



**S.A.P.I.EN.S**

Surveys and Perspectives Integrating Environment and Society

**3.1 | 2010**  
**Vol.3 / n°1**

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## Is recycling “part of the solution”? The role of recycling in an expanding society and a world of finite resources

**François Grosse**

Gaëll Mainguy (éd.)

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### Édition électronique

URL : <http://journals.openedition.org/sapiens/906>

ISSN : 1993-3819

### Éditeur

Institut Veolia

### Référence électronique

François Grosse, « Is recycling “part of the solution”? The role of recycling in an expanding society and a world of finite resources », *S.A.P.I.EN.S* [En ligne], 3.1 | 2010, mis en ligne le 10 février 2010, consulté le 23 octobre 2020. URL : <http://journals.openedition.org/sapiens/906>

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## Perspectives

# Is recycling “part of the solution”? The role of recycling in an expanding society and a world of finite resources

François Grosse

Veolia Propreté. Special Advisor to the CEO.

Correspondence to: francois.grosse@veolia-proprete.fr

### Abstract

Since the 1990s, recycling of waste has become a core element of sustainable development. However, in this article, analysis of the flow modelling shows that recycling in itself is inefficient to perform the necessary “decoupling” of economic development and the depletion of non-renewable raw materials. The depletion of the natural resource of raw material is inevitable when its global consumption by the economy grows by more than 1% per annum. Recycling can delay for some years or decades at best.

Decoupling the economy and its material needs must be understood as a double decoupling, the two components of which being inoperative if they are implemented separately. Only the combination of the two makes a significant impact on the problem of resources:

(i) A fundamental decoupling, namely to restrain the growth of total consumption of raw material (virgin or recycled)

(ii) A relative decoupling to reduce, through recycling and reuse, the share of primary resources (virgin) in the total production of raw material.

In this perspective, the actual role of recycling to protect the resources is not significant for non-renewable materials which consumption tends to grow more than 1% per year. Conversely, once the fundamental decoupling is performed by other means, so that the growth of total consumption of raw materials is reduced below 1% per year, recycling becomes indispensable if the rate of effectiveness is very high globally. Only recycling rates above 80% allow a significant slowdown of the depletion of natural resources.

In conclusion, sustainable development policies can not rely primarily on recycling, even though it is an important component. These policies should primarily aim at reducing the consumption of each non renewable raw material so that the annual growth rate remains under 1%. And in any case, to be efficient as the indispensable second part of these policies, recycling should be developed to much higher rates than the ones observed for most recycled materials in the world today.

**Keywords:** Recycling, exponential growth, limits to growth, commodities, reduce, consumption.

## TABLE OF CONTENTS

1. Introduction
2. The example of steel production
3. The impossible “extension of the curves”
  - 3.1. Economic growth drivers: demography
  - 3.2. Economic growth drivers: standard of living
  - 3.3. Economic growth drivers: no alternative today
4. Limits of recycling in an expanding economy
5. Recycling today in the event of a curb on future consumption
6. Stabilisation or regression in the need for raw materials
7. A map of recycling’s contribution to conservation of resources
  - 7.1. Generic map of the impact of recycling
  - 7.2. Exemple of iron and oil
  - 7.3. The case for lead
8. The essential dual “decoupling” of the economy
9. Decoupling economic development from materiality
10. The appropriate role of recycling
11. Resources and recycling: an adjustment of priorities

## 1. INTRODUCTION

Biodiversity erosion, climate change, degradation of soils and ecosystems and so forth all show that the constant acceleration of material development in our societies is bringing closer, and at accelerating speed, limits which reveal our “planet confinement”<sup>1</sup>.

The depletion of non-renewable resources is a particularly acute issue. Metal ores stem from non-renewable resource stocks. Predictions as to how long world reserves of the different metals will last depend on a host of different assumptions, notably about the pace of economic growth, price trends and technological development (OECD, 2008). Nevertheless, for many metals and most scenarios, with current production and consumption patterns, and considering estimates of total world resources (USGS, 2009), natural stocks will run out some time this century or in the early years of the next.

To tackle these problems, the 3Rs Conceptual framework—Reduce, Reuse, Recycle—sits imposingly on the international political agenda as illustrated by the 3R Initiative, officially launched at the Ministerial Conference in Tokyo in 2005, or the Kobe 3R Action plan (G8, 2008). The 3Rs Conceptual framework aims to establish a sound material-cycle society which does not waste valuable goods or materials and limits the impacts of economic development on non-renewable resources.

If recycling can reduce energy consumption and greenhouse gas emissions, it is primarily expected to play a key role in curbing the exponentially accelerating human consumption of non-renewable natural resources. Accordingly, the paramount importance of recycling is now widely shared by decision makers, industries and citizens.

Yet, in this work we show that the impacts of recycling are very limited if the growth of total consumption of raw material exceed 1% per year—a prospect difficult to envision today.

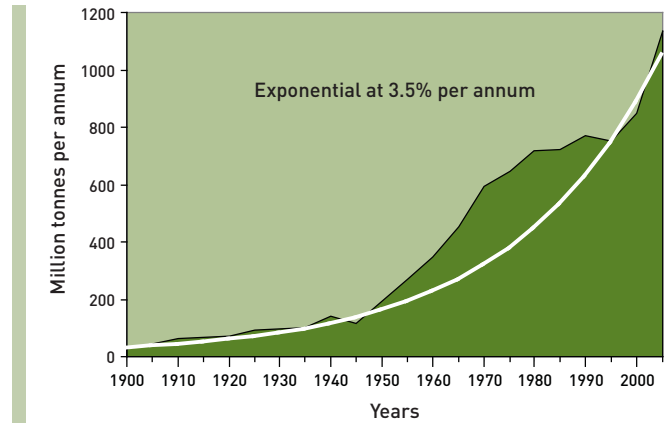


Figure 1: Global crude steel production. Source: IISI & (Dourille, 1981)

## 2. THE EXAMPLE OF STEEL PRODUCTION

The example of steel is emblematic of industrial economies. Annual production of steel has increased on average by 3.5% per annum between 1950 and 2007 (see Figure 1). It was multiplied by 30 during the 20th century. To feed that growth, global iron ore production grew at the pace of 10% per annum from 2002 to 2007 (Chalmin & al, 2010).

Figure 1 shows that the exponential growth concept is appropriate. The curve in white is an exponential with a 3.5% annual growth. For 70 out of the 105 years under consideration, it is a faithful representation of actual developments with a single notable divergence in the boom years between 1950 and 1970, after which it gradually re-converges over the next twenty years. The global GDP growth rate in recent times resembles that of steel production. Between 1950 and 1998, it was 3.9% on average per annum (Maddison, 2003).

One of the key challenges of ‘sustainable development’ lies obviously in extrapolating such curves, which is in itself no great news. If the annual growth of 3.5% for steel production in the 20<sup>th</sup> century is extended over 150 years, the figures are impressive (figure 2):

In one century, in 2110, annual production would have to be multiplied again by more than 30 (but this time based on today’s figures).

In 135 years, production would have to be multiplied by 100 times, which means that in one year as much steel would be produced as in a century at today’s rate.

Within a century, aggregate production would equal 878 times the production of year 1. This means that, at this accelerated rate, we will have produced during the 21<sup>st</sup> century almost as much steel as in a millennium at today’s rate.

The flattened part of the curve, on the left, is still exponential. It corresponds to the curve for the production of steel between 1900 and 2008, shown in the previous diagram. This illustrates how difficult it is

<sup>1</sup> As coined in a recent book (Lebeau, 2008).

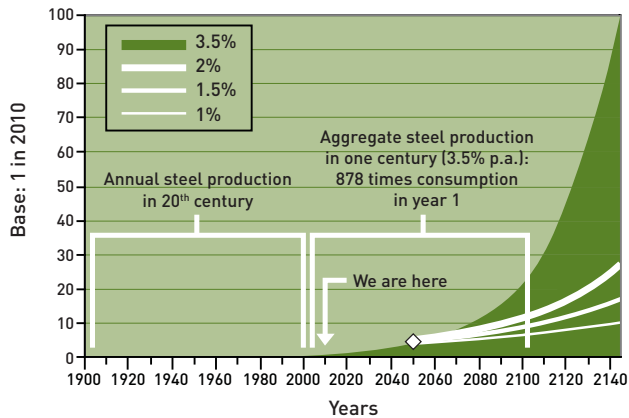


Figure 2: Extrapolation of a steady annual growth at different growth rates

to imagine and transpose the accumulated effects of an exponential progression in real terms, even at the apparently innocuous annual rate of 3.5%. If the 3.5% growth rate is perpetuated, the reasoning applies also for the following 135 years: again annual production is multiplied by 100. This would mean that, in 270 years, we would be producing 10,000 times more steel than today!

This plainly shows that the model is absurd. Most probably, we will not be producing on this earth in 270 years 10,000 times more metal than today with industrial processes comparable to those we are using now, nor even with revolutionary technological innovation. Nor we will be extracting annually 10,000 times more ore than we are doing now.

Above all, iron ore world resources are estimated to exceed 800 billion tons of crude ore containing more than 230 billion tons of iron (USGS, 2009). Given that the annual global production of iron ore was 1.6 billion tons in 2007 (Chalmin & al, 2010), these world resources should be exhausted by 2129 with only a 2% annual growth rate of extraction, and before the end of the century with a 3.5% growth rate.

### 3. THE IMPOSSIBLE “EXTENSION OF THE CURVES”

Economic and industrial development will not therefore be simply an “extension of the curves”, which is hardly a surprise.

There are three possible alternatives, which are not mutually exclusive:

The most obvious would be a slowing down of the annual growth of the global economy, together with a decline of industrial production and therefore of the production and extraction of raw materials. This is the scenario proposed by the Meadows report in 1972.

The second scenario would be an economy shifting increasingly to services, to the detriment of industry, decoupling thereby the need for raw materials from the economic growth.

The third possibility is that the use of virgin resources by industrial production progressively dwindles and switches massively to inputs obtained via recycling.

#### 3.1 ECONOMIC GROWTH DRIVERS: DEMOGRAPHY

The medium scenario published by the United Nations (2006), forecasts a relative stabilisation of global population around 9 billion human beings with an annual growth of only 0.37% in 2050. For the sake of comparison, the average growth in population was 1.37% per year in the 20<sup>th</sup> century and 1.77% between 1950 and 2007 (Maddison, 2003).

The demographic component of global economic development is expected to decline considerably in the next few decades, particularly in the emerging countries where growth is now the strongest.

But population growth is far from being the only driver of recent economic expansion. The process by which emerging countries catch up with the standard of living of more advanced economies is, in fact, an even more powerful actuator.

#### 3.2 ECONOMIC GROWTH DRIVERS: STANDARD OF LIVING

In 2008, 16% of humanity, i.e. one billion people, produced 57% of the world’s GDP in purchase power parity (WDI, 2009). In 40 years time, according to the UN medium variant, there will be some 9 billion human beings (UN, 2006). In 2050, the global production would have to triple to raise the entire human population to the average level of economic development now enjoyed by the most prosperous countries. It would roughly mean adding about 150 trillion US dollars GDP to the 60 trillion that humankind altogether now produces. The likelihood of such a scenario is not the subject of this discussion which is solely concerned with its consequences on resources.

To bring about such an increase in economic activity over the space of 40 years, for example (2010-2050), would correspond to an annual growth rate of 3.0% which is not far from the historic progression of steel production. This rate of growth, however, would not accommodate the appetite of rich countries for maintaining their own growth rate in parallel, which would contribute 0.5 - 1% to the above value.

This therefore concurs with the views that the global economy should continue to grow (at 3 to 3.5% per annum) to allow the poor to emerge from poverty.

That being so, and even if this turns out to be realistic, once the global population has stabilised somehow and the underprivileged have attained the same standard of living as developed countries following our hypothetical pattern, the economy would be left with another important driver.

#### 3.3 ECONOMIC GROWTH DRIVERS: NO ALTERNATIVE TODAY

Today, a stable economic and social model without growth is not conceivable. There is no country in the world which rejoices, for

the sake of future generations, in the prospect of negative population growth or of economic recession. This is not only for reasons of national pride, but also because both trends have a direct effect on increasing the burden of public deficits and unemployment. On the contrary, “sustainable development” consists precisely in reconciling continuing economic development with a very long term view.

To this question, a number of economists will therefore respond by assuming that, in the very long term, humanity having become relatively rich in most parts of the world, there should be a pattern of economic growth similar to what is currently the case in the richer western countries, where population growth has already more or less stabilised, i.e. to about 1.5 to 2.5% per annum (average annual growth of GDP in the Euro zone between 1996 and 2005: 2.1%, OECD, 2009).

Figure 2 compares different rates from 1 to 3.5%, depending on the extent to which the substitution of services for the production of material could reduce the needs for raw materials.

The smaller the rate the flatter the increase but all curves present the same pattern of exponential growth. Even for a 1% scenario, we will be consuming about 18 times as much during the 21<sup>st</sup> century as we did in the 20<sup>th</sup> century. And 65 times as much in the 22<sup>nd</sup> century. In the very long term, a sea change in the economy and production processes is still just as necessary — and therefore as certain — as it was with a higher rate.

If the economy is to continue to grow in the very long term, even very slowly, it will therefore be at the price of a substantial decoupling from the use of non-renewable raw materials, and the disconnection is imminent.

#### 4. LIMITS OF RECYCLING IN AN EXPANDING ECONOMY

Could recycling play a major role in this decoupling between economic development and the need for material resources? Intuitively, the answer seems to be “yes”: if we recycle massively, we will be reducing the consumption of virgin raw materials just as massively. For example, recycling 80% of a raw material means that the need for natural resource is divided by five. This impressive figure suggests that if a resource is recycled efficiently, it would take five times longer to exhaust this resource. A lifespan of 100 years would become 500 years thanks to recycling. The magnitude is certainly disputable in geological terms or in regard to the history of mankind, but it is still worthy of notice and esteem in terms of public policies and quite sufficient to serve as a springboard for energetic action. The very long-term problem is not entirely solved, but it does seem to be significantly lessened.

Unfortunately, this rationale is faulty. Or rather, it would only be correct in a situation where consumption is either in linear progression, stable or in regression.

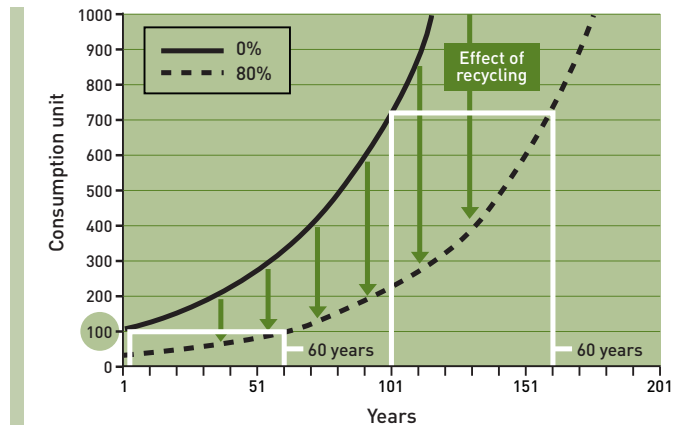


Figure 3: Effect of recycling if annual growth rate of raw material consumption is constant. The annual consumption curve of virgin material is flattened by the effect of recycling. But when, after 60 years, consumption with recycling also overtakes the 100 value point, the dashed curve becomes identical to the other curve, except for a shift of 60 years. In this example, after 100 years, only 200 will be drawn from the natural resources with recycling at 80%, whereas it would already be 700 without recycling. But the 700 mark will be reached only 60 years later with recycling and we will never gain more than 60 years with recycling if the progression of total consumption remains unchanged.

*In this example: the annual growth is 2% and the average residence time in the economy for the material under consideration is 7 years.*

If there is sustained or exponential economic expansion, even very moderately so, the analysis must be dynamic instead of static and the conclusions are radically different:

- no, mankind will not be heading much more slowly towards total resource depletion if we recycle, we will just get there a bit later
- no, the scarcity at the end of 100 years without recycling will not be reached in 500 years with 80% recycling; but only in 135 years if annual consumption growth is 3% (160 years if annual growth is 2%<sup>2</sup>).

In fact, if consumption grows steadily at a constant rate, *the consumption curve of a natural resource remains identical in time, with or without recycling (see figure 3).*

The only effect of recycling is that the curve is delayed. After some time, the values revert to exactly what they would have been without recycling. And the “delay” is identical after 50, 100 or 200 years.

This can be explained very easily: if consumption increases by 2% a year, and annual recycling is constant, the consumption of the virgin material (not recycled) also increases by 2% a year. At some point, the level that would have been reached in year 1 without recycling is arrived at and, from then on, the two annual consumption curves become identical - but they are staggered.

So, what is the maximum amount of time recycling can provide before a resource is depleted?

<sup>2</sup> For residence in the economy of the material for 7 years (see below)



Calculating the relationship between the duration of the aggregate consumption deferment of a virgin material, its recycling rate, and the growth rate of its annual consumption provides a measure of the role of recycling, in the various circumstances.

Another parameter needs to be introduced for this operation: the time during which a material remains resident in the economy. The material is first produced in a usable form, based on both “primary” and “secondary” raw materials: ore (taken from non renewable resource) or recycled waste; it then goes through a manufacturing and distribution circuit before going to the consumer who, after using it, makes it once more possibly available in the form of scrap material or waste. Depending on whether the material concerned is lithium for batteries or iron for reinforcement bars, the total time separating initial production from return to waste product varies considerably: we call this duration ‘residence time in the economy’<sup>3</sup>.

The residence time is crucial for our analysis, since it defines the quantities of material which are available for recycling at a given time. Defining these values is extremely difficult, particularly when the material is used for a variety of purposes. For instance, iron is used for tinned foods, for cars and for housing construction which have obviously different residence times.

An empirical approach consists in evaluating the total quantity of material available in the form of waste and comparing the increase in this estimated deposit with the annual production curve of the material. The time lag between the two curves would be the average length of residence in the economy for the material in question.

With this approach, the recycling rate is defined, not as the amount of recycled material compared to the total production of the raw material at a given point in time, but as the amount of the material effectively available in the waste which is reintegrated thanks to recycling in the production circuits.

Let’s take lead as an example. The production of lead owes 51% to recycling and is used to 80% for batteries<sup>4</sup>. With an assumed average residence time in the economy of 7 years, and taking into account the annual growth of production of 3.4% per annum in recent times, 1999-2007<sup>5</sup>, quantities produced today are 26% greater than those produced 7 years ago — that is those available hypothetically in waste, in one form or another. The recycling rate is therefore some 64% of the quantities released in waste, and therefore much higher than the apparent rate of 51%.

The calculations for the mathematical relationships between these various values are detailed in the annex. The two equations below provide respectively the time lag for accumulated consumption<sup>6</sup> and the recycling rate, in relation to the other parameters.

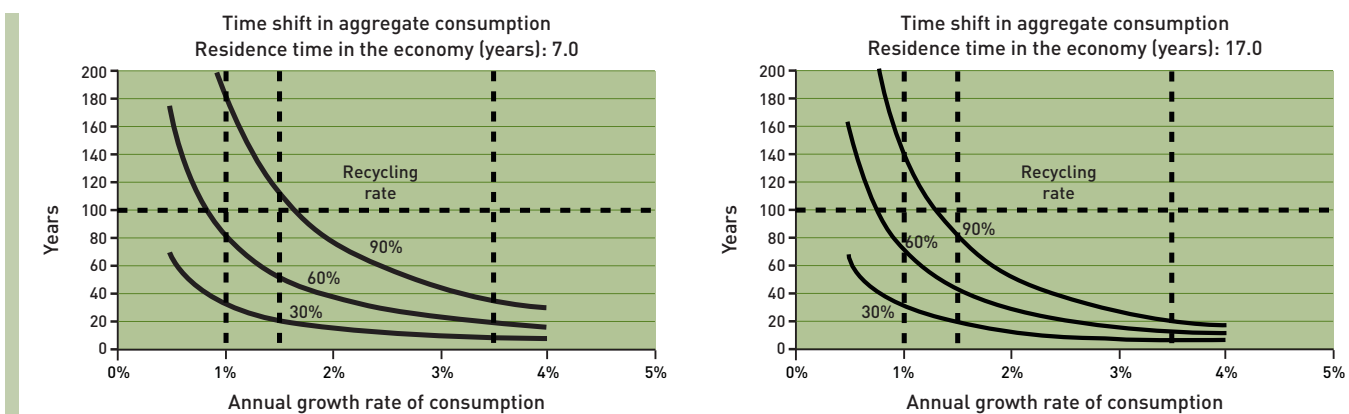
$$d = ts - \frac{\log(a^{ts} - R)}{\log a} \quad R = a^{ts} (1 - 1/a^d)$$

R	%	Recycling Rate
ts	Years	Residence time of the material in the economy
a	%	Raw material needs growth rate
d	Years	Time lag of aggregate consumption

This is the time lag between the situation *with* and the situation *without* recycling. In order to evaluate the impact on time of a change in the recycling rate, for example from 20% to 60%, all that is needed is to observe the difference in duration produced by the two rates.

Figures 4 pictures the time lag for aggregate consumption as a function of the growth rate in the consumption of a material— which could be lithium, lead, any material—, for various recycling rates between 30 and 90%.

Coming back to the original question “what is the maximum amount of time recycling can provide before a resource is depleted?” it appears that:



Figures 4: Time lag for aggregate consumption as a function of the growth rate in the consumption of a material. Two situations are illustrated: an average residence time in the economy of 7 years on the left panel and 17 years on the right panel.

<sup>3</sup> Residence Time is a broadly useful concept that expresses how fast something moves through a system in equilibrium. Here it is the interval of time between the date a material is produced and the date it ceased to be used.  
<sup>4</sup> Source: International Lead and Zinc Study Group - www.ilzsg.org  
<sup>5</sup> Source: US Geological Survey - www.usgs.gov  
<sup>6</sup> Or, to be more precise, the maximum value of this time gap that is the upper limit when the time elapsed tends to infinity.

- The time lag for aggregate consumptions highly depends on the total growth rate of consumption of a material. The slower the growth, the more recycling contributes to “a time gain” before the resource becomes scarce.
- It is almost impossible to attain, by recycling alone, a time lag greater than 100 years if the growth rate is higher than 2% per annum.
- For a growth rate higher than 3%—as in the last 100 hundred years for the production of steel—recycling only has a minor if not marginal effect on conservation of the resource.
- For materials which stay in the economic cycle for a significant length of time (e.g. iron), recycling cannot provide a gain of more than twenty years of aggregate consumption.
- Steel is far and away the material which is subjected to the most recycling, worldwide. And yet, at the present rate at which it is increasingly produced and consumed, (i.e. 3.5% annually over the 20<sup>th</sup> century, see above):
  - The recycling rate, currently about 62% globally<sup>7</sup>, is only saving mankind approximately 12 years before iron becomes scarce. This means that the aggregate consumption of iron ore over time will be in 2013, what it would have been in 2000 if there was no recycling at all and, in 2063, what it would have been in 2050 if we now stopped recycling altogether.
  - Unless the increase in global steel consumption is slowed down, reaching a 90% level of recycling would only produce a gain of 7 extra years.
- For growth rates in consumption of the raw material greater than 2% per year, recycling could only claim a contribution to preserving the resource if it was extremely ambitious: a rate of under 60% would only yield 20 to 40 years of extra time before scarcity.

- For a growth rate of about 1 to 1.5%, a dynamic recycling policy could yield 50 to 120 years of reprieve.
- Below an annual growth rate of 1%, the positive effect of recycling on the resource is greater and could yield significantly over 100 years of extra time.

## 5. RECYCLING TODAY IN THE EVENT OF A CURB ON FUTURE CONSUMPTION

In the above, reasoning was based on the current context of a significant growth in consumption of the various raw materials. But the curves shown in the first section confirm that this is no longer a sustainable option. One way or another, sooner or later, the increase in the need for raw materials will have to slow down, since for example, multiplying by 10,000 the production of steel and the extraction of ore in the next 270 years is simply inconceivable.

Should we therefore ignore the current trends in our discussion of recycling and evaluate the consequences of our current policies exclusively in the light of these future developments?

From the strict point of view of the quantitative impact on the conservation of resources for future generations, this means we must investigate the weight of past actions on aggregate consumption in the event of a major slow down of consumption of those resources in future.

Let us return to the example of steel production, supposing for instance that it continues with an average increase of 3.5% annually until 2050 and then, suddenly becomes stable (figure 5). The cumulative efforts to recycle scrap iron during the whole of the 20<sup>th</sup> century represent, post 2070, only 5 years' worth of iron ore consumption and under 2 years of steel production.

Apart from the prospect of an imminent slowing down in consumption growth, the contribution of recycling to preserving a resource in an expanding economy must therefore be appreciated solely in relation to the current economic situation.

## 6. STABILISATION OR REGRESSION IN THE NEED FOR RAW MATERIALS

The possibility of stagnation, or even regression in the need for raw materials obviously throws an entirely different light on the situation. The role of recycling would then match the intuitive approach outlined at §4: it does not delay future developments by a few years, it slows them down proportionately.

Figure 5 shows this change in perspective on the right hand side, after 2070, when production and recycling become constant in our scenario.

By recycling 50% of a material for which global needs are constant, we are no longer merely delaying inevitable outcomes by 30 or 40 years. In fact, we are doubling the lead time to those outcomes, however far away they may be.

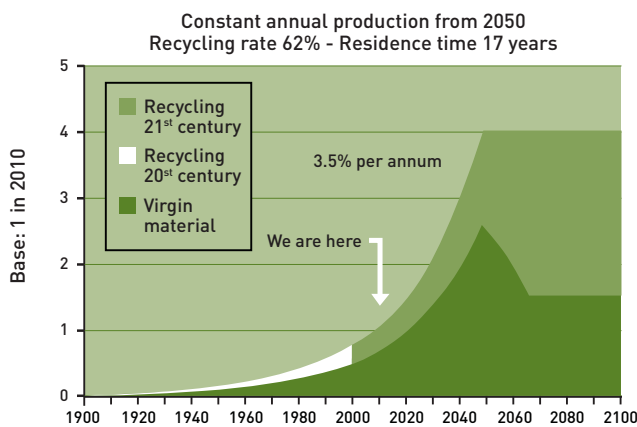


Figure 5: Case of a stable annual production after 2050. The progression over two centuries of total production<sup>5</sup> is depicted, with the addition of the shares represented by recycling (above) and by the virgin material, i.e. the ore (below). The area in white represents the accumulated quantities of scrap iron recycled in the 20<sup>th</sup> century. The plain area in grey is the total amount of steel produced over two centuries using ore. In fact, the first area is minute compared to the second one.

<sup>7</sup> Author's calculation, based on IISI data and (Chalmin, 2009, Chalmin & al, 2010). According to these sources, with 479 million tonnes scrap collected in 2007 and a steel production that year of 1,345 million tonnes, the apparent recycling rate of steel is 36%. Assuming a 17 year residence time in the economy, and with an annual production of 770 million tonnes in 1990, the 'real recycling rate' would be 62%: proportion of steel entering the economy in 1990 which is recycled 17 years later, having theoretically become waste in the meantime.

<sup>8</sup> By a way of simplification, steel production over the 20<sup>th</sup> century is shown as exponential in the figure. Anomalies are not represented.



And if needs were to regress with time, recycling could even claim to satisfy the major portion, or even theoretically, all of those needs, depending on the assumptions. But the effect of that slowing down again is greater by far than that produced by recycling (cf. figure 6).

## 7. A MAP OF RECYCLING'S CONTRIBUTION TO CONSERVATION OF RESOURCES

The above shows that an assessment of the contribution of recycling to preserving a natural resource does not lead directly to one single conclusion. Highly contrasted situations must be entered into the equation depending on the characteristics in economic terms of the raw material involved.

The essential issue in this respect is the one we have been considering all along: how much time does such a policy buy for future generations before they are faced with a depletion of the resource?

### 7.1 GENERIC MAP OF THE IMPACT OF RECYCLING

Depending on the way global needs for the raw material concerned evolve, the contribution of recycling can be summarised on a map (see figure 6).

By positioning some of the materials on this diagram we gain an indication of the current situation:

- One material with a long residence time, such as iron (17 years in this case).
- Two materials with a short residence time, such as lead or oil (in this case, 7 years).

### 7.2 EXEMPLE OF IRON AND OIL

As apparent on figure 6, although recycling scrap iron plays a major role in the global economy, it only makes a trifling contribution to avoiding a depletion of iron resources, taking into account the growth rate of steel production. As long as the growth rate of global production is greater than 3%, recycling can only be powerless in delaying depletion of deposits.

We can also consider oil, a non-renewable raw material required for the manufacture of plastics. After a growth rate of around 6% per annum until 1970, the growth in production of crude oil has fallen to less than 2% annually since 1985. Plastics, however, only represent some 4% of the use of crude oil<sup>9</sup>. Even though much plastics are recycled worldwide, clearly the effect on the conservation of this resource is bound to be of little consequence on the depletion of the resource (which does not affect on the other hand the significant role of plastics recycling in limiting CO<sub>2</sub> emissions).

### 7.3 THE CASE FOR LEAD

Finally, while the recent growth in production and the rate of recycling for lead are similar to the figures for steel, the recycling

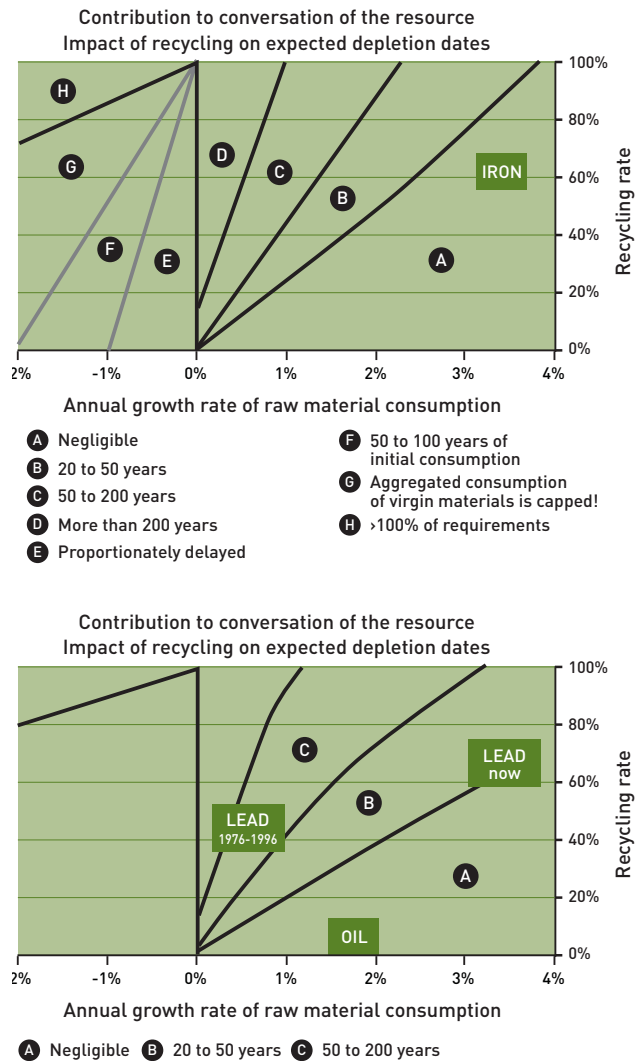


Figure 6: Map of the impact of recycling on expected depletion dates. The graph is represented for a residence time in the economy of 17 years (above) or 7 years (below).

results for lead are slightly more favourable from the point of view of its contribution to preserving resources: its residence time in the economy being shorter than that of steel, recycling efforts apply to available quantities which are proportionately higher, despite the growth in production. Lead, furthermore, is a particularly good illustration of our analysis, because statistics for global production using virgin or recycled material have been relatively well documented for the last thirty years and its recent history shows two relatively consistent, but distinctly different, phases of growth in production (see figure 7).

During the 80s, the underlying trend in the growth of global lead production was of the order of 0.7% per annum, whereas it then shifted significantly to approximately 3.4% per annum<sup>10</sup>. In parallel, its recycling rate increased considerably on a global scale, from approximately 45% in the 80s to roughly 64% now (real rate).

<sup>9</sup> Source: PlasticsEurope - www.plasticseurope.org  
<sup>10</sup> Source: US Geological Survey - www.usgs.gov



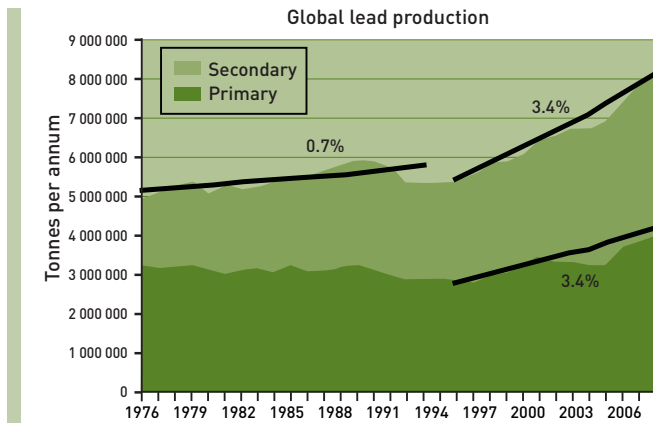


Figure 7: Global lead annual production and trends.

And yet, production statistics show that recycling in the 80s, however moderate, was sufficient to stop the global consumption growth of virgin material and that its gradual increase, due to some extent to the fact that lead was increasingly used for batteries (more easily recycled), led even to a very slight downturn in global mining production. But once the rate of growth of consumption progressed to over 3%, the high recycling rate was no longer able to compensate for the increased extraction.

As of 1995, the underlying growth of primary production became identical to that of total production (3.4%), conforming to our theoretical approach, and if this rate continues, primary production in 2015 will be close to total production in 1995, evidencing the time lag of around 20 years that was also foreseen by the theoretical approach<sup>11</sup>.

## 8. THE ESSENTIAL DUAL “DECOUPLING” OF THE ECONOMY

In the first part of this work, we saw that the economy is not providing any evidence of spontaneous symptoms, nor even of discernible signs of some imminent trend in the direction of a decrease in global needs for raw materials. And yet, recent economic developments in their consumption, if they were to continue unabated, would lead to such preposterous orders of magnitude within a century or two, or even within a few decades, for us to confidently predict that some changes in industrial and economic processes are bound to occur in the relatively short term.

The last part of our analysis confirms the intuition that recycling must needs be the major component of a sustainable resources policy, providing that economic needs for raw materials are stabilised, or nearly stabilised or even made to regress.

However the central thrust of this reflection also leads to an important conclusion: recycling can only play a minor role in this “cooling down” of the raw materials consumption dynamics. Recycling will never make a significant contribution to a

decoupling of sustained economic development from growth in the consumption of raw materials. It is only once the need for raw materials is stabilised, by other means, that recycling can contribute appreciably, or even enormously, to the conservation of natural resources for future generations.

This conclusion is in direct contradiction with one of the most widely held convictions, i.e. that the development of a “circular economy”, based mainly on recycling and re-use, would be the cornerstone of the necessary decoupling of economic development from the depletion of natural resources. In essence, this is the stated aim of the law on Circular Economy which came into force in China in 2009, the motivations of which the introduction to a recent World Bank report sums up as follows:

*“China’s rapid economic growth over the past decades has been accompanied by substantial depletion of natural resources, degradation of major ecosystems, and serious environmental pollution with adverse impacts on human health. China’s government fully recognizes that such trends cannot continue indefinitely and therefore is committed to building a resource-saving and environmentally- friendly society as a stated national policy. It has adopted the Circular Economy (CE) approach (sometimes also translated as “recycling economy”), where CE can be translated as an economy that maximizes reduce/reuse/recycle strategies (referred to as the 3R approach) to reduce resource inputs and pollution discharges per unit of production. CE is becoming a core component of its sustainable development strategy. The ultimate objective of the CE approach is to achieve the decoupling of economic growth from natural resource depletion and environmental degradation. [...]”* (World Bank, 2009).

With a GDP growth range between 7.6 and 14% per annum over the last 15 years (OECD, 2009), based mainly on the still higher progression of its industrial production, it is obvious in the light of our analysis that China will be unable to decouple, via recycling, the continuation of its economic development from the depletion of natural resources. It is true that the Chinese programme includes the first of the three “R”s, to be understood here as a reduction in the use of resources (or improving efficiency in the use of resources). But its priority indeed seems to be closing the “loop of resource development, production, consumption, waste generation, and recycling”. The World Bank report notes furthermore, in the chapter “More Efforts are Needed”: “*The rapid economic growth of China presents a major challenge: overall resource consumption in China since the introduction of initial CE measures has continued to grow. The effects of increasing growth on resource use were not offset by improvements in resource use efficiency. Even with increased use of the 3R principle, total net resource use continued to grow. In some cases, puzzlingly, recycling rates even declined*”. On this subject, the report quotes the steel recycling rate, which declined from 23.49% in 2000 to 20.1% in 2004.

<sup>11</sup> Calculated time lag: 21 years for 7 years of presence, 64% recycling and 3.4% growth.



In fact, with an average growth rate of steel production of nearly 22% per annum between 2003 and 2007 (Chalmin & al. 2009), China cannot hope to solve the thorny problem of maintaining its iron resources by the use of a circular economy. Chinese imports of recycled scrap metal represent a bare 1 to 3% of its total production and its own recycling applies to available annual volumes inherited from the era preceding the economic boom (through the effect of the "residence time" in the economy), so that they are extremely low in proportion to current needs (Chalmin, 2009, Wu, 2006). The 20.1% recycling rate is the apparent rate (the amount of recycled metal in the steel production inputs) and is equivalent to a very high real rate in the framework of this analysis, because of the very high economic growth rate, as the author of the report rightly emphasises (Wu, 2006). The recent acceleration of steel production growth in fact explains mechanically the drop in the apparent rate. But even if a real recycling rate of 80% is chosen, applying the formula described above leads to an aggregate consumption time lag of about 6 months with an underlying growth of only 15%, or 7 weeks if the 22% growth observed between 2003 and 2007 is selected!

In France, the "Grenelle Environmental Consultation" emphasises two opinions in parallel:

– *"The environment, economic development and social progress can all be served, but production and consumption practices will need to be thoroughly revised [...]"*

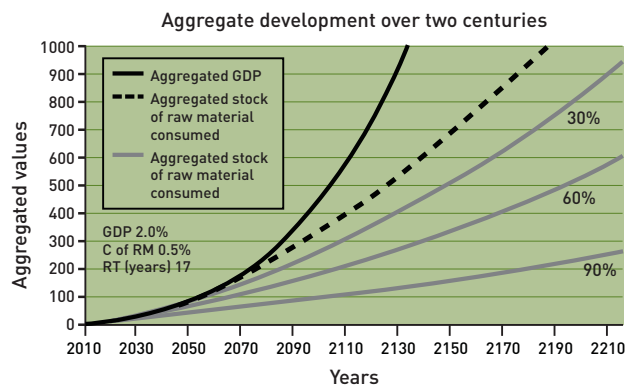
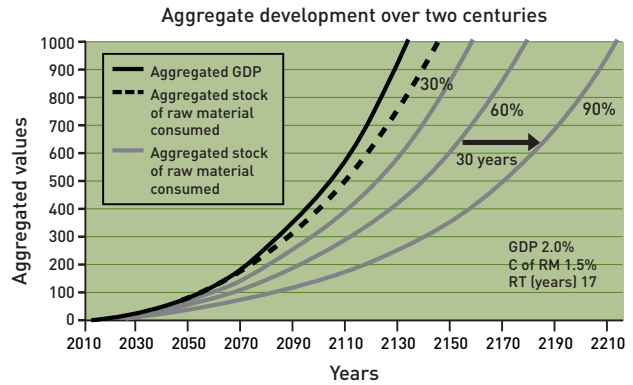
*"This revision must be part of a more general strategy decoupling the creation of wealth from the consumption of energy, natural resources and materials [...]"*<sup>12</sup>

In France, as in China (and elsewhere), sustainable continuation of economic growth, in a climate of scarcity, or rather despite it, is a declared national objective.

The "Grenelle" document then points out two paths to achieve this decoupling of development from raw materials: *"a circular economy, based on waste reduction and recycling [...]"* and *"an economy of functionality, (product-service system) replacing the marketing of goods by marketing their use."* Expecting recycling to be the main springboard for decoupling the economy from resources is not realistic for France, just as it is not for China (on a different scale, given the different growth rates).

In the final analysis, to reconcile sustainable development and the constraint imposed by the scarcity of resources, two successive steps of decoupling must be orchestrated worldwide, not just one:

- The *fundamental decoupling* of economic development from total consumption of the raw material, be it primary or secondary (virgin or recycled);
- Followed by the *relative decoupling* of total consumption of raw materials from consumption of virgin materials, through increased recycling.



Figures 8: Impact of fundamental decoupling and of recycling on raw material's aggregate consumption. Base 1 is GDP 2010 - Total consumption of raw material in 2010.

As we have already demonstrated, the second kind of decoupling has no significant impact if it is not preceded by the first kind.

As we shall see below, the first kind can only lead to disappointment if it is not followed by the second.

By throwing together, under the single concept of decoupling, a whole range of instruments, pertinent certainly, but listed without any order of priority, it is suggested that their effects can be cumulative. But in fact, they should be multiplied: which means that the effect of the whole is nil or almost nil if one of the two decouplings is incomplete.

Figures 8 illustrates, in another form, the distinction to be made between the two decouplings and also their complementarity. They represent the aggregate consumption stocks (or production) from 2010 onwards, instead of, as before, the annual consumption. The assumption is an annual GDP and consumption of materials growth of 3.5% until 2050, after which a drop to 2% for GDP and to 1.5% (respectively 0.5%) for total consumption of the raw material.

In the 1.5% scenario, (above), decoupling between economic development and the need for materials is inadequate since the growth in total needs for raw materials is still too high and

<sup>12</sup> Le Grenelle Environnement – Groupe VI - Promouvoir des modes de développement écologiques : « Synthèses et principales mesures »

recycling only has the temporary and marginal effect discussed above: the amount of virgin raw material consumed — and therefore the depletion of a non-renewable natural resource — grow at a dizzying rate and recycling only provides, just once, a few extra years. In the absence of fundamental decoupling, relative decoupling is pointless.

In the event of an annual growth of 0.5% in the need for raw materials, (below) decoupling of economic development from the need for raw materials is achieved. But this fundamental decoupling alone is clearly insufficient, as is shown by the shape of the dotted curve (total stock of aggregate raw material consumption, therefore stock of aggregate consumption of the virgin material in the absence of recycling).

But it does allow (at last!) recycling to have an effect, provided it is very ambitious, and to offer several centuries of extra remission — which, transposed to a contemporary historic scale (two hundred years in this instance), leads to a notable flattening of the aggregate drawdown curves for the resource.

As regards the conservation of non-renewable raw materials, the first priority and the greatest economic and social challenge for sustainable development is definitely not increasing recycling and promoting a circular economy. Before even broaching the issue of recycling, what needs to be done is simply to slow down, worldwide, the growth in the consumption of raw materials to well under 1% per annum. There is no other way out of the quandary.

## 9. DECOUPLING ECONOMIC DEVELOPMENT FROM MATERIALITY

This challenge is by no means a natural evolution for economically developed societies. It is sometimes mentioned in conjunction with the undeniable deindustrialisation of the most developed countries: since the economy of rich countries is becoming more service-based, this would mean that the creation of wealth is moving in the direction of dematerialisation. This is absolutely not the case: some services are based on material assets, some of which may be produced in other countries, but contribute to the creation of wealth in the user countries. In fact, the quantity of waste that is produced is a fairly direct indicator of the materiality of wealth: wherever the material is manufactured, the place where it becomes waste material is the one where it contributed ultimately to the creation of wealth. In France, for example, household consumption increased on average by 2% per annum between 1975 and 2004<sup>13</sup>, while the total amount of household waste (including recyclables) grew by 3.3% per annum during the same period<sup>14</sup> (10 million tonnes in 1975 increasing to 26 million tonnes in 2004). The economy “*materialised*” more than ever.

A “cooling down” in the consumption of raw materials could, in the future, be the result of an underlying upturn in prices, supposedly reflecting their growing scarcity or their lesser accessibility.

Three considerations, however, mitigate this optimistic assumption:

- The history of variation in the price of raw materials does not generally endorse theoretical approaches to the economics of scarcity, in particular “Hotelling’s rule” which stipulates that the marginal rent of a non-renewable resource grows in theory at the same pace as the economy’s interest rate (Krautkraemer, 1998). On the one hand, while the finiteness of a given resource is a theoretical certainty on a planetary scale, in practice it remains a hazy and quantitatively fluctuating entity, constantly reviewed in the light of newly discovered deposits, diversity in the quality of ores and developments in extraction and production technology. On the other hand, fluctuations in demand, an imperfect market and developments in the cost of extraction and production never cease to disturb the “scarcity-price” signal (Krautkraemer, 1998).
- It is in no way substantiated that the empirically pertinent time scale on the raw materials market is compatible with what is required for the adaptation of economic models, particularly in a sector where uncertainty rules. It might even be true that the natural operating mode of the “price” signal in an economic scarcity environment is to trigger acute crises rather than a succession of anticipations.
- Finally, it is not yet at all clear why spontaneous market regulation should necessarily lead, in due course, to confining global production of a given raw material within the bounds of a certain growth rate, nor why, furthermore, this rate would be precisely 1% or less than 1%.

While it is hardly to be doubted that an increase in the price of raw materials will contribute to more rational consumption habits, it is no less obvious that the market’s natural mechanisms cannot, alone, be the foundation for controlled sustainable development—meaning sustainability not based on wishful thinking.

This suggests two possible routes for fundamentally decoupling the economy from materials, both of which would be encouraged by a rise in the price of raw materials:

- An approach through services providing the economy with decoupling solutions for development;
- An approach through responsibility, by implementing or extending new forms of management of externalities.

The first of these is generally included in the concept of a “product-service system economy”, designated in the case of France as one of the two priorities in this respect by the Grenelle Environnement, which “*replaces the marketing of products by marketing their use.*” In this case, one of the first priorities is to lengthen the time during which material products are used so as to minimise consumption of the resources required for the manufacture of their replacement.

<sup>13</sup> Gonzales G. En 2007, la consommation des ménages demeure solide. INSEE Première, n°1192, May 2008. And CCI Dijon. « La consommation des ménages en 2008 », *Info économie*, July 2009

<sup>14</sup> ADEME. Les déchets en chiffres, Publ. 2007



If the life cycle of a product is lengthened by 20%, because those who manufacture it earn a little more by making it available than by replacing it, then consumption of the raw material necessary for its manufacture is delayed by the same length of time and there is a 20% statistical reduction in the flow of the raw material. In the light of our earlier analysis, the considerable and immediate effect of such a process on the economy is clear, as are also the two limitations it places on our objective:

- by doing this, we have also lengthened by 20% the “residence time of the material in the economy”, which will lessen to some degree the positive effects that recycling will have, once the first decoupling is achieved.
- But, above all, by sustainably reducing the material flow by 20% (in our example), all else being equal, it is clear that the product-service system effect on the life cycle extension of the goods is of the same nature, with the same limitation, as recycling: if the economy is in continuous expansion, this effect, by itself, staggers the curves in time, but does not flatten them out.

By prolonging, in a certain proportion, the lifetime of products, product-service systems do not, therefore, contribute any more than recycling to the fundamental decoupling of economic development from increased need for materials. They do not contribute, *on that account*, to the priority objective of quasi-stabilisation of the total needs for raw materials.

Nevertheless, it is probably an important step in the right direction to trigger decoupling, not so much in relation to a specific objective of lengthening the life cycle of products, the limitations of which we have just noted, but because of the changed paradigm that this approach brings about in the behaviour of economic actors, and of its consequences.

Exactly as we proceeded for the economy in general, we must consider this new approach from a dynamic angle integrating both space and time, not a static one. The first virtue of the “product-service system” (and its sole virtue from the point of view of the fundamental decoupling objective) is that it can offer, on the basis of the same essential needs as before for economic actors, an apparently unlimited scope for future economic development, the intrinsic logic of which is no longer consuming more material (to sell more products), but, on the contrary, consuming less (to reduce the costs of the service being sold).

By assuming a 20% extension of life time, as though, by doing so we had set the scene in stone for aeons to come, we clearly did not do full justice to this new approach: to be strictly logical, there is no a priori limit to the conceivable life cycle of a car or of a telephone set, as long as we apply changes in design and maintenance processes, as well as technological progress.

Furthermore, gains are also achieved in space, by optimising the density of use of certain products (shared vehicles, etc.) and the material basis itself is not set once and for all: selling motorcars

or selling a certain distance to be covered are two different things entirely, and even more different is selling travel itself or even *exchange*.

More generally, if the decoupling objective is taken as reached, that is if the economy continues to expand at an appreciable rate while total consumption of raw materials is completely or almost entirely at a standstill, then most growth must be the outcome of the development of more services: services provided by economic actors to other economic actors, or services rendered with an added value by the products themselves using the same amount of material. Be that as it may, it is truly in the increase of the intangible value of goods and services, that is more their usable value than their actual quantity, that the major portion of extra economic development will necessarily reside.

The second approach to achieve the fundamental decoupling of a growing economy from stagnation of needs for raw materials, is that of *responsibility*, which can take various forms but all with one essential characteristic in common: they challenge the traditional segmentation of responsibility regarding the future of materials in economic circuits.

One of these forms borrows from the “circular economy” concept and consists in seeking to reduce quantities of waste (the first “R” in the “3R” approach). In fact, in this case the object is not so much to reduce the amount of waste but rather, in so doing, to encourage a reduction of the quantities of materials used to make the products which will later become waste. The most popular approach is the principle known as “extended producer responsibility” which places the responsibility of the future of an item of waste on the initial producer of that good, instead of on the last owner as in traditional segmentation (Walls, 2006). Already extensively used in Europe since the 90’s with the management of waste arising from the packaging of household items, it is now being extended to new sectors and has become one of the priorities of the new European Framework Directive on waste. It is also sometimes spontaneously chosen by some manufacturers who include in the sale of the goods they produce the future recovery and processing service for the product at the end of its useful life.

Another form of this approach is rationing—the form already used in fighting global warming with tradable quotas. Finally, another form is through taxes, the aim being that economic actors bear the estimated cost of negative externalities—in this case the relative depletion of the collective capital of “accessible material” on the planet; it corresponds for example to the auctioning of European carbon quotas as of 2013, or the “carbon tax” in preparation in France.

The success of these policies is easily measured: it will be proven once the underlying global production growth rates of various major non-renewable materials settle well below 1% annually. Then and then only, will it be possible to observe the fundamental decoupling of the economy from raw materials and give priority

to the second component, that is the relative decoupling generated by recycling.

## 10. THE APPROPRIATE ROLE OF RECYCLING

Recycling stands against a background of scarce resources, but it also includes other problem areas.

Firstly, there is the question of the growing scarcity of non-renewable resources, or their diminishing accessibility, which comes to the same thing, leading in the long term to a rise in the price of virgin materials. The flow of secondary raw materials permanently available via waste products would, in such a scenario, become an increasingly attractive source on the commodities market, in comparison with ever less accessible natural deposits. Indeed it seems likely that technological advances will not be able to compensate entirely for the increasing complexity of extraction. For example, mining for gold at a depth of 4,000 meters in the South African Tau Tona mine will be more expensive, per ounce, than running the same mine 50 years ago with less sophisticated technical equipment of course, but at much more accessible depths<sup>15</sup>.

Secondly, the dramatic rise in the demand for ores in the last few decades has resulted in greater concentration in the sector, both industrially, with the arrival of global giants following very recent merger and acquisitions, and in geo-political terms with control of a major part of global production by one or a few countries for most ores.

For example, Chile and Argentina alone produce 90% of the global supplies of lithium<sup>16</sup>, and China accounts for 95% of the world's output of rare earths<sup>17 18</sup>.

The example of iron, which we have already abundantly referred to above, is also significant in this regard: with the rise in Chinese production, the five biggest producers — Brazil, Russia, India, China and Australia (“BRICA”) — alone accounted for 80% of the world's output in iron ore in 2008 (table 1).

IRON ORE		2003		2008	
<b>Global production</b>		<b>1 074</b>	<b>100%</b>	<b>1 723</b>	<b>100%</b>
of which	China	123	11%	366	21%
	Brazil	246	23%	346	20%
	Australia	212	20%	350	20%
	India	99	9%	214	12%
	Russia	92	9%	99	6%
	Ukraine	62	6%	72	4%
	United States	48	4%	53	3%
	<b>Total BRICA</b>	<b>772</b>	<b>72%</b>	<b>1 375</b>	<b>80%</b>

Table 1: Iron ore global production, and biggest producers (in millions of tonnes). Source: Steel Statistical Yearbook, IISI, quoted by CYCLOPE 2010.

For each net importing country of a raw material, the secondary raw material, available within its own borders, is therefore a national source and a powerful factor of strategic independence, useful to counteract possible growing tension for access to resources.

Thirdly, recycling a material, generally speaking, produces less carbon emission than using the natural resource. On the basis of life cycle assessments (LCA), to be calculated for each sector, recycling becomes a decisive environmental motivation due to its contribution to fighting global warming. We can note in passing that the dynamic analysis in case of resource depletion should not be transposed directly to global warming, on the one hand because of the extreme imminence of the catastrophic consequences of warming and, on the other hand, because of the relative determination already stated by governments to seek solutions and implement them.

Fourthly, recycling a material, often fairly close to where it will be consumed, avoids having to create more pollution, further away at the site of extraction of the original virgin material.

## 11. RESOURCES AND RECYCLING: AN ADJUSTMENT OF PRIORITIES

We can now finally formulate the essential conclusions of this analysis.

First of all, a sustainable development policy cannot, in its section on “non-renewable resources”, choose recycling at its primary goal, nor count indiscriminately on a range of non-prioritised instruments: recycling, on its own, is inadequate to “decouple” economic development from raw materials needs.

In order to curb the soaring drain on non-renewable resources, an inescapable condition is to bring down the underlying growth rate of global consumption of raw materials to below 1% a year. A raw material which continues to be consumed at a rate significantly above 1% per annum cannot be subjected to any successful measure to slow down the depletion of the resource; the best that can be done, thanks to recycling, is to achieve a one-off time gain of a few years or a few decades.

Decoupling the economy from its need for raw materials, which is often recommended, must therefore be understood as being a dual decoupling, the components of which are both essential and need to be combined in order to arrive at a significant effect on the issue of resources:

- *Fundamental decoupling*, consisting in curbing the growth of global needs for raw materials,
- *Relative decoupling*, aiming to reduce, through recycling and re-use, the share of primary resources in the production of raw materials.

<sup>15</sup> Daycard-Heid S. Une mine sud-africaine prolonge l'âge d'or. Challenges, January 29th, 2009

<sup>16</sup> D'Armagnac B. La Chine accroît sa mainmise sur les métaux rares. Le Monde, September 8th, 2009

<sup>17</sup> Lafarge Th. La course aux gisements de lithium est lancée. Les Echos, September 14th, 2009

<sup>18</sup> Mineral Commodities Summaries, quoted by [Chalmin Ph. & al, 2010]



This being the case, the *current* role of recycling is totally inconsequential for the preservation of resources as regards all non-renewable materials with a consumption growth rate by the economy greater than 1% per annum.

Moreover, so that, eventually (meaning once fundamental decoupling has been otherwise achieved) it can have a positive effect on the decoupling process, recycling must be sufficiently intensive worldwide. No meaningful effect on the depletion of natural resources can be expected unless recycling rates exceed 80%.

Recycling must therefore, according to this analysis, wait on the sidelines of resource control, since most materials are consumed at a rate far exceeding the critical 1%, excepting the effects of the economic crisis.

As a result, other motivations for recycling take on added importance:

- Climate: Effect to be measured for each sector by LCA
- Pollution: Pollution avoided at the site of raw material extraction
- Strategy: A factor of national independence for imported resources
- Business: Growing attractiveness of secondary raw materials as commodities.

As regards resources, while our analysis puts the effects of our immediate action in a marginal position regarding materials on an upward consumption curve, it also contains a stronger requirement for a highly ambitious recycling policy:

- For materials on a “stabilised” consumption curve, because it is already an essential factor for the success of a sustainable development policy,
- For materials whose consumption is not stabilised, i.e. most of them at this point in time, so as to prepare economic and social actors for the next phases in which recycling will play a major role in the conservation of the resource.

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# ANNEX A:

## DETERMINING THE LENGTH OF THE TIME LAG IN AGGREGATE CONSUMPTION

The issue under consideration is to calculate the length of the time lag between aggregate consumption of virgin material, with or without recycling, depending on the assumptions for the consumption dynamics of total raw material.

Model:

We are considering exclusively a given natural material, (metal, for example) and we assume a total consumption by human society growing at an annual constant rate.

The material has a residence time in the economic circuit before it becomes waste: the time of its distribution and use as consumer goods, or depending on the life time of the investments involved. Obviously, its duration varies considerably depending on use in each particular case.

A portion of the material present in the waste is recycled. The effectiveness of recycling is described as the “recycling rate”, defined as follows: the portion of the deposit of that material effectively present in all types of waste which is recycled.

Since we are in a growth economy, this amount will necessarily take into account the duration of residence time of the material. By definition, the quantity of material present in waste is the total quantity which was consumed a few years previously — the difference being the residence time in the economy.

If the material resides on average 10 years in the economic circuit before it becomes waste and in those 10 years, global consumption has progressed from 100 million tonnes to 150 million tonnes per annum, the waste will only contain the 100 million tonnes consumed 10 years ago, so that a 100% recycling operation can only satisfy two thirds of current needs. In fact, the “missing” third is in no way to be blamed on a faulty recycling system; it is simply the inevitable effect of growth in consumption over time. The recycling rate, in the meaning of this model, is therefore to be taken as the proportion of the 100 million tonnes available in waste which is effectively recycled. If the rate is only 50%, this means that only 50 million tonnes will be recycled into the production circuits and, out of the 150 million tonnes consumed in toto, 100 million will have to be taken out of the natural resource, i.e. two thirds of actual requirements.

We shall calculate the gap in aggregate consumption, that is, depending on the recycling rate, the time difference between the aggregate consumption curves, with or without recycling.

### SYMBOLS:

Values will be shown as follows:

R	Ratio	Recycling Rate
ts	Years	Residence time of the material in the economy
$\alpha$	Ratio	Raw material needs growth rate
$a = 1 + \alpha$	Ratio	Annual growth ratio of raw material needs
d	Years	Time lag of aggregate consumption
$u_n (U_n)$	Mass	Annual consumption (respectively aggregate) without recycling, or Total annual consumption [virgin + recycled] with recycling
$v_n (V_n)$	Mass	“ ” “ ” “ ” of virgin material, with recycling.

### CALCULATION:

Total annual consumption increases each year in proportion a:

$$u_{n+1} = a \cdot u_n \Rightarrow u_n = u_0 \cdot a^n$$

aggregate consumption over the years is the sum of annual consumptions and represents a well-known geometric sequence:

$$U_n = \sum_0^n u_i = u_0 \cdot \sum_0^n a^i \Rightarrow U_n = u_0 \cdot (a^{n+1} - 1) / (a - 1)$$

annual consumption of virgin material, in the scenario with recycling, is the gap between total mass consumed and mass recycled during that same year. The latter is equal to the product of the recycling rate by the mass of material available in waste, i.e. the total quantity consumed in the previous year corresponding to the residence time of the material in the economy, ts:

$$v_n = u_n - R \cdot u_{n-ts} = u_n - u_0 \cdot R \cdot a^{n-ts} = u_n \cdot (1 - R / a^{ts})$$

Aggregate consumptions of virgin material with or without recycling are therefore linked as follows:

$$V_n = \sum_0^n v_i = (1 - R / a^{ts}) \cdot U_n$$

Problem: Find the duration of gap d, such as the aggregate consumption without recycling in year n,  $U_n$ , is only reached in year n+d with recycling.



To simplify calculation, reasoning will be based on year  $n-1$  instead of year  $n$ :

$$d \cdot V_{n+d-1} = U_{n-1}$$

Let us replace  $V$  by its previously calculated  $U$  equivalent:

$$(1 - R/a^{ts}) \cdot U_{n+d-1} = U_{n-1}$$

Then let us replace  $U$  by the value calculated above:

$$(1 - R/a^{ts}) \cdot u_0 \cdot (a^{n+d} - 1) / (a - 1) = u_0 \cdot (a^n - 1) / (a - 1)$$

Which is successively simplified as:

$$(1 - R/a^{ts}) \cdot (a^{n+d} - 1) = a^n - 1$$

$$(1 - R/a^{ts}) \cdot (a^d - 1/a^n) = 1 - 1/a^n$$

Finally, if  $n$  tends to infinity, that is if we consider the maximum time lag attained after a great number of years, we arrive at the limit at:

$$\text{If } n \rightarrow \infty, \text{ then: } (1 - R/a^{ts}) \cdot a^d = 1$$

That is:

$$a^d = 1 / (1 - R/a^{ts}) = a^{ts} / (a^{ts} - R)$$

The logarithms are also equal:

$$d \cdot \log a = ts \cdot \log a - \log (a^{ts} - R)$$

We finally arrive, for the limit gap for aggregate consumption with or without recycling, at the following formula:

$$d = ts - \frac{\log (a^{ts} - R)}{\log a}$$

We can then easily calculate the recycling rate  $R$  required to obtain a given gap  $d$ :

$$(d - ts) \cdot \log a = - \log (a^{ts} - R)$$

Therefore  $a^{ts-d} = a^{ts} - R$ , et :

$$R = a^{ts} - a^{ts-d}$$

$$R = a^{ts} (1 - 1/a^d)$$



# ANNEX B:

## SUSTAINABLE DECLINE IN TOTAL NEEDS FOR RAW MATERIALS

The case of a reduction in needs uses the same geometric sequence modelling method.

In this instance, we are not seeking to define the consumption gap which is not very relevant. In the presence of an exponential decline, aggregate consumption over time is limited by a given multiple of consumption in the first year.

The problem of decline therefore involves defining the influence of recycling on that multiple, that is the number of years of initial consumption represented by "infinite" aggregate consumption, with or without recycling. This is a very theoretical problem, because the curves for decline flatten out at the same rate as the growth curves rise, and a sustainable negative exponential function, even a very flat one, seems therefore totally incompatible with sustainable development: it seems hardly likely that total (virgin + recycled) consumption of iron will be thirty times less in a century than it is today, with a more or less stable global population and increased "prosperity" in the meantime.

### MODEL:

The same assumptions and definitions are used as in the problem considered in annex 1:

Values and their description are unchanged (reminder):

R	Ratio	Recycling Rate
ts	Years	Residence time of the material in the economy
$\alpha$	Ratio	Raw material needs growth rate
$a = 1 + \alpha$	Ratio	Annual growth ratio of raw material needs
d	Years	Time lag of aggregate consumption
$u_n (U_n)$	Mass	Annual consumption (respectively aggregate) without recycling, or Total annual consumption [virgin + recycled] with recycling
$v_n (V_n)$	Mass	" " " " of virgin material, with recycling.

In this case, " $\alpha$ " is negative and "a", therefore, is less than 1.

We are using the same identity relations as established above:

$$u_{n+1} = a \cdot u_n \implies u_n = u_0 \cdot a^n$$

aggregate consumption over the years is the sum of annual consumptions and represents a well-known geometric sequence:

$$U_n = \sum_0^n u_i = u_0 \cdot \sum_0^n a^i \implies U_n = u_0 \cdot (a^{n+1} - 1) / (a - 1)$$

$$v_n = u_n - R \cdot u_{n-ts} = u_n - u_0 \cdot R \cdot a^{n-ts} = u_n \cdot (1 - R / a^{ts})$$

$$V_n = \sum_0^n v_i = (1 - R / a^{ts}) \cdot U_n$$

Aggregate consumption of virgin material  $V_n$ , is therefore equal to:

$$V_n = (1 - R / a^{ts}) \cdot u_0 \cdot (a^{n+1} - 1) / (a - 1)$$

If  $n \rightarrow \infty$ , then:  $a^n \rightarrow 0$ , since  $a < 1$

Therefore:

$$U_n \rightarrow U = u_0 / (1 - a) = u_0 / \alpha$$

And:

$$V_n \rightarrow V = u_0 \cdot (1 - R / a^{ts}) \cdot / (1 - a) = -(u_0 / \alpha) \cdot [1 - R / (1 + \alpha)^{ts}]$$

And again:

$$V = U \cdot (1 - R / a^{ts})$$

It is to be noted that the equations are only meaningful if consumption of virgin material is positive:

$$v_n > 0 \implies R / a^{ts} < 1$$

Otherwise, recycling products exceed total raw material needs.

Condition  $R = a^{ts}$  therefore defines the exact equality between recycling products and total raw material needs. This requires a society with total raw materials consumption decrease ( $a < 1$ ) since recycling rate R is itself, by definition, lower than 1.