 14).

In many circumstances the poor substitutability case ($\theta > 1$) is the most realistic, consequently technological progress is considered as alternative for economic sustainability.

- TECHNOLOGICAL PROGRESS

The following CES production function

$$Y = \left(\alpha K^{\phi} + \beta L^{\phi} + \varepsilon E^{\phi} + \gamma (A\, V)^{\phi}\right)^{\frac{1}{\phi}}$$

is characterized by a resource-saving technological parameter, $A = e^{\lambda\, t}$, exogenously increasing at rate λ.

If technological progress compensates natural resources exhaustion, i.e. if λ is higher than the rate of decline of the non-renewable resources, then the “effective” resource input is no longer diminishing over time. Consequently, even in the poor substitution case, the scarcity of natural resources is overcome, at least from a formal point of view as analyzed by Solow 1974 and Stiglitz 1974. Note that here, in a typical neoclassical way, technological progress occurs exogenously in the economy, falling like “manna from heaven”.

A particular form of technological progress is the “backstop technology”. This is defined as a new technology producing a close substitute to an exhaustible resource by using relatively abundant alternative production inputs and rendering the reserves of the scarce natural resource obsolete when the average cost of production of the close substitute falls below the spot price of the exhaustible resource (Dasgupta, Heal 1979). For instance, the technology of harnessing solar energy can be considered a backstop technology to fossil resources. In the case of a backstop technology, the existence of a technology allowing the economy to switch to alternative input factors is assumed and no investments in research are needed. Production decisions are reduced to a mere comparison of inputs costs. The only uncertain point is the time when the switch will occur rendering the consumption path economically, and maybe environmentally, sustainable.

Once again, the fact that a backstop technology is available, without any investment and research process, is not observed in reality for many exhaustible resources. Actually technological progress does not proceed smoothly and higher investment levels enhance the probability of a technological breakthrough. The aim of the innovation-based models in endogenous growth theory is to explain how technological change comes about and how it shapes economic growth. Technological progress is seen as determined by purposeful decisions by firms in search for monopoly profits on innovations.

A second class of endogenous growth models is identified by accumulation-based models, attempting to integrate human capital, defined in various ways, and/or public sector in the economy.

In general the term “endogenous growth” refers to models where sustained positive growth in output per capita is driven by some internal mechanism, in contrast to exogenous technological progress (Groth 2007, page 129).

This approach, also known as new growth theory, started being utilized only from the late 1980s.

- INCREASING RETURN TO SCALE

Increasing returns to scale may help overcoming finiteness of resources. This is not the case for a CES production function with poor substitutability between inputs, but with a Cobb-Douglas specification, in which the sum of output elasticity of inputs is higher than unity, positive growth of consumption per capita may be possible (see Stiglitz 1974).

CHAPTER 3: A NEOCLASSICAL FRAMEWORK MODEL WITH SOME CIRCULAR ECONOMY FEATURES

In our pessimistic benchmark economic growth is limited by the finite amount of natural resources.

Exhaustible resources problem is not the only threat to development and long run sustainability of present living standards. Indeed, the more economies became industrial intensive and consumption levels grew, it became always clearer that the flows of wastes generated by human activities cannot be absorbed by nature. The consequences of these flows are climate change, which will surely, seriously affect everyday life of a consistent share of population all over the world in the next decades, and the depletion of environmental quality, accounting for a loss of amenity and sometimes even representing a danger for human health.

All world economies are nowadays characterized by linear economic, material and energetic flows: resources are extracted from the natural environment, employed in production sector or in the energy one, consumed and eventually discarded; their life-cycle is usually single, i.e. a second life-cycle is most of the times excluded. This linear extraction-production-consumption-dump scheme is unsustainable.

Sustainable development was originally defined in the famous Bruntland report as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

The most logical alternative to the linear fashion of the material and energetic flow characterizing current economies seems being its reverse: a circular fashion. This is one of the fundamental ideas of the circular economy concept. According to Korhonen (2017, p.39), circular economy can be defined as:

> an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical material flows, renewable energy sources and cascading-type energy flows. Successful circular economy contributes to all the three dimensions of sustainable development, namely social, environmental and economic dimension. Circular economy limits the throughput flow

to a level that nature tolerates and utilizes ecosystem cycles in economic cycles by respecting their natural reproduction rates.

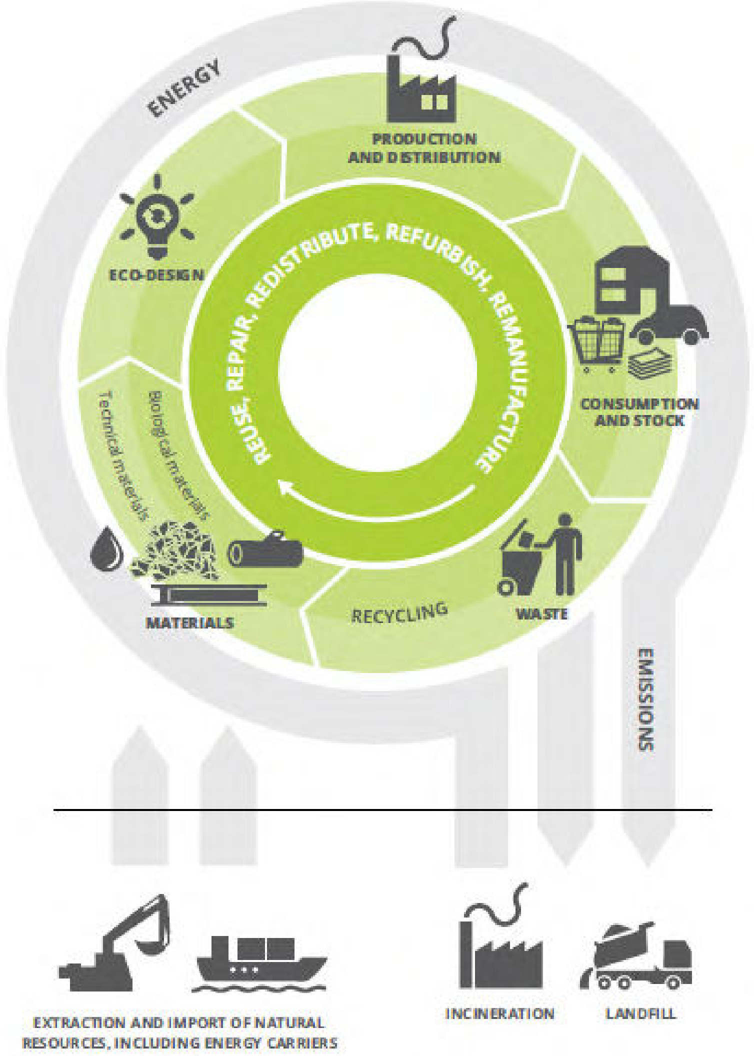

Fig. 3 A simplified model of the circular economy for materials and energy. Source: EEA 2017.

Figure 3 sketches the circular economy concept: design of consumption products in an ecologically-efficient way, extension of products life cycles, efficient use of energy flows and, eventually, recycling of raw materials are the devices to seek to achieve the aims of diminishing dependency on and extraction of resources from the natural system and minimizing emission of pollutants and other human activities' byproducts to the environment.

In circular economy concept nature is no longer seen as part of the economy, but the economy is a subsystem of nature. This unique system is closed: on the one side, exhaustible resources are given in a certain stock and renewable ones regenerate themselves at a natural rate which cannot be incremented while, on the other side, human activities' byproducts cannot flow out of the system, they are hardly absorbed by nature and they must be taken into account when seeking to maximize economic subsystem welfare in the long-run.

The circular economy concept, as defined above, looks quite idealistic given the features of current economic systems. Indeed, in this thesis, it will only represent the optimistic benchmark and I will consider in the following theoretical model just some of its most concrete specificities.

More specifically, to formally modify the linear flow of materials in our benchmark model, two modifications are introduced.

First, a recycling process is considered. In this way the materials are allowed to flow back from the "waste pile" where they end up after consumption to the production process. An economic framework in which a consistent share of material production inputs are supplied by a recycling sector, able to treat a large part of waste generated, would permit to switch from a perception of waste as a problem to one of waste as a valuable input. Recycling represents a tool to move towards sustainability both from an income and production point of view, extending the conservation of non-renewable resources, and from an environmental one. In fact recycling would reduce the amount of waste flowing into the environment, ending up in more pollutant treatment methods as landfilling or incineration.

Second, a material balance constraint is imposed: it states that matter can neither be created nor destroyed, but can only be transformed. This is the way to incorporate Lavoisier's law of conservation of mass into the settings of economic flows. The material balance principle constraints economic production possibilities, as all material resources extracted from nature are employed in production and eventually flow back to the environment as waste, after final products are consumed, and so it is needed to check the evolution of the waste stock. The material balance principle is present in Di Vita (2001), Di Vita (2002), Di Vita (2007), Lafforgue, Rouge (2017), Pittel et al. (2005), Pittel et al. (2010), in order to introduce sound material flows.

As said, this is a stylization of the circular economy concept: in the model that will follow virgin resources are still essential to production and I do not take into account renewable resources. In a strict interpretation of the circular economy conception, substitution of the latter to the former is necessary to achieve complete circularity of flows. Dealing with renewable resources also, and with considerations on the energy sector, would lead the work on a further and distinct field of analysis. Products' life extension is also an element of circular economy not modeled here.

The first objective of this extension of the D-H-S-S model is to verify if and under which conditions the features of a circular economy lead to sustainability, at least from a production/consumption point of view. Secondly, the consequences of a higher or lower recycling rate, i.e. more or less circular economy, and the effects of two realistic market failures are going to be investigated. This will make it possible to draw some policy implications conclusions (section 3.4).
Considerations on the possible benefits of circular economy on the environment will follow in the next chapter.

3.1 MODEL SET-UP

I consider a closed economy model which can be compared to the formerly presented Dasgupta-Heal-Solow-Stiglitz model as baseline. This model consists in a modification of the one presented in Pittel et al. 2010.

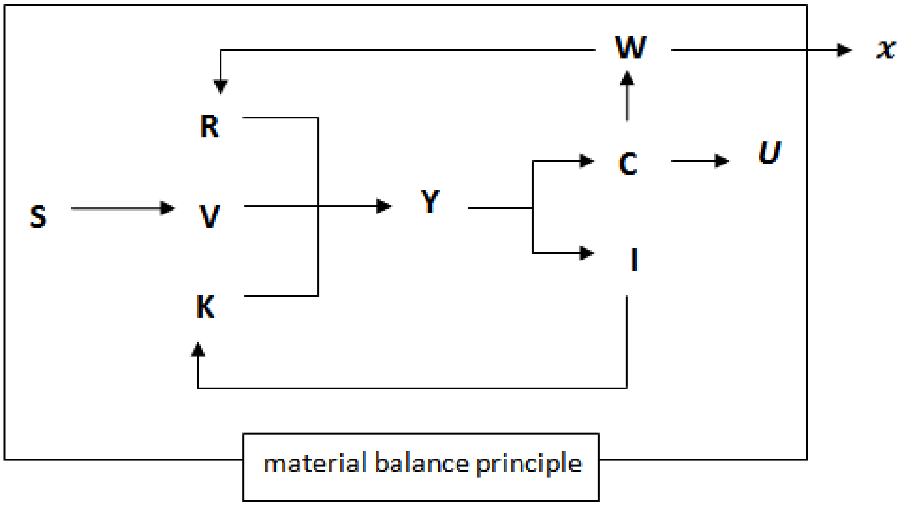

Fig. 4 Stylized economic and material flows for the model with circular economy features. Source: own illustration.

- HOUSEHOLD SECTOR

As in the D-H-S-S model, household derives utility only from consumption and she maximizes her discounted lifetime utility facing the wealth accumulation path $\dot{D}$:

$$\max(C)\int_0^\infty e^{-\rho t}U(C_t)dt \qquad s.t.\ \ \dot{D}=\frac{dD}{dt}=rD-C \tag{11}$$

where D denotes household wealth, represented by a stock of government bonds, yielding interest r. The price of the consumption good is normalized to one. Population is assumed to be constant and normalized to one.

Clearly the household is not compensated for the waste she produces. This represents a first market failure.

A constant inter-temporal elasticity of substitution (CIES) specification for the utility function is adopted:

$$U(C)=\frac{C^{1-\sigma}-1}{1-\sigma} \qquad \sigma>0,\sigma\neq 1;\ \ U'(C)>0,U''(C)<0 \tag{12}$$

- PRODUCTION SECTOR

Three kinds of firms are present. All of them operate in perfect competition in each sector.

The first two sectors are specialized in the production of material inputs, natural virgin resources and secondary raw materials respectively, and the third one deals with consumption good production.

INPUT SUPPLIERS: VIRGIN RESOURCES EXTRACTING FIRMS

Virgin resources suppliers seek to maximize their stream of profits subject to the usual constraint represented by finiteness and non-renewability of this kind of final good production input:

$$\max(V)\int_0^\infty p_V V e^{-\int_0^t r(v)dv}dt \qquad s.t.\ \ \dot{S}_t=-V_t \tag{13}$$

where V, S and r are defined as before and p_V represents virgin resources price.

Their cost of extraction from the environment is neglected.

INPUT SUPPLIERS: RECYCLING FIRMS

The recycling sector represents one of the features of circular economy which are added to the basic D-H-S-S scheme. Recycling firms extract raw materials from the goods that are discarded after consumption, at a null cost, and they supply them to final output producers without any further processing. Accordingly the profit maximization of these firms reads:

$$\max(R)\int_0^{\infty} p_R R e^{-\int_0^t r(v)dv} dt \quad s.t.\ \dot{W} = -R + W_C \tag{14}$$

where R represents recycled input and p_R its price. The constraint to the profits maximization is constituted by the evolution of the finite stock of waste $\dot{W}$, which is reduced by the flow of materials recycled R and regenerated by the exogenous flow of waste coming from consumption W_C. Note that this last, continuous flow makes recycled materials a semi-renewable input. This is a first representation of the material balance constraint, introduced in its entirety in the sector of final output production.

FINAL OUTPUT PRODUCERS

Final output production employs man-made capital K, virgin exhaustible natural resources V and secondary raw materials R. The production function is, once again, of the Cobb-Douglas type: all inputs are essential, but their marginal productivity is allowed to be different, and it is characterized by typical neoclassical features (see page 7).

$$Y = AK^{\alpha}V^{\beta}R^{\gamma} \qquad \alpha,\beta,\gamma > 0, \qquad \alpha+\beta+\gamma = 1 \tag{15}$$

Note that a double system of units is considered in this model: virgin and recycled inputs are measured in mass terms, while output, capital and consumption are measures in units terms.

With respect to our pessimistic benchmark model, production is enhanced by an efficiency-augmenting parameter A. Production efficiency depends on the technology level and it is increasing at an exogenous rate g_A:

$$\frac{\dot{A}}{A} = g_A$$

I decided not to deviate from the exogenous technological progress form as the aim of this model is not to explain or consider the possible sources of technological progress, introducing mechanisms for endogenous growth, but it is to check if the concrete features of circular economy introduced in the formerly presented neoclassical framework can be a tool to achieve sustainability. The effects of the introduction of these features is much clearer simplifying other mechanisms, even if exogenous technological progress is of course, in general, not a satisfying assumption when one seeks to develop the most complete possible model. Mine is simply another approach.

Final output can be allocated either on investment in man-made capital or on consumption.

Capital accumulation is determined by investment and its depreciation rate is null:

$$\dot{K}_t = Y_t - C_t \tag{16}$$

Note that this is not a flow in economic terms only, but it is also a material flow: material resources are employed in physical capital creation and, because this is not decaying, they are bound there forever.

Instead, when income is allocated on consumption it determines household's utility, but also generates waste as a byproduct. The evolution of the stock of waste is defined by the material balance condition.

Assume a stock of waste W_0 is present in the environment at t_0, because accumulated in past periods. The waste pile is increased in each period by the amount of materials used for final output production, consumed and discarded: V_t and R_t enter the production process in each period, so the share of materials in final output is $(V_t + R_t)/Y_t$; of these materials just the ones which are allocated on consumption are discarded into the waste stock. Production process is assumed not to generate any form of byproducts. The waste pile is instead reduced by the amount of materials picked up by recycling firms. Thus:

$$W_{t+1} = W_t - R_t + (V_t + R_t)\frac{C_t}{Y_t}$$

and in the continuous time version:

$$\dot{W} = -R + (V + R)c \qquad\qquad c \equiv C/Y$$

Note that c does not only represents the consumption share of output, but also the "reflux rate": the share of material inputs ending up into the waste pile.

Furthermore nature regeneration rate is null: waste cannot be absorbed by the environment.

In this framework the natural/economic system is completely closed. When the flow of waste coming from consumption is entirely recycled, complete circularity of material flows is achieved at least in the sense that, although virgin resources are still essential for production, waste does not accumulate and completely flows back to production.

In Ecological Economics literature a theoretical debate, based on thermodynamics laws, on the possibility of complete recycling arose (confront Georgescu-Roegen 1971 and Ayres 1999). But apart from theoretical speculations, it's very clear (confront Chapter 4) that the fashion of material/economic flows is currently linear on a global scale and, even in the most virtuous communities, complete recycling is not observed. For this reason I deviate from Pittel et al. 2010 model, in order to introduce incomplete recycling and move to a much more realistic assumption.

Consider a share x of resources cannot be recycled after consumption. This is due to technical reasons and not to consumers behavior. In practice this share x of materials flows out of the system after consumption and W can be interpreted now as the stock of recyclable waste. The material balance constraint is modified:

$$\dot{W} = -R + (V + R)c(1 - x) \tag{17}$$

Basically, after introducing mechanisms allowing for a completely circular flow of materials from the environment, through economic activities, and then back in a loop, this mechanism is partially broken allowing for a leakage of resources from the system. Because of this, I will make reference to the share x also with the expression "material loss"[5].

- MARKET FAILURES

The considered economy is characterized by two market failures.

First, with the introduction of secondary raw materials in production, waste becomes a valuable input. Consumers, who generate waste, should be able to sell it on a market where the demand is coming from recycling firms. If no market for waste exists, consumers are not compensated for the provision of secondary materials to production, as shown by household's budget constraint in (11). This situation is currently largely diffused.

Second, secondary raw materials suppliers and virgin materials suppliers do not take into account that a part of the inputs they provide to the final output producers will again be available through the reflux of materials after consumption. Obviously virgin resources suppliers do not consider a possible reuse of materials in their pricing decisions as they cannot make any profit from this; recycling firms do not internalize the effect of their activity on future availability of waste because they operate in perfect competition and the size of each firm is irrelevant.

Both of these market failures look realistic. In particular, examples of markets for waste are rare and except specific cases, like junk cars, households are not remunerated for their waste.

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[5] Because consumption is the only argument of household's utility function, the effect on household's welfare of this share of materials which are not recycled, and so represent a form of pollution, e.g. loss of amenity or danger for human health, are not taken into account in a formal way.

Consequently the market failures will lead to different conclusions when considering a decentralized solution of the model (section 3.3), compared to a social planner one (section 3.2).

3.2 SOCIALLY OPTIMAL ECONOMY

- OPTIMIZATION PROBLEM

First the optimal economy solution is derived. The social planner seeks to maximize household's inter-temporal utility (12), subject to the evolution paths of man-made capital (16), of virgin resources (3) and of waste stock (17). This optimization problem is summarized by the present value Hamiltonian[6]:

$$\mathrm{H} = U(C)e^{-\rho t} + \psi_1\dot{K} + \psi_2\dot{S} + \psi_3\dot{W}$$

where ψ_1, ψ_2 and ψ_3 represent capital, virgin and recycled resources shadow prices respectively.

The following first-order conditions can be derived:

$$\mathrm{H}_C:\ U'(C)e^{-\rho t} + \underbrace{\psi_3 m(1-x)}_{RVC} - \psi_1 = 0 \qquad m \equiv (V+R)/Y \tag{18}$$

$$\mathrm{H}_K:\ -\dot{\psi}_1 = \psi_1 F_K \quad \underbrace{-\psi_3 F_K m\, c(1-x)} \tag{19}$$

$$\mathrm{H}_V:\ \psi_2 \quad \underbrace{-\psi_3 c(1-x)} = \psi_1 F_V \quad \underbrace{-\psi_3 F_V m\, c(1-x)} \tag{20}$$

$$\mathrm{H}_R:\ \psi_3 \quad \underbrace{-\psi_3 c(1-x)}_{RER} = \psi_1 F_R \quad \underbrace{-\psi_3 F_R m\, c(1-x)}_{RVP} \tag{21}$$

$$\mathrm{H}_S:\ 0 = -\dot{\psi}_2 \tag{22}$$

$$\mathrm{H}_W:\ 0 = -\dot{\psi}_3 \tag{23}$$

These first order conditions can be evaluated further (Pittel et al. 2010, p.384) and compared to D-H-S-S model ones (compare to Appendix A).

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[6] Transversality conditions $\lim_{t\to\infty}\psi_1 K = 0$, $\lim_{t\to\infty}\psi_2 V = 0$ and $\lim_{t\to\infty}\psi_3 R = 0$ must also hold, together with boundaries and non-negativity conditions: $K_0 = K(0),\ K(t) \geq 0;\ S_0 = S(0),\ S(t) \geq 0;$ $W_0 = W(0),\ W(t) \geq 0.$

According to (22) and (23) it is optimal not only to exhaust virgin resources in the long-run, like in D-H-S-S model, but also recycled ones. This happens because the waste stock is source of valuable inputs under the circular economy features which have been introduced: not recycling part of waste and leaving it in the waste pile cannot be optimal when secondary raw materials are scarce and essential input to production.

The consumption-savings arbitrage condition (18) implies that the shadow price of capital, i.e. the value of one unit of output bound in the capital stock, must be equal to the sum of discounted marginal utility from consumption and the "potential marginal recycling value as a byproduct of consumption (RVC)", i.e. the value of the same unit of output when allocated on consumption. Comparing to our pessimistic benchmark model - see equation $(A.1)$ -, RVC is now taken into account because the reflux of materials after consumption increases the value of an output unit allocated on consumption.

In equations (20) and (21) the left hand side represents the net marginal opportunity cost of extracting one more unit of virgin or recycled resource respectively and employing it in production. The shadow values of resources constraints are diminished by the "rental element of consumption (RER)", which is due the fact that share c of each unit of extracted materials can be used again in future production.

Eventually, the right hand side of equations (20), (21) and (19) shows the benefits of disposing of an additional unit of virgin resources, of secondary materials or of capital. The increase of any production input rises output level not only directly, but also indirectly through the generation of valuable waste. Because of this the last term of these equation can be interpreted as "the marginal recycling value of inputs in production (RVP)".

RVC, RVP and RER represent the effects of the features of circular economy that have been introduced in the D-H-S-S model. Note that the magnitude of all of these is reduced by the material loss.

- KEYNES RAMSEY RULE AND HOTELLING RULES

Combining the first-order conditions the Keynes-Ramsey rule (KKR) for this specific model is derived.

Define $z = U'(C)e^{-\rho t} = C^{-\sigma}e^{-\rho t}$, considering adopted CIES specification for the utility function[7]. Equation (18) can now be rewritten as:

$$\psi_1 = z + \psi_3 m(1-x) \tag{24}$$

Inserting this in equation (19) one gets:

$$-\dot{\psi}_1 = F_K\big(z + \psi_3 m(1-x)\big) - \psi_3 F_K m\, c(1-x)$$

$$\dot{\psi}_1 = -F_K z - \psi_3 m(1-x)(1-c)F_K$$

Differentiating (24) with respect to time one obtains $\dot{\psi}_1 = \dot{z} + \psi_3\dot{m}(1-x)$, which inserted in the last expression yields:

$$\frac{\dot{z}}{z} = -F_K - \psi_3\dot{m}(1-x)\frac{1}{z} - \psi_3 m(1-x)(1-c)F_K\frac{1}{z}$$

$$\frac{\dot{z}}{z} = -F_K - \frac{\psi_3}{z}[m(1-c)F_K + \dot{m}](1-x)$$

Consider now equation (21) and rearrange it as:

$$\psi_3 - \psi_3 c(1-x) = \big(z + \psi_3\, m\,(1-x)\big)\, F_R - \psi_3\, m\,(1-x)c\, F_R$$

$$\psi_3[1 - c(1-x) - m(1-x)F_R + m\,(1-x)c\, F_R] = z\, F_R$$

$$\frac{\psi_3}{z} = \frac{F_R}{[1 - c(1-x) - m(1-x)F_R + m\,(1-x)c\, F_R]}$$

Insert this expression, denoting the term in squared brackets as A, into the expression for $\dot{z}/z$ found above:

$$\frac{\dot{z}}{z} = -F_K - \frac{F_R}{A}[m(1-c)F_K + \dot{m}](1-x)$$

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[7] A typo in Pittel et al. 2010, page 391 is present: v definition should not contain $c = C/Y$ but aggregate consumption C.

Eventually, considering the definition of z in growth rates terms $\dot{z}/z = -\sigma\left(\dot{C}/C\right) - \rho$ the Keynes-Ramsey rule is obtained:

$$\sigma\, g_C = F_K - \rho + \frac{F_R\, m\, [(1-c)F_R + g_m]}{\frac{1}{1-x} - c - mF_R + mcF_R} \tag{25}$$

Comparing with the KKR of our pessimistic benchmark, an additional term on the right-hand side is present. This term, due to the introduction of incomplete recycling and material balance constraint, enhances the consumption path and extends the lifetime of the economy as far as it is positive; it depends, among the rest, positively on the growth rate of material content of output g_m and negatively on the share of materials which cannot be recycled.

The new features of the model also lead to different Hotelling rules (for the derivation see Appendix B), for recycled and for virgin materials respectively:

$$\frac{\dot{F}_R}{F_R} = F_K + \left[\frac{F_R}{1-c(1-x)}\,(\dot{mc})(1-x) - \frac{\dot{c}(1-x)}{1-c(1-x)}\right] \tag{26}$$

$$\frac{\dot{F}_V}{F_V} = F_K + \left[\frac{F_R}{1-c(1-x)}\,(\dot{mc})(1-x) - \frac{\dot{c}(1-x)}{1-c(1-x)}\frac{F_R}{F_V}\right] \tag{27}$$

D-H-S-S model’s Hotelling rule, of course defining an arbitrage condition between virgin, exhaustible materials and man-made capital only, is enhanced by the terms in squared brackets which reflects the semi-renewability of secondary raw materials stock W. In both cases, if additional recycling causes a change of the share of resources flowing back after consumption, $m\,c(1-x)$, this influences the amount of output which can be produced in future. A change of the reflux rate c, instead, affects the availability of materials for recycling: a positive growth rate for this flow of materials from consumption, for instance, increases the stock of recyclable waste, ceteris paribus; this implies a lower opportunity cost of extraction: the growth rate of materials price is reduced. As in the other case, this effect has a lower magnitude the bigger is the share of resources that cannot be recycled and flows out of the system.

When considering there is no material loss, $x = 0$, the solutions for the Keynes-Ramsey rule and for the Hotelling rules coincide with the ones found in Pittel et al. 2010, where complete recycling is assumed.

- BALANCED GROWTH PATH

A balanced growth path describes the long-run equilibrium of an economy; along it all variables grow at a constant, possibly null, rate. As the social planner solution of the model is being analyzed, balanced growth path growth rates will be denoted by the superscript "SP".

In this context the aim is to check if the economy is sustainable and, secondly, these results will represent a benchmark for the decentralized economy.

Appendix C reports the procedure to obtain the growth rate of consumption, output (income) and capital along the balanced growth path of the optimal economy:

$${g_C}^{SP} = {g_Y}^{SP} = {g_K}^{SP} = \frac{1}{\sigma}\left(\frac{1}{\beta+\gamma} g_A - \rho\right) \tag{28}$$

Furthermore, the rate of use of the two material inputs is also obtained in Appendix C:

$${g_R}^{SP} = {g_V}^{SP} = \frac{1}{\sigma}\left[(1-\sigma)\frac{1}{\beta+\gamma} g_A - \rho\right] \tag{29}$$

Now the question is: under which conditions is this economy sustainable?

Consider equation (29) first. Since along the balanced growth path the growth rate of V should be negative, meaning that always less of the exhaustible virgin resource is used, it ensues that the following condition must hold:

$$(1-\sigma)\frac{g_A}{\beta+\gamma} < \rho$$

This always holds for $\sigma > 1$: when the parameter is relatively high, the inter-temporal elasticity of substitution of the household is low, meaning that a smooth consumption path is preferred. This would, indeed, imply a low growth rate for consumption, as shown by equation (28).

Secondly, taking into account equation (28), to observe a positive consumption growth rate along the balanced growth path it must be that:

$$\frac{1}{\beta+\gamma} g_A > \rho \tag{30}$$

This condition depends on the joint production elasticity of material inputs, on the rate at which the household discounts future utility, i.e. household's impatience, and to the rate of technological progress. When this condition is respected the economy is sustainable in the long run[8]. In conclusion, when the condition above is fulfilled, the introduction of circular flows for resources, through recycling and the material balance principle, constitute a solution to overcome the "starvation of mankind".

Nevertheless technological progress is shown to be an essential element for sustainability. Indeed, when the efficiency of the production system is not increasing, equation (30) reduces to: ${g_C}^{SP} = -\rho/\sigma$, meaning that the economy will collapse in the long run. This is due to the fact that virgin natural resources are still an essential input and, when a mechanism improving resources efficiency of production is not present, their depletion makes production impossible and recycling cannot compensate.

It is already possible to note that the growth rates along the balanced growth path are independent of the initial stocks of virgin and recyclable resources. This will be a key point when comparing optimal and decentralized economy.

Moreover, it can be seen from these conditions that incomplete recycling is not affecting the growth rates, but I am going to show it influences materials reflux rate, and consequently the production level, and initial price of recycled input.

- CONSUMPTION LEVEL

The level of consumption c along the balanced growth path is calculated here. Remind that this also accounts for the share of materials which ends up in the waste pile after consumption: the reflux rate.

Consider again $\dot{z}/z = -\sigma\, g_C - \rho$ and H_K: $\dot{\psi_1} = -\psi_1 F_K + \psi_3 F_K m\, c(1-x)$.

---

[8] As I already highlighted, the first-order condition H_W implies that in the long run it is optimal to exhaust recyclable resources, i.e. waste. This is because, introducing those features of circular economy, waste is not perceived as a problem anymore, but as a resource. Partially abstracting from the assumptions of this model, as the environmental impacts of the wastes of human activities is not considered, this gives a clue of sustainability of circular economies from an environmental point of view. The former optimality condition would fit with Brock, Taylor 2005 definition of sustainable growth: a balanced growth path with increasing environmental quality and ongoing growth in per capita income.

It was shown that: $\dot{\psi}_1 = \dot{z} + \psi_3 \dot{m}(1-x)$. Hence along the balanced growth path, where $\dot{m} = 0$: $\dot{z}/z = \dot{\psi}_1/\psi_1$.

Equalizing the two expressions one gets:

$$\sigma\, g_C + \rho = \alpha \frac{Y}{K}(1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c) \tag{31}$$

Inserting ${g_C}^{SP}$ (28) :

$$\frac{1}{1-\alpha} g_A = \alpha \frac{Y}{K}(1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c)$$

Rearranging the evolution path of capital (16) as $Y = \dot{K} - C$ and substituting this in the above, expression one obtains:

$$\frac{g_A}{1-\alpha} = \left[\alpha\, g_K +\ \alpha\ \frac{C}{K}\right](1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c)$$

$$\frac{g_A}{1-\alpha} = \left[\alpha\, g_K +\ \alpha \frac{C}{Y}\frac{Y}{K}\right](1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c)$$

Solving (31) for the ratio Y/K and inserting the result in the expression above:

$$\frac{g_A}{1-\alpha} = \left[\alpha\, g_Y +\ \alpha\, c\ \frac{g_A}{(1-\alpha)\alpha(1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c)}\right](1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c)$$

$$\frac{g_A}{1-\alpha} = \alpha\, g_Y(1-\ \psi_3\, \psi_1^{-1}(1-x)m\, c) +\ c\ \frac{g_A}{1-\alpha}$$

Eventually, rearranging, the reflux rate observed in the socially optimal economy is found:

$$c^{SP} = 1 - \frac{g_Y}{g_A}(1-\alpha)\alpha\ [1-\ \psi_3\, \psi_1^{-1} m\, c^{SP}(1-x)] \tag{32}$$

The most interesting aspect for our analysis is that the lower is the material loss x, and so the more the economy is circular (considering our definition of circularity), the higher is the reflux rate, i.e. the consumption level along the balanced growth path. The maximum level of consumption is reached under perfect recycling, i.e. $x = 0$.

3.3 DECENTRALIZED ECONOMY

The decentralized solution shows the effects of the two market failures which have been introduced (see model set-up). The equilibrium in each sector is analyzed separately.

- EQUILIBRIUM IN HOUSEHOLD SECTOR

Household's maximization problem is described by (11) and it leads to the following Hamiltonian and first-order conditions:

$$\mathrm{H} = \frac{C^{1-\sigma} - 1}{1 - \sigma}\, e^{-\rho t} + \lambda\,(r\,D - C)$$

$$\mathrm{H}_C\!: \; e^{-\rho t} C^{-\sigma} - \lambda = 0$$

$$\mathrm{H}_D\!: \; \lambda\, r = \, -\dot{\lambda}$$

Combining them, the Keynes-Ramsey rule (KRR) can be derived:

$$\sigma\, g_C + \rho = r \tag{33}$$

The missing market for waste changes household's consumption-savings decisions. Indeed, comparing this to the socially optimal Keynes-Ramsey rule (25), it is clear that the potential recycling value of the byproduct of consumption is not taken into account (RVC). A first externality arises.

- EQUILIBRIUM IN FINAL OUTPUT SECTOR

The final output market is characterized by perfect competition, thus firms' profit maximization[9] leads to the well-known equalities between the price of each production input and its marginal productivity:

$$r = \alpha \frac{Y}{K} \qquad p_V = \beta \frac{Y}{Z} \qquad p_R = \gamma \frac{Y}{R} \tag{34}$$

where p_V and p_R represent virgin and recycled materials prices.

---

[9] Final output producing firms' profit function reads: $\pi = p_Y Y - p_K K - p_V V - p_R R$. Normalizing $p_Y = 1$ and taking derivatives w.r.t. each production input eqs.(34) are obtained.

Comparing the marginal revenues of the production inputs expressed by (34) and the first-order conditions in the optimal economy it is clear that firms do not take into account the potential recycling value of each production factor (RVP): they do not internalize the effect that their input decisions have on the evolution of the waste stock. A second externality arises.

As the rate of return of capital equals capital marginal productivity only, KRR (33) coincide with the one derived for our pessimistic benchmark model (7).

- EQUILIBRIUM IN MATERIAL INPUT PRODUCING SECTORS

The profit maximization of virgin and secondary raw materials producers is described by (13) and (14). Both kinds of firms do not internalize the reflux of the resources they supply to the waste pile, so its semi-renewability is not taken in consideration in their maximizing decisions. In other words they do not perceive that the flow of resources is partially circular and alleviates exhaustion problem.

Under these assumptions the only possible solution for the dynamics of equilibrium prices of material inputs is represented by the standard Hotelling rule (confront D-H-S-S model Hotelling rule (6)):

$$g_{p_V} = g_{p_R} = r \tag{35}$$

This does not represent the social optimum.

- BALANCED GROWTH PATH

Next, the growth rates of the economy under the market solution are derived. The balanced growth path growth rates are in this case denoted by the superscript “MKT”.

Express the equilibrium conditions for material inputs prices in growth rates terms:

$$g_{p_V} = g_Y - g_V$$

$$g_{p_R} = g_Y - g_R$$

According to Hotelling rule (35), these two expressions are equal, implying ${g_V}^{\mathrm{MKT}} = {g_R}^{\mathrm{MKT}}$: along the balanced growth path the rate of extraction of the two resources is the same.

In steady state $g_Y = g_K$. Hence, considering the production function in growth rates terms $g_Y = g_A + \alpha\, g_K + \beta\, g_V + \gamma\, g_R$, it follows that:

$$g_V = -\frac{1}{1-\alpha} g_A + g_Y$$

Inserting this into (35) the result obtained is:

$$r = g_Y - g_V = \frac{1}{1-\alpha} g_A = \frac{1}{\beta-\gamma} g_A$$

Eventually, substituting this in the Keynes-Ramsey rule (33) the growth rate of consumption, output and capital along the balanced growth path of the decentralized economy is derived:

$$g_C{}^{MKT} = g_Y{}^{MKT} = g_K{}^{MKT} = \frac{1}{\sigma}\left(\frac{1}{\beta+\gamma} g_A - \rho\right) \tag{36}$$

Not only incomplete recycling, but also market failures do not affect the long-run dynamics of the economy: growth rates in case of decentralized economy coincide with the ones obtained by the social planner (compare to (29)).

The result that, in an exogenous growth model with a Cobb-Douglas technology, the growth rate is not affected by market failures is well-known from the literature (Pittel et al. 2010, page 386).

But this is not true for the level of economic activity.

- CONSUMPTION LEVELS AND INITIAL RECYCLING LEVELS

Consider the Keynes-Ramsey rule (33) and prices optimality condition (34). Equalize the two expressions for r:

$$\sigma\, g_C + \rho = \alpha \frac{Y}{K}$$

Making use now of capital accumulation (16) and economy growth rates (36) and proceding in a very similar way to the case of optimal economy, the value for the reflux rate of materials after consumption for the case of the decentralized economy is derived:

$$c^{MKT} = 1 - \frac{g_Y}{g_A}(1-\alpha)\alpha \tag{37}$$

The absence of the term $[1 - \psi_3\, \psi_1^{-1} m\, c^{SP}(1-x)] < 1$ in the expression for the consumption level in the decentralized economy when comparing to the one for the optimal economy (32), implies that the latter is bigger than the former. This term in brackets is the result of the effect of the circularity of materials flow after consumption, which shapes consumption-saving decision of the household, but only when no market failures arise and at least a part of consumed resources can be recycled. Indeed from the expression for c^{SP}it is clear that the higher is the material loss, the lower is the consumption level along the balanced growth path; at the extremes:

- for $x \to 1$: $c \to c^{MKT}$
- for $x \to 0$: $c \to c^{*}$

From now on I will denote with an asterisk the level of variables under optimal economy and complete recycling, i.e. the (ideal) first best for the economy, and with superscript "SP" the same measure but with $0 < x < 1$. The ultimate result is:

$$c^{MKT} < c^{SP} < c^{*}$$

Whenever the reflux rate is lower than in the case for optimal economy and perfect circularity of resources flow after consumption, this translates in a suboptimal level of recycling at each point in time and this causes a suboptimal level of output at each point in time. To see this more clearly, one can integrate the whole evolution of the waste stock along the balanced growth path, i.e. the material balance condition, to obtain the initial level of recycling R_0:

$$\int_0^\infty \dot{W}\, dt = \int_0^\infty [-R + (V+R)c(1-x)]dt$$

$$\int_0^\infty \dot{W}\, dt = -\int_0^\infty \left[\big(1 - c(1-x)\big)R\right] dt + \int_0^\infty V\, c(1-x)\ dt$$

$$\int_0^\infty \dot{W}\, dt = -\big(1 - c(1-x)\big)\int_0^\infty R\, dt + c(1-x)S_0$$

$$\int_0^\infty R\, dt = -\frac{1}{1-c(1-x)}[-W_0 - c(1-x)S_0]$$

$$R_0 \equiv R_0(c) = |g_V| \frac{W_0 + c(1-x)S_0}{1 - c(1-x)} \tag{38}$$

where it was made use of the facts that the economy will seek to completely extract the available stocks of resources, $W_\infty = S_\infty = 0$, and that along the balanced growth path the extraction dynamics are the same for both material inputs, $g_V = g_R$.

From (38) it is clear that the initial use or recycled materials depends positively on the consumption level and negatively on the magnitude of material loss:

- ${R^*}_0 > {R_0}^{SP} \equiv R_0(c^{SP})$ because of the incomplete circularity of materials flow after consumption;
- ${R^*}_0 > {R_0}^{MKT} \equiv R_0(c^{MKT})$ because $c^{MKT} < c^*$ due to the effect of the market failures.

Taking now into account that the growth rates are the same under socially optimal and under market solution, a lower initial recycling level determines a lower use path of waste and, because also the capital accumulation dynamic coincide in the two regimes, this determines a lower level of aggregate output.

3.4 ECONOMIC AND ENVIRONMENTAL POLICIES

In this section some possible policies to restore social optimality of the economy and reach the first best situation are presented.

As shown in the previous chapter, consumption and output levels are suboptimal when the flux of materials from consumption cannot be completely recycled and/or when a market for waste is not present and firms do not take into account the effect of their production decisions on the regeneration of recyclable waste stock. It follows that two kinds of policies, consistent with the model, can be adopted.

- IMPROVING CIRCULARITY OF RESOURCES FLOWS

Consider again (32) in a comparative statics perspective.

$$c^{SP} = 1 - \frac{g_Y}{g_A}(1-\alpha)\alpha \left[1 - \psi_3 \psi_1^{-1} m \, c^{SP}(1-x)\right]$$

It is reasonable to assume that the level of material loss is negatively correlated to R&D efforts in "economy circularity". In the first place, this specific form of technological progress is represented, in practical terms, by innovations increasing the share of recyclable materials after consumption: waste separation and materials collection technologies, like more efficient mechanical biological treatment (MBT) technologies or thermal treatments for example. In the second place, also manufacturing technologies, producing outputs more adapt to be recycled, would serve to the scope; indeed aligning production technologies to circular economy objectives is one of the main aims pinpointed by the European Union to promote circular economy (European Parliament 2017). In the first case innovations would have a recycling firms end, in the second they would be final output producers oriented.

R&D investments in recycling process could be implemented, for instance, through a lump-sum tax or allocating on that public expenditure (note household already invests in government bonds as one can see from the optimization problem described by (11), but the allocation of revenues by government is not specified). If we assume that the investment will lead for sure to an innovation which reduces the material loss at a certain point in time t, the lump-sum tax or the temporary allocation of government expenditure on research would lead to a permanent, higher output level from t on. This can be seen from (38) also: for $x \to 0$, ${R_0}^{SP} \to {R^*}_0$. If the investment in R&D would be financed by government issuing new debt, then, after the higher income level is reached, an income tax could be levied once for all to restore the balance of state budget.

The suitability of a package of policies to improve the circularity of resources flow is supported by data on the share of recovered materials after their first use cycle. Figure 5 shows that, even in the most successful cases for recycling of a certain material, steel and plastics for example, a large share of the value of the resource is lost after the first use cycle. This is due to both the quality of the material after it has been used – production technologies, more adapt to circular economy scopes and flows, could play a role here – and to the quantity of materials which can be recycled after the first use. Of course, when considering real data, one should also take into account consumers' recycling behavior, which could be more or less virtuous (recall material loss only depends on technical reasons in the model).

OECD 2015 assessment of technological innovations in the waste management sector highlights a stagnation of the number of filed patents, which in 2013 was lower than in 1997. This reinforces the argumentation of suitability of investments in "R&D for economy circularity".

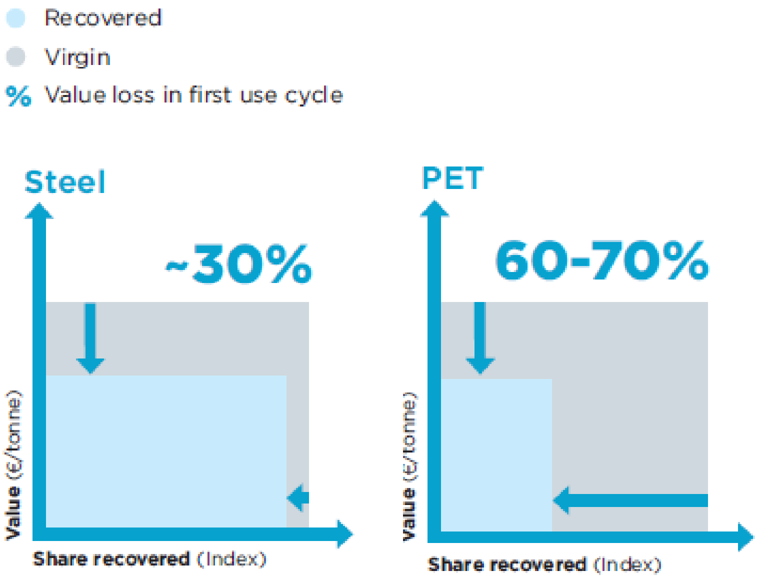

Fig. 5 Value loss for steel and plastic (PET) after the first use cycle. Source: Allen MacArthur Foundation, 2015.

- MARKETS-END POLICIES

In order to reach the first-best economy production level, the externalities due to the two market failures must be corrected. The aim here is to close the gap between the consumption level observed in the decentralized economy, c^{MKT}, and the first-best idealistic case where the reflux of materials after consumption is total, c^{*}, and not the one between c^{MKT} and c^{SP}, which is observed in case of positive material loss and represents only a second-best situation. I follow Pittel et al. 2010 argumentation.

The fist market failure is represented by the absence of a market for waste in the sense that households are not remunerated for the waste they produce. Introducing this mechanism, household income constraint is modified. Indeed an additional source of income dependent on the price of the recycled materials p_R, by the flow of consumption and by the material intensity of output m is obserded:

$$\dot{D} = rD - (1 - p_R m)C$$

Household maximization problem reads now:

$$\mathrm{H} = U(C)e^{-\rho t} + \omega(rD - C + p_R m\, C)$$

$$\mathrm{H}_C: \quad U'(C)e^{-\rho t} = \omega(1 - p_R m) \qquad (39)$$

$$\mathrm{H}_D: \quad \dot{\omega} = -r\,\omega$$

where ω is the shadow price of household's wealth. Instead $1 - p_R m$ represents the net cost of consumption: it accounts for the difference between the price of one unit of consumption good, normalized to one, and the revenue from selling the waste generated per unit of consumption to recycling firms. H_C is analogous to the one under optimal economy (18)[10] showing the internalization of RVC.

The introduction of a market for waste also corrects the externality due to the missing consideration of RVP by final output producers. It can be shown that expressing profits in terms of the net costs of consumption and maximizing, one obtains first-order conditions analogous to the ones for production inputs derived in the social planner solution, except for the "rental element in the pricing of recycled materials"[11].

To correct for this last externality, due to the fact that material input producers do not take into account the semi-renewability of the waste stock, a system of corrections for material inputs prices can be introduced.

In order to calculate the optimal subsidy for the two material inputs, their initial prices must be calculated. Consider equation (34) for p_R, insert (38) for R_0 and recall that $Y = [g_Y/(1-c)]\,K$ to derive:

$$p_{R_0}(c) = \gamma \frac{1}{|g_V|} \frac{1 - c(1-x)}{W_0 + (1-x)c\,S_0} \frac{g_Y}{(1-c)} K_0$$

$$p_{R_0}(c) = \gamma \frac{g_Y}{|g_V|} \frac{K_0}{W_0 + (1-x)c\,S_0} \frac{1 - c(1-x)}{1-c}$$

which is the general expression for the initial price of recycled resources. This is useful to show that the higher is the material loss, the higher is the initial price for the recycled input, clearly due to the lower initial level of secondary raw materials use, R_0.

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[10] Rearrange eq. (18) as H_C: $U'(C)e^{-\rho t} = \psi_1(1 - \psi_3\,\psi_1^{-1}\,m)$. The analogy with (39) implies $p_R = \psi_3\,\psi_1^{-1}$.

[11] Express final output producers' profit function as $\pi = (1 - p_R m)Y - p_K K - p_V V - p_R R$. Deriving with respect to R and considering $p_R = \psi_3\,\psi_1^{-1}$, one obtains $\psi_1 F_R - \psi_3 F_R m\,c - \psi_3 = 0$, which equals (21) without RER.

Because the aim is to achieve the first best situation, complete recycling is assumed, so that:

$$p_{R_0}(c) = \gamma \frac{g_Y}{|g_V|} \frac{K_0}{W_0 + c\, S_0}$$

Considering instead (34) for the price of virgin materials, p_V, and insert (38) for R_0 and $Y = [g_Y/(1-c)]\, K$, one gets the initial price for virgin resources as function of the reflux rate:

$$p_{V_0}(c) = \gamma \frac{g_Y}{|g_V|} \frac{K_0}{(1-c)\, S_0}$$

The difference, that arises between initial market prices $p_{R_0}(c^{MKT})$ and $p_{V_0}(c^{MKT})$ and initial socially optimal prices $p_{R_0}(c^*)$ and $p_{V_0}(c^*)$ respectively, determines the optimal prices corrections system:

$$\tau_R = \gamma \frac{g_Y}{|g_V|} K_0 \left[\frac{1}{W_0 + c^* S_0} - \frac{1}{W_0 + c^{MKT} S_0}\right]$$

$$\tau_V = \beta \frac{g_Y}{|g_V|} K_0 \left[\frac{1}{1-c^*} - \frac{1}{1-c^{MKT}}\right]$$

Because $c^{MKT} < c^*$ and initial stocks of both resources are strictly positive, the optimal correction for recycled resources price τ_R is negative, meaning that, to achieve the first best situation, the initial market price for recycled waste has to be lowered by τ_R. On the opposite, the correction for the initial market price for virgin resources makes them more expensive, as $\tau_V > 0$. The conclusions drawn on this point in Pittel et al. 2010 (p. 389,390) stating that a "subsidization" with respect to virgin resources is also optimal, looks confusing to me, as the correction for the initial price of virgin resources actually constitutes a tax.

The subsidy-tax system compensate for the missing RER in material inputs producers' optimizing decisions.

To summarize: the introduction of a market for waste and the introduction of a subsidy on recycled resources and of a tax on virgin ones represent two of the possible devices to restore social optimality of the economy. Increasing the level of recycling, which was shown to be the cause of the suboptimal level of output, these measures also shift the composition of final output towards a more recycled resources-intensive one, making it more sustainable.

CHAPTER 4: EMPIRICAL ASSESSMENT

After having formally derived theoretical results for the effects of the introduction of some features of the circular economy concept in a neoclassical framework growth model considering exhaustible natural resource, I move now to an empirical approach.
Testing numerically the results of the model presented in Chapter 3 is beyond the scope of this thesis. The aim of this part of the work is to examine some of the relationships depicted by the model and to verify the evolution of some of its variables, considering real data for European countries.

In particular, the analysis will follow three steps. Since from the model derives that “more circular” economies are characterized by a higher income level, the first question arising is if this is observed in reality; this is done using an econometric approach. Secondly, the features of the waste management system at a European level and its evolution in terms of efficiency and environmental sustainability are examined; European Union policies to support circular economy are also taken into account. Finally, some indexes are used to understand the current level of circularity the European Union economies and some critical considerations on the effectiveness of the contribution of recycling for sustainability are provided.

The data utilized for the following considerations were analyzed and manipulated using the software Stata or Excel and they were taken from the source Eurostat.

4.1 ON THE CORRELATION BETWEEN CIRCULARITY OF ECONOMIES AND INCOME LEVEL

The theoretical model showed that in economies with a completely circular flow of material resources after consumption, a higher output and consumption level is observed, when comparing to the cases of material loss and presence of market failures.
Taking into account equation (38) it was argued that more recycling causes a higher income level. The aim of this section is to try to check this result.
To do so some regressions were implemented, by using the software Stata. A random-effects and a fixed-effects regression models were considered to check the correlation between annual gross domestic product per capita and recycling rate per capita, that we could interpret as a proxy for circularity of the economy. Once again, this is a very stylized representation of the circular economy concept.

- DATASET DESCRIPTION

The panel dataset contains observations for 31 European countries[12], running from 1995 to 2016. The number of observations for the dependent variable, gross domestic product per capita, and for the independent one, recycling rate per capita, amount to 636.
Data in per capita terms are suitable to eliminate the effects of population growth in each country.

Data for recycling rate per capita were calculated personally, in order to extend the series provided by Eurostat running from 2000 to 2016 only. To calculate the variable the amounts of waste going to composting, anaerobic digestion and material recycling, which represent the three processes constituting the recycling treatment[13] were summed and then divided by the total amount of waste generated.
In order to have more observations, data for municipal waste were used to calculate the amount of waste going to recycling treatment, instead of data referring to total waste generated in each country, which are available from 2004 on only. The amount of municipal waste generated consists of waste collected by municipal authorities and disposed of through the waste management system; it consists to a large extent of waste generated by households. The use of municipal waste as an indicator for waste generation and treatment has a long tradition in Europe, according to Eurostat. Municipal waste constitutes only around 10 % of total waste generated, but because of its heterogeneous composition the environmentally sound management is challenging. Thus, the way municipal waste is managed gives a good indication of the quality of the overall waste management system.

- TWO DIFFERENT APPROACHES

Two different approaches are considered in order to obtain the best estimation.

Consider in general the regression model $Y_{i\,t} = \beta\, X'_{i\,t} + \alpha_i + \varepsilon_{i\,t}$, where $Y_{i\,t}$ represents an outcome variable (GDP per capita in our case), $X'_{i\,t}$ is a vector of independent variables (recycling rate per capita in our case), α_i denotes an individual-specific time-constant effect, $\varepsilon_{i\,t}$ represents independent and identically distributed error term; subscript i denotes the panel dimension

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[12] Countries of the dataset: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom.

[13] Recycling of waste is defined as any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. (Eurostat)

(country) and t the time dimension (year). More specifically, the term α_i captures the impact of unobserved variables which are constant over time for a given country, but which can vary between countries. Because these country-specific characteristics are not observable in data, they cannot be included directly in the regression model.

The choice of the estimation model depends first of all on the assumption that α_i is a random variable or not.

In the first case the dependent variable is not correlated with the unobserved characteristic, $Cov(X_{i\,t}, \alpha_i) = 0$, and a bias due to omitted variable is not distorting the estimated effect on the dependent variable.

In the second, more realistic, case the unobserved characteristic is correlated with the independent variable, $Cov(X_{i\,t}, \alpha_i) \neq 0$, and with the dependent one. In this case if one does not consider α_i in the estimation, its effect would be captured by the error term and would lead to distorted results for the effect of the independent variable on the dependent one. In this case an "endogeneity problem" realizes. For a formal demonstration see Angrist, Pischke 2015.

If one adopts the assumption of non-correlation between recycling rate and unobserved, individual-specific time-constant characteristics, then a "Random-Effects" (RE) or "Pooled Ordinary Least Squares" approach should be considered. In this case between effects as well as within effects are taken into account. Between effects are due to the differences in GDP per capita and covariates between different countries. Within effects are due to differences in GDP per capita and covariates for the same individual over time.

The results of the estimation are shown in Table 1 under column 1. The interpretation is the following: the regression is significant, meaning that a correlation between recycling rate per capita and income level per capita exists, and that an increase of the recycling rate by one per cent leads to a growth of annual per capita income of approximately 435 euro on average. This monetary figure, however, may be not so indicative if we consider the differences of income levels across the 31 European countries of the sample.

To check for the consistency of this result, the assumption of non-correlation of possible unobserved characteristics is eliminated and a "Fixed-Effects" (FE) approach is adopted. Imagine, for instance, that recycling rate in a specific country is influenced by some cultural peculiarities, like a historical orientation towards sustainability and environmental quality protection, or by the availability of a certain, more efficient technology for waste recycling. If these country-specific characteristics, captured by α_i, are constant over time, de-meaning all variables and performing an OLS regression leads to unbiased results. In practice this fixed-effects estimator uses within variations only, i.e. it does not consider across country variations.

The results of the fixed-effects model reinforce the ones obtained with the random-effects one: a positive correlation between recycling rate per capita and GDP per capita is found. The monetary average increase in per capita annual income due to a one per cent increase of recycling rate is only slightly reduced to 423 euro (results in Table 1, column 2).

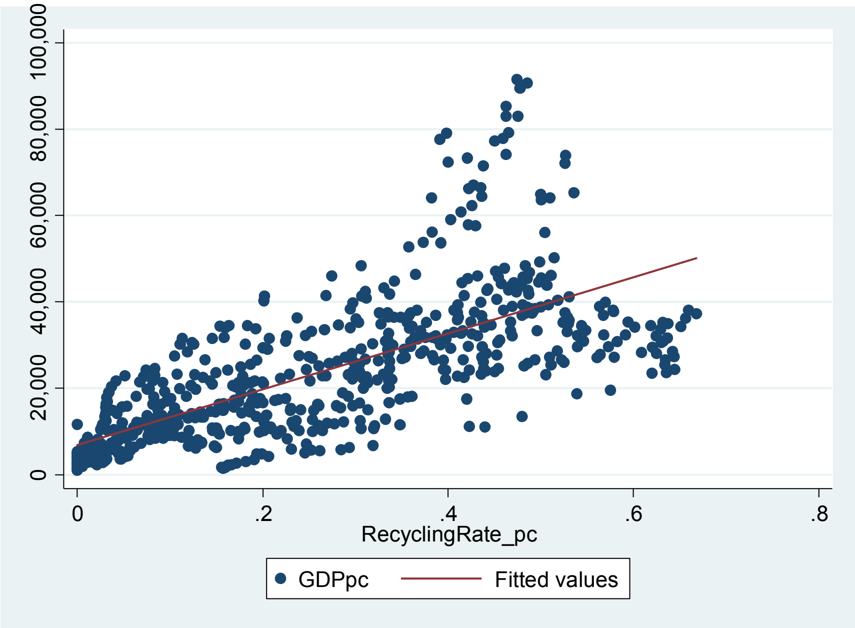


Fig. 6 Scatter plot for GDP per capita levels. On the horizontal axis: recycling rate per capita observations; on the vertical axis: annual GDP per capita, euro. Each observation is referred to a specific year and country. Source: own illustration.

Eventually, a Hausman test is used to determine which of the two estimations would be better to consider ultimately. The test shows that RE estimator is inconsistent, whilst FE is consistent and so it must be preferred to the former estimator, despite its variance is (slightly) higher.

Even considering a fixed-effects approach, which was proved to improve the estimation, one should still be aware of some possible distortions:

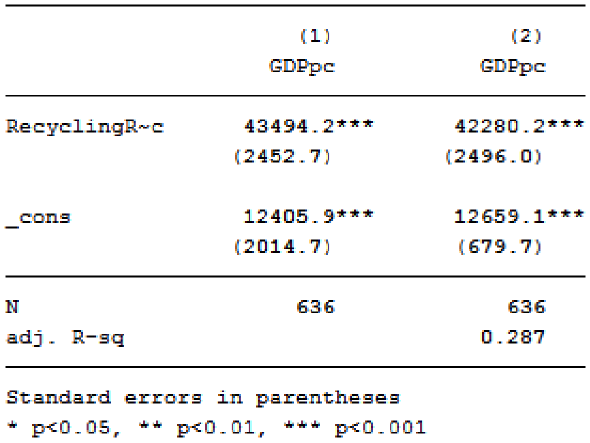
I) omitted variables bias: some variables could be correlated with recycling rate and with income level and, when they are not constant in time for each country, they would lead to distortions;

II) country-specific effects (observed or unobserved characteristics) may be non-constant over time: a FE estimation would not completely exclude biases;

III) “simultaneity” problem: this is observed when two variables are codetermined, with each affecting the other. This case is in my opinion plausible - hopefully, even if the estimation would be biased then - : it should be that the recycling rate influences income level, but it may also be that the income level determines recycling rate (e.g. because while the income level grows, the value (utility) attached to environmental quality also increases).

Nevertheless, taking into account graphic and econometric results, the thesis that a higher per capita income level is observed in “more circular” economies, i.e. in countries characterized by a higher recycling rate, can be supported in my opinion.

Obviously, econometric techniques show correlation between variables, but do not state causal inference between them: the attempt for this was done with the previously presented formal model.



	(1) GDPpc	(2) GDPpc
RecyclingR~c	43494.2***	42280.2***
	(2452.7)	(2496.0)
_cons	12405.9***	12659.1***
	(2014.7)	(679.7)
N	636	636
adj. R-sq		0.287

Standard errors in parentheses
* p<0.05, ** p<0.01, *** p<0.001

Tab. 1 Results of the regression between recycling levels per capita and GDP per capita. Under column (1): results for random-effects estimation. Under column (2): results for fixed-effects estimation. N denotes number of observations. Source: own illustration.

4.2 THE EUROPEAN WASTE MANAGEMENT SYSTEM AND EUROPEAN UNION POLICIES TO SUPPORT CIRCULAR ECONOMY.

Waste disposal can have serious environmental impacts. The discarded materials can be treated in three different ways: recycling (via composting, anaerobic digestion and material recycling), landfilling and incineration. Landfill[14], for example, takes up land space and may cause air, water

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[14] Landfill is the deposit of waste into or onto land. It includes specially engineered landfill sites and temporary storage of over one year on permanent sites. (Eurostat)

and soil pollution, while incineration[15] may result in emissions of air pollutants. These are the two most detrimental treatments. For more detailed environmental impacts of waste treatment methods consult: European Parliament "Towards a circular economy – Waste management in the EU", 2017 (p. 132-134).

Thus, in the first instance I personally calculated the ratio for waste going to final disposal, via incineration or landfilling treatments, over total amount of waste generated. Data refer to municipal waste, to the European Union aggregate, to the period 1995-2016 and are expressed in mass terms.

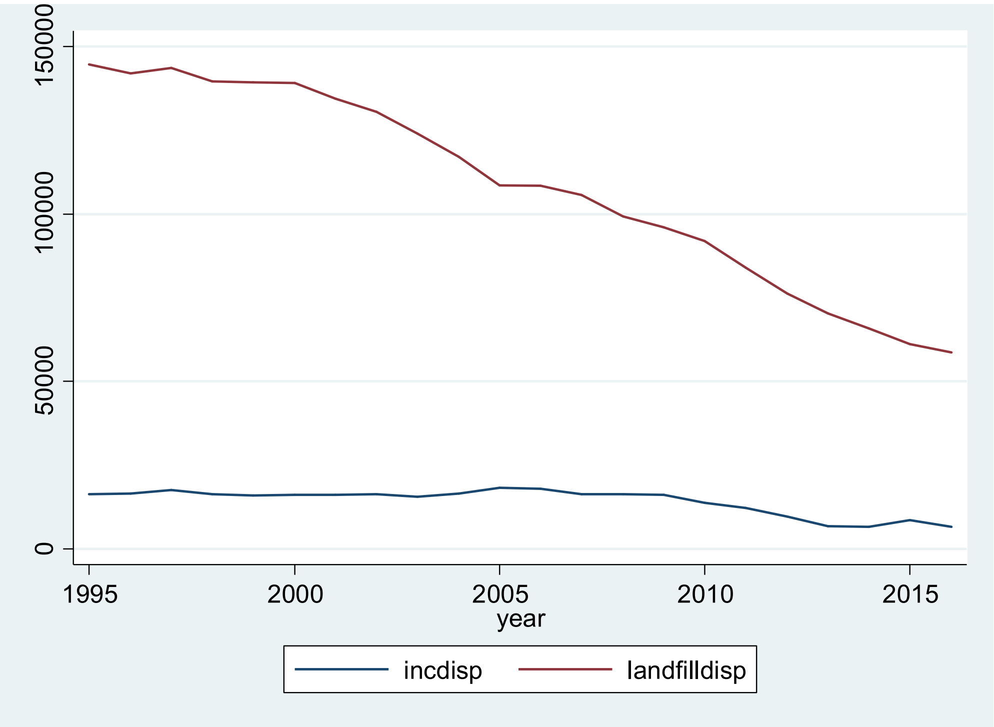

Fig. 7 Trends for the amount of municipal waste going to incineration (incdisp) and landfilling (landfilldisp) treatments. Measure: thousand tons. Period: 1995-2016. Data for European Union 27 aggregate. Source: own illustration.

The total amount of waste going to final disposal decreased by 59%, mostly because of the reduction of the use of landfilling treatment; data for the evolution of the amount of waste being

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[15] Incineration is a method of waste disposal that involves the combustion of waste. Incineration can have pure disposal aim or disposal and energy recovery aim. Incineration with energy recovery refers to incineration processes where the energy created in the combustion process is harnessed for re-use, for example for power generation. Incineration without energy recovery means the heat generated by combustion is dissipated in the environment. (Eurostat)

landfilled or incinerated are provided in Figure 7. The total amount of municipal waste generated, on the contrary, rose by 8% from 1995, but it is interesting to note that the figure decreased in the last 10 years (see Figure 8). Considering the ratio of these two figures, it is possible to see from Figure 9 that the share of municipal waste going to disposal in the EU felt from 71% in 1995 to 27% in 2016: a 63% decrease.

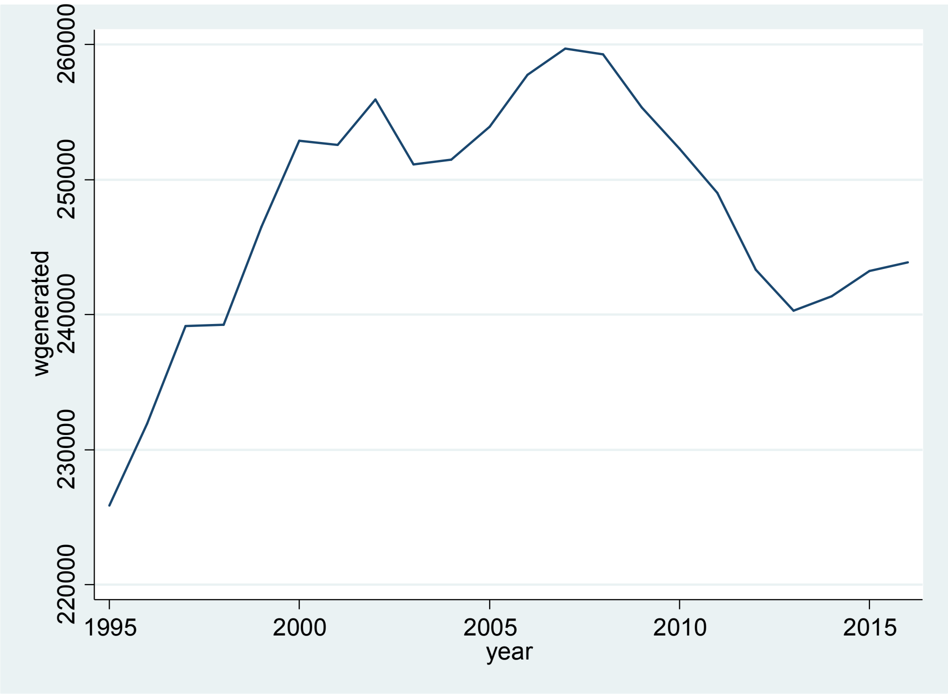

Fig. 8 Total amount of municipal waste generated (wgenerated).
Measure: thousand tons. Period: 1995-2016. Data for European Union 27 aggregate. Source: own illustration.

Also notice that this figure is the closest possible estimator of what I called material loss in the theoretical model, if one restricts the case to municipal waste only. Indeed, this share of materials going to disposal is not reused or recycled in any way, it is simply flowing out of the economic system and so it is not generating any increase of utility for individuals.

Secondly, data for total waste were considered, excluding major mineral waste[16]. The time series for this figure relative to the European Union aggregate, available for the period 2004 – 2014, show a decrease of 7.4% in tons terms and of roughly 10% in per capita terms, as European population grew in that period.

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[16] Over 90% of mineral and soil waste come from the mining and construction sectors, which are subject to considerable fluctuation over time. Waste generation from which major mineral wastes are excluded reflects general trends more accurately than statistics on total waste generated.

This is a surprising result because it is against theoretical predictions. Indeed, while some "Environmental Kuznets Curves (EKC)", i.e. inverted U shape dynamics for certain pollutants emissions, are observed at the increase of income per capita both in reality and theoretical predictions, there is no finding for such fashion for the case of produced waste. For a survey on EKC predictions for many pollutant substances and waste dynamics see Lieb 2003. Interestingly, the only exception to these predictions of monotonically increasing amounts of waste generated is represented by the model found in Pittel 2006, based on assumptions and on a structure very similar to the one presented on Chapter 3. There, waste is considered a resource for the production and optimality requires the total use of it in the long-run.

The reason for the observed trend for EU data is due to the increasing efficiency in terms of waste generation observed in the production sector. Indeed the annual flow of industrial waste decreased by 9.3% from 2004 to 2014, while, as shown in Figure D.1, municipal waste, which is largely constituted by households' waste and so it is a byproduct of the consumption process, started declining after 2007 only.

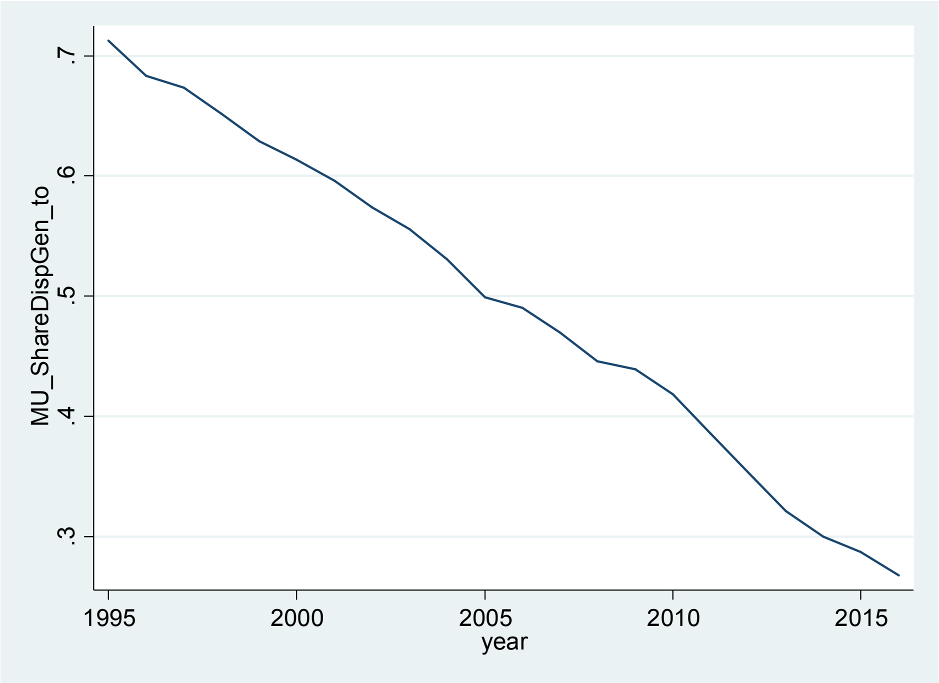

Fig. 9 Trend for the share of municipal waste going to final disposal over total municipal waste generated. Measure: percentage. Period: 1995-2016. Data for European Union 27 aggregate. Source: own illustration.

Two conclusions can be drawn:

- European countries' waste management systems became on average more environmentally friendly in the last twenty years, by consistently reducing the share of waste going to final disposal.
  The reduction of this flow of materials leaving the economic system and representing in a concrete way the concept of material loss should represent a positive fact for production, according to the previously presented theoretical model, and it accounts for a higher resources efficiency[17] of the economic system, possibly reducing Europe dependence on virgin resources extraction.
- European Union production sector is becoming more efficient in terms of waste generated, leading to a monotonic decline of total waste generated since 2004.

These two observed trends are in line with the objectives of the European Union waste management policies, the guidelines of which are given by European Commission's Circular Economy Action Plan and by Europe 2020 Strategy. The depicted objectives are the reduction of the environmental and health impacts of waste and the improvement of the EU's resource efficiency. The long-term goal is to turn Europe into a "recycling society" (European Commission, "Thematic strategy on the prevention and recycling of waste", 2011) to minimize the extraction of additional natural resources.

Accordingly, the 2008 Waste Framework Directive introduced a five-step waste hierarchy where prevention is the best option, followed by re-use, recycling and other forms of recovery, with disposal as the last resort. In line with this hierarchy, the 7th Environment Action Programme sets the following priority objectives for waste policy in the EU: reduce the amount of waste generated; maximize recycling and re-use; limit incineration to non-recyclable materials; phase out landfilling of waste; ensure full implementation of the waste policy targets in all EU Member States. EU waste policy objectives are consistent with the ones implied by the theoretical model presented in Chapter 3 (with the exception of total waste generated reduction as in the model waste represents solely a resource).

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[17] Resource efficiency is a measure of the total amount of materials used by an economy in relation to GDP. It provides insights into whether decoupling between the use of natural resources and economic growth is taking place.

4.3 “ALL THAT GLITTERS AIN’T GOLD”

The questions which consequently arise from these trends found for the European waste management system are: Is the European Union really becoming a “recycling society”, characterized by a circular economy? And what could concretely be the contribution of recycling to the alleviation of exhaustible natural resources problem?

On the one side the recycling rate (of municipal waste) almost doubled since year 2000, reaching 45.8% of total waste generated in the EU. On the other side, the figure differs widely across European countries and 54.2% of waste is not recycled, leaving consistent room for improvement. This also means that we are far from those idealized assumptions of complete recycling sometimes adopted in circular economy papers and also present in Pittel et al. 2010.

Furthermore, Eurostat “circular material use rate (CMU)” indicator[18] increased by three percentage points in the period 2004-2014 and it accounts for a mere 11.4% (2014). This is due to the composition of recycled waste, to the quality of secondary raw materials, to the absence of a market for waste in some cases and to the fact that secondary raw materials flow is insufficient. Such a low figure for this sustainability indicator means that the amount of secondary raw materials contributing to overall material input for domestic use in the EU allows for a small reduction of virgin raw materials extraction. Consequently, the alleviation of exhaustible resources problem is still minimal, as for the dependency of EU on natural resources import.

It is also intuitive that, because even recycling 45% of waste, circular material use rate is still so low, complete recycling would not be enough to overcome virgin resources extraction, ceteris paribus. This leads to the conclusions: that virgin resources are still an essential input in production, and they probably would be even in the idealistic case of complete recycling; that technological progress is essential in order to improve resource efficiency of the production system and to provide higher quality secondary raw materials.

Note, once again, how these findings are consistent with the presented theoretical model and with its policy implications.

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[18] The indicator measures the degree of circular (secondary) materials in the economy in relation to the overall material use. The CMU is calculated as the ratio of the amount of secondary raw materials to the overall material input for domestic use.

CHAPTER 5: CONCLUSIONS AND PERSONAL REMARKS

The main aim of this thesis is to link the concept of circular economy and formal modeling in economic growth context. This concept depicts an economic system characterized, first of all, by different material flows with respect to actual current ones and could theoretically represent a device to alleviate both problems of natural resources depletion and accumulation of wastes due to human activities in the environment. Because in the literature the circular economy concept is quite idealistic, only some concrete aspects of it were considered in order to modify the pessimistic benchmark model with typical neoclassical features presented in Chapter 2.

It was shown that introducing a recycling sector and the material balance principle (but also exogenous technological progress) the long-run sustainability of the considered economy may be achieved. This depends on the household's inter-temporal elasticity of substitution, on the joint production elasticity of material inputs, on the rate at which the household discounts future utility and on the growth rate of technological progress, which must be positive.

Even though the economy growth rates are not affected by incomplete recycling and by market failures, it was demonstrated that the consumption level, also accounting for the reflux of materials to production after consumption, as well as the output level are suboptimal when those distortions are taken into account. Furthermore, material loss and market failures reduce the initial level of recycling and, consequently, they increase the initial price of secondary raw materials.

The first-best outcome for the economy in terms of output and consumption levels can be achieved: reducing the share of materials which are not flowing back to the production process through investments in forms of R&D aiming to improve the circularity of resources flow; introducing a market for waste and a system of corrections for initial prices of material inputs. It was noted that actual European Union policies to support circularity of economies are not at odds with the presented theoretical ones.

The perception of waste as a valuable input in this kind of economic system implies that the waste stock is completely exhausted in the long-run. This is a clue for environmental sustainability of circular economies.

A positive correlation between the recycling level and the level of income per capita is found in real data for European countries. The European waste management system became more environmentally friendly during the last two decades, as reflected by the decline of the amount of waste going to landfilling and incineration treatments, representing a proxy for the material loss measure. Nevertheless European economies are far from being significantly circular. This leaves large room for improvements, but recycling must be accompanied with an enhanced resources efficiency of production processes in order to substantially overcome the problem of natural resources depletion.

An interesting modification of the model presented in Chapter 3 could be the introduction of the level of environmental quality, reduced by waste accumulation, in the household's utility function.

- IS IT STILL WORTH TO TALK ABOUT ECONOMIC GROWTH?

Some environmentalists, but also economists (Serge Latouche in the first place), political parties like Italian Movimento 5Stelle and even spiritual leaders like Pope Francis[19] are supporters of a "degrowth" perspective. But, to be realistic, is humanity ready to accept this Post-Development perspective? In my opinion no.

If the term degrowth identificates a reduction or phase out of certain specific consumption and production schemes, which are environmentaly harmful, with the objective of establishing an equilibrium relationship between man and nature, then degrowth should be encouraged. But this approach cannot be accepted if it is identified by foregoing to improve the living standards, generally and globally. Two are the reasons. I think that giving up on standards of living, which have been already achieved, would not be accepted by the majority of people; not trying to improve own living conditions is simply not in human nature. Secondly, a large share of world population still lives in poverty conditions, which are sometimes extreme: development is necessary.

For these reasons it is surely still worth to talk about economic growth and development. However, it is necessary that the economic systems get away, progressively but rapidly, from the current models strictly based on the exploitation of natural resources, and approaching models founded on resources efficiency, environmental sustainability and circularity.

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[19] See Pope Francis "Encyclical letter: Laudato si'. On the care of our common home", Vatican city, 2015.
I found interesting to note that the subtitle of this encyclical is very close to the original meaning of the word "economy": management, administration of the house.

Appendix A: D-H-S-S model first-order conditions.

$$\mathrm{H}_C:\ \ U'(C)e^{-\rho t} - \psi_1 = 0 \qquad (\mathrm{A}.1)$$

$$\mathrm{H}_K:\ \ \psi_1 F_K = -\dot{\psi}_1 \qquad (\mathrm{A}.2)$$

$$\mathrm{H}_V:\ \ \psi_1 F_V - \psi_2 = 0 \qquad (\mathrm{A}.3)$$

$$\mathrm{H}_S:\ \ 0 = -\dot{\psi}_2 \qquad (\mathrm{A}.4)$$

It is reasonable that, as stated by equation $(\mathrm{A}.4)$, it is optimal to completely exhaust the finite stock of natural resources. The other first-order conditions represent the optimal consumption-investment statement (H_C) and the equality between the opportunity costs of using one additional unit of a certain input and the benefits ensuing from this in terms of output generated, (H_K) and (H_V).

The Keynes-Ramsey rule is obtained deriving $(\mathrm{A}.1)$ with respect to time and combining the result with $(\mathrm{A}.2)$. The Hotelling rule is derived taking the derivative of $(\mathrm{A}.3)$ with respect to time and combining it with $(\mathrm{A}.2)$ and $(\mathrm{A}.4)$.

Appendix B: Hotelling rules for the model with circular economy features.

For the derivation of the Hotelling rule for recycled material inputs rearrange equation (21) for H_R as:

$$F_R = \frac{1 - c(1-x)}{\psi_1\, \psi_3^{-1} - c(1-x)m}$$

Differentiating this with respect to time yields:

$$\frac{\dot{F_R}}{F_R} = -\frac{\dot{c}(1-x)}{1 - c(1-x)} - \frac{\dot{\psi}_1 \psi_3^{-1} - (1-x)(\dot{mc})}{\psi_1\, \psi_3^{-1} - c(1-x)m}$$

Rewrite again (21) as:

$$\frac{1}{\psi_1\, \psi_3^{-1} - c(1-x)m} = \frac{F_R}{1 - c(1-x)}$$

and equation (19) for H_K as:

$$\dot{\psi}_1 = -\psi_1 F_K + \psi_3 F_K m\, c(1-x)$$

Now insert both into the expression for $\dot{F_R}/F_R$ found above to obtain:

$$\frac{\dot{F_R}}{F_R}=-\frac{\dot{c}(1-x)}{1-\ c(1-x)}-\frac{F_R}{1-\ c(1-x)}\left[-\,\psi_1\,\psi_3^{-1}F_K+F_K m\,c(1-x)-(1-x)(\dot{mc})\right]$$

Rearrange once again (21):

$$\frac{\psi_1}{\psi_3}=\frac{1-c(1-x)+F_R\;m\,c(1-x)}{F_R}$$

and substitute this into the expression above:

$$\frac{\dot{F_R}}{F_R}=-\frac{\dot{c}(1-x)}{1-\ c(1-x)}-\frac{F_R}{1-\ c(1-x)}*$$

$$*\left[-\frac{F_K}{F_R}\big(1-c(1-x)+F_R\;m\,c(1-x)\big)\;+F_K m\,c(1-x)-(1-x)(\dot{mc})\right]$$

$$\frac{\dot{F_R}}{F_R}=-\frac{\dot{c}(1-x)}{1-\ c(1-x)}+\frac{F_K\big(1-c(1-x)+F_R\;m\,c(1-x)\big)}{1-c(1-x)}-\frac{F_K\big(F_R\;m\,c(1-x)\big)}{1-c(1-x)}$$

$$+\frac{F_R(1-x)(\dot{mc})}{1-c(1-x)}$$

Simplifying this expression the Hotelling rule for secondary raw materials (26) is determined.

Next the Hotelling rule for virgin resources is derived.

Add and subtract ψ_3 to the left-hand side of equation (20) for H_V:

$$\psi_2-\ \psi_3 c(1-x)+\ \psi_3-\ \psi_3=F_V\;(\psi_1-\ \psi_3 m\,c(1-x))$$

$$F_V\;=\;\frac{\psi_2-\ \psi_3-\ \psi_3\;\big(1-c(1-x)\big)}{\psi_1-\ \psi_3 m\,c(1-x)}$$

Differentiating with respect to time and considering $H_S\colon 0=-\dot{\psi}_2$ one obtains

$$\frac{\dot{F_V}}{F_V}=-\frac{\psi_3(1-x)}{\psi_2-\ \psi_3-\ \psi_3\;\big(1-c(1-x)\big)}\;\dot{c}-\;\frac{\dot{\psi}_1-\psi_3(\dot{m\,c})(1-x)}{\psi_1-\ \psi_3 m\,c(1-x)}$$

Rearrange (19) as:

$$\frac{\dot{\psi}_1}{\psi_1 - \psi_3 m\, c(1-x)} = -F_K$$

and again (20) as: $\psi_2 - \psi_3 - \psi_3\left(1 - c(1-x)\right) = F_V\left(\psi_1 - \psi_3 m\, c(1-x)\right)$.

Use both in the last expression for $\dot{F_V}/F_V$ to get:

$$\frac{\dot{F_V}}{F_V} = -\frac{\psi_3(1-x)}{F_V\left(\psi_1 - \psi_3 m\, c(1-x)\right)}\,\dot{c} + F_K + \frac{(\dot{m\,c})(1-x)}{\psi_1\,\psi_3^{-1} - m\, c(1-x)}$$

$$\frac{\dot{F_V}}{F_V} = \frac{1}{\psi_1\,\psi_3^{-1} - m\, c(1-x)}\left[-\frac{(1-x)\dot{c}}{F_V} + F_K\left(\psi_1\,\psi_3^{-1} - m\, c(1-x)\right) + (\dot{m\,c})(1-x)\right]$$

Eventually, rewriting (20) as: $\left(1 - c(1-x)\right)^{-1} F_R = \left(\psi_1\,\psi_3^{-1} - m\, c(1-x)\right)^{-1}$ and inserting this result in the above expression, it equals the Hotelling rule for virgin resources (27) .

Appendix C: derivation of growth rates along the balanced growth path for the case of socially optimal economy.

Consider first-order condition (21) and rearrange it as:

$$\psi_3 = \frac{\psi_1 F_R}{1 - c(1-x) + F_R\, m\, c(1-x)}$$

$$\psi_3 = \frac{\gamma\, Y}{R\left(1 - c(1-x)\right) + \gamma\,(V+R)\, c(1-x)}\psi_1 \qquad (\mathrm{C}.1)$$

Substituting this in equation (18) for H_C:

$$-C^{-\sigma}e^{-\rho t} = \psi_1\left[-1 + m(1-x)\frac{\gamma\, Y}{R\left(1 - c(1-x)\right) + \gamma\,(V+R)c(1-x)}\right] \qquad (\mathrm{C}.2)$$

Denoting the term in squared brackets *B* and differentiating the whole expression with respect to time one gets:

$$\rho\, e^{-\rho t}\, C^{-\sigma} - e^{-\rho t}\left(-\sigma\,\frac{C^{-\sigma}}{C}\right)\dot{C} = \dot{B}\,\psi_1 + B\,\dot{\psi}_1$$

To obtain growth rates of variables, the expression is divided by $(\mathrm{C}.2)$. The result is:

$$-(\sigma\, g_C + \rho) = g_{\psi_1} + g_B \tag{C.3}$$

In the long-run steady state of the economy $\dot{C} = \dot{Y} = \dot{c} = 0$.

This implies the coincidence of the Hotelling rule for virgin materials with the one for recycled resources in steady state:

$$\frac{\dot{F_R}}{F_R} = \frac{\dot{F_V}}{F_V} \tag{C.4}$$

Exploiting this result it can be shown that the use of the two material inputs grows at the same rate in steady state. Recall, indeed, that $F_R = A\, K^{\alpha}\, V^{\beta} \gamma R^{\gamma-1}$ and $F_V = A K^{\alpha} \beta V^{\beta-1} R^{\gamma}$; from $(\mathrm{C}.4)$ it follows:

$$\frac{\gamma\left[\dot{A}\, K^{\alpha}\, V^{\beta} R^{\gamma-1} + \alpha\, A\, K^{\alpha-1}\, V^{\beta} R^{\gamma-1}\, \dot{K} + \beta\, A\, K^{\alpha}\, V^{\beta-1} R^{\gamma-1}\, \dot{V} + (\gamma-1) A\, K^{\alpha}\, V^{\beta} \gamma R^{\gamma-2} \dot{R}\right]}{F_R}$$
$$= \frac{\beta\left[\dot{A}\, K^{\alpha}\, V^{\beta-1} R^{\gamma-1} + \alpha\, A\, K^{\alpha-1}\, V^{\beta-1} R^{\gamma-1}\, \dot{K} + (\beta-1) A\, K^{\alpha}\, V^{\beta-2} R^{\gamma-1}\, \dot{V} + \gamma\, A\, K^{\alpha}\, V^{\beta-1} \gamma R^{\gamma} \dot{R}\right]}{F_V}$$

which reduces to:

$$\dot{R}/R = \dot{V}/V$$

Thus, because along the balance growth path $g_C = g_Y$ and $g_R = g_V$, it is possible to conclude that the term *B* is constant.

Add and subtract ψ_3 to the left-hand side of (20):

$$\psi_2 - \psi_3 c(1-x) + \psi_3 - \psi_3 = F_V\, (\psi_1 - \psi_3 m\, c(1-x))$$

$$\psi_2 - \psi_3 = F_V\, \psi_1 - [F_V\, c\, m(1-x) + 1 - c(1-x)]$$

Insert now the expression for ψ_3 given by $(\mathrm{C}.1)$ and rearrange to obtain:

$$\psi_2 - \psi_3 = \psi_1 \left[\beta \frac{Y}{V} - \frac{\gamma\, Y \left(F_V\, c\, m(1-x) + 1 - c(1-x)\right)}{R\left(1 - c(1-x)\right) + \gamma\, (V+R) c(1-x)}\right]$$

$$\psi_2 - \psi_3 = \psi_1 \beta \frac{Y}{V}\left[1 - \frac{\gamma}{\beta} * \frac{\beta\,(V+R)c(1-x) + V\,\big(1-c(1-x)\big)}{R\,\big(1-c(1-x)\big) + \gamma\,(V+R)c(1-x)}\right]$$

Because in steady state $\dot{c} = 0$ and $g_R = g_V$, it follows that the term in brackets is constant. Considering now first-order conditions (22) and (23), it is possible to conclude from the expression above that:

$$g_{\psi_1} = g_V - g_Y \tag{C.5}$$

Expressing the production function (15) in growth rate terms:

$$g_Y = g_A + \alpha\, g_K + \beta\, g_V + \gamma\, g_R$$

and recalling that $(\alpha + \beta + \gamma) = 1$ and that in steady state $g_R = g_V$ and $g_Y = g_K$, the expression above gives:

$$(1-\alpha) g_Y = g_A + (\beta + \gamma) g_V$$

$$g_V = -\frac{1}{1-\alpha} g_A + g_Y \tag{C.6}$$

Inserting expressions $(\mathrm{C}.5)$ and $(\mathrm{C}.6)$ into equation $(\mathrm{C}.3)$ the growth rate of consumption, output (income) and capital along the balanced growth path of the optimal economy is derived: equation (28).

Furthermore, substituting the result (28) in expression $(\mathrm{C}.6)$ the rate of use of the two material inputs is obtained: equation (29).

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