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Thèse de Doctorat

Nadia Jamali-Zghal

*Mémoire présenté en vue de l'obtention du
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Environmental Assessment Tools For Sustainable Resource Management

JURY

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Extended Abstract in French

Introduction

Les ressources naturelles constituent la base de l'économie. En conséquence, leur usage inconsidéré et leur épuisement rapide peuvent déstabiliser la prospérité de l'humanité. En 1987, la commission sur l'environnement et le développement des Nations-Unies définissait le développement soutenable/durable par “*un développement qui répond aux besoins actuels sans compromettre les capacités des générations futures à répondre au leur*”. Cette définition vise à améliorer/maintenir la qualité de vie de l'humanité avec le temps en perspective. Le développement durable met en exergue trois actions: la diminution des besoins, l'utilisation d'énergies propres et renouvelables et le recyclage.

Cette thèse vise à proposer des éléments de réponses à trois questions scientifiques :

RQ1 : *Comment évaluer l'impact environnemental résultant de l'exploitation des ressources minérales, en tenant en compte de leur abondance, de leur composition chimique, de leurs propriétés physiques et des effets de leur extraction?*

RQ2 : *Comment évaluer la performance du recyclage, en prenant en compte les différentes pertes (de quantité et de qualité)?*

RQ3 : *Substituer de l'énergie fossile par de la biomasse s'inscrit-il toujours dans le cadre du développement durable?*

La méthode émergétique est principalement utilisée pour cette recherche. Elle est complétée par l'exergéto-écologie, l'empreinte carbone ou l'analyse exergétique du cycle de vie.

Evaluation des ressources minérales

Dans cette section, les éléments de réponse à la question **RQ1** sont proposés, voir Chapter 2.

L'évaluation des ressources minérales, et notamment l'effet de l'épuisement des mines, requiert de repartir des fondements de l'émergie. Des citations littérales de Odum [Odum 1996, Odum 2000a] permettent de positionner les principes généraux à respecter:

« Materials of biochemical cycles are hierarchically organized because of the necessary coupling of matter to the universal energy transformation hierarchy » (Odum [Odum 2000a])

« ... any increase in concentration of material requires an increase in the energy per mass. When concentration increase in some

part of a biogeochemical cycle, the emergy per mass increases.»
(Odum [Odum 2000a])

« When material disperses, the stored emergy decreases.»
(Odum [Odum 2000a])

« In general, the scarce products from the Earth are those that required more work for their formation and concentration. Therefore they tend to have higher Emergy contents. Burnett [Burnett 1981] found that materials with more emergy contribution were less abundant.» (Odum [Odum 1996], p.117)

« Emergy per unit mass (seJ/g) indicates the position a mineral has on the scale of Earth scarcity and unit value.»
(Odum [Odum 1996], p.121)

« Kangas (1983), evaluating the emergy of landforms and their colonization by ecosystems, found that irregular, post-mining lands, which had 20-40 yr of natural restoration through ecological succession and other processes, were more valuable than those lands that were bulldozed flat in well-intentioned restoration.»
(Odum [Odum 1996], p.123)

Des travaux antérieurs [Cohen 2007, Brown 2007] ont évalué l'émergie des ressources minérales, en supposant que l'émergie spécifique d'une réserve minérale em_R est une fonction linéaire d'un facteur dit d'enrichissement EF_R , voir Eq. (1).

$$em_R = B_R \cdot EF_R \quad (1)$$

Le facteur d'enrichissement d'un minéral, voir Cohen et al. [Cohen 2007] et Brown [Brown 2007] dépend des capacités techniques et de la demande économique. Cette approche n'est donc que partiellement conforme aux citations précédentes, notamment [Odum 1996], p.123.

En outre, pour proposer une évaluation émergétique des ressources minérales, il faut aussi prendre en compte la remarque de Sciubba [Sciubba 2010]:

« It is recommended therefore that Emergy Analysis be not used to assess the global resource consumption caused by anthropic activities, because its results are misleading when it comes to estimate the exergy destruction enacted by real industrial transformations.»
([Sciubba 2010])

L'évaluation thermodynamique des minéraux effectuée par Szargut [Szargut 2005] et prolongée par Valero et al. [Valero 2009] peut, d'une part permettre de s'affranchir du facteur d'enrichissement proposé par Cohen et al. [Cohen 2007] et Brown [Brown 2007], et d'autre part éviter l'écueil souligné par

Sciubba [Sciubba 2010]. En effet, la description de trois états “thermodynamiques” théoriques de formation de la croûte, cf Fig. 1, propose un cadre novateur pour l’évaluation émergétique.

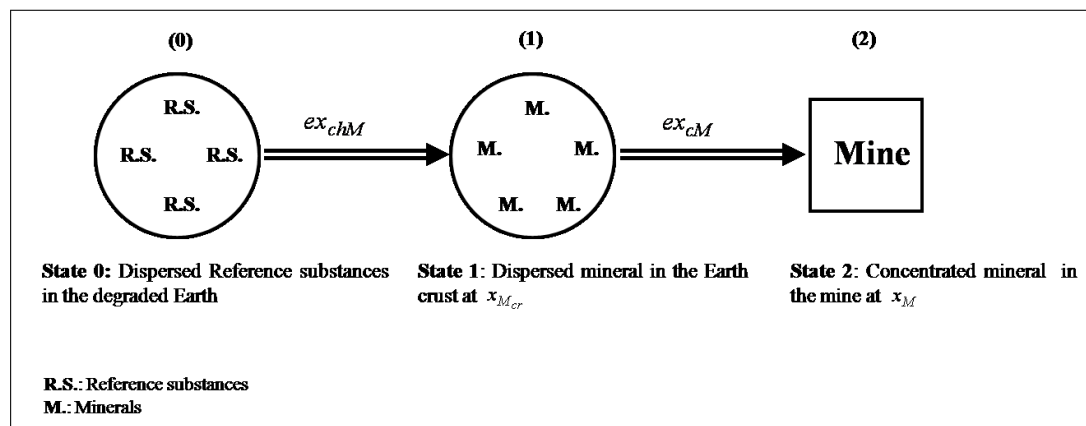


Figure 1: Transformation théorique de la formation d’un minéral, de l’environnement de référence à la mine

1. Etat 0 (Environnement de référence): Toutes les substances sont dispersées et mélangées et dans un état thermodynamique d’équilibre \Rightarrow L’exergie est nulle.
2. Etat 1 (Minéraux dispersés): Les réactions chimiques ont eu lieu, les minéraux sont formés et dispersés dans la croûte terrestre, à la concentration $x_{M_{cr}}$, l’exergie spécifique d’un minéral dispersé $ex_M(x_{M_{cr}})$ est:

$$ex_M(x_{M_{cr}}) = ex_{chM} \quad (2)$$

3. Etat 2 (Minéraux concentrés): Le minéral dispersé est localement concentré dans une mine, concentration notée x_M , l’exergie spécifique du minéral concentré $ex_M(x_M)$ s’exprime par:

$$ex_M(x_M) = ex_{chM} + ex_{cM}(x_M) \quad (3)$$

La transposition de l’approche thermodynamique sous l’angle de l’analyse émergétique est proposée dans la Fig. 2.

L’évaluation de l’énergie spécifique des minéraux dans une mine, avant exploitation, est proposée sur la base des hypothèses et des propositions suivantes.

Hyp.1 : *Emergie des minéraux dispersés*

Chaque minéral est supposé être un co-produit de la croûte terrestre:

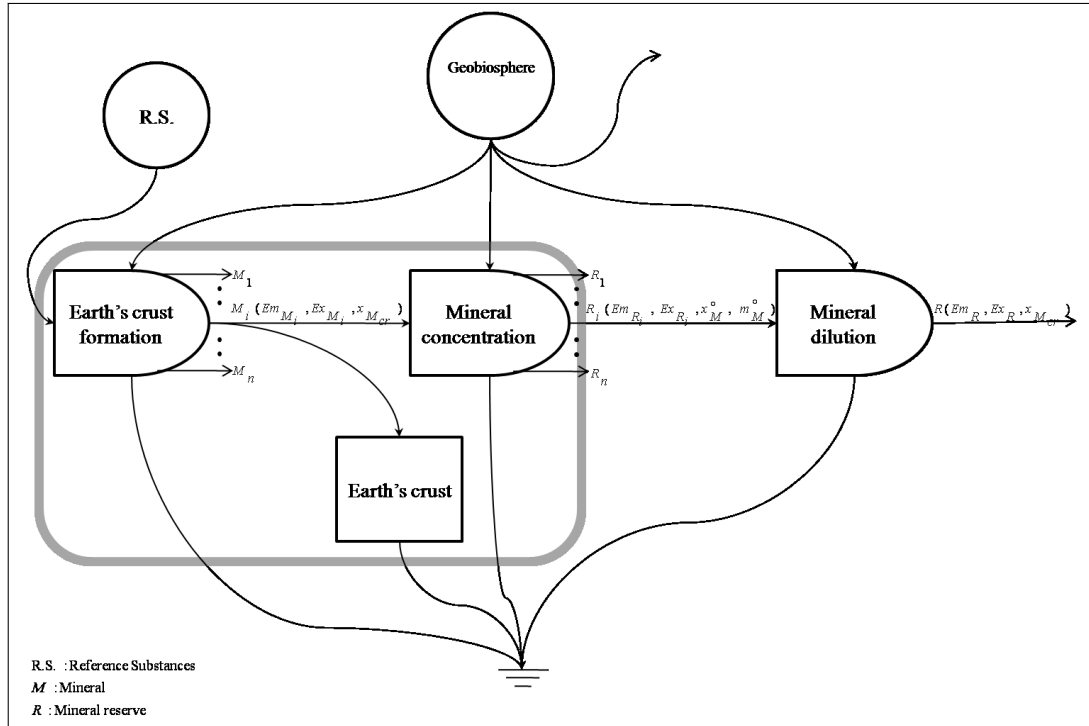


Figure 2: Transformation théorique des réserves de minéraux: approche émergétique

l'énergie totale de chaque minéral $Em_M(x_{M_{cr}})$ est égale à l'énergie totale de la croûte elle-même Em_{cr} .

$$Em_M(x_{M_{cr}}) \stackrel{def}{=} Em_{cr}$$

Hyp.2 : *Énergie des réserves de minéraux*

Les sources d'énergie servant à la constitution des minéraux dispersés dans la croûte terrestre sont supposées être les mêmes que lors de la concentration d'une partie de ces minéraux en réserve.

$$\tau_F \stackrel{def}{=} \frac{Em_M(x_{M_{cr}})}{Ex_M(x_{M_{cr}})} \stackrel{def}{=} \frac{Em_R(x_M^o)}{Ex_R(x_M^o)} \quad (4)$$

Prop.1 : *Référence et facteur d'enrichissement d'une réserve de minéral*

L'énergie spécifique du minéral dispersé est prise comme référence:

$$B_R(x_{M_{cr}}) \stackrel{def}{=} em_M(x_{M_{cr}}) \quad (5)$$

Le facteur d'enrichissement est défini comme le rapport d'exergie spécifique du minéral dans la réserve (avant exploitation) $ex_R(x_M^o)$ et celle de ce même minéral dans l'état dispersé (tel que défini par Szargut [Szargut 2005])

$ex_M(x_{M_{cr}})$:

$$EF_R(x_M^o) \stackrel{def}{=} \frac{ex_R(x_M^o)}{ex_M(x_{M_{cr}})} \quad (6)$$

Hyp.3 : *Diminution de l'énergie lors de l'exploitation d'une réserve de minéral*

L'extraction d'un minéral d'une mine peut être assimilée à une dilution naturelle de son état initial x_M^o vers une plus faible concentration x_M , dilution générée par les mêmes sources d'énergie qui avaient été considérées lors de la concentration:

$$\tau_F \stackrel{def}{=} \frac{Em_R(x_M^o)}{Ex_R(x_M^o)} \stackrel{def}{=} \frac{Em_R(x_M)}{Ex_R(x_M)} \quad (7)$$

Prop.2 : *Référence et facteur de diminution d'une mine*

L'énergie spécifique initiale est prise à la référence:

$$B_R(x_M^o) \stackrel{def}{=} em_R(x_M^o) \quad (8)$$

Le facteur de diminution est défini comme le rapport entre l'exergie spécifique du minéral en fin d'exploitation de la mine $ex_R(x_M)$ et sa valeur initiale (avant exploitation) $ex_R(x_M^o)$:

$$DF_R(x_M) \stackrel{def}{=} \frac{ex_R(x_M)}{ex_R(x_M^o)} \quad (9)$$

Hyp.4 : *Energie des mines*

L'énergie totale d'une mine Em_{Mine} est égale à l'énergie totale du minerai contenu Em_R :

$$\begin{aligned} Em_{Mine}(x_M) &= Em_R(x_M) \\ m_M &= x_M \cdot m_{Mine} \end{aligned} \quad (10)$$

Remarque: ceci est la distinction faite entre les expressions "mine" et "réserve de minéral": la mine est la réserve de minéral mais contient aussi d'autres éléments.

Prop.3 : *Transformité de la croûte terrestre*

La transformité de la croûte terrestre τ_F est supposée être égale à la transformité moyenne de la géobiosphère τ_{geobio} .

Le Table 1 croise les travaux de Valero et al. [Valero 2012] (sur l'exergie de la croûte terrestre) et ceux de Brown and Ulgiati [Brown 2010] (sur l'énergie de la géobiosphère).

$$\tau_F \stackrel{def}{=} \tau_{geobio} = 4.2 \text{ seJ/J}$$

m_{cr} [kg]	M_{cr} [g/mol]	ex_{cr} [J/mol]	Ex_{cr} [J]	τ_F [seJ/J]	Em_{cr} [seJ]
1.08E+22	155.2	3.63E+3	2.53E+26	4.2	1.06E+27

Table 1: Grandeurs thermodynamique et émergétiques de la croûte terrestre

Sur la base de ces hypothèses et de ces propositions, l'énergie spécifique initiale (avant exploitation) des 42 minéraux les plus utilisés dans l'industrie a été proposée. L'ensemble des résultats est présenté dans le Chapter 2.

Emergie des produits recyclés

Dans cette section, les éléments de réponse à la question **RQ2** sont proposés, voir Chapters 3 and 4.

L'analyse émergétique du recyclage a fait l'objet de différents travaux:

- Brown and Buranakarn [Brown 2003] ont proposé une étude approfondie de différents matériaux (verre, aluminium, etc . . .) issus de la construction. Dans cette étude, le premier recyclage est considéré.
- Amponsah et al. [Amponsah 2011b] et Amponsah [Amponsah 2012] ont montré que l'énergie spécifique d'un produit recyclé est une fonction croissante du nombre de cycles. En ayant fixé un chemin à la matière première, une équation récurrente a été formulée, dans un cadre restrictif, cf. Fig. 3.

L'équation à temps discret s'exprime sous la forme Eq. (11) et la condition initiale Eq. (12)

$$Em_p(n) = (1 - q) \cdot Em_i + q \cdot Em_p(n - 1) + q \cdot Em_c \quad (11)$$

$$Em(0) = Em_i \quad (12)$$

En supposant les grandeurs indépendantes du cycle, une série géométrique apparaît, cf Eq. (13):

$$Em(n) = Em_i + q \cdot \frac{q^n - 1}{q - 1} \cdot Em_c \quad (13)$$

Néanmoins, il est paradoxal que l'énergie d'un matériau issu d'une mine soit inférieure à celle de ce même matériau issu d'un recyclage (puisque pour recycler, il faut apporter un travail supplémentaire et donc une énergie associée). Une comparaison d'un point de vue émergétique pourrait amener à des conclusions erronées

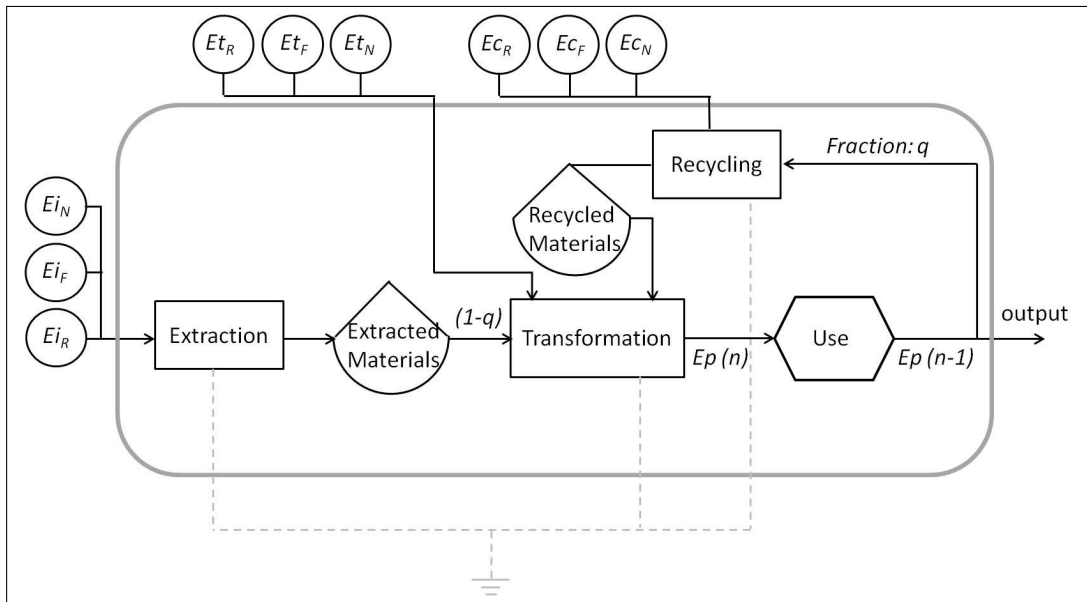


Figure 3: Multiple recyclage (adapté de [Amponsah 2011b])

sur le recyclage. Ulgiati et al. [Ulgiati 2004] proposent d'affecter uniquement la part de l'énergie additionnelle (celle nécessaire au recyclage lui-même) au produit recyclé.

« [...] recycling has the same role in human productive systems as the detritus chain in natural systems. Both take a high transformity input at the end of its life cycle, break it down to simpler components and feed them back to lower hierarchical levels. The recycled component then re-enter the same productive cycles through which it had already passed (may be many times), and therefore it would be "double counting" to assign to it the whole emergy it bore when it was still in the finished product form.[...] If wastes are treated and re-enter a production process as a substitute material or resource, only the emergy invested in the treatment and recycling process should be assigned to recycled resources. » ([Ulgiati 2004])

Cette proposition revient à définir une autre grandeur mais ce n'est plus exactement de l'énergie, cf les citations littérales de Brown [Brown 2004b] et Odum [Odum 1996].

« An energy transformation is a work process that converts one or more kinds of available energy into a different type of available energy. » ([Brown 2004b])

« In any energy transformation, many joules of available energy of one kind are required in a transformation process to produce a

unit of energy of another kind. The energy thus generated by the work of transformation constitutes a higher level in the series of transformation. » ([Odum 1996])

Pertes de masse lors de recyclage dans une analyse émergétique

Une analyse émergétique suppose de définir les limites du système et la période de temps étudié. Dans le travail développé, trois cas, de complexité croissante, ont été étudiés.

Le premier cas, cf. Fig. 4 correspond au schéma précédent, avec l'introduction de deux pertes de matières, notées ε_1 (rejet de tri ou autres) et ε_2 (perte lors de la mise en fusion par exemple).

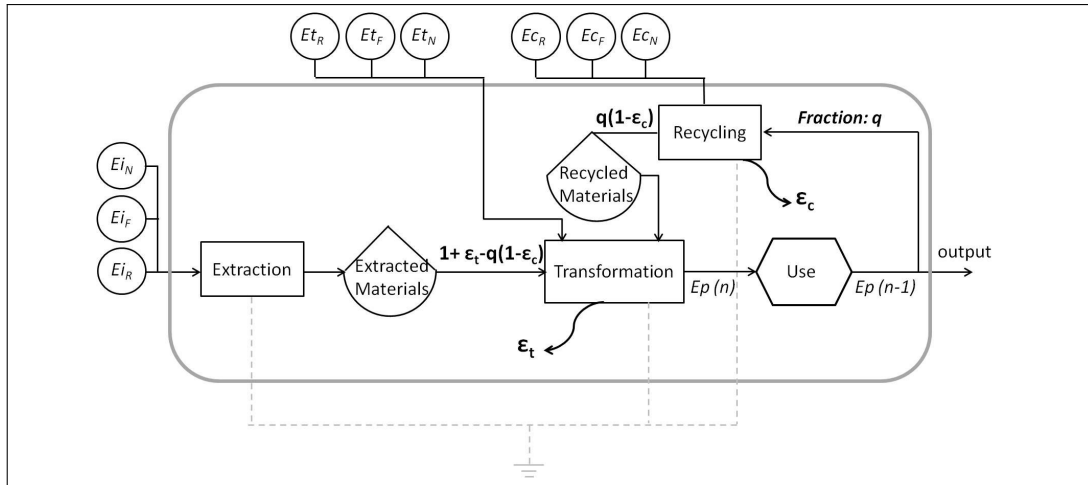


Figure 4: Recyclage en cycle fermé avec pertes de masse (même origine)

L'équation à temps discret de l'émergie spécifique du matériau en fonction du nombre de cycle s'exprime Eq. (14) et sa valeur initiale Eq. (15).

$$Em_p(n) = (1 - q + \varepsilon_t + q \cdot \varepsilon_c) \cdot Em_i + q \cdot (Em_p(n-1) + Em_c) + (1 + \varepsilon_t) \cdot Em_t \quad (14)$$

$$Em_p(0) = (1 + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t) \cdot Em_t \quad (15)$$

En supposant les grandeurs indépendantes du cycle, une série géométrique ap-

parait, cf. Eq. (16):

$$Em_p(n) = (1 + \varepsilon_t + q \cdot (\varepsilon_c + \varepsilon_t)) \cdot \frac{q^n - 1}{q - 1} \cdot Em_i + (1 + \varepsilon_t) \cdot \frac{q^{n+1} - 1}{q - 1} \cdot Em_t + q \cdot \frac{q^n - 1}{q - 1} \cdot Em_c \quad (16)$$

Pour le second cas, cf Fig. 5, un réservoir de stockage reçoit les produits recyclés. Sa sortie est donc composée de fraction de matière ayant subi un recyclage, deux recyclages, etc . . . jusqu'à $n - 1$.

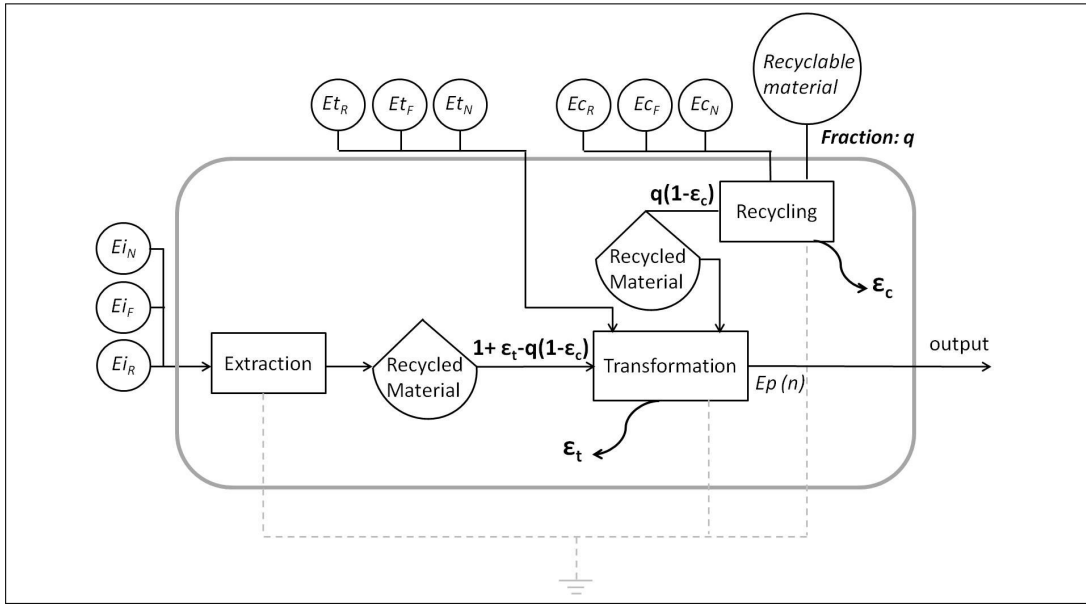


Figure 5: Closed-loop recycling with mass losses (reservoir made of mixed recycled material)

L'équation à temps discret du matériau recyclé est Eq. (17) et sa valeur initiale Eq. (18).

$$\bar{E}m_p(n) = (1 + \varepsilon_t - q) \cdot Em_i + q \cdot (\bar{E}m_p(n - 1) + Em_c) + (1 + \varepsilon_t) \cdot Em_t \quad (17)$$

$$\bar{E}m_p(0) = (1 + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t) \cdot Em_t \quad (18)$$

$\bar{E}m_p$ est l'énergie moyenne de matériau provenant du stock de recyclage:

$$\bar{E}m_p(n - 1) = \sum_{j=0}^{n-1} x_{j,n} \cdot Em_p(j) \quad (19)$$

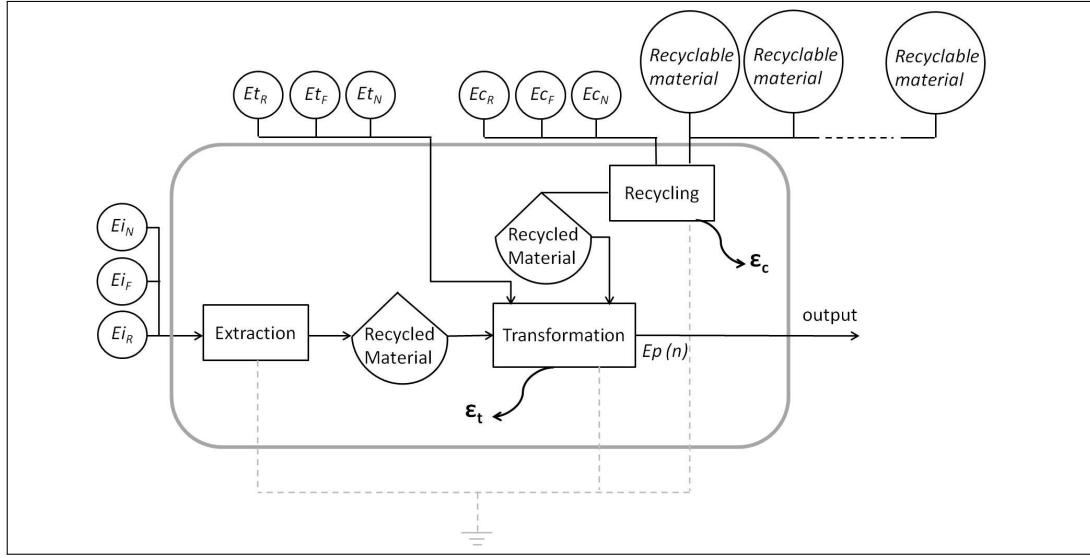


Figure 6: Recyclage en cycle fermé avec pertes de masse (matériau recyclé d'origine multiple)

Après n cycle, l'énergie spécifique moyenne s'exprime sous la forme, cf Eq. (20):

$$\bar{E}m_p(n) = \bar{E}m_p(0) + \left(\sum_{k=0}^{n-1} \sum_{j=k}^{n-1} x_{j,n} \cdot q^{k+1} \right) ((\varepsilon_c + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t) \cdot Em_t + Em_c) \quad (20)$$

Pour le dernier cas, cf. Fig. 6, la matière recyclée est considérée comme une entrée.

L'équation à temps discret du matériau recyclé est Eq. (21) et sa valeur initiale Eq. (22).

$$e\bar{m}_p(n) = (1 + \varepsilon_t - q \cdot \varepsilon_c) \cdot em_i + q \cdot \bar{s}_p(n) + em_c + (1 + \varepsilon_t) \cdot em_t \quad (21)$$

$$e\bar{m}_p(0) = em_i + em_t \quad (22)$$

Avec \bar{s}_p l'énergie du matériau provenant du stock de recyclage:

$$e\bar{m}_p(n) = (1 + \varepsilon_t - q - q \cdot \varepsilon_c) \cdot em_i + q \cdot \left(\sum_{j=0}^{n-1} x_{j,n} \cdot s_p(j) + em_c \right) + (1 + \varepsilon_t) \cdot em_t \quad (23)$$

Après n cycle, l'énergie spécifique moyenne s'exprime sous la forme, cf Eq. (24):

$$\begin{aligned}
e\bar{m}_p(n) = & (1 + \varepsilon_t - q - q \cdot \varepsilon_c) \cdot em_i + q \cdot em_c + (1 + \varepsilon_t) \cdot em_t \\
& + q \cdot \left[(1 + \varepsilon_t) \cdot (em_i + em_t) \cdot \sum_{j=0}^{n-1} x_{j,n} \cdot \left(\frac{1 + \varepsilon_t}{1 - \varepsilon_c} \right)^j \right] \\
& + q \cdot \left[((1 - \varepsilon_t) \cdot em_t + em_c) \cdot \left(1 + \frac{1 - \varepsilon_c}{1 + \varepsilon_t} \right) \cdot \left(\sum_{j=0}^{n-1} x_{j,n} \cdot \frac{1 + \varepsilon_t}{1 - \varepsilon_c} \right)^j \right] \quad (24)
\end{aligned}$$

L'ensemble des résultats, et notamment l'application sur le cas de l'aluminium, est présenté dans le Chapter 3.

Pertes de qualité lors de recyclage dans une analyse émergétique

Lors de recyclages, la qualité des matériaux peut être dégradée. L'énergie spécifique étant le rapport entre les énergies nécessaires pour obtenir un matériau avec la qualité du matériau (représentée par son exergie), son évaluation nécessite d'intégrer cette dégradation d'exergie. Le recyclage de matériaux métalliques est plus particulièrement étudié, cf. Fig. 7.

Le recyclage d'un matériau métallique se décompose en quatre étapes principales:

1. Collecte et démantèlement, 2. Broyage et tri, 3. Fusion, 4. Dilution.

Remarque :

- Dans la section précédente, l'évaluation émergétique porte sur le matériau avant son usage. Dans cette section, l'évaluation émergétique porte sur le matériau en sortie de recyclage (avant sa mise en forme, sa transformation) en produit fini (destiné à son usage).
- Par rapport à la section précédente, dans une but de clarté, un réservoir de stockage de matière recyclé n'a pas été considéré.

Le Table 2 synthétise la démarche associant analyse du cycle de vie et exergie (exergético-analyse du cycle de vie) et le Table 3 présente les pertes de matière et de qualité en fonction des étapes du recyclage, lors du premier cycle.

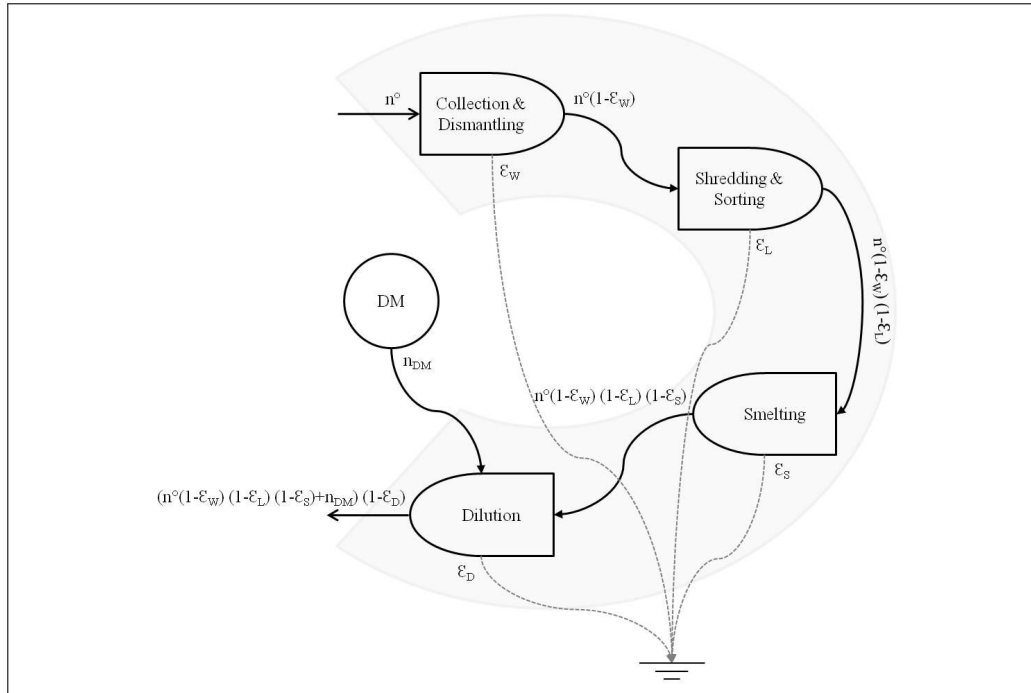


Figure 7: Schéma des étapes lors d'un recyclage d'un matériau métallique

Pertes exergetique lors du recyclage d'un matériau métallique		
Etape de recyclage	Type de pertes	ΔEx [J]
<i>Collecte & Démantèlement</i>	Pertes de matière	ΔEx_W
<i>Broyage & Tri</i>	Pertes de matière, dégradation de la qualité	ΔEx_L
<i>Fusion</i>	Pertes de matière, dégradation de la qualité	ΔEx_S
<i>Dilution</i>	Pertes de matière, dégradation de la qualité	ΔEx_D

Table 2: Exergetico-analyse du cycle de vie du recyclage d'un matériau

Evaluation emergetique lors du recyclage d'un matériau métallique			
Item	Quantité	Energie spécifique [seJ/g]	Energie solaire équivalente [seJ]
Materiau			
Matière première	m°	em_{PM}	$m^\circ \cdot em_{PM}$
Fabrication			
Transformation	m°	em_{Mfg}	$m^\circ \cdot em_{Mfg}$
Recyclage			

Continued on next page...

Item	Quantité	Energie spécifique [seJ/g]	Energie solaire équivalente [seJ]
Collecte & Démantèlement	m^o	em_W	$m^o \cdot em_W$
Broyage & Tri	$m^o(1 - \varepsilon_W)$	em_L	$m^o(1 - \varepsilon_W) \cdot em_L$
Fusion	$m^o(1 - \varepsilon_W)(1 - \varepsilon_L)$	em_S	$m^o(1 - \varepsilon_W)(1 - \varepsilon_L) \cdot em_S$
Dilution	$m^o(1 - \varepsilon_{W\&L\&S} + \gamma)$	em_D	$m^o(1 - \varepsilon_{W\&L\&S} + \gamma) \cdot em_D$
Total	$m^o(1+\gamma)(1 - \varepsilon_{Rcg})$	em_{RM}	Em_{RM}

Table 3: Evaluation émergétique lors du premier recyclage, intégrant les pertes de matière et de qualité

Le cycle de recyclage étudié est présenté sur la Fig. 8.

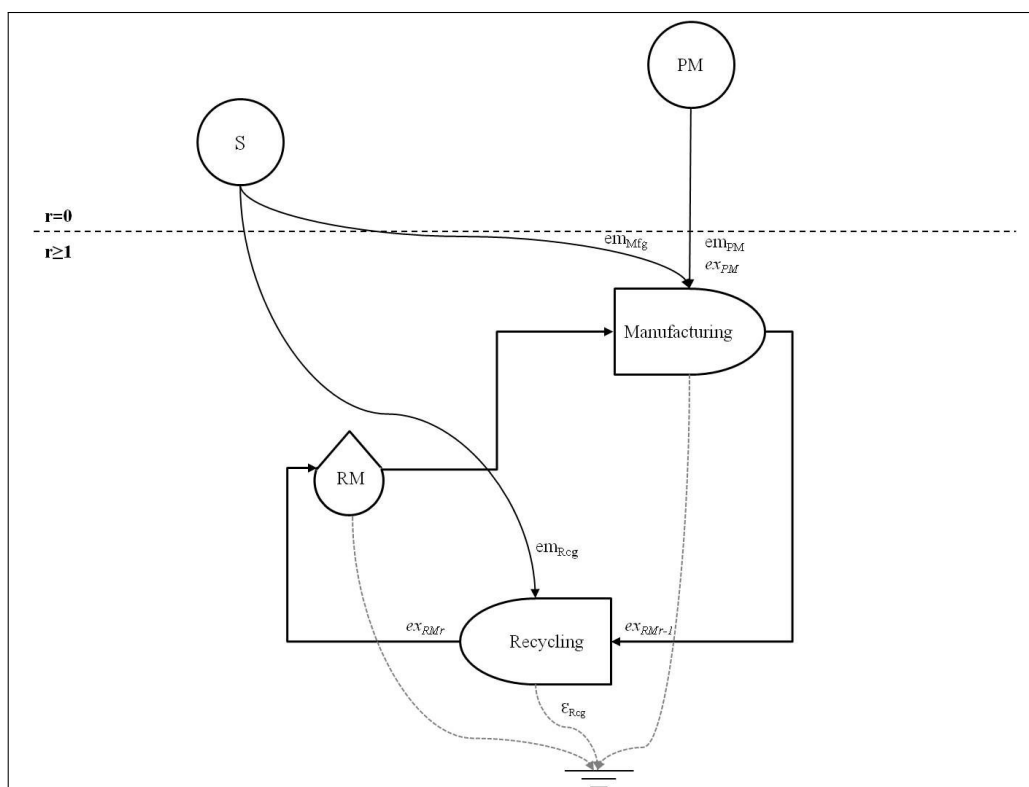


Figure 8: Représentation conceptuelle de recyclages consécutifs d'un matériau métallique

L'équation à temps discret du matériau recyclé est Eq. (25).

$$\left\{ \begin{array}{l} \text{For } r = 1, em_{RM1} = \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{PM} + \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{Mfg} + em_{Rcg1} \\ \text{For } r > 1, em_{RMr} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{RMr-1} + \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{Mfg} + em_{Rcgr} \end{array} \right. \quad (25)$$

En supposant les pertes indépendantes du cycle, l'énergie spécifique du matériau recyclé peut s'écrire, cf. Eq. (26):

$$\begin{aligned} em_{RMN} = & \prod_{r=1}^N \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{PM} + \\ & \sum_{k=1}^N \prod_{r=k}^N \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{Mfg} + \\ & \sum_{k=1}^{N-1} \prod_{r=k+1}^N \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{Rcgk} + em_{RcgN} \end{aligned} \quad (26)$$

Avec :

$$\begin{aligned} em_{RcgN} = & \frac{1}{(1 + \gamma_N)(1 - \varepsilon_{RcgN})} [em_W + (1 - \varepsilon_{WN}) \cdot em_L + (1 - \varepsilon_{WN})(1 - \varepsilon_{LN}) \cdot em_S \\ & + (1 - \varepsilon_{W\&L\&SN} + \gamma_N) \cdot em_{DN}] \end{aligned} \quad (27)$$

La transformité de ce matériau au cycle N est :

$$\tau_{RMN} = \frac{em_{RMN}}{\tilde{e}x_{RMN}} \quad (28)$$

L'énergie spécifique du matériau recyclé peut aussi s'écrire, cf Eq. (29):

$$\begin{aligned} em_{RMN} = & \left[\frac{1}{(1 + \gamma)(1 - \varepsilon_{Rcg})} \right]^N \cdot em_{PM} + \sum_{r=1}^N \left[\frac{1}{(1 + \gamma)(1 - \varepsilon_{Rcg})} \right]^r \cdot em_{Mfg} + \\ & \sum_{k=1}^N \left[\frac{1}{(1 + \gamma)(1 - \varepsilon_{Rcg})} \right]^{N-r} \cdot em_{Rcg} \end{aligned} \quad (29)$$

En considérant la proposition de Ulgiati [Ulgiati 2004], il est possible de définir

une émergie, notée $e\check{m}$, du matériau recyclé:

$$e\check{m}_{RMr} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot e_{Mfg} + em_{Rcgr} \quad (30)$$

Avec:

$$em_{Rcgr} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} [em_W + (1 - \varepsilon_{Wr}) \cdot em_L + (1 - \varepsilon_{Wr})(1 - \varepsilon_{Lr}) \cdot em_S + (1 - \varepsilon_{W\&L\&Sr} + \gamma_r) \cdot em_{Dr}] \quad (31)$$

L'idée développée dans cette thèse, cf. Chapter 4, est de considérer que si le matériau a subi plusieurs recyclages alors il a eu plusieurs applications. L'exergie spécifique considérée doit tenir compte de l'ensemble des usages (lors de son usage en sortie de mine jusqu'au cycle considéré). Ainsi dans la proposition 1, une transformité moyenne est proposée. Les propositions suivantes sont des rapports permettant de quantifier une solution qualifiable de "éco-conception".

Prop.1 : *Transformité moyenne d'un matériau recyclé $\bar{\tau}_{RM}$*

La transformité moyenne d'un matériau recyclé est définie comme le rapport entre l'émergie des intrants de toutes les étapes antérieures et toutes les exergies associées lors de ses usages respectifs. La transformité moyenne d'un matériau au recyclage N est donc :

$$\bar{\tau}_{RMN} = \frac{em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})} \cdot em_{Mfg} + \sum_{r=1}^N em_{Rcgr}}{e\check{x}_{PM} + \sum_{r=1}^N e\check{x}_{RMr}} \quad (32)$$

Où, em_{PM} est la somme des émergies spécifiques du minerai, de l'extraction et du raffinage de la matière première (i.e. ne contenant pas de recyclage).

Cette proposition évite l'écueil d'avoir une transformité croissante (comme avec Odum) ou constante (comme avec Ulgiati). Ainsi, ce critère peut être utilisé pour comparer deux matériaux (avec des pourcentages de matière recyclée différents) pour un même usage.

Prop.2 : *Rapport de l'efficacité de la ressource α*

Le rapport de l'efficacité de la ressource est défini comme le rapport entre l'émergie utilisée lors d'un recyclage em_{Rcgr} et l'émergie du matériau sans recyclage em_{PM} . Ce rapport est une mesure de l'efficacité de la ressource dans un cycle de recyclage. Un rapport α inférieur à 1 indique que le recyclage économise des ressources naturelles.

$$\alpha_r = \frac{em_{Rcgr}}{em_{PM}} \quad (33)$$

Prop.3 : *Rapport de qualité β*

Le rapport de qualité est défini comme le rapport entre l'exergie (la qualité) d'un matériau recyclé, pour un cycle r donné, et l'exergie du matériau premier (sans recyclage). Ce rapport mesure la dégradation de la qualité d'un matériau recyclé lors d'un recyclage. Ce ratio de performance ne peut pas être supérieur à 1, plus il se rapproche de l'unité moins il y a de perte de qualité lors d'un recyclage.

$$\beta_r = \frac{\tilde{e}x_{RMr}}{\tilde{e}x_{PM}} \quad (34)$$

Prop.4 : *Rapport d'éco-conception χ*

Le rapport d'éco-conception est le rapport entre l'énergie mobilisée lors de la transformation du matériau en produit em_{Mfg} et l'énergie du matériau premier em_{PM} . La capacité d'un produit à être recyclé à la fin de sa vie (d'usage) dépend essentiellement de sa conception, de sa production et des matériaux utilisés. Le rapport d'éco-conception mesure la "recyclabilité" d'un matériau, sur la base de ses propriétés et de sa complexité de transformation.

$$\chi = \frac{em_{Mfg}}{em_{PM}} \quad (35)$$

En introduisant les rapports α et β dans Eq. (32), la transformité moyenne d'un produit recyclé au cycle N peut s'exprimer sous la forme:

$$\left\{ \begin{array}{l} \bar{\tau}_{RMN} = \frac{\sum_{r=0}^N \alpha_r \cdot em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})} \cdot em_{Mfg}}{\sum_{r=0}^N \beta_r \cdot ex_{PM}} \\ \text{with} \\ \alpha_0 = \beta_0 = 1 \end{array} \right. \quad (36)$$

Afin de déterminer si un recyclage s'inscrit dans un cadre soutenable, la transformité moyenne $\bar{\tau}_{RMN}$ peut être comparée à la transformité du matériau premier, voir Eq. (37). Le recyclage peut être considéré comme une option soutenable, si et seulement si la transformité moyenne du matériau recyclé est inférieure à celle du matériau premier. Par conséquent, plus τ_{RMr} est faible par rapport à τ_{PM} , plus le recyclage s'inscrit dans le cadre du développement soutenable.

$$\tau_{PM} = \frac{em_{PM}}{\tilde{e}x_{PM}} \quad (37)$$

La valeur limite de $\bar{\tau}_{RMN}$ est la valeur du matériau premier τ_{PM} :

$$\bar{\tau}_{RMN} \leq \tau_{PM} \quad (38)$$

A partir de Eq. (37), on obtient:

$$\frac{\sum_{r=0}^N \alpha_r \cdot em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})} \cdot em_{Mfg}}{\sum_{r=0}^N \beta_r \cdot \tilde{e}x_{PM}} \leq \frac{em_{PM}}{\tilde{e}x_{PM}} \quad (39)$$

Et,

$$\frac{\sum_{r=0}^N \alpha_r \cdot em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})} \cdot em_{Mfg}}{\sum_{r=0}^N \beta_r \cdot em_{PM}} \leq 1$$

Deux inégalités se déduisent:

$$\frac{\sum_{r=0}^N \alpha_r}{\sum_{r=0}^N \beta_r} \leq 1 \quad (40a)$$

$$\chi \leq \frac{\sum_{r=0}^N \beta_r}{\sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})}} \quad (40b)$$

Dans le cas où β , γ et ε_{Rcg} sont constants, on peut ré-écrire Eq. (40b) :

$$\chi \leq \frac{1 + N \cdot \beta}{(1+\gamma) \cdot (1-\varepsilon_{Rcg})} \quad (41)$$

On obtient alors :

$$\chi \leq \frac{(1+\gamma) \cdot (1-\varepsilon_{Rcg})}{N} + \beta \cdot (1+\gamma) \cdot (1-\varepsilon_{Rcg}) \quad (42)$$

Ainsi, une valeur limite du rapport d'éco-conception χ peut être déterminée quand N tend vers l'infini (i.e. un grand nombre de recyclages):

$$\chi_{Limit} = \beta \cdot (1+\gamma) \cdot (1-\varepsilon_{Rcg}) \quad (43)$$

On peut aussi pour un rapport d'éco-conception χ connu, déterminer le nombre maximum de recyclages possibles, en utilisant Eq. (40b):

$$N \leq \frac{(1 + \gamma) \cdot (1 - \varepsilon_{Rcg})}{(\chi - \beta \cdot (1 + \gamma)) \cdot (1 - \varepsilon_{Rcg})} \quad (44)$$

Soit,

$$N_{Limit} = \frac{(1 + \gamma) \cdot (1 - \varepsilon_{Rcg})}{\chi - \chi_{Limit}} \quad (45)$$

Ce résultat établit que le nombre de recyclage d'un matériau dépend essentiellement du rapport d'éco-conception. Cela sous-tend que la "recyclabilité" d'un produit doit être considérée dès sa conception.

Une application numérique sur de l'aluminium est présentée dans le Chapter 4.

Energie et bilan CO₂

Dans cette section, les éléments de réponse à la question **RQ3** sont proposés, voir Chapters 5 and 6.

L'un des intérêts de l'énergie est de permettre la comparaison de deux solutions technologiques, et de dégager celle qui peut être la plus favorable (ou la moins néfaste) vis-à-vis de l'environnement. Le site de la chantrerie venant d'être équipé d'une chaufferie bois, comparer l'approche "bilan carbone" avec l'approche émergétique semble intéressant. Ce travail a été prolongé à la co-combustion biomasse/charbon pour une centrale de grande puissance.

Comparaison entre une chaufferie bois et une chaufferie gaz naturel

Le synoptique d'une chaufferie bois est présenté sur la Fig. 9. Le système considéré a pour frontière:

- le bois et son transport
- les employés
- la collecte des cendres

Dans un bilan carbone, la combustion de bois est considérée comme n'émettant pas de CO₂ (le CO₂ émis étant supposé être capté par du bois replanté). Par contre, dans l'approche émergétique il faut tenir compte de l'énergie du bois.

Le synoptique d'une chaufferie est présenté sur la Fig. 10.

L'ensemble des équations (bilan de masse, d'énergie et d'énergie) est présenté dans le Chapter 5.

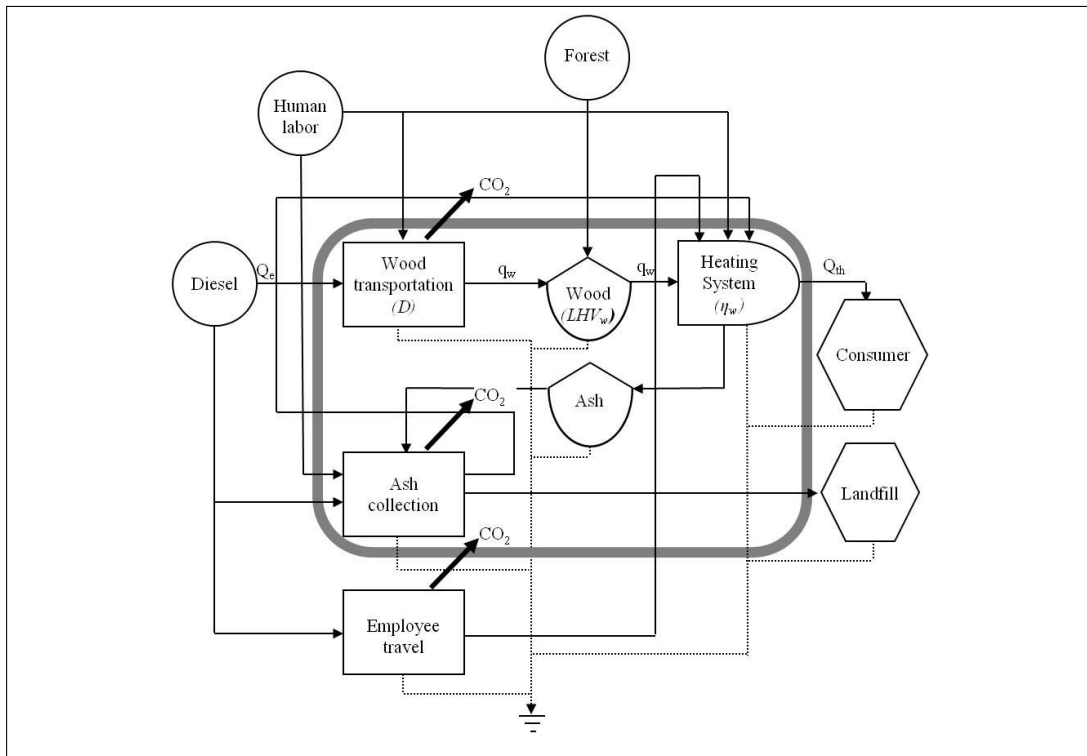


Figure 9: Synoptique d'une chaufferie bois

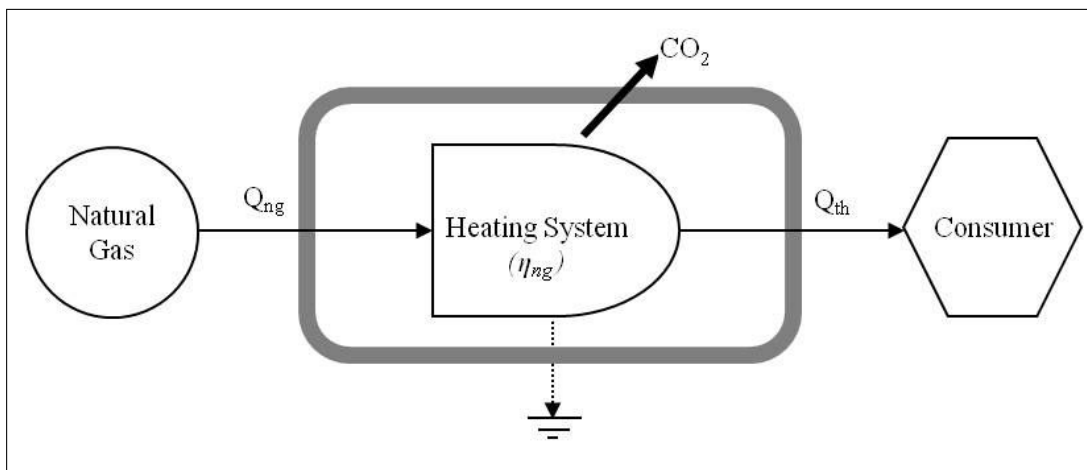


Figure 10: Synoptique d'une chaudière gaz naturel

L'une des nouveautés de ce travail est la définition de la distance limite de transport du bois.

Ainsi, en notant CO_2^{ng-b} le bilan CO_2 de la chaudière gaz naturel, et $CO_2^{w-b} \cdot (D^{cf})$ le bilan CO_2 de la chaufferie bois, il est possible de définir une distance limite

de transport du bois D_{max}^{cf} , distance bilan CO₂, par:

$$CO_2^{ng-b} = CO_2^{w-b} \cdot (D_{max}^{cf}) \quad (46)$$

De même, en notant Em_{ng-b} l'énergie annuelle de la chaudière gaz naturel, et $Em_{w-b} \cdot D^E$ l'énergie annuelle de la chaufferie bois, il est possible de définir une distance limite de transport du bois D_{max}^E , distance émergie, par:

$$Em_{ng-b} = Em_{w-b} \cdot D_{max}^E \quad (47)$$

Le rapport de ces distances peut s'exprimer sous la forme:

$$\frac{D_{max}^E}{D_{max}^{cf}} = K \cdot \left(\frac{\eta_w - \eta_{min}^E}{\eta_w - \eta_{min}^{cf}} \right) \quad (48)$$

avec η_w le rendement de la chaufferie bois.

La Fig. 11 présente ce rapport. Si le rendement effectif de la chaudière bois devient inférieur à une limite, notée η_{min}^E , la chaufferie bois n'est plus une solution favorable pour l'environnement, quand bien même le bilan CO₂ reste positif.

La Fig. 12 a pour abscisse la différence de CO₂ émis entre la chaudière gaz naturel et la chaufferie bois et pour ordonnée la différence entre l'énergie annuelle des deux mêmes solutions. Se trouver dans le quadrant 1 est positif d'un point de vue bilan CO₂ et émergie, on remarque cependant qu'il existe une limite à cette situation: une distance de transport de bois nulle (chaufferie à l'intérieur de la forêt). Dans le quadrant 2, la chaufferie bois reste efficiente d'un point de vue CO₂ mais n'est plus opérante d'un point de vue émergie. Dans le quadrant 3, la solution chaufferie bois ne se justifie plus ni d'un point de vue CO₂ ni de celui de l'émergie.

Co-combustion biomasse/charbon

Le synoptique de la centrale étudiée est présentée sur la Fig. 13. De manière similaire à la section précédente, la comparaison porte sur l'analyse émergétique et le bilan CO₂ des combustibles, i.e. le charbon transporté par train tracté par des moteurs diesel et la biomasse (paille, bois, etc...) par camion.

Les originalités de ce travail, notamment par rapport au précédent, sont:

- prise en considération de la période géologique de formation du charbon, cf. [Brown 2010].

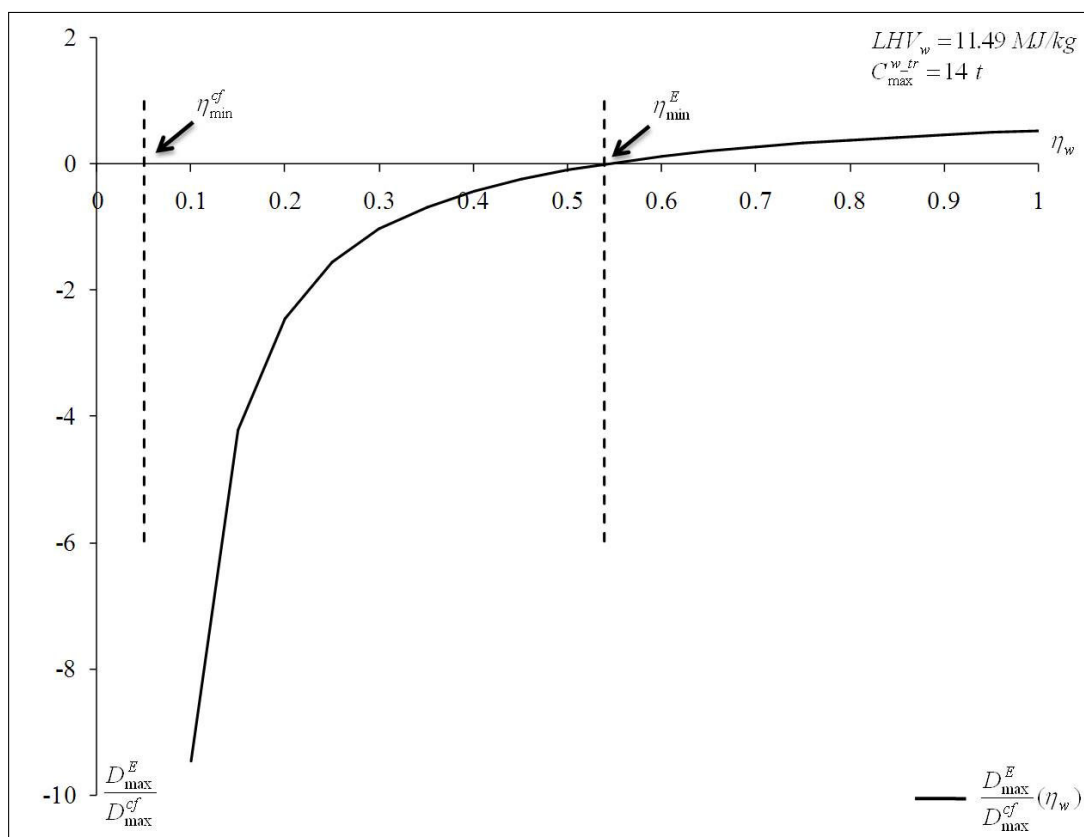


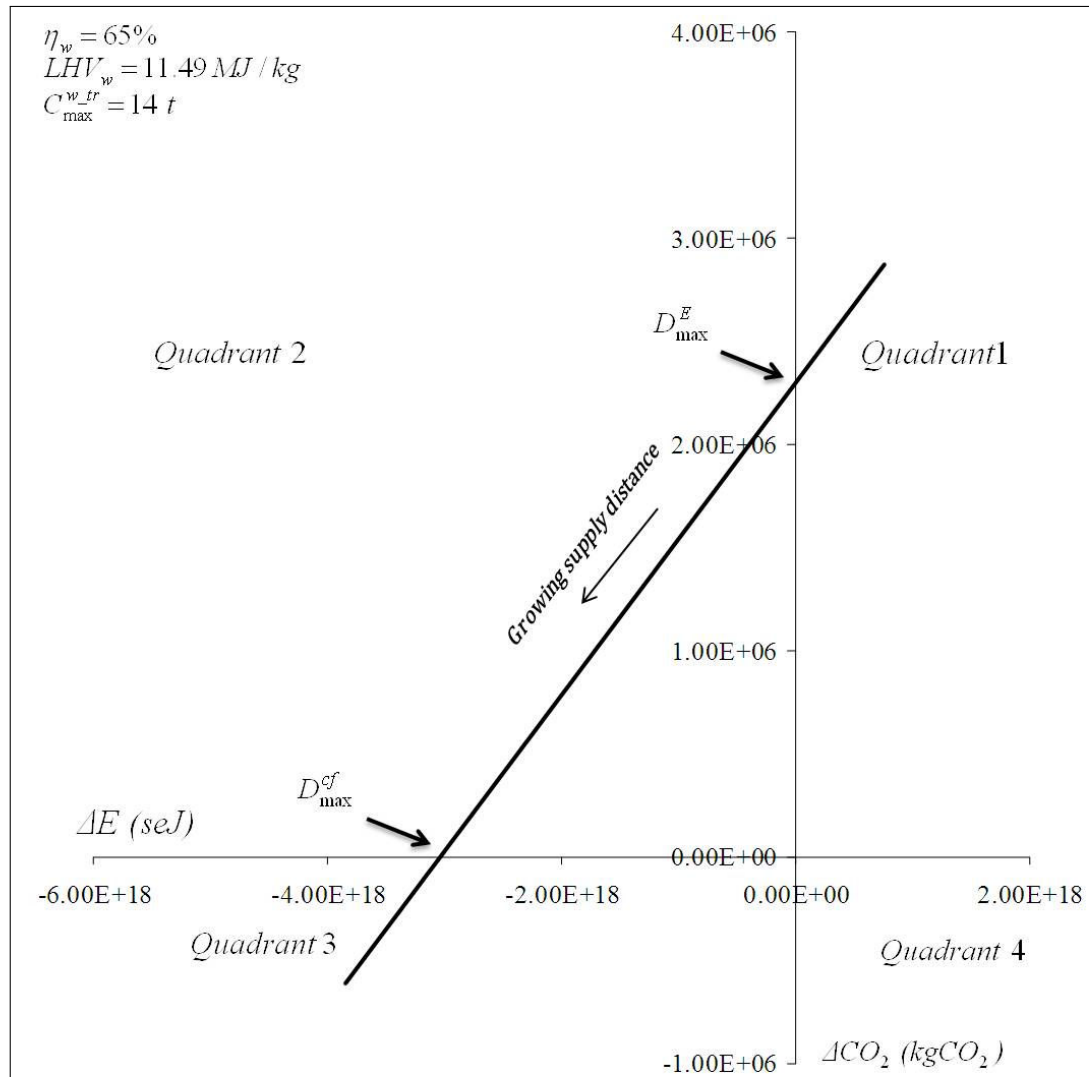
Figure 11: Rapport distance variant avec le rendement de la chaufferie bois

Transformité du charbon selon l'âge géologique de formation		
Age géologique	Transformité PCS > 30.0 MJ/kg ^a	Transformité PCS < 30.0 MJ/kg ^b
	[seJ/J]	[seJ/J]
Dévonien	1.06E+05	7.33E+04
Carbonifère	1.07E+05	7.96E+04
Permien	9.02E+04	6.56E+04
Trias	9.11E+04	6.63E+04
Jurassique	2.57E+05	1.83E+05
Crétacé	4.96E+04	3.67E+04
Tertiaire	5.08E+04	3.75E+04
Moyenne massique	1.09E+05	3.75E+04

^a, ^b valeurs incluant l'extraction et le broyage

Table 4: Transformité du charbon selon l'âge géologique de formation

- la composition, dont l'humidité, la teneur en matières minérales non combustibles (cendres)

Figure 12: Diagramme Energie-bilan CO₂

Composition du charbon (incluant cendre et humidité)							
Charbon	Carbone [%]	Hydrogène [%]	Oxygène [%]	Nitrogène [%]	Soufre [%]	Cendre [%]	Humidité [%]
Anthracite	82.16	3.22	2.24	1.25	0.63	6.00	4.50
Bitumineux	74.93	4.62	9.14	1.27	0.54	4.20	5.30
Sub-bitumineux	59.82	4.38	11.67	1.33	1.10	11.20	10.50
Lignite	37.42	2.27	12.23	0.58	0.21	10.40	36.90

Table 5: Composition du charbon, source: [Hingman 2008]

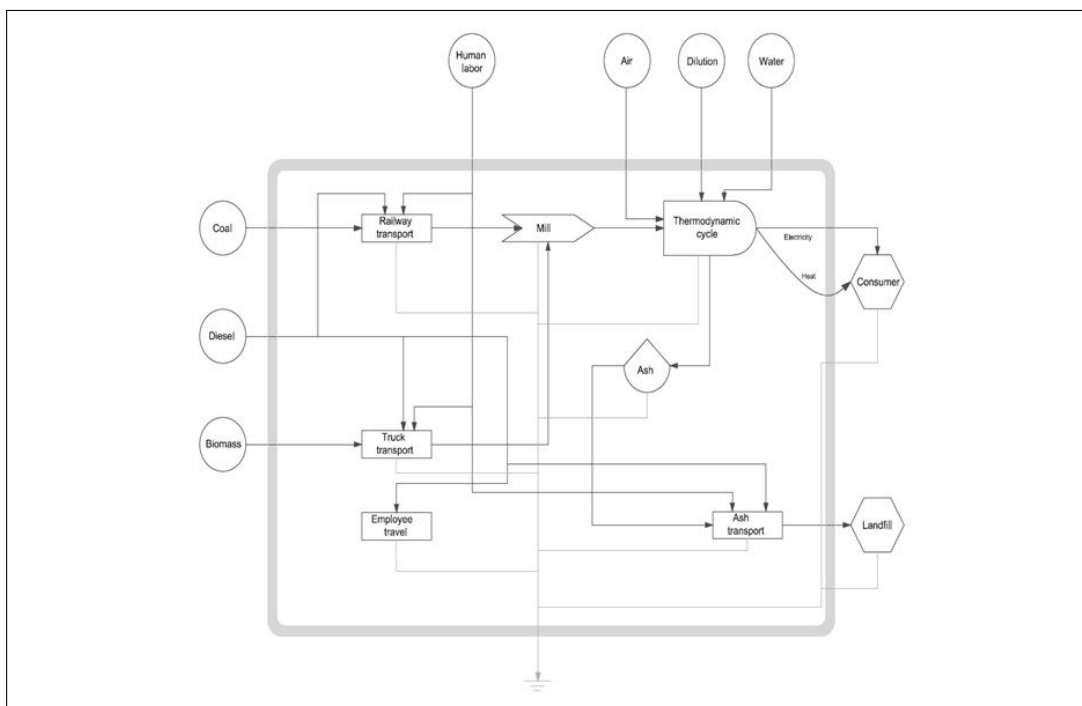


Figure 13: Synoptique d'une usine en co-combustion

Composition de la biomasse (incluant cendre et humidité)							
Biomasse	Carbone [%]	Hydrogène [%]	Oxygène [%]	Nitrogène [%]	Soufre [%]	Cendre [%]	Humidité [%]
Bois	49.50	6.08	44.01	0.12	0.06	0.20	7.80
Saule	49.10	6.01	42.79	0.59	0.05	1.40	10.10
Orge	49.08	5.90	41.55	0.66	0.12	4.70	11.50
Paille	44.16	5.07	40.27	0.90	0.12	9.50	12.40

Table 6: Composition de la biomasse, source: [Vassilev 2013]

- analyse effectuée sur des ratios permettant de distinguer les contributions en renouvelable R , non-renouvelable N et venant du secteur marchand F , voir Odum [Odum 1996] and Brown and Ulgiati [Brown 1997b].

1. Le rapport Energy Yield Ratio est le rapport entre la somme des émergies et l'émergie du secteur marchand. Plus ce rapport est proche de 1, plus l'émergie provenant du système marchand est importante dans la création du bien/service/produit

$$EYR = \frac{Y}{F} \quad (49)$$

2. Le rapport Emery Investment Ratio est le rapport entre l'émergie provenant du système marchand et les ressources renouvelables ou non-

renouvelables.

$$EIR = \frac{F}{R + N} \quad (50)$$

3. Le rapport Energy Loading Ratio est le rapport entre la somme de l'énergie provenant du système marchand et l'énergie non-renouvelable, et l'énergie des renouvelables. Plus ce rapport est faible, plus la part d'énergie renouvelable est importante dans la création du bien/service/produit, plus il est considéré comme s'inscrivant dans le concept de "développement durable".

$$ELR = \frac{F + N}{R} \quad (51)$$

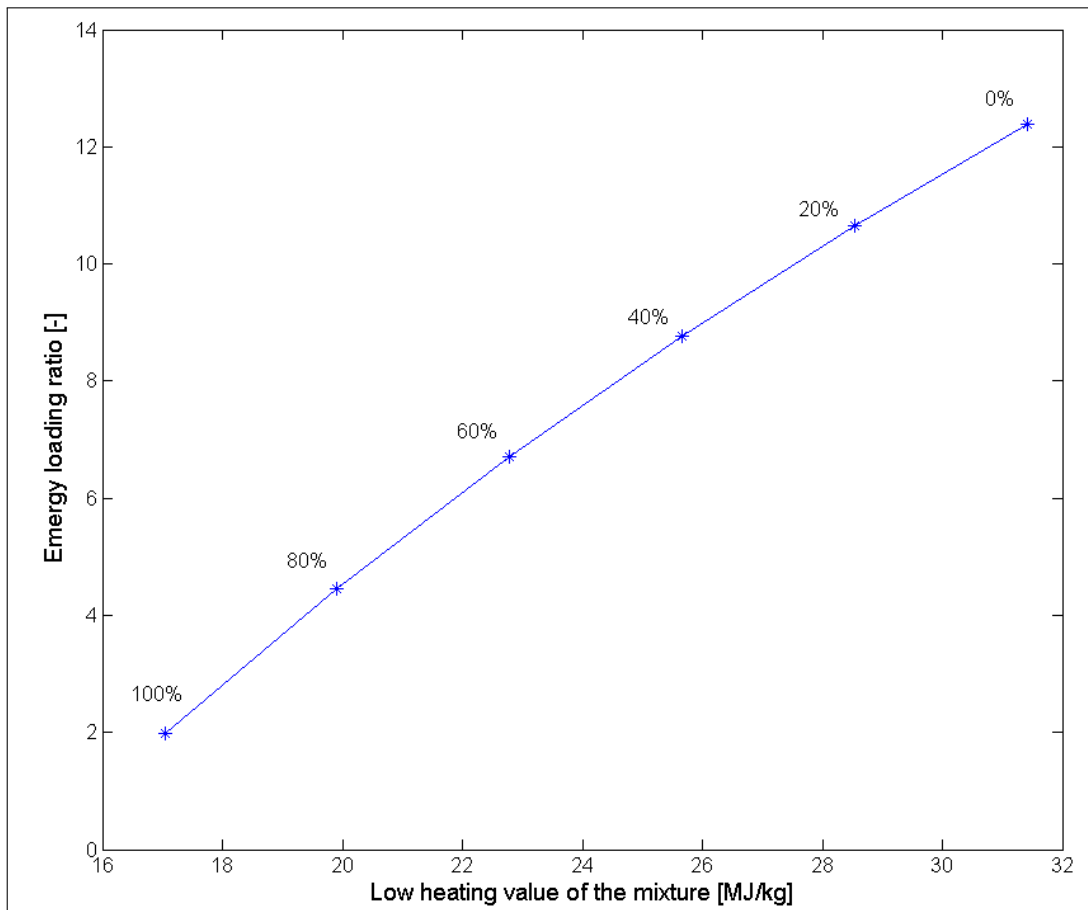


Figure 14: Influence du *PCI* d'un mélange biomasse-charbon sur le rapport *ELR* ($\alpha_{aa} = 1.4$, $\alpha_{bw} = 0.25$, $\alpha_{bwl} = 0.25$, $\alpha_{bba} = 0.25$, $\alpha_{bs} = 0.25$, $D_c = 800km$, $D_a = 200km$, $D_b = 240km$, $d_{em} = 20km$)

Même s'il n'est pas pratiquement possible de substituer 100% de charbon par de la biomasse (dans une installation conçue initialement pour fonctionner au charbon),

le calcul a été mené d'un point de vue théorique. Sur la Fig. 14, le rapport ELR est présenté.

Le lecteur est invité à lire le Chapter 6 pour plus de détails.

Conclusion

Le questionnement scientifique de cette thèse portait sur 3 aspects:

RQ1 *Comment évaluer l'impact environnemental résultant de l'exploitation des ressources minérales, en tenant en compte de leur abondance, de leur composition chimique, de leurs propriétés physiques et des effets de leur extraction?*

En partant d'une revue bibliographique, notamment les travaux de Odum [Odum 1996, Odum 2000a] et l'approche thermodynamique initialement développée par Szargut [Szargut 2005], il a été possible de poser des hypothèses et d'effectuer des propositions afin de calculer l'énergie spécifique (avant le début d'exploitation d'un gisement) de 42 minéraux en fonction de leur concentration, de leur composition chimique et de leur propriété chimique. L'un des résultats remarquables de cette thèse est que l'énergie spécifique d'un minéral ne peut pas être considérée comme une constante.

RQ2 *Comment évaluer la performance du recyclage, en prenant en compte les différentes pertes (de quantité et de qualité)?*

En partant des travaux de Amponsah [Amponsah 2012], il a été possible de quantifier l'effet de pertes de masse lors du recyclage dans une analyse émergétique. En reprenant les travaux de Szargut [Szargut 2005], il a été possible d'inclure à l'analyse précédente une perte de qualité du matériau lors du recyclage. Quatre propositions ont été faites :

Prop.1 : *Transformité moyenne d'un matériau recyclé $\bar{\tau}_{RM}$*

La transformité moyenne d'un matériau recyclé est définie comme le rapport entre l'énergie des intrants de toutes les étapes antérieures et toutes les exergies associées. La transformité moyenne d'un matériau au recyclage N est donc :

$$\bar{\tau}_{RMN} = \frac{em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})} \cdot em_{Mfg} + \sum_{r=1}^N em_{Rcgr}}{\tilde{e}x_{PM} + \sum_{r=1}^N \tilde{e}x_{RMr}} \quad (52)$$

Cette proposition évite l'écueil d'avoir une transformité croissante (comme avec Odum) ou constante (comme avec Ulgiati). Ainsi, ce critère peut être utilisé pour comparer deux matériaux (avec des pourcentages de matière recyclée différents) pour un même usage.

Prop.2 : *Rapport de l'efficacité de la ressource α*

Le rapport de l'efficacité de la ressource est défini comme le rapport entre l'énergie utilisée lors d'un recyclage em_{Rcgr} et l'énergie du matériau sans recyclage em_{PM} . Ce rapport est une mesure de l'efficacité de la ressource dans un cycle de recyclage. Un rapport α inférieur à 1 indique que le recyclage économise des ressources naturelles.

$$\alpha_r = \frac{em_{Rcgr}}{em_{PM}} \quad (53)$$

Prop.3 : *Rapport de qualité β*

Le rapport de qualité est défini comme le rapport entre l'exergie (la qualité) d'un matériau recyclé, pour un cycle r donné, et l'exergie du matériau premier (sans recyclage). Ce rapport mesure la dégradation de la qualité d'un matériau recyclé lors d'un recyclage. Ce ratio de performance ne peut pas être supérieur à 1, plus il se rapproche de l'unité moins il y a de perte de qualité lors d'un recyclage.

$$\beta_r = \frac{\tilde{e}x_{RMr}}{\tilde{e}x_{PM}} \quad (54)$$

Prop.4 : *Rapport d'éco-conception χ*

Le rapport d'éco-conception est le rapport entre l'énergie mobilisée lors de la transformation du matériau en produit em_{Mfg} et l'énergie du matériau premier em_{PM} . La capacité d'un produit à être recyclé à la fin de sa vie (d'usage) dépend essentiellement de sa conception, de sa production et des matériaux utilisés. Le rapport d'éco-conception mesure la "recyclabilité" d'un matériau, sur la base de ses propriétés et de sa complexité de transformation.

$$\chi = \frac{em_{Mfg}}{em_{PM}} \quad (55)$$

RQ3 *Substituer de l'énergie fossile par de la biomasse s'inscrit-il toujours dans le cadre du développement durable?*

L'intérêt d'une substitution d'un combustible fossile par de la biomasse est limitée par le transport de cette dernière. Par exemple, substituer du charbon transporté par train par de la biomasse transportée par camion peut induire une consommation supérieure de ressources, quantifier soit en CO2 soit en énergie. Dans cette partie, il a été introduit la notion de "*distance limite de transport*". Un diagramme CO2 - énergie a aussi été introduit.

Personal contribution

Le corps de ce manuscrit de thèse est un recueil d'articles soit publiés soit en soumission. Il est composé de 5 chapitres et d'une annexe. Une cohérence scientifique a donné la structure finale de ce manuscrit : en utilisant l'expression consacrée « du berceau à la tombe » (de la mine à la décharge). Néanmoins, afin d'explicitier la contribution de l'auteur à ces travaux co-signés, l'ordre chronologique est repris ci-après car il permet de mettre en exergue d'une part les contributions scientifiques propres et d'autre part l'autonomie acquise par l'auteur. 23 septembre 2011, N. Amponsah [Amponsah 2011a] soutient sa thèse. Cette thèse est la première dans le domaine de l'analyse émergétique à l'Ecole des Mines de Nantes. Dès le début de ma thèse, ma participation à la conférence biennale sur l'éMergie en 2012, se tenant en Floride, fût décidée. Une communication [Jamali-Zghal 2013] fût donc soumise, acceptée et présentée. Le retour de l'assemblée fût très positif. Le travail fût sélectionné par le comité d'organisation comme base pour un Special Issue de Journal of Cleaner Production. Le texte initial fût largement amélioré. J'ai introduit deux contributions marquantes dans cet article, cf. Chapter 5, le diagramme CO₂-émergie, Fig. 5.5 et donné l'interprétation de chaque quadrant. L'expression analytique entre le bilan CO₂ et l'émergie sur la distance de transport, sur le cas considéré.

Lors de cette soumission, j'ai donc appris la préparation d'une conférence, le niveau d'une publication international dans un journal de premier plan (et le processus d'expertise associé).

En parallèle à ce travail, j'ai participé à la publication [Amponsah 2011b] dans le journal Resources, Conservation & Recycling, comme co-auteur. Comme mes contributions scientifiques ne sont pas des plus significatives dans ce travail, j'ai choisi de le mettre en annexe.

A partir du second semestre 2012, une grande liberté m'a été offerte. La ligne directrice à suivre était : associer les travaux de Antonio et Alicia Valero [Valero 2008a, Valero 2008b, Valero 2002d, Valero 2002b, Valero 2009, Valero 1998, Valero 2002c, Valero 2005a, Valero 2002a] et l'éMergie pour l'évaluation des minéraux. Un travail bibliographique m'amena à approfondir les travaux de Szargut [Szargut 1987, Szargut 2005, Szargut 2002, Szargut 1989] mais aussi ceux de Hazen [Hazen 2010b, Hazen 2010a], et bien sûr ceux de Brown [Cohen 2007, Brown 2004d, Brown 2010] et de Odum [Odum 2000b, Odum 1996]. Sur la base de ce travail, je fus en mesure d'identifier les limites des travaux publiés, notamment la dépendance aux conditions économiques [Cohen 2007]. En explicitant des hypothèses, je fus en mesure de formuler des propositions afin de rendre le calcul de l'émergie des minéraux plus cohérent vis-à-vis des idées formulées par Odum [Odum 1996]. Ce travail fût publié dans Ecological Modeling, [Jamali-Zghal 2014]. Le retour de l'expertise de la revue fût extrêmement positif dès la soumission originale : modification mineure.

En Septembre 2013, je fus l'encadrante scientifique de K. Deutz, un deuxième année de Master PM3E (Project Management for Environmental and Energy En-

gineering), sur un projet recherche se déroulant sur un semestre. Il fût décidé que l'objectif serait de participer à la conférence biennale sur l'éMergie en 2014. Son sujet consistait à reprendre les travaux de N. Amponsah et de répondre aux interrogations formulées par le Prof. Brown, Univ. de Floride, lors de sa soutenance de thèse: tenir compte des pertes de masses lors des différentes étapes et cycles lors de recyclages. J'ai conduit le travail de K. Deutz et une communication fût soumise, acceptée et qu'il présenta. A la suite de cette présentation, une invitation à un Special Issue du journal Ecological Modeling fût reçue. Le texte de la communication fût largement amélioré et est actuellement en soumission. Le chapitre 3 (Chapter 3) correspond à ce travail. Mes contributions personnelles sont diverses: notion de cycles fermés lors de recyclages, notion de co-produits, principalement en m'appuyant sur la bibliographie.

En parallèle à cet encadrement, j'ai proposé d'intégrer la dégradation de la qualité du produit recyclé dans l'analyse émergétique. Il est ainsi possible de prolonger le travail antérieur sur l'émergie des minéraux en tenant compte de la dégradation de l'exergie lors du recyclage. Ce travail est actuellement en soumission à Resources, Conservation & Recycling. En effectuant une étude bibliographique spécifique, je fus amenée à approfondir le concept « exergetic life assessment » (Chapter 4), ainsi que le travail de Ulgiati [Ulgiati 2004]. Après avoir formulé des hypothèses, j'ai assez naturellement été amenée à définir trois nouveaux ratios :

- Resource efficiency ratio
- Performance ratio
- Eco-design ratio

Ces ratios correspondent à ma contribution scientifique majeure dans cet article, outre la recherche bibliographique.

Toujours en Septembre 2013, j'ai eu l'opportunité de collaborer avec un autre étudiant I. Andric, qui débutait sa thèse. L'idée de ce travail était de prolonger le travail de comparaison entre le bilan CO₂ et l'émergie [Jamali-Zghal 2013], appliquée sur un autre système et en tenant compte de la période géologique de formation du charbon. J'ai pu le conseiller sur la bibliographie, sur la rédaction et lors du processus d'expertise de la revue, en résumer lui transmettre mon expérience sur la manière d'écrire un article scientifique. Le texte fût soumis à un Special Issue de Journal of Cleaner Production. Des modifications majeures furent demandées. A la suite du travail additionnel, des modifications mineures furent requises. L'article est accepté pour publication.

Pour conclure, les travaux de recherche développés ont donc été soutenus au début par une date limite liée à la conférence biennale de 2012 et une collaboration avec un doctorant en fin de thèse. L'article dans le Special Issue bouscula un peu le planning de la thèse. A la fin du processus d'expertise de la revue, je pus me

concentrer sur mon sujet initial avec une grande autonomie. Débutant ma dernière année, j'ai eu l'occasion d'encadrer un Master et de collaborer avec un doctorant en première année. L'objectif fût soit une conférence soit un article : dans les deux cas, j'ai pu transmettre ma méthodologie pour la bibliographie, sur la manière d'écrire un texte de conférence ou de journal mais aussi lors de processus d'expertise de la revue.

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CHAPTER 1

Introduction

Natural resources are the backbone of every economy. But the way in which resources are used and the speed at which they are being exploited is undermining the environmental resource base on which our prosperity and growth depend. The first oil crisis in the 1970's was the initial proof of the scarcity of resources. In this time period, developed countries were becoming aware about the increasingly shortage of natural resources and the need of sustainable development. In 1987, the United Nations World Commission on Environment and Development defined sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". The aim is to continuously improve the quality of life for both current and future generation without increasing the use of natural resources beyond the Earth's carrying capacity. The entire life-cycle of natural resources, from their extraction to their final disposal as waste, engenders negative environmental impacts. To ensure that natural resources are managed in a sustainable way, the environmental impacts of resource use should be identified and reduced. Two main sources can be distinguished:

- *Resource depletion*
- *Pollution*

Resource depletion refers to the consumption of a resource faster than the planet's capacity to regenerate it. *Pollution* refers to the contamination of the natural environment due to waste and emissions. In a certain way, *pollution* contributes to the *resource depletion* because it degrades the quality of resources as air, water or land.

If current patterns of resource use are maintained, the chance of future generations to access the resources necessary for future economic and social development will be endangered. Waste recycling and the substitution of excessively polluting resources with alternatives are considered as the key components of sustainable resource management. In this context, this thesis has a dual purpose of: on the one hand, evaluating the environmental impacts of natural resource exploitation and on the other hand, assessing the environmental performance of waste recycling and resource substitution.

1.1 Research approach

The work is essentially based on the *emergy approach*, but also other environmental assessment tools has been used such as the *exergoecology approach*, the *exergetic life cycle assessment* and the *carbon footprint*:

- The *Emergy* spelled with an "m" can be considered as an "energy footprint" which memorizes all energies and materials in their original forms, converted in solar energy (seJ, Solar emjoule), consumed or transformed to create a

product or a service [Odum 1996]. As the production complexity and the ability to do work can be very different from one form of energy to another, the emergy concept posits that the energy flows of the universe are organized in an energy transformation hierarchy [Odum 1996, Brown 2004d]. The position of any kind of energy in this hierarchy is given by its transformity which is by definition, the ratio between the emergy contribution (input) and the exergy (output). While assuming that the real wealth of the environment is the work of the geobiosphere, the annual emergy flow of the geobiosphere is considered to be the baseline reference from which all other unit emergy flows are directly or indirectly derived from [Odum 2000b, Brown 2010].

- The *exergoecology approach*, introduced by [Valero 1998], is based on exergetic analysis and allows to assess the physical cost that would be required to produce, with today's best technology, natural resources from its components in a defined reference environment (which is assigned as the most degraded state of the resource) to the physical and chemical conditions as they are found in Nature. This thermodynamic tool permits to provide a realistic value of the energy that Nature stored in form of concentrated mineral resources and that will be irreversibly lost when these minerals are used up.
- The *exergetic life cycle assessment* is an extension of the life cycle approach including exergy analysis. It is an evaluation method that permits to measure the energy and environmental burden of a process or an activity by identifying and assessing the resources consumed and the wastes released in the environment [Curran 2013, Finnveden 2014]. Based on the first and second law of thermodynamics, it makes possible to measure the depletion of natural resources due to the irreversibility of life cycles. This tool permits not only to measure the thermodynamic imperfection of the process but also to find out where the exergy destruction occurs [Cornelissen 2002, Dincer 2007].
- The *carbon footprint* has become widely used concept in carbon-dioxide emissions assessments. This method has been applied to determine emission factors at different levels, such as industrial parks [Dong 2013], national parks [Villalba 2013], cities [Lin 2013] and the whole countries [Larsen 2011]. It is a measure of total amount of carbon-dioxide released into the atmosphere in the given time frame that is directly or indirectly caused by an activity to provide service or a product.

The flow of the work is formalized in the following three research questions (*RQ*) which are central to this thesis:

- ***RQ1:*** *Is it possible, and if so how, to assess the environmental impacts resulting from the exploitation of mineral resources, taking into account their abundance, their chemical and physical properties and the effects of their extraction?*

- **RQ2:** *Is it possible, and if so how, to evaluate the environmental performance of recycling, taking into account the chemical, physical and thermodynamic limits of the process?*
- **RQ3:** *To which extent a partial or complete substitution of fossil fuels with biomass is an environmentally friendly solution?*

1.2 Thesis contribution

This section explains the contribution of this thesis to answer the forgoing research questions.

RQ1: *Is it possible, and if so how, to assess the environmental impacts resulting from the exploitation of mineral resources, taking into account their abundance, their chemical and physical properties and the effects of their extraction?*

Chapter 2 relates to the impact of declining mineral reserves. The underlying question of how to calculate the emergy invested by Nature to produce mineral resources, with the physical and chemical conditions as they are found in the Earth's crust, was used as the starting point of the study. Based on what he called "*the 6th energy law*", Odum [Odum 2000a] emphasized that the emergy per mass (or specific emergy) of a mineral vary with its abundance. The more the mineral is abundant the lower the emergy needed to generate a unit of it. The same reasoning can be applied to mineral deposits: the concentration of dispersed minerals requires available energy i.e. the higher the concentration of the mineral deposit (ore grade) is, the more available energy has been downgraded and the higher the emergy per mass should be. Otherwise, when concentrated minerals become dispersed (minerals are extracted from the mine), available energy is lost and the stored emergy diminishes. Based on this, the assumption was made that every group of mineral dispersed in the Earth's crust is an individual component of the latter. Every group of mineral is characterized by its specific chemical composition and its abundance, and thus it may be considered, from an emergy point of view, as co-product of the Earth's crust formation process. This means that every group of mineral has the same absolute emergy as the Earth's crust and that its specific emergy is proportional to the specific emergy of the Earth's crust and to its crustal concentration. In order to calculate the specific emergy of mineral reserves, the assumption was made that the sources of energy that created dispersed minerals, concentrated further a part of them into mines. Hence, the specific emergy of a mineral reserve can be calculated by using the mineral's exergy, the specific emergy of the dispersed mineral and the ore grade of the deposit. In order to calculate the variation of the specific emergy of the ore deposit with mining, the assumption was done that the extraction of the mineral is assimilated to a natural dilution of the ore body generated by the same sources of energy that concentrated it before. Finally, in order to assess the degradation of

mines due to mineral extraction and the efforts that should be applied to remedy the mining impacts, the assumption was made that the emergy of the whole mine is equal to the total emergy of its mineral reserves.

RQ2: Is it possible, and if so how, to evaluate the environmental performance of recycling, taking into account the chemical, physical and thermodynamic limits of the process?

Amponsah et al. [Amponsah 2011b] (see Appendix A) focuses on the impacts that might have the number of times a material has been recycled on emergy ratios. The study analyzes the effects of using materials that was recycled several times in buildings. New definitions have been proposed to determine how the emergy yield ratio (*EYR*) and the environmental loading ratio (*ELR*) vary with the frequency the material has been recycled. Chapter 3 broaden the multi-recycling emergy accounting. The enhanced evaluation model takes into account the material losses at each cycle, as well as the two possible types of closed-loop recycling (single-source and multi-source). The developed equations has been applied to the case of aluminum recycling. Based on the recycling benefit ratio (*RBR*), the influence of several parameters (recycling rate, number of cycles, mass losses) on the environmental benefit of both single-source and multi-source recycling has been studied.

Chapter 4 lays the theoretical foundation for answering this research question. The purpose of this chapter is to assess the efficiency of metallurgical recycling, from both a donor- and user-side perspective, by using the emergy evaluation combined with an exergetic life cycle assessment (*ELCA*). According to the *Energy hierarchy principle* developed by Odum [Odum 1996], consecutive cycles can be considered as an energy transformation chain, where every transformation process (in this case recycling cycle) generates an output (recycled material) at a higher energy level (i.e. higher transformity). This means that the transformity of recycled materials increases with every cycle. The developed model, based on this approach, allows the comparison of different processes (for the same material) at several cycles, based on the occurring material and quality losses. It allows then to choose the most environmental friendly option (i.e. with the lower transformity). Nevertheless, and due to the fact that the transformity is always increasing with each recycling process, the emergy approach is not able to determine neither the benefits nor the limits of the recycling. In order to deal with this issue, Ulgiati et al. [Ulgiati 2004] suggest to reset the memory of all previous processes that generated the recovered material and to consider only the inputs required for the recycling and treatment of the latter. The recycled material, however, is the result of all previous (manufacturing and recycling) processes the material has been passed through. Thus, the use of an average transformity has been proposed which can be calculated by dividing the emergy inflows of all previous processes by their exergy outputs. This allows to assess the environmental performance of consecutive recycling from both a donor- and user-side perspective and to avoid "double counting". To further assess the benefits and limits of consecutive recycling processes, three sustainability ratios are

proposed:

- *Resource efficiency ratio α* : The ratio of the emergy used in the recycling process to the emergy of the primary material. It is a measure of the resource efficiency of the recycling process.
- *Quality ratio β* : The ratio between the exergy (quality) of the recycled material obtained through cycle r and the exergy (quality) of the primary material. It measures the quality degradation of the recovered material during the recycling process.
- *Eco-design ratio χ* : The ratio of the emergy used in the manufacturing process and the emergy of the primary material. The ability of the product to be recycled at the end of its life cycle depends essentially on its design, on its production process and on the selected materials. The eco-design ratio measures the recyclability of the material, based on its properties and on the complexity of the manufacturing process.

Finally, the proposed evaluation model shows that for constant quality degradation and material losses, a limit value of the number of recycling and the eco-design ratio can be calculated.

RQ3: To which extent a partial or complete substitution of fossil fuels with biomass is an environmentally friendly solution?

In order to assess the limits and benefits of using biomass as substitute for fossil fuels, two concrete examples has been studied.

Chapter 5 provides a comparative study between two heating systems: one is fired with wood, transported by trucks and the other one is fired with natural gas transported by pipelines. Contrary to natural gas, the combustion of wood is considered as carbon neutral. Hence, the environmental performance of a wood fired heating system depends mostly on the mode and distance of wood transportation. A carbon footprint analysis and an emergy evaluation have been used to realize the eco-environmental quality assessment of the two heating systems. These two environmental indicators have been chosen to cover all relevant aspects of the heat production process that may have an environmental impact. Carbon footprint analysis permits to measure the effect on the climate, in terms of the amount of CO_2 emitted during heat production, while the emergy evaluation accounts for all forms of energy and resources used in the process. In order to compare and visualize the distance limitation of emergy evaluation and carbon footprint, an original emergy versus carbon footprint diagram is defined. For a better understanding and interpretation of the large discrepancy between the results of the emergy evaluation and the carbon footprint, the possibility of a relationship between the two approaches has been investigated. Finally a sensitivity analysis has been performed to identify the impacts of different parameters such as the efficiency of the wood boiler, the low

heating value of wood, the load capacity of trucks used to transport wood and the distance crossed to remove ash.

Chapter 6 provides a comparative study between the pure coal firing and co-firing of coal and biomass for electricity and heat production. The carbon footprint and emergy evaluation has been chosen to determine the maximum supply distance of biomass that allows the co-firing of coal and biomass to be more environmentally efficient than the pure coal combustion. All inputs for plant operation has been considered in the evaluation study: fuel input, transportation, human labor and renewable environmental resources such as air and water. Environmental performances of co-firing are identified for various types of coal with different geological origins and compositions, and biomass consisted of wood and diverse agricultural residues (straw, barley and willow). In order to calculate the emergy flow of air dilution process, simplified box model is used. The box dimensions are determined by the length of the area upwind of a receptor and the height of the boundary layer. In order to assess the sustainability of the process, three emergy ratios have been used: the emergy yield ratio (*EYR*), the emergy investment ratio (*EIR*) and the emergy load ratio (*ELR*). Finally, to examine the influence of various parameters, a sensitivity analysis has been conducted. This analysis takes into account possible changes in fuel types and their respective proportions in the combustion mixture, as well as capacities of means of transportation and distances of the power plant from the fuel stocks.

**Mineral resource assessment:
Compliance between Emergy and
Exergy respecting Odum's
hierarchy concept**

Mineral resource assessment: Compliance between Emergy and Exergy respecting Odum's hierarchy concept

Abstract: In this chapter, authors suggest to combine the exergoecology and the emergy concept in order to evaluate mineral resources, taking into account their abundance, their chemical and physical properties and the impact of their extraction. The first proposition of this work is to consider that every group of mineral, dispersed in the Earth's crust, is a co-product of the latter. The specific emergies of dispersed minerals are, then, inversely proportional to their abundance. The results comply with the material hierarchy as the specific emergy of a dispersed mineral rise with its scarcity. The second is an emergy evaluation model based on the chemical and concentration exergy of the mineral, its condition in the mine and its abundance. This model permits to assess the decline of mineral reserves and its impact on the ecosystem. The dispersed specific emergy of 42 main commercially used minerals has been calculated. Furthermore, the emergy decrease of some Australian mineral reserves has been studied, as well as the land degradation of US copper mines.

Keywords: Emergy, Exergoecology, Mineral resource depletion, Material hierarchy

Nomenclature

Acronyms

OGC Ore grade cutoff [-]

Greek Symbols

λ Ratio between the molar mass of mineral M_M and the average molar mass of the mixture M_{tot} , $\lambda_M = \frac{M_{tot}}{M_M}$ [-]

α Part of the energy of the geobiosphere that contributed to the Earth crust formation

τ Transformity [seJ/g]

Roman Symbols

B Baseline [seJ/g]

Δg_f Specific Gibbs free energy of mineral formation [J/g]

ER Enrichment factor, $ER = \frac{OGC}{x_{Mcr}}$ [-]

Em Total emergy [seJ]

em Specific emergy [seJ/g]

Ex Total exergy [J]

ex Specific exergy [J/mol]

k Unit exergy replacement cost [-]

M Molar mass [g/mol]

m mass [g]

R Universal gas constant [8.314 J/mol K]

T° Standard ambient temperature [298.15 K]

x Massic fraction [g/g]

y Molar fraction [mol/mol]

Superscripts

$^\circ$ Initial conditions

r Real exergy cost

Subscripts

c Concentration

ch Chemical

cr Crust

F Earth crust formation

<i>geobio</i>	Geobiosphere
<i>i</i>	Component <i>i</i>
<i>M</i>	Mineral
<i>Mine</i>	Mine
<i>R</i>	Mineral reserve
<i>rem</i>	Removed
<i>Rest</i>	Restoration

2.1 Introduction

Emergy can be considered as an "energy footprint" which memorizes all energies in their original forms, converted in solar energy (seJ, Solar emjoule), consumed or transformed to create a product or a service [Odum 1996]. As the production complexity and the ability to do work can be very different from one form of energy to another, the emergy concept posits that the energy flows of the universe are organized in an energy transformation hierarchy [Odum 1996, Brown 2004d]. The position of any kind of energy in this hierarchy is given by its transformity which is by definition, the ratio between the emergy contribution (input) and the exergy (output). While assuming that the real wealth of the environment is the work of the geobiosphere, the annual energy flow of the geobiosphere is considered to be the baseline reference from which all other unit emergy flows are directly or indirectly derived from [Odum 2000b, Brown 2010].

To evaluate mineral resources Odum proposed what he called "*the 6th energy law*" (see Citation 2.1) to relate material cycles to the energy hierarchy concept, which permits to classify hierarchically materials from the point of their specific emergies (seJ/g). The emergy concept posits that the universe is hierarchically classified, describing the diminution of available energy with each transformation process. The transformity, defined as the emergy driving the process per unit of available energy, indicates the position of any transformation process in the hierarchy, since the latter enhances the quality of the produced energy but reduces the amount of available energy. Thus, the greater the transformity is, the more available energy of a lower level of the hierarchy has been involved in the transformation process. The same reasoning can be applied to material cycles: the concentration of dispersed minerals requires available energy i.e. the higher the concentration of the mineral deposit is the more available energy has been downgraded and the higher the emergy per mass should be. Otherwise, when concentrated minerals becomes dispersed, available energy is lost and the stored emergy diminishes.

Citation 2.1 (*An energy hierarchy law for biochemical cycles*)

« Materials of biochemical cycles are hierarchically organized because of the necessary coupling of matter to the universal emergy transformation hierarchy » (Odum [Odum 2000a])

Previous studies [Cohen 2007, Brown 2007] have been carried out to evaluate the emergy of mineral resources, expecting that the specific emergy of a mineral reserve em_R varies linearly with its enrichment factor EF_R , see Eq. (2.1).

$$em_R = B_R \cdot EF_R \quad (2.1)$$

Cohen et al. [Cohen 2007] and Brown [Brown 2007] used both an enrichment factor based on the ore grade cutoff OGC and the crustal concentration $x_{M_{cr}}$ of the mineral, which is by definition the minimum ore grade a mine should have to be exploited profitably. The value is very variable, it depends essentially on the current level of technology and the market demand of the mineral. An universal baseline B_R was applied because the different rock types from which the minerals are extracted, are considered to have little varying specific emergies. Cohen et al. [Cohen 2007] first, used the specific energy of land cycle (calculated by Odum [Odum 1996]) as baseline. Brown [Brown 2007], later, updated this work by adopting the specific energy of the Earth's crust that he calculated. In addition, a regression model relating the cutoff concentration to the price and abundance has been elaborated to estimate the specific energy of those minerals for which the cutoff concentration were not available. The results of these studies, however, as they are based on the ore grade cutoff of the mineral, do not represent the real energy that Nature invested to create the mineral reserve, but rather an evaluation in view of standards set by society, because the results only reveals the minimum specific energy a reserve should have to be beneficially extracted. Besides, integrating market prices to estimate the specific energy of ore deposits seems not to be an adequate solution because the prices rarely vary with the condition of the mineral in the mine but often with economic, financial and geopolitical circumstances. Thus, the highest specific energy obtained by this approach do not correspond to scarce materials as expected by Odum who emphasized in his book that scarce minerals require more work for their creation and concentration (see Citations 2.2 and 2.3), but to those with high ore grade cutoffs. This shows that the evaluation of mineral resources by this method is limited in particular because the chemical composition and the decline of the reserves is not taken into account.

Citation 2.2 (*Environmental accounting*)

«*Emergy per unit mass (seJ/g) indicates the position a mineral has on the scale of Earth scarcity and unit value.*»
(Odum [Odum 1996], p.121)

Citation 2.3 (*Environmental accounting*)

«*In general, the scarce products from the Earth are those that required more work for their formation and concentration. Therefore they tend to have higher Emergy contents. Burnett [Burnett 1981] found that materials with more emergy contribution were less abundant.*» (Odum [Odum 1996], p.117)

Several scientists even go further in their criticism, claiming that contrarily to exergy analysis, emergy evaluation is not suitable to assess mineral resources. Martinez et al. [Martinez 2007] concluded, after comparing the evaluation of Earth's

mineral resources via both emergy and exergy analysis that the latter method is more adequate for accurate mineral valuation. Sciubba [Sciubba 2010] stated that energy accounting is unable to evaluate the degradation of mineral resources caused by human consumption, see Citation 2.4. As well as Valero et al. [Valero 2008b] who contested the rigorousness of mineral resource assessment via emergy analysis, see Citation 2.5.

Actually, when exergy analyses are used to evaluate natural capital, it should be kept in mind that exergy is a state function. Thus, it does not describe the processes that generated natural capital, but only the results of these processes i.e. the distance from their thermodynamic equilibrium, without any consideration for the followed path and for the origin of the required energy. It can therefore be concluded that the exergy method permits to assess accurately the energy required to replace mineral resources with present technology but that it is unable to evaluate the work that was done by Nature to form ore deposits.

The aim of this chapter is to combine the emergy and the exergy approach, in order to evaluate the real wealth of mineral resources, taking into account their physical and chemical conditions and the driving forces behind their evolution. This work tries to develop a methodology that permits not only to quantify the quality decrease of ore deposits during mining but also to illustrate the impact caused by mineral extraction and the work that should be done to restore the post-mining land.

Citation 2.4 (*On the Second-Law inconsistency of Emergy Analysis*)

« *It is recommended therefore that Emergy Analysis be not used to assess the global resource consumption caused by anthropic activities, because its results are misleading when it comes to estimate the exergy destruction enacted by real industrial transformations.* » (Sciubba [Sciubba 2010])

Citation 2.5 (*Exergy evolution of the mineral capital on earth*)

« *No matter how much solar energy is received from the sun, the quantity of gold or iron for instance on Earth, will not change. Consequently, the rigorousness of the transformities for mineral resource assessment is doubtful.* » (Valero et al. [Valero 2008b], p.8)

2.2 Methodology

2.2.1 Scope of the study

The production of non-fuel minerals for economic use involves a series of physical and chemical processes, see Fig. 2.1. These complex processes are either natural or man-made, therefore it is recommended to distinguish between natural and anthropogenic exergy in assessing mineral resources. The minerals' natural exergy represents the effort invested by Nature to create them with their chemical and physical properties as they are found in the mine. The minerals' anthropogenic exergy, however, represents the energies that should be mobilized by man to make the mineral suitable for commercial use.

In this work only the natural exergy of the mineral has been studied with the aim of quantifying the environmental impact of mineral resource depletion.

2.2.2 Exergy analysis of non-fuel mineral reserves

Minerals are limited, non-renewable natural resources offered by Nature and exploited by human society. Any natural resource is characterized by its specific composition and concentration, which distinguish it from its environment. These intrinsic properties permit to measure the thermodynamic value of a natural resource, called material's exergy [Riekert 1974], which is defined as the minimum theoretical work that Nature should invest to produce it with its specific structure and concentration. A number of exergy-based approaches have been proposed to evaluate natural resources. The most common concept may be the Thermoecological cost analysis introduced by [Szargut 2002]. This method proposes to measure, in terms of exergy and energy, the ecological cost of non-renewable natural resource depletion. Therefore the cumulative consumption of non-renewable exergy connected with the fabrication of particular products, including the abatement processes of the resulting emissions and wastes is accounted for. The exergoecology approach, introduced by [Valero 1998] and used in this study, differs fundamentally from Szargut's method as it is not interested in the exergy costs of the production processes but rather on the physical cost that would be required to produce, with today's best technology, natural resources from its components in a defined reference environment (which is assigned as the most degraded state of the resource) to the physical and chemical conditions as they are found in Nature. This thermodynamic tool permits to provide a realistic value of the energy that Nature stored in form of concentrated mineral resources and that will be irreversibly lost when these minerals are used up. It should be noted that the exergoecology should not be confused with the eco-exergy concept, introduced by Jorgensen [Jorgensen 2006] and applied to measure the development and health of an ecosystem

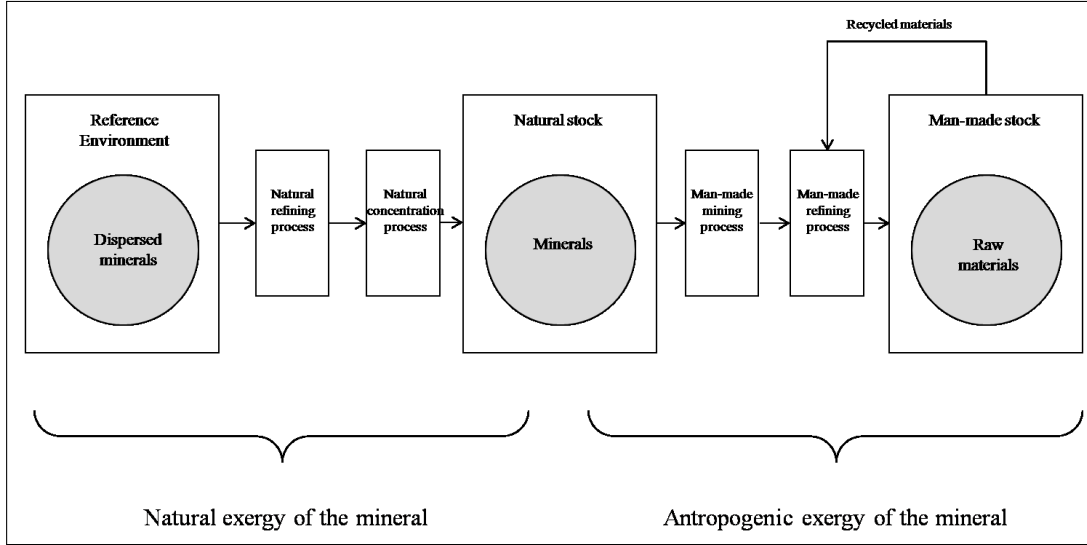


Figure 2.1: Process of raw material production [Valero 2005b]

2.2.2.1 Exergy of non-fuel minerals

In this work, the thermodynamic evaluation of minerals is based on Szargut's reference environment methodology [Szargut 2005]. The chemical composition and the thermodynamic properties of this hypothetical environment permits to calculate the theoretical minimum work that must be invested to reproduce from the reference substances the composition of the Earth crust, in form of a homogeneous solid layer where all minerals are uniformly distributed at their average concentration $x_{M_{cr}}$. The reference environment is considered as a source of heat and reference substances. The process is assumed to be reversible. The mineral's specific chemical exergy ex_{chM} can be calculated by using the exergy balance of a reversible reaction, as the reference substances are supposed to be at a standard ambient temperature and pressure and standard concentration in the natural environment [Szargut 1989, Valero 2002b], see Eq. (2.2).

$$ex_{chM} = \Delta g_f + \sum_i y_i \cdot ex_{chi} \quad (2.2)$$

Δg_f represents the specific Gibbs free energy of mineral M and y_i and ex_{chi} are respectively the molar fraction and the specific chemical exergy of component i of mineral M .

Ore deposits are naturally occurring aggregates of minerals, their ore grade represents the mineral content of the rock which is much higher than the average concentration of the mineral in the Earth's crust. Concentrated minerals in mines can

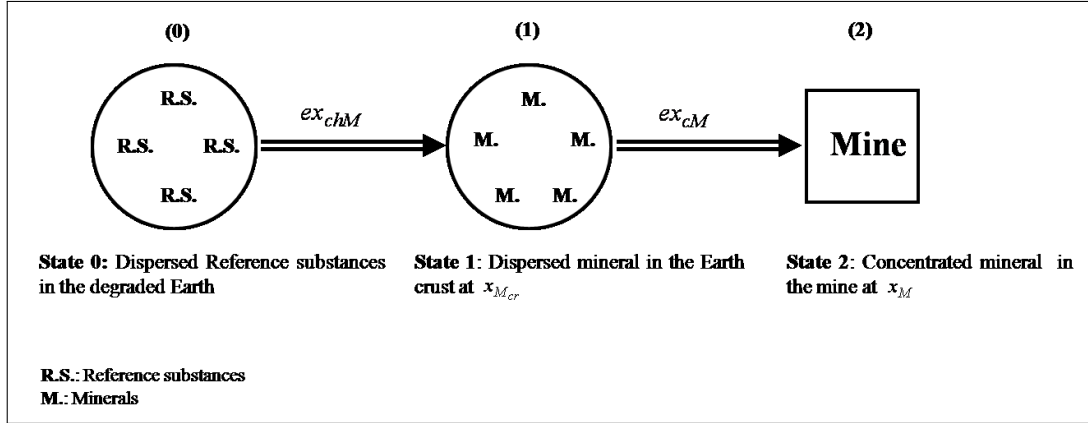


Figure 2.2: Theoretical formation process of the mineral, from the reference environment to the conditions in the mine

be easily extracted with present technology, compared to other parts of the Earth's crust where the mineral is dispersed. Thus, according to Szargut's reference environment methodology, any mineral resource with higher concentration would have an amount of energy provided by Nature, which differentiate it from its dispersed state in the reference environment. The concentration exergy is defined by Valero et al. [Valero 2009] to be the minimum required work to concentrate, in a reversible way, the dispersed mineral in the Earth's crust into mines. Assuming, that an ore deposit is an ideal mixture of a mineral M and rock, the specific concentration exergy of the mineral ex_{cM} can be equated to the minimum amount of work that should be furnished to separate the mineral (concentrated at x_M) from the rock, see Eq. (2.3). It can be seen that the higher the ore grade, the lower the effort needed to extract the mineral from the mine, pointing to the fact that concentrated minerals represent a natural energy contribution, easing its extraction.

$$ex_{cM}(x_M) = -RT^\circ \left\{ \ln(\lambda_M x_M) + \frac{(1 - \lambda_M x_M)}{\lambda_M x_M} \ln(1 - \lambda_M x_M) \right\} \quad (2.3)$$

Where R represents the universal gas constant, T° the standard ambient temperature and λ_M the molar mass ratio between the mineral and the mixture of rock and mineral.

Valero identifies three theoretical states of mineral evolution to calculate the exergy that should be invested to form mineral deposits from the reference environment, see Fig. 2.2:

1. State 0 (Reference environment): All the reference substances are dispersed, mixed and in thermodynamic equilibrium \Rightarrow The exergy is Zero.

2. State 1 (Dispersed minerals): Chemical reactions took place, the minerals are formed and dispersed at their crustal concentration $x_{M_{cr}}$ on the Earth crust, the specific exergy of the dispersed mineral $ex_M(x_{M_{cr}})$ of the mineral is:

$$ex_M(x_{M_{cr}}) = ex_{chM} \quad (2.4)$$

3. State 2 (Concentrated minerals): The dispersed mineral is concentrated at x_M into mines, the specific exergy of the concentrated mineral $ex_M(x_M)$ is then:

$$ex_M(x_M) = ex_{chM} + ex_{cM}(x_M) \quad (2.5)$$

Valero's evaluation model [Valero 2002d] is based on hypothetical reversible conditions, far from real processes where friction and dissipation losses can not be neglected. The real exergy requirements are, then, much more greater than the thermodynamic value which represents only the minimum work that should be invested to form a given mineral from the reference environment to the conditions in the mine. In this context, Valero proposes to introduce physical unit costs, k_{chM} and k_{cM} , respectively of the refining and the concentration process of the mineral. This permits to identify the real exergetic value of minerals, taking into account the limits of the current available technology, see Eq. (2.6).

$$ex_M^r(x_M) = k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M) \quad (2.6)$$

2.2.2.2 Exergy decrease of declining non-fuel mineral reserves

The exergy of a mineral reserve depends on the grade and size of the ore body. To evaluate the exergy lost by mineral extraction, the whole life cycle of the reserve should be considered, from its formation until its depletion. Three main theoretical stages can be distinguished:

- *Calculation of the ore deposit's chemical exergy (pre-mine)*, The mineral is dispersed at its crustal concentration $x_{M_{cr}}$. The specific exergy of the mineral reserve $ex_R(x_{M_{cr}})$ is, then, equal to the real specific exergy of the dispersed mineral $ex_M^r(x_{M_{cr}})$. Its total exergy $Ex_R(x_{M_{cr}})$ tends to zero as the mass of extractable mineral m_M is still negligible:

$$\begin{aligned} ex_R(x_{M_{cr}}) &= ex_M^r(x_{M_{cr}}) = k_{chM} \cdot ex_{chM} \\ Ex_R(x_{M_{cr}}) &\rightarrow 0 \end{aligned} \quad (2.7)$$

It should be noted that only concentrated chemical exergy can be used because it is impossible to extract dispersed minerals with present technology.

- *Calculation of the ore deposit's concentration exergy (enrichment)*, The mine is viewed as the result of a natural enrichment process with concentrated minerals. Before extraction, the initial specific exergy of the mineral reserve $ex_R(x_M^\circ)$, is then equal to the real specific exergy of the concentrated mineral $ex_M(x_M^\circ)$. At this stage the stored exergy $Ex_R(x_M^\circ)$ reaches its maximum.

$$\begin{aligned} ex_R(x_M^\circ) &= ex_M^r(x_M^\circ) = k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M^\circ) \\ Ex_R &= m_M^\circ \cdot M_M \cdot ex_R(x_M^\circ) \end{aligned} \quad (2.8)$$

m_M° is the initial total mass of mineral in the mine, M_M is the molar mass of the mineral and x_M° is the initial ore grade of the mine.

- *Calculation of the ore deposit's exergy decrease (depletion)*, During extraction, the ore grade x_M of the reserve is diminishing ($x_{Mcr} \leq x_M \leq x_M^\circ$) and the mineral reserve is losing exergy.

$$\begin{aligned} ex_R(x_M) &= ex_M^r(x_M) = k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M) \\ Ex_R(x_M) &= m_M \cdot M_M \cdot ex_R(x_M) \end{aligned} \quad (2.9)$$

m_M is the remaining mass of mineral in the deposit after extraction and x_M is its corresponding ore grade. It should be stressed that the concentration exergy of the mineral decreases with its ore grade, while the chemical exergy remains constant. When all the mineral is extracted, the mine becomes depleted, the extractable quantity of mineral m_M becomes insignificant, and hence its ore grade x_M tends to the crustal concentration of the mineral x_{Mcr} . The specific exergy of the reserve ex_R tends then to its specific exergy before enrichment and the stored total exergy Ex_R becomes negligible:

$$\begin{aligned} \lim_{x_M \rightarrow x_{Mcr}} ex_R(x_M) &= k_{chM} \cdot ex_{chM} \\ \lim_{x_M \rightarrow x_{Mcr}} Ex_R(x_M) &= 0 \end{aligned} \quad (2.10)$$

Fig. 2.3 represents the specific exergy of the mineral reserve at different evolution stages. It can be seen that the exergy analysis distinguishes two main energy levels, a degraded one and an enriched one, corresponding respectively to the dispersed and the concentrated state of the mineral.

2.2.3 Emergy evaluation model of non-fuel mineral reserves

An emergy evaluation model is proposed that permits to assess the impact of declining non fuel mineral reserves. This method permits to assess on the one hand the emergy that Nature invested to form mineral deposits and on the other hand the emergy required to compensate the damages caused by mining.

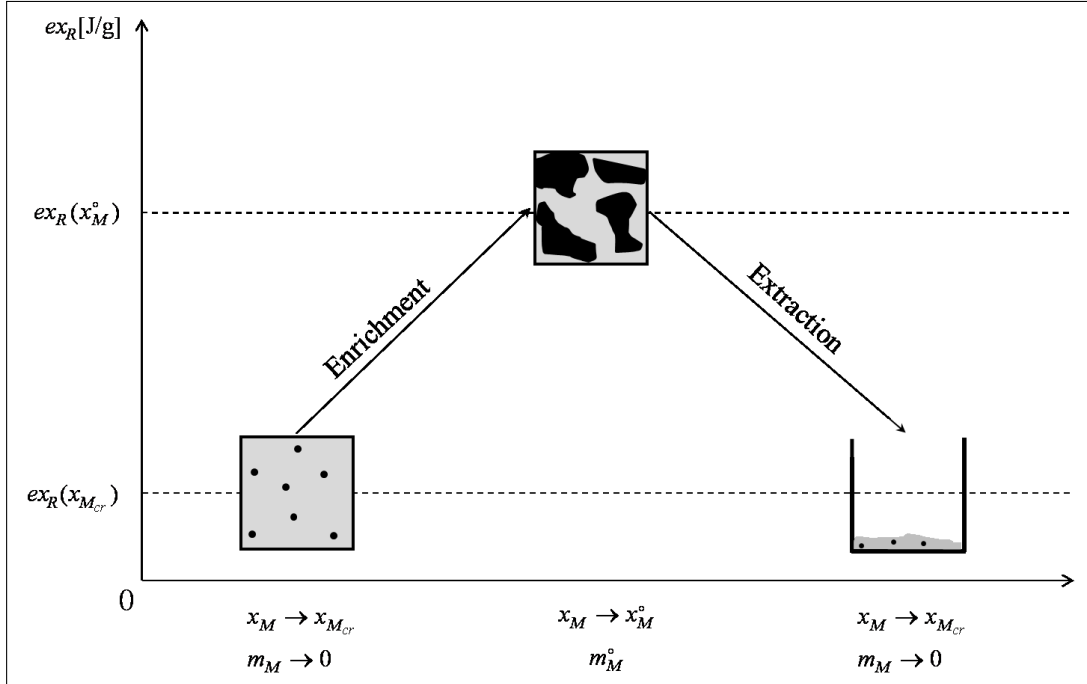


Figure 2.3: Specific exergy of an ore deposit at different evolution stages

2.2.3.1 Energy decrease of declining non-fuel mineral reserves

In order to evaluate the emergy that would be lost by extracting the mineral from the mine, the energy required to create such mineral reserves should be determined. Three main theoretical evolution processes ought to be taken into account, see Fig. 2.4.

1. *Earth's crust formation process:* Hazen's mineral evolution theory [Hazen 2010a, Hazen 2010b] and other proposed scenarios of Earth's crust formation [McCoy 2010, Valley 2002, Jørgensen 2009, Sverjensky 2010] illustrate the complexity and breath of the processes that participated, over eons, in developing the mineralogy of the Earth's crust to its present diversification and distribution (see Section 2.4). It will be very difficult if not impossible to determine exactly the energies that drove terrestrial mineral evolution, because little is known about these processes which are no longer observed in today's world. Nevertheless, different studies had been performed to evaluate the energy of the Earth's crust. Based on the work of Garrels et al. [Garrels 1975], Odum [Odum 1996] estimated the specific energy of global sediment to be about $1.62 \text{ E}+9 \text{ seJ/g}$. Brown [Brown 2007] calculated a specific energy of the Earth's crust of about $1.35 \text{ E}+8 \text{ seJ/g}$, assuming a turnover time of $2.5 \text{ E}+8 \text{ yrs}$ (the values have been converted into the emergy baseline of $1.52 \text{ E}+24 \text{ seJ/yr}$ [Brown 2010]). In the next section, a methodology is pro-

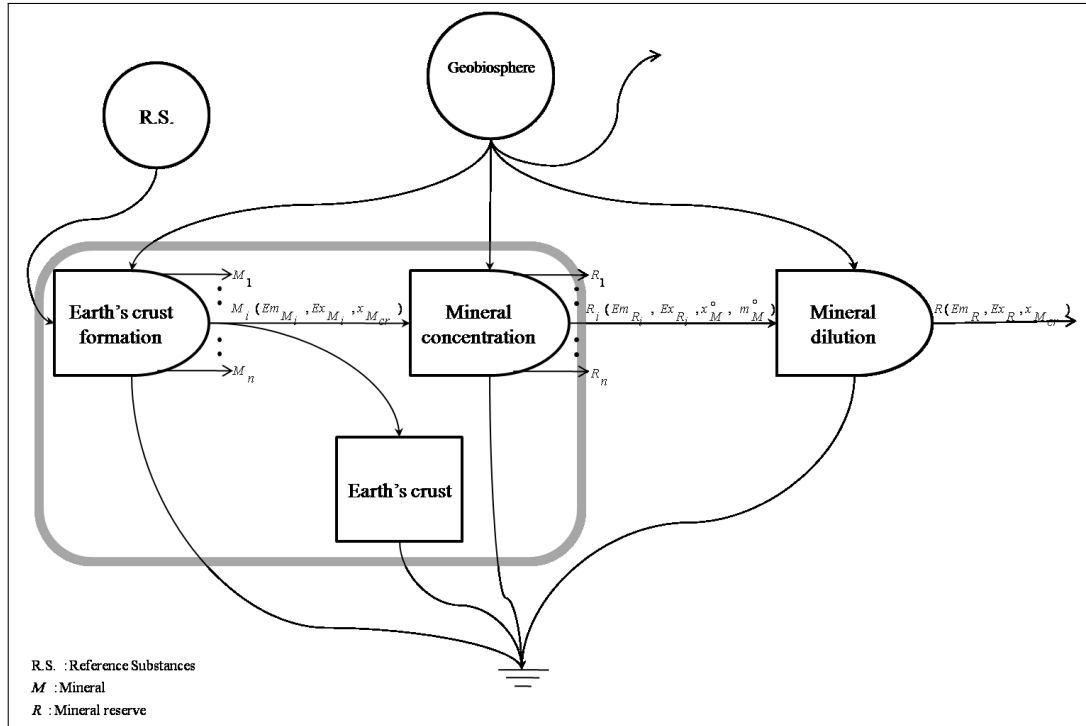


Figure 2.4: Theoretical evolution process of mineral reserves

posed to calculate the emergy of Earth's crust formation by using its chemical exergy.

Every group of mineral dispersed in the Earth's crust is regarded as individual component of the latter, characterized by its specific chemical composition and its abundance, and thus it may be considered, from an emergy point of view, as co-product of the Earth's crust formation process¹, see Fig. 2.4. This means that every group of mineral has the same total emergy as the Earth's crust and that its specific emergy $em_M(x_{M_{cr}})$ is proportional to the specific emergy of the Earth's crust em_{cr} and to its crustal concentration $x_{M_{cr}}$, see Eq. (2.11):

Assumption 2.1 (Emergy of dispersed minerals)

Every group of mineral is assumed to be a co-product of the Earth's crust: The total emergy of any mineral group $Em_M(x_{M_{cr}})$ is equal to the absolute emergy of the Earth's crust Em_{cr} .

$$Em_M(x_{M_{cr}}) \stackrel{def}{=} Em_{cr}$$

$m_{M_{cr}}$ represents the mass of the mineral in the Earth's crust and m_{cr} rep-

¹The calculation of the emergy of minerals is still under debate, some researchers suggest to consider that all minerals are splits of the original effort of biosphere to cycle them all within Earth.

resents the total mass of the Earth's crust. Hence the specific energy of a dispersed mineral M , $em_M(x_{M_{cr}})$ can be expressed as follows:

$$\begin{aligned} m_{M_{cr}} &= x_{M_{cr}} \cdot m_{cr} \\ em_M(x_{M_{cr}}) &= \frac{Em_{cr}}{m_{M_{cr}}} \\ &= \frac{em_{cr}}{x_{M_{cr}}} \end{aligned} \quad (2.11)$$

Odum (see Citation 2.2) emphasized that the energy per mass (or specific energy) of a mineral vary with its abundance in the Earth's crust. The more the mineral is abundant the lower the energy contribution was to create it. The results of Eq. (2.11) meets exactly what Odum expected (Citations 2.2 and 2.3), scarce minerals present higher energy contribution than abundant one. It should be noted, that $em_M(x_{M_{cr}})$ represents the lowest position of the mineral in the material hierarchy, because the mineral cannot be dissipated spontaneously further than its crustal concentration $x_{M_{cr}}$.

Citation 2.6 (*An energy hierarchy law for biochemical cycles*)

«... any increase in concentration of material requires an increase in the energy per mass. When concentration increase in some part of a biogeochemical cycle, the energy per mass increases.» (Odum [Odum 2000a])

2. *Concentration of minerals into ore deposits:* Odum (Citation 2.6) stressed that compared to its dispersed state (at crustal concentration $x_{M_{cr}}$), concentrated minerals required more work to be formed and thus, the more the mineral is concentrated the more available energy had been degraded and the higher the energy per mass will be (i.e. the higher its position in the material hierarchy). Actually, the quality of a mineral reserve depends on the quantity m_M° and on the concentration of the stored mineral x_M° . In this work, it is considered that the same sources of energy (τ_F is the average transformity of these sources) that created dispersed minerals, concentrated further a part of them into mines, see Fig. 2.4. Thus, the specific energy of the mineral reserve em_R can be calculated by using the mineral's exergy, the specific energy of the dispersed mineral $em_M(x_{M_{cr}})$ and the ore grade of the deposit x_M° .

Assumption 2.2 (*Emergy of mineral reserves*)

The sources of energy that created dispersed minerals in the Earth's crust are expected to be the same source that concentrated a part of them into mineral reserves.

$$\tau_F \stackrel{def}{=} \frac{Em_M(x_{M_{cr}})}{Ex_M(x_{M_{cr}})} \stackrel{def}{=} \frac{Em_R(x_M^\circ)}{Ex_R(x_M^\circ)} \quad (2.12)$$

The initial specific emergy $em_R(x_M^\circ)$ of an ore reserve of mineral M with an ore grade x_M° can be calculated, then, by using Eq. (2.13) :

$$\begin{aligned} em_R(x_M^\circ) &= em_M(x_{M_{cr}}) \cdot \frac{ex_R(x_M^\circ)}{ex_M(x_{M_{cr}})} \\ &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[\frac{k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M^\circ)}{k_{chM} \cdot ex_{chM}} \right] \\ &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[1 + \frac{k_{cM} \cdot ex_{cM}(x_M^\circ)}{k_{chM} \cdot ex_{chM}} \right] \end{aligned} \quad (2.13)$$

The total amount of emergy $Em_R(x_M^\circ)$ stored initially in the mine can be expressed as follows:

$$Em_R(x_M^\circ) = m_M^\circ \cdot em_R(x_M^\circ) \quad (2.14)$$

It should be underlined that $em_R(x_M^\circ)$ and $Em_R(x_M^\circ)$ are the highest values the mine can ever reach during its life cycle.

It can be noted that the results of Eq. (2.13) are consistent with the material hierarchy. The specific emergy of the mineral reserve increases with its ore grade x_M° and conversely when its ore content decline to its lowest value ($x_{M_{cr}}$), the specific emergy of the deposit tends to its lowest level in the material's hierarchy, which corresponds to the crustal specific emergy of the mineral:

$$\lim_{x_M^\circ \rightarrow x_{M_{cr}}} em_R = em_M(x_{M_{cr}})$$

Besides, when the abundance of the mineral $x_{M_{cr}}$ tends to 1 (which means that the whole Earth's crust is composed of mineral M), the specific emergy of the mineral reserve tends to the specific emergy of the Earth's crust:

$$\lim_{x_{M_{cr}} \rightarrow 1} em_R = em_{cr}$$

In order that Eq. (2.1) proposed by [Cohen 2007] and [Brown 2007] will be coherent with the material hierarchy concept, the enrichment factor is expected to express the real work that Nature had invested to concentrate the mineral and the baseline should be the minimum specific emergy the mineral

could reach naturally when it is dispersed. Therefore, to enhance this methodology the results of Eq. (2.13) may be used. Instead of an universal baseline B_R for any mineral reserve, the crustal specific energy of the corresponding mineral $em_M(x_{M_{cr}})$ is proposed, since its most natural degraded state is when it is dispersed. The enrichment factor ER_R can be defined as the ratio between the specific exergy of the concentrated ore reserve $ex_R(x_M^\circ)$ and the crustal specific exergy of the mineral $ex_M(x_{M_{cr}})$. This permits to integrate the effort invested by Nature to upgrade the mineral from its dispersed state to its concentrated state in the mine.

Proposition 2.1 (*Baseline and enrichment factor of mineral reserves*)

The baseline is assumed to be the crustal specific energy of the mineral:

$$B_R(x_{M_{cr}}) \stackrel{def}{=} em_M(x_{M_{cr}}) \quad (2.15)$$

The enrichment factor is defined as the ratio between the specific exergy of the concentrated ore reserve $ex_R(x_M^\circ)$ and the crustal specific exergy of the mineral $ex_M(x_{M_{cr}})$:

$$EF_R(x_M^\circ) \stackrel{def}{=} \frac{ex_R(x_M^\circ)}{ex_M(x_{M_{cr}})} \quad (2.16)$$

It should be underlined that for an appropriate energy evaluation, first the sources and pathways should be identified. Thus, it seems unreal to equate, as done in Eq. (2.1), the specific energy of mineral reserves without considering their formation process. Therefore, Proposition 2.1 was made after defining a theoretical evolution process of mineral reserves, illustrated in Fig. 2.4. The results reflects, then, the pathway of mineral reserve formation as the specific energy of the reserve depends on the chemical properties and abundance of the mineral and the initial conditions of the reserve, see Eq. (2.13).

Citation 2.7 (*An energy hierarchy law for biochemical cycles*)

« When material disperses, the stored energy decreases. »
(Odum [Odum 2000a])

3. *Extraction of the mineral from the mine:* Owing to its chemical and concentration potential, a mineral reserve can be considered as an emergy reservoir furnished by Nature to meet human needs. With the extracted mineral the mine loses chemical and concentration potential, the mineral content m_M and grade x_M of the ore body diminishes ($m_M < m_M^\circ$; $x_M < x_M^\circ$) which leads to a reduction of its stored energy. It is expected that, during the mining,

not only the total emergy of the ore body Em_R diminishes but also its specific emergy em_R , as its concentration potential decreases with its ore grade. Complying with the energy hierarchy concept, see Citation 2.7 this means that during extraction, the mine loses its available energy (in form of chemical and concentration exergy) and descend, then, to a lower level in the energy hierarchy.

The present study is not concerned with assessing the work required to extract the mineral from the mine but instead with estimating the emergy that would be definitely lost due to mineral exploitation. Therefore, in order to calculate the variation of the specific emergy of the ore deposit with mining, the extraction of the mineral can be simulated by a natural dilution of the ore body generated by the same sources of energy that concentrated it before, see Fig. 2.4. This means that the ore body of the reserve will be diluted from its initial ore grade x_M° to a lower concentration x_M after mining.

Assumption 2.3 (*Emergy decrease of declining mineral reserves*)

The extraction of the mineral from the mine can be assimilated to a natural dilution of the ore body from its initial ore grade x_M° to a lower concentration x_M , generated by the same sources of energy that previously concentrated the mineral into the mine.

$$\tau_F \stackrel{def}{=} \frac{Em_R(x_M^\circ)}{Ex_R(x_M^\circ)} \stackrel{def}{=} \frac{Em_R(x_M)}{Ex_R(x_M)} \quad (2.17)$$

Thus the specific emergy of the declining ore reserve $em_R(x_M)$ can be expressed as follows :

$$em_R(x_M) = em_R(x_M^\circ) \cdot \frac{ex_R(x_M)}{ex_R(x_M^\circ)}$$

According to Eq. (2.13):

$$\begin{aligned} em_R(x_M) &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[\frac{k_{chM} \cdot ex_{chM} + k_{cM} \cdot ex_{cM}(x_M)}{k_{chM} \cdot ex_{chM}} \right] \\ &= \frac{em_{cr}}{x_{M_{cr}}} \cdot \left[1 + \frac{k_{cM} \cdot ex_{cM}(x_M)}{k_{chM} \cdot ex_{chM}} \right] \end{aligned} \quad (2.18)$$

The remaining stored emergy after mining $Em_R(x_M)$ with an ore grade x_M containing a quantity m_M of extractable mineral, is then:

$$Em_R(x_M) = m_M \cdot em_R(x_M) \quad (2.19)$$

Once the ore reserve has been exhausted, its ore grade and specific energy approaches respectively the crustal concentration $x_{M_{cr}}$ and the crustal specific energy of the mineral $em_R(x_{M_{cr}})$. Theoretically, the consumed reserve is at the lowest position in the material hierarchy that it can ever attain naturally. The stored energy of the reserve tends to zero. The chemical potential of the mineral in the mine is no longer exploitable.

$$\begin{aligned}\lim_{x_M \rightarrow x_{M_{cr}}} em_R(x_M) &= em_M(x_{M_{cr}}) \\ \lim_{x_M \rightarrow x_{M_{cr}}} Em_R(x_M) &= 0\end{aligned}\tag{2.20}$$

Analogous to Eq. (2.1), the specific energy of a declining mineral reserve $em_R(x_M)$ may be expressed, as a function of its baseline B_R and its depletion factor DF_R . To be in conformity with the material hierarchy, the baseline should represent the highest specific energy of the mine during its life cycle, and the depletion factor is expected to quantify the concentration ability of the mine at any stage of degradation. According to Eq. (2.18), $em_R(x_M^\circ)$ can be defined as the baseline of the reserve, the ratio between the specific exergy of the ore body after mining $ex_R(x_M)$ and the initial specific exergy of the mine $ex_R(x_M^\circ)$ can be considered as the depletion factor of the reserve.

Proposition 2.2 (Baseline and depletion factor of declining mineral reserves)

The initial specific energy of the mineral is proposed as baseline:

$$B_R(x_M^\circ) \stackrel{def}{=} em_R(x_M^\circ)\tag{2.21}$$

The depletion factor is defined as the ratio between the specific exergy of the ore body after mining $ex_R(x_M)$ and the initial specific exergy of the mine $ex_R(x_M^\circ)$:

$$DF_R(x_M) \stackrel{def}{=} \frac{ex_R(x_M)}{ex_R(x_M^\circ)}\tag{2.22}$$

2.2.3.2 Energy evaluation of land degradation due to mining

A mine can be considered as a part of the Earth's crust containing high concentrated mineral ores. The extraction of these ores not only causes the loss of mine's chemical and concentration potential but also the devastation of the landscape. Contrarily to the previous section where only the depletion of the mineral reserve has been studied, the present section deals with the degradation of the whole mine due to its exploitation and the efforts that should be applied to remedy the mining impacts.

The concentrated mineral content of the mine differentiates it from its environment. It can be assumed, then, that the total emergy of the mine Em_{Mine} is equal to the total emergy of its mineral reserve Em_R .

Assumption 2.4 (Emergy of mines)

The total emergy of the whole mine Em_{Mine} is equal to the total emergy of its mineral reserve Em_R :

$$\begin{aligned} Em_{Mine}(x_M) &= Em_R(x_M) \\ m_M &= x_M \cdot m_{Mine} \end{aligned} \tag{2.23}$$

According to Eq. (2.18) the specific emergy of the mine em_{Mine} can be expressed as follows:

$$\begin{aligned} em_{Mine} &= x_M \cdot em_R(x_M) \\ em_{Mine}(x_M) &= em_{cr} \cdot \frac{x_M}{x_{M_{cr}}} \cdot \left[1 + \frac{k_c \cdot ex_c(x_M)}{k_{ch} \cdot ex_{ch}} \right] \end{aligned} \tag{2.24}$$

When the mine is completely exhausted its ore grade tends to the crustal concentration of the mineral $x_{M_{cr}}$ and the stored emergy in form of mineral reserves approaches zero because the quantity of extractable mineral becomes negligible. Based on Eq. (2.24) the specific emergy of the depleted mine tends to the specific emergy of the Earth's crust em_{cr} :

$$\lim_{x_M \rightarrow x_{M_{cr}}} em_{Mine}(x_M) = em_{cr} \tag{2.25}$$

This shows that the depleted mine lost all its specific potentials that differentiate it from the rest of the surrounding land (where the average specific emergy is em_{cr}). In terms of material hierarchy, this means that the mine is at the lowest position that it can ever reach in the hierarchy. Besides, during mining, the Earth in the mine has been removed to obtain the mineral. Hence, the total emergy of the empty mine tends to zero, and the post-mining ecosystem is out of balance because a part of the Earth's crust is missing. Additional work is required to restore the devastated land. It is possible to bulldoze the Earth into the mine, but Odum specified (see Citation 2.8) that natural restored post-mining land is more valuable than artificially recovered land. Thus, the theoretical total emergy that Nature should invest to restore for itself the balance of the ecosystem Em_{Rest} can be calculated by multiplying the removed mass of the mine m_{rem} with the specific emergy of the Earth's crust em_{cr} .

$$Em_{Rest} = m_{rem} \cdot em_{cr} \tag{2.26}$$

It should be outlined that Em_{Rest} represents the theoretically minimum work that should be done to reestablish the post-mining land, because after restoration the former mine becomes an ordinary part of the Earth's crust without any particularly chemical or concentration potential, as the mined mineral has been replaced by ordinary earth. Besides pollution and other impacts of mining are not taken into account.

Citation 2.8 (*Environmental accounting*)

« Kangas (1983), evaluating the emergy of landforms and their colonization by ecosystems, found that irregular, post-mining lands, which had 20-40 yr of natural restoration through ecological succession and other processes, were more valuable than those lands that were bulldozed flat in well-intentioned restoration. » (Odum [Odum 1996], p.123)

Fig. 2.5 represents the life cycle of the mine, taking into account the restoration process after mining. It can be seen that this evaluation model distinguishes three phases: a degraded, an enriched and a destroyed one where natural additional work is required for restoration. This shows that contrarily to the exergy analysis (see Fig. 2.2) this emergy approach permits to evaluate the impact of mining and the work that should be done to restore the post-mining ecosystem.

2.3 Results

2.3.1 Proposition of Earth's crust emergy calculation

The evolution and diversification of terrestrial minerals is a consequence of all the physical, chemical and biochemical processes through which the Earth has passed since its creation four and a half billion years ago. The degree of mineral complexity of the planet is a result of local, regional and global selective processes enforced by Nature. The diversity and distribution of its terrestrial minerals reflect the intensity of the cyclic processes that have affected the Earth during its formation. Thus, to evaluate the emergy of the Earth's crust the historical context of mineral genesis should be studied. Or, it seems to be almost impossible to evaluate the energies involved in the Earth's crust formation with today's emergy scale because the Earth, at this time, was exposed to large sources of energy much more greater than present work of the geobiosphere. Indeed, the internal and external sources of heat were considerably more important (the radioactive heat generation was about five times higher than today [Valley 2002]). Besides, the planet was subjected to heavy meteorite bombardments [Jørgensen 2009] and extreme climate change [Hazen 2010a].

Recent studies had been performed to calculate the chemical exergy of the continental crust [Valero 2012], the results may be used to determine the emergy

of Earth's crust formation by using the appropriate transformity. Valero et al. [Valero 2011] emphasized that the abundance of concentrated chemical exergy is negligible compared to the whole Earth's crust since concentrated mineral resources (fuel and non-fuel origin) only represent 0.001% of the Earth's upper crust mass. And as their concentration exergies ex_c (without adding unit exergy costs) are much more lower than their chemical exergies ex_{ch} [Valero 2008a], the concentration potential of the Earth's crust can be neglected compared to its chemical potential, and its total exergy can be assimilated to its chemical exergy. Valero et al. [Valero 2012] proposed a thermodynamic evaluation tool which permits to calculate the chemical exergy wealth of the Earth's crust based on a framed model of the crust in its dispersed state, comprising about 300 of the most abundant minerals. The study is based on the crepuscular crust model developed previously by [Valero 2011] to determine the chemical composition of the upper continental crust and on Szargut's Reference Evaluation Methodology [Szargut 2005] to calculate the chemical exergy of any substance in the upper crust. The molar chemical exergy of the Earth's upper crust is estimated to be about $ex_{cr} = 3.63 \text{ E}+3 \text{ J/mol}$ which indicates an total chemical exergy of $Ex_{cr} = 2.53 \text{ E}+26 \text{ J}$, for a molar weight of $M_{cr} = 155.2 \text{ g/mol}$. The results are manifestly very rough and need further updates, but they inform well enough about the order of magnitude of the chemical wealth of the Earth crust.

To calculate the emergy of the Earth's crust Em_{cr} basing on Valero's exergy analysis, the adequate transformity should be identified. Or, it is very difficult at this state of knowledge to evaluate precisely where the energies, involved in the Earth's crust evolution, are placed in the universal energy hierarchy. The emergy approach consider that sunlight, tidal energy and geothermal heat are the three main sources of energy that drove the complex processes of the geobiosphere and that these sources contributed to the Earth crust formation [Odum 1996]. Thus, the emergy Em_{cr} can be expressed as follows:

$$Em_{cr} = \alpha \cdot Em_{geobio} \cdot t \quad (2.27)$$

Where Em_{geobio} is the annual emergy of the geobiosphere, α is the part of this emergy that generated the Earth crust formation and t is the turnover time. In terms of exergy Em_{cr} is then:

$$Em_{cr} = \tau_{geobio} \cdot \alpha \cdot Ex_{geobio} \cdot t \quad (2.28)$$

Where Ex_{geobio} is the annual exergy of the geobiosphere and τ_{geobio} is the average transformity of the geobiosphere. Hence, to calculate Em_{cr} the values of α and t should be determined as Ex_{geobio} and τ_{geobio} are known. Brown [Brown 2007], for example, considered that the entire annual exergy of the geobiosphere drove the Earth crust formation (i.e. $\alpha = 1$) and that the turnover time was about $2.5 \text{ E}+8$ yrs.

m_{cr} [kg]	M_{cr} [g/mol]	ex_{cr} [J/mol]	Ex_{cr} [J]	τ_F [seJ/J]	Em_{cr} [seJ]
1.08E+22	155.2	3.63E+3	2.53E+26	4.2	1.06E+27

Table 2.1: Thermodynamic and emergetic properties of the Earth's upper crust

Basing on this, it can be assumed that the term " $\alpha \cdot Ex_{geobio} \cdot t$ " reflects the pathway of the Earth crust formation and that the exergy of the Earth crust Ex_{cr} calculated by Valero et al. [Valero 2012] represents the result of this formation process:

$$\alpha \cdot Ex_{geobio} \cdot t \approx Ex_{cr} \quad (2.29)$$

And thus, according to Eq. (2.28) Em_{cr} can be expressed as follows:

$$Em_{cr} = \tau_{geobio} \cdot Ex_{cr} \quad (2.30)$$

For the numerical application the average transformity of the geobiosphere calculated by Brown and Ulgiati [Brown 2010] is used. Nevertheless, it should be underlined that the proposed evaluation method remains valid what ever value of Em_{cr} or τ_F is chosen.

Proposition 2.3 (*Transformity of the Earth's crust*)

The transformity of Earth's crust formation τ_F is assumed to be equal to the average transformity of the geobiosphere τ_{geobio} .

$$\tau_F \stackrel{def}{=} \tau_{geobio} = 4.2 \text{ seJ/J}$$

The emergy of the Earth's crust is obtained, then, by multiplying its exergy by the transformity, which gives an emergy of about $Em_{cr} = 1.06 \text{ E}+27 \text{ seJ}$, see Table 2.1.

$$Em_{cr} \stackrel{def}{=} \tau_F \cdot Ex_{cr} \quad (2.31)$$

Chemical properties of the main commercially used mineral									
Name	Chemical Formula	M_M [g/mol]	$x_{M_{cr}}$ E-6	OGCE-2	ER_R	k_{cM}	k_{chM}	ex_{chM} [kJ/mol]	
Aluminium	Al_2O_3	102	8.00E+04	1.70E+01	2.10E+00	3.96E+02	1	3.49E+01	
Antimony	Sb_2S_3	339.7	2.00E-01	1.00E+01	5.00E+05	2.84E+01	10	2.52E+03	
Arsenic	$FeAsS$	162.8	1.50E+00	2.00E+00	1.33E+04	7.99E+01	10	1.43E+03	
Barium	$BaSO_4$	-	5.50E+02	5.80E+00	1.06E+02	NA	1	-	
Beryllium	$6SiO_2 \cdot Al_2O_3 \cdot 3BeO$	537.6	3.00E+00	4.00E+00	1.33E+04	1.12E+02	1	6.58E+01	
Bismuth	Bi_2S_3	514.2	1.27E-01	5.00E+00	3.94E+05	8.98E+01	10	2.23E+03	
Cadmium	CdS	144.5	9.80E-02	4.00E-01	4.08E+04	8.04E+02	10	7.44E+02	
Cesium	$CsCl$	-	3.70E+00	2.00E+01	5.41E+04	NA	1	-	
Chrome	$FeCr_2O_4$	223.8	3.50E+01	2.30E+01	6.57E+03	3.67E+01	1	1.95E+02	
Cobalt	CoS_2	123.1	1.00E+01	2.00E-01	2.00E+02	1.26E+03	10	1.39E+03	
Copper	$CuFeS_2$	183.5	2.50E+01	5.00E-01	2.00E+02	3.86E+02	10	1.53E+03	
Fluoride	CaF_2	78.1	6.50E+02	1.00E-01	1.50E+00	1.70E+00	1	5.03E+01	
Gallium	$Ga(OH)_3$	-	1.70E+01	1.00E-02	5.90E+00	-	1	-	
Germanium	GeO_2	-	1.60E+00	6.00E+00	3.75E+04	-	1	-	
Gold	Au	197	1.80E-03	1.50E-03	8.33E+03	4.09E+05	1	5.99E+01	
Hafnium	HfO_2	-	5.80E+00	4.00E-02	6.90E+01	-	1	-	
Indium	InS	146.9	5.00E-02	1.00E-02	2.00E+03	-4.39E+01	10	9.13E+02	
Iron	Fe_2O_3	159.7	3.50E+04	5.00E+01	1.43E+01	4.40E+01	1	1.64E+01	
Lead	PbS	239.3	2.00E+01	4.00E+00	2.00E+03	2.12E+02	10	7.41E+02	
Lithium	$LiAlSi_2O_6$	186.1	2.00E+01	3.00E+00	1.50E+03	1.58E+02	1	2.87E+01	
Magnesium	$MgCl_2$	95.2	1.33E+04	1.00E-01	1.00E-01	1.00E+00	1	1.61E+02	

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Name	Chemical Formula	M_M [g/mol]	$x_{M_{cr}}$ E-6	OGCE-2	ER_R	k_{cM}	k_{chM}	ex_{chM} [kJ/mol]
Manganese	MnO_2	86.9	6.00E+02	2.50E+01	4.17E+02	2.84E+02	1	3.49E+01
Mercury	HgS	232.7	8.00E-02	1.00E-01	1.25E+04	1.71E+03	10	6.79E+02
Molybdenum	MoS_2	160.1	1.50E+00	3.00E-01	2.27E+03	9.47E+02	1	1.72E+03
Nickel	NiS	90.7	2.00E+01	9.00E-01	4.50E+02	3.37E+02	10	7.66E+02
Niobium	Nb_2O_5	-	2.50E+01	5.00E-01	1.88E+02	NA	1	-
Phosphorous	P_2O_5	142	7.00E+02	1.48E+01	2.11E+02	4.39E+01	1	3.59E+02
Platinum	PtS	-	1.00E-02	1.95E-03	1.95E+03	NA	1	-
Potassium	KCl	74.56	2.80E+04	1.50E+01	5.77E+04	3.86E+01	1	1.96E+01
Rhenium	ReS_2	250.3	4.00E-04	3.00E-01	3.00E+06	1.94E+03	10	1.62E+03
Selenium	SeO_2	-	5.00E+01	2.50E-04	2.50E+01	NA	1	-
Silicon	SiO_2	60.1	3.08E+05	4.00E+01	1.30E+00	1.89E+00	1	8.20E-01
Silver	Ag_2S	247.8	5.00E-02	1.00E-02	2.00E+03	7.05E+03	10	7.06E+02
Sodium	$NaCl$	58.4	2.90E+04	2.00E+01	6.90E+00	3.81E+01	1	1.44E+01
Tantalum	Ta_2O_5	441.1	2.20E+00	1.00E-01	2.50E+02	1.25E+04	1	4.56E+01
Tellurium	TeO_2	-	1.00E-03	1.00E-04	1.00E+02	NA	1	-
Tin	SnO_2	150.7	5.50E+00	4.00E-01	6.36E+02	1.49E+03	1	4.26E+01
Titanium	$FeTiO_3$	151.7	3.00E+03	1.00E+01	3.33E+01	3.48E+02	1	1.30E+02
Tungsten	$CaWO_4$	288	2.00E+00	6.00E-01	3.00E+03	3.10E+03	1	7.21E+01
Vanadium	V_2O_5	182	6.00E+01	6.00E-01	4.29E+01	5.72E+02	1	3.23E+01
Zinc	ZnS	97.4	7.10E+01	3.50E+00	4.93E+02	6.28E+01	10	7.44E+02
Zirconium	$ZrSiO_4$	183.3	1.90E+02	2.00E+00	1.05E+02	7.74E+03	1	3.08E+01

Table 2.2: Chemical properties of the main commercially used minerals

Specific emergy of mineral reserves at their ore grade cutoff					
Name	Chemical Formula	$em_R^1(x_M)$ [se.J/g]	$em_R^2(x_M)$ [se.J/g]	$em_R(x_M)$ [se.J/g]	$em_R(x_M)$ [se.J/g]
Aluminium	Al_2O_3	3.40E+09	2.84E+08	2.25E+07	2.25E+07
Antimony	Sb_2S_3	8.10E+14	6.75E+13	1.86E+10	1.86E+10
Arsenic	$FeAsS$	2.16E+13	1.80E+12	8.71E+09	8.71E+09
Barium	$BaSO_4$	1.71E+11	1.42E+10	-	-
Beryllium	$6SiO_2 \cdot Al_2O_3 \cdot 3BeO$	2.16E+13	1.80E+12	1.32E+12	1.32E+12
Bismuth	Bi_2S_3	6.38E+14	5.31E+13	1.01E+11	1.01E+11
Cadmium	CdS	6.61E+13	5.51E+12	2.86E+12	2.86E+12
Cesium	$CsCl$	8.76E+13	7.30E+12	-	-
Chrome	$FeCr_2O_4$	1.06E+13	8.87E+11	1.15E+10	1.15E+10
Cobalt	CoS_2	3.24E+11	2.70E+10	1.18E+10	1.18E+10
Copper	$CuFeS_2$	3.24E+11	2.70E+10	1.30E+09	1.30E+09
Fluoride	CaF_2	2.43E+09	2.03E+08	5.60E+06	5.60E+06
Gallium	$Ga(OH)_3$	9.56E+09	7.97E+08	-	-
Germanium	GeO_2	6.08E+13	5.06E+12	-	-
Gold	Au	1.35E+13	1.12E+12	8.35E+18	8.35E+18
Hafnium	HfO_2	1.12E+11	9.32E+09	-	-
Indium	InS	3.24E+12	2.70E+11	-	-
Iron	Fe_2O_3	2.32E+10	1.93E+09	4.68E+07	4.68E+07
Lead	PbS	3.24E+12	2.70E+11	2.66E+09	2.66E+09
Lithium	$LiAlSi_2O_6$	2.43E+12	2.03E+11	4.91E+11	4.91E+11
Magnesium	$MgCl_2$	1.62E+08	1.35E+07	3.02E+05	3.02E+05

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Name	Chemical Formula	$em_R^1(x_M)$ [se.J/g]	$em_R^2(x_M)$ [se.J/g]	$em_R(x_M)$ [se.J/g]
Manganese	<i>MnO</i> ₂	6.75E+11	5.63E+10	1.92E+10
Mercury	<i>HgS</i>	2.03E+13	1.69E+12	7.23E+12
Molybdenum	<i>MoS</i> ₂	3.67E+12	3.06E+11	6.81E+11
Nickel	<i>NiS</i>	7.29E+11	6.08E+10	3.28E+09
Niobium	<i>Nb</i> ₂ <i>O</i> ₅	3.05E+11	2.54E+10	-
Phosphorous	<i>P</i> ₂ <i>O</i> ₅	3.42E+11	2.85E+10	2.27E+08
Platinum	<i>PtS</i>	3.16E+12	2.63E+11	-
Potassium	<i>KCl</i>	9.35E+13	7.79E+12	2.59E+07
Rhenium	<i>ReS</i> ₂	4.86E+15	4.05E+14	1.16E+15
Selenium	<i>SeO</i> ₂	4.05E+10	3.38E+09	-
Silicon	<i>SiO</i> ₂	2.11E+09	1.76E+08	5.17E+05
Silver	<i>Ag</i> ₂ <i>S</i>	3.24E+12	2.70E+11	3.70E+13
Sodium	<i>NaCl</i>	1.12E+10	9.32E+08	3.60E+07
Tantalum	<i>Ta</i> ₂ <i>O</i> ₅	4.05E+11	3.38E+10	1.86E+14
Tellurium	<i>TeO</i> ₂	1.62E+11	1.35E+10	-
Tin	<i>SnO</i> ₂	1.03E+12	8.59E+10	1.02E+13
Titanium	<i>FeTiO</i> ₃	5.39E+10	4.50E+09	7.62E+08
Tungsten	<i>CaWO</i> ₄	4.86E+12	4.05E+11	4.20E+13
Vanadium	<i>V</i> ₂ <i>O</i> ₅	6.95E+10	5.79E+09	3.32E+11
Zinc	<i>ZnS</i>	7.99E+11	6.66E+10	1.81E+08
Zirconium	<i>ZrSiO</i> ₄	1.71E+11	1.42E+10	1.50E+12

Table 2.3: Specific emergies of mineral reserves at their *OGC* calculated by different approaches

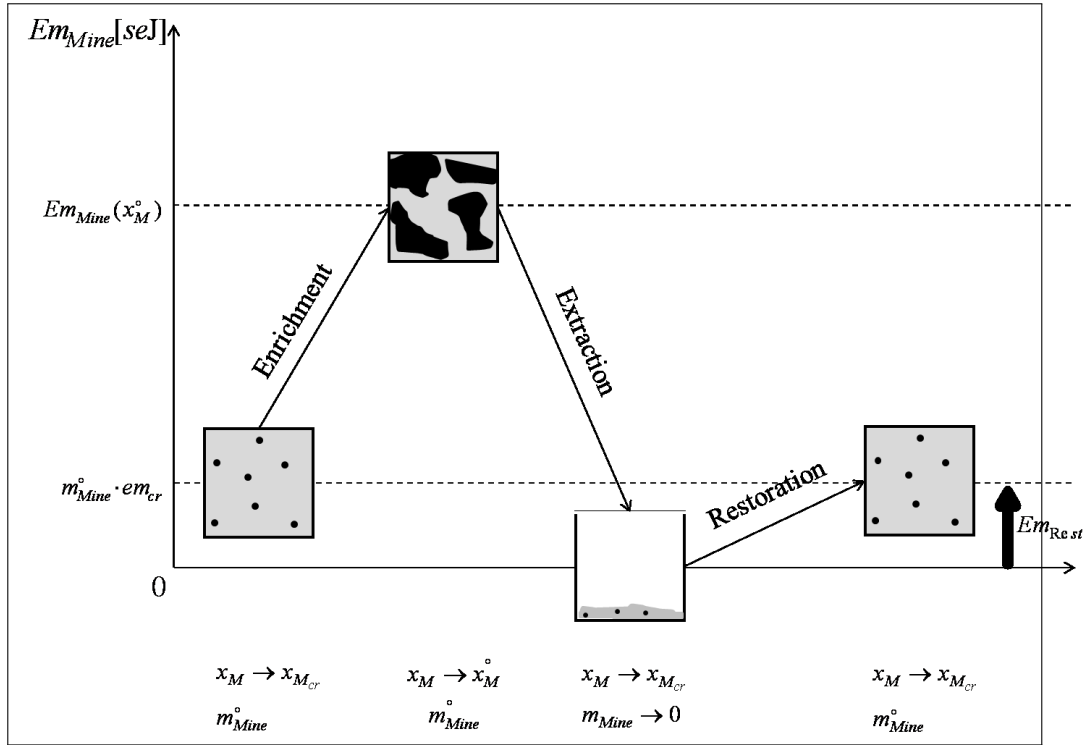


Figure 2.5: Total energy of a mineral reserve during its life cycle with restoration process

2.3.2 Application to the main commercially used minerals

Dispersed minerals are considered as co-products of the Earth's crust, thus total energy of the dispersed mineral is equal to the total energy of the Earth's crust. In this work, 42 of the main commercially used minerals has been studied. Table 2.2 summarizes the chemical properties of these minerals [Valero 2009]. Table 2.4 displays the specific energy of dispersed minerals, calculated by Eq. (2.11). It can be seen that the results are consistent with the material's hierarchy, as scarce minerals like gold or silver have higher crustal specific energies than abundant minerals like iron or nickel. In Table 2.3 the specific energy of mineral reserves are calculated based on different approaches. The specific energy em_R^1 and em_R^2 are both based on Eq. (2.1), the first used a baseline of $1.62 \text{ E}+9 \text{ seJ/g}$ proposed by Cohen et al. [Cohen 2007] and the second a baseline of $1.35 \text{ E}+8 \text{ seJ/g}$ updated by Brown [Brown 2007]. The last column represents the specific energy of mineral reserves calculated by the method proposed in the current work (see Eq. (2.18)), using the ore grade cutoff of the mine (OGC , see Table 2.3). It can be noted that the order of magnitude of em_R is mostly closer, to Brown's results em_R^2 who used the specific energy of the Earth's crust as baseline. Nevertheless, significant divergence for some minerals can be observed such as gold, tantalum or zinc. This can be

explained by the fact that Brown [Brown 2007] used, similarly to this work, the average transformity of the geobiosphere τ_{geobio} to calculate the specific energy of the Earth crust, see Fig. 2.3. But choosing the latter as universal baseline for all minerals is not sufficient because this is not consistent with the material hierarchy and does not include the chemical potential of the mineral.

2.3.3 Application to the emergy decrease of mineral reserves: Case of some Australian mineral reserves

Since the late 18th century several mining booms occurred in Australia. In this section the emergy decrease of some Australian mineral reserves such as gold, copper, nickel, silver, lead, zinc and iron has been studied, the required data has been taken from Valero [Valero 2008a]. Table 2.5 represents the main characteristics of these reserves since their discovery until now. The initial specific energies $em_R(x_M^\circ)$ and the current specific energy $em_R(x_M)$ have been calculated by using Eq. (2.18) and respectively the initial and current ore grades x_M° and x_M , listed in Table 2.5. The last column of this table represents, in percent, the specific energy decrease of mineral reserves D . The results reveal that, over the past century, especially gold, copper and lead reserves suffered from a drastic decrease by about 30% in specific energy, due to the fact that their ore grades have notably declined. Whereas, in spite of the huge quantities of iron that are mined every year the ore grade of iron reserve little changed due to the abundance of iron rich deposits in Australia and thus the specific energy of iron reserve remains almost constant.

Dispersed specific energy of the main commercially used mineral		
Name	Chemical Formula	$em_M(x_{M_{cr}})$ [seJ/g]
Aluminium	Al_2O_3	1.23E+03
Antimony	Sb_2S_3	4.92E+08
Arsenic	$FeAsS$	6.56E+07
Barium	$BaSO_4$	1.79E+05
Beryllium	$6SiO_2.Al_2O_3.3BeO$	3.28E+07
Bismuth	Bi_2S_3	7.75E+08
Cadmium	CdS	1.00E+09
Cesium	$CsCl$	2.66E+07
Chrome	$FeCr_2O_4$	2.81E+06
Cobalt	CoS_2	9.84E+06
Copper	$CuFeS_2$	3.94E+06
Fluoride	CaF_2	1.51E+05
Gallium	$Ga(OH)_3$	5.79E+06
Germanium	GeO_2	6.15E+07
Gold	Au	5.47E+10

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Name	Chemical Formula	$em_M(x_{M_{cr}})$ [seJ/g]
Hafnium	HfO_2	1.70E+07
Indium	InS	1.97E+09
Iron	Fe_2O_3	2.81E+03
Lead	PbS	4.92E+06
Lithium	$LiAlSi_2O_6$	4.92E+06
Magnesium	$MgCl_2$	7.40E+03
Manganese	MnO_2	1.64E+05
Mercury	HgS	1.23E+09
Molybdenum	MoS_2	6.56E+07
Nickel	NiS	4.92E+06
Niobium	Nb_2O_5	3.94E+06
Phosphorous	P_2O_5	1.41E+05
Platinum	PtS	9.84E+09
Potassium	KCl	3.51E+03
Rhenium	ReS_2	2.46E+11
Selenium	SeO_2	1.97E+06
Silicon	SiO_2	3.19E+02
Silver	Ag_2S	1.97E+09
Sodium	$NaCl$	3.39E+03
Tantalum	Ta_2O_5	4.47E+07
Tellurium	TeO_2	9.84E+10
Tin	SnO_2	1.79E+07
Titanium	$FeTiO_3$	3.28E+04
Tungsten	$CaWO_4$	4.92E+07
Vanadium	V_2O_5	1.64E+06
Zinc	ZnS	1.39E+06
Zirconium	$ZrSiO_4$	5.18E+05

Table 2.4: Crustal specific emergy of the main commercially used minerals

2.3.4 Application to the land degradation of ore deposits: Case of US copper mines

The aim of this section is to evaluate the emergy loss of US copper deposits when all their reserves are exhausted and to estimate the minimum emergy that Nature should invest to replace the extracted mineral from the mines. In order to use the methodology proposed in Eq. (2.24) and Equation Eq. (2.26), it is assumed that US copper reserves represent a huge mine with an initial ore grade x_{Copper}° and an initial mineral content m_{Copper}° . Because of data unavailability, the mining activity before the year 1900 has been neglected. The initial copper mass m_{Copper}° has been determined by cumulating the primary copper production from 1900 to 2001, adding them the reserve base of the year 2001 [USGS 2011]. This permits to

obtain an ore mass of about $m_{Copper}^{\circ} = 1.84E+11$ kg, the initial ore grade of copper in 1900 was about 2% [Valero 2008a]. The calculation reveals that the emergy $Em_{Mine}(x_{Copper}^{\circ})$ lost irreversibly by the ecosystem when all the mineral is extracted is about $7.26 E+20$ seJ and that the emergy Em_{Rest} required to replace the mined mineral by ordinary earth is about $1.81E+16$ seJ (it is considered that only the mineral reserve would be removed from the mine i.e. $m_{rem} = m_{Copper}^{\circ}$). The results are summarized in Table 2.6.

Characteristics of Australians mineral reserves							
Mineral reserve	$x_{M_{cr}}$	x_M°	x_M	Δt [yr]	$em_R(x_M^{\circ})$ [seJ/g]	$em_R(x_M)$ [seJ/g]	D [%]
Gold	1.80E-09	3.73E-05	2.02E-06	1859-2000	6.76E+22	4.78E+22	29.3
Copper	2.50E-05	2.60E-01	1.33E-02	1844-2004	1.70E+13	1.14E+13	33.0
Nickel	2.00E-05	4.57E-02	1.16E-02	1967-2004	3.07E+13	2.52E+13	17.9
Silver	5.00E-08	3.00E-03	8.00E-04	1884-2004	3.94E+17	3.47E+17	12.0
Lead	2.00E-05	7.80E-01	4.32E-02	1879-2000	2.87E+13	1.98E+13	30.9
Zinc	7.10E-05	1.70E-01	8.50E-02	1905-2004	1.69E+12	1.53E+12	9.3
Iron	3.50E-02	6.80E-01	6.20E-01	1907-2004	4.70E+11	4.50E+11	4.4

Table 2.5: Characteristics of Australians mineral reserves

x_{Copper}°	m_{Copper}° [kg]	$x_{Copper_{cr}}^{\circ}$	m_{rem} [kg]	$Em_{Mine}(x_{Copper}^{\circ})$ [seJ]	Em_{Rest} [seJ]
0.02	1.84E+11	2.5E-5	1.84E+11	7.26E+20	1.81E+16

Table 2.6: Emergy loss and mine restoration of US copper reserves

2.4 Conclusion of the chapter

1. Emergy and exergy assessment tools have been combined to evaluate the environmental impact of mining, considering only the natural exergy of the mineral. Every group of dispersed mineral is assumed to be a co-product of the Earth's crust. The specific emergy of about 40 main commercially used minerals have been calculated, respecting the material hierarchy as the specific emergy rise with scarcity.
2. An evaluation model was proposed that permits to calculate the specific emergy of mineral reserves based on the chemical and concentration exergy of the mineral, its abundance and concentration in the mine. The application to some Australian mineral reserves shows that the specific emergy of the reserve decreases with its ore grade. Theoretically, when all the reserve is exhausted its specific emergy tends to the crustal specific emergy of the mineral

$em_M(x_{M_{cr}})$, representing the lowest position that the reserve can ever reach in the material hierarchy.

3. To make the methodology realized by Cohen et al. [Cohen 2007] and Brown [Brown 2007] consistent with the material hierarchy, it is proposed to use instead of an universal baseline the crustal specific emergy of the mineral $em_M(x_{M_{cr}})$ and as enrichment factor the ratio between the specific exergy of the concentrated ore reserve $ex_M(x_M^\circ)$ and the crustal specific exergy of the mineral $ex_M(x_{M_{cr}})$ (see Proposition 2.1).
4. To assess the impact of mining on the ecosystem, a methodology is introduced that permits to quantify the theoretical minimum emergy that Nature should invest to restore the post-mining land. The application to the US copper mines reveals that the ecosystem will loose about $7.26 \text{ E}+20 \text{ seJ}$ when all the copper reserves have been extracted and that Nature should invest at least about $1.81 \text{ E}+16 \text{ seJ}$ to restore the post-mining land.
5. Although different methods could be envisaged to calculate the emergy of the Earth's crust, the proposed evaluation model remains valid whatever numerical value of the latter is chosen

Appendix 2A

The energy approach considers that sunlight, tidal energy and geothermal heat are the three main sources of exergy that drive the complex processes of the geobiosphere Odum [Odum 1996]. The annual global energy budget is calculated by multiplying the annual exergy flows of these sources by their transformities, as shown in Table 2.7. Admitting that the transformity of solar is equal to one, the transformities of tidal and geothermal heat have been calculated by establishing two equations: one expressing the exergy contributions to geothermal heat and the other the exergy contributions to ocean geopotential. The average transformity of the geobiosphere τ_{geobio} is then the ratio between the annual energy flow of the geobiosphere Em_{geobio} and its exergy flow Ex_{geobio} , see Eq. (2.32). All the unit energy values used in this work are based on the annual energy budget of the geobiosphere calculated by Brown and Ulgiati [Brown 2010], see Table 2.7.

$$\tau_{geobio} = \frac{Em_{geobio}}{Ex_{geobio}} \quad (2.32)$$

Inflow	$Ex[J/yr]$	$\tau[seJ/J]$	$Em[seJ/yr]$
Solar energy absorbed	3.6E+24	1	3.6E+24
Crustal heat sources	1.6E+20	20300	3.3E+24
Tidal energy absorbed	1.15E+20	72400	8.3E+24
Geobiosphere	3.6E+24	-	15.2E+24

Table 2.7: Global energy budget of the geobiosphere [Brown 2010]

Appendix 2B: The evolution of minerals

Conventionally, minerals are evaluated by their chemical and physical properties without any regard to their historical context. A dynamic approach of mineral evolution was first proposed by Robert M. Hazen and his team [Hazen 2010b]. The new concept consider time as fourth dimension of geology, the Earth's history is used to better understand the background of mineral genesis. The evolution and diversification of terrestrial minerals is a consequence of all the physical, chemical and biochemical processes trough which the Earth has passed since its creation four and a half billion years ago. The minerals of the planet has evolved from about a dozen of different species present in the pre-stellar molecular clouds to more than 4400 known minerals. Hazen highlights that, according to studies of other planets and moons, the mineralogical complexity and abundance of the Earth is largely due to the development of life on the planet. Actually, the degree of mineral complexity of a body is a result of local, regional and global selective processes enforced by nature. The diversity and distribution of its terrestrial minerals reflect the intensity of the cyclic processes that have affected the planet during its formation. The mineral evolution concept divide the Earth's mineral evolution into 3 eras and 10 stages see Table 2.4 [Hazen 2010a].

Era/Stage	Age (Ga)	Cumulative nD of species
Prenebular "Ur-Minerals"	> 4.6 Ga	12
Era of Planetary Accretion (>4.55 Ga)		
1. Primary chondrite minerals	>4.56 Ga	60
2. Achondrite and planetesimal alteration	>4.56 to 4.55 Ga	250
Era of crust and Mantel Reworking (>4.55 to 2.5 Ga)		
3. Igneous rock evolution	4.55 to 4.0 Ga	350 to 500
4. Granite and pegmatite formation	4.0 to 3.5 Ga	1000
5. plate tectonics	>3.0 Ga	1500
Era of Biologically Mediated Mineralogy (>2.5 Ga to present)		
6. Anoxic biological work	3.9 to 2.5 Ga	1500
7. Great oxidation event	2.5 to 1.9 Ga	>4000
8. Intermediate ocean	1.9 to 1.0 Ga	>4000
9. Snowball Earth events	1.0 to 0.542 Ga	>4000
10. Phanerozoic era of biomineralization	0.542 Ga to present	4400+

Table 2.8: The eras and stages of Earth's mineral evolution

- **The "Ur-Minerals"**

It took millions of years after the Bing Bang before the first minerals appeared

in the presolar nebula, in form of micro-sized primeval crystals. The environment were rich on carbon, diamond and graphite were the most abundant minerals in the pre-stellar molecular clouds.

- **ERA 1: Planetary Accretion (>4.55 Ga)**

Chondrules present in the gaseous accretion disc around the sun, clumped into millions of planetesimals which collide to form the Earth. The accretion and differentiation of planets was the starting point of mineral evolution. More than 250 different mineral species accrued in the planetesimals due to thermal alteration, impact of collisions and reaction with water.

1. *Primary chondrite minerals*

At this early point of our solar system formation, the primitive chondritic meteorites present about 60 different mineral phases. Traces of the "ur-minerals" are found in these ancient meteorites which prove their existence before the chondrites.

2. *Achondrite and planetesimal alteration*

Asteroidal accretion and differentiation, partial melting of the meteorites and the presence of water, generated about more than 200 new minerals. All of these 250 minerals formed in the first era of mineral evolution are found in every rocky planet and in several meteorites that fall to Earth [McCoy 2010].

- **ERA 2: Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)**

The Earth, primordially a sphere of molten rock, began the cooling by dissipation of heat to space. A thin basaltic crust appeared, representing the "protocrust" of the planet. At this time, the Earth was exposed to large sources of energy. The internal and external sources of heat were considerably more important (the radioactive heat generation was about five times higher than today [Valley 2002]). The planet was subjected to a spike of heavy meteorite bombardments which has continuously open new holes in the crust, immediately filled with magma [Jørgensen 2009]. During this continuous remelting and reforming of the "protocrust", the heavy elements with higher density like iron tended to sink toward the center of the Earth, while the lighter elements rich in silicates floated on the surface. Progressively, the basaltic "protocrust" disappeared, giving the place to the present-day granitic crust. The mineral species on Earth expanded to more than 1500 during the Earth crust formation process. Three different evolutionary states can be distinguished within this era of dynamic crust and mantle.

3. *Igneous rock evolution*

The energetic high convective movements of the Earth's mantle continuously fissured the thin basaltic "protocrust". The magma erupted from the depths of the planet cooled off, to form igneous rocks. At this stage of evolution about 500 different minerals can be identified.

4. *Granite and pegmatite formation*

Due to the high temperature of the Earth's center and volcanic activity, partial part of the basaltic "protocrust" melted to form igneous rocks called granitoids. The repeated melting and solidifying of these granitoid rocks and the interaction with water bore more than 500 new minerals.

5. *Plate tectonics*

One of the most important mineral forming processes was the emergence of small continents on Earth called cratons. Because of their low density, these rigid tectonic plates kept riding on the surface driven by continuous mutual movements due to the convection of the magma between the hot core of the Earth and the cooled lithosphere. The continental crust was permanently gobbled up into the mantle at subduction zones, while new crust was formed by volcanism. Thanks to the tectonic activity of the Earth crust the mineral diversity of the planet increased to more than 1500 species.

- **ERA 3: Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)** The processes of continent formation produced about 1500 different mineral phases, very far from the about 4400 minerals present in the modern-days upper crust of our planet. Hazen and his team states that biological processes have directly or indirectly contributed to the mineralogical abundance of today's Earth crust. The presence of life contributed to a large diversification of Earth's mineralogy which differentiates it from all other planets or moons.

6. *Anoxic biological world*

The primordial atmosphere was still oxygen-deficient as the first organisms appeared. These primitive microorganisms did not influence the near-surface environment of the planet.

7. *Great oxidation event*

The "Great Oxidation Event" marked a significant increase of oxygen in the atmosphere, produced by photosynthesis of primitive blue-green algae called stromalites. Even if the concentration of oxygen did not exceed 1% of present-days level, its impact on mineral evolution was considerable [Sverjensky 2010]. The Earth's surface became red because the ferrous iron minerals (Fe^{2+}) in the basaltic crust oxyded into hematite and other rust-red ferric iron (Fe^{3+}). More than 2500 mineral species developed during this "Red Earth" epoch.

8. *Intermediate ocean*

The "Intermediate Ocean" period is also called "Boring Billion". Obviously, the near-surface mineralogy of the Earth remained stagnant, little is known about rock formations at this time. The ocean chemistry, however, underwent important changes generated by microbial activity to develop an "intermediate ocean".

9. *Snowball Earth events*

The "Snowball Earth" period was marked by extreme temperature changes. The planet switched maybe two or four times between a very cold icebox and a warm hotbox. Even if the glacial phases did not contribute to the development of new mineral species, the ice ages changed drastically the distribution of surface minerals. The warm interglacial periods, however, represented new impetus of mineral creation.

10. *Phanerozoic era of biomineralization*

The oxygen rate of the atmosphere rose considerably and a protective ozone layer formed around the Earth, absorbing the harmful ultraviolet radiation of the sun. Little by little, the planet assumed a familiar look with ocean, rivers and lakes, rigid continents and an oxygen-rich atmosphere. The important overgrowth of vegetation led to a rapid biochemical alteration of rocks. The emergence of plants and fungi was the strongest boost in mineral evolution, clearing the way for more than 4400 mineral species identified in today's earth surface.

**Accounting for material losses in
recycling processes using Emergy
analysis**

Accounting for material losses in recycling processes using Emergy analysis

Abstract: Emergy analysis is applied to different configurations of closed-loop recycling processes. Emergy balance gives a discrete-time equation which is solved under assumptions. To extend the literature, two material losses have been taken into consideration, the first one at the level of treatment (collection, dismantling, etc.) and the second one at the transformation level. Since the emergy value of a product (after the transformation process) increases with the number of cycles, the *Recycling Benefit Ratio* is defined as the ratio of emergy used in providing a material to the emergy used in recycling at each stage of recycling. A case study is developed on aluminum for which *RBR* have a decreasing trend: the first recycles have an important impact, and the asymptotic behavior occurred after 5-6 cycles. By applying the discrete-time emergy equation, the collection time-effect is plotted on *RBR* too, based on the global shared of recycled and primary aluminum.

Keywords: Emergy assessment, Closed loop recycling, Recycling Benefit Ratio, Aluminum

Nomenclature

Acronyms

<i>LCA</i>	Life Cycle Analyse
<i>LRR</i>	Landfill to Recycle Ratio
<i>MSW</i>	Municipal Solid Waste
<i>RBR</i>	Recycled Benefit Ratio
<i>RYR</i>	Recycled Yield Ratio

Greek Symbols

ε	Material losses [%]
---------------	---------------------

Roman Symbols

<i>Em</i>	Emergy [seJ]
<i>m</i>	Mass [kg]
<i>q</i>	Fraction reintroduced in the recycling process [%]
<i>S</i>	Emergy for storage [seJ]
<i>x</i>	Mass fraction [kg/kg]

Superscripts

-	Average
---	---------

Subscripts

<i>c</i>	Recycling
<i>i</i>	Raw material
<i>p</i>	Product
<i>t</i>	Transformation

3.1 Introduction

Recycling is generally identified as a good practice to limit the use of raw material, energy and to limit the environmental impacts of an industrial activity. The assessment of recycling has been widely studied in the literature thanks to the collection of tools and/or methods: life cycle analysis [Shen 2010, Heijungs 2007], ecological footprint [Herva 2013, Rees 1994], exergy analysis [Szargut 1987, Castro 2007], energy analysis [Odum 1996]... The latter is an accounting method that enables to quantify flows of resources used in processes, systems, products or goods by using the common reference of Solar energy [Brown 1996]. Numerous studies have been carried out to develop the theory associate to the emergy analysis and various case studies have been considered during the last decades. These different approaches of assessment have been compared all together by Kharrazi et al. [Kharrazi 2014] and/or combined [Duan 2011]. These approaches are not inter-competitive, and on the contrary, they should complement each other. Ulgiati et al. [Ulgiati 2004] consider that the life cycle analysis is more user-side oriented, and thus presented the emergy accounting as a donor-side oriented approach. This aspect of comparison and/or integration of emergy and LCA is also studied by Rauegi et al. [Rauegi 2014].

According to Brown and Buranakarn [Brown 2003], application of the emergy analysis to the study of material cycles and recycle options is facilitated by the use of a set of indices and ratios defined by the authors:

- *Recycle Benefit Ratio (RBR)*: is the ratio of the emergy used in providing a material from raw resources to the emergy used in recycling the material (the higher the ratio, the greater advantage of recycling).
- *Recycle Yield Ratio (RYR)*: is the ratio of the material emergy to the emergy used to recycle (a large ratio means a higher yield). This ratio is similar to the Emergy Yield Ratio (*EYR*) used to express the net benefice to society from energy sources [Brown 1997a].
- *Landfill to Recycle Ratio (LRR)*: is the ratio of emergy used for landfilling to the emergy used for recycling (the higher the ratio the larger the benefit to society)

The authors used these ratios to assess recycling potential for building materials and comparison of three recycle trajectories (standard recycle where materials are used again as the same material, by-product-use and adaptive re-use). Added to the three previous indicators, the authors identified the emergy per mass as a good indicator of recycleability. A similar reasoning is used in the study of Marchettini et al. [Marchettini 2007], who used close indices to compare the different solutions of municipal solid waste (*MSW*) treatment (solutions investigated were incineration, landfilling and composting). These ratios and indices, specific for recycling analysis, complete the classical ones used in the emergy analysis [Ulgiati 2004, Ulgiati 1995,

Brown 1997a]: Transformity, Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), Emergy Investment Ratio (EIR), Index of Sustainability (ESI).

[Bakshi 2000] introduced an emergy analysis method for industrial application where waste treatment was considered. In this study the author considered both ecological and economical input to analyse industrial processes. Recycling is taken into account by considering waste as a source of material in the emergy diagram. A similar recycling accounting has been done by Yang et al. [Yang 2003] who included the emergy indices defined above to assess the impact of industrial waste on the environment. Furthermore, in recycling, two kinds of loop must be considered [EPA 2008]:

- *Closed-loop recycling*: recycling system in which the particular mass of material is re-manufactured into the same product [Meng 2006].
- *Open-loop recycling*: recycling system in which a product made from one type of material is recycled into a different type of product [Williams 2010, Shen 2010].

Yuang et al. [Yuan 2011] used the emergy recycling indices to compare the different options for construction and demolition ($C\&D$) waste recycling in the building sector (case of crushed concrete): landfilling, open-loop recycling and closed-loop recycling. Their study underlines the influence of the recycling options on the three pillars of sustainability: economic, social, environment.

Most of the studies that include recycling in the emergy analysis do not consider the number of reuse for the material. Amponsah et al. [Amponsah 2011b] and Amponsah [Amponsah 2012] analyzed the influence of a multiple reuse of material on the product emergy. Recycling during the lifetime of a product can be represented with the emergy scheme of Fig. 3.1.

In this figure Em_i is the emergy of the raw material that enters the process, Em_p is the emergy of the product and Em_c is the necessary additional emergy for recycling. After its use, part of the material of the product is landfilled whereas a fraction q of it is reintroduced in the process through the recycling. For the authors [Amponsah 2011b], the successive recycle use of a material corresponds to a recursive use of a fraction q (at each cycle), with one fraction consisted of raw material, and the other one from the recycled material (from the previous cycle). The accounting of the recursive reuse of the output "composite" material can be described by the time discrete equation (Eqs. (3.1) and (3.2)), which can be developed under the assumption of a constant recycling rate (Eq. (3.3)):

$$Em_p(n) = (1 - q) \cdot Em_i + q \cdot Em_p(n - 1) + q \cdot Em_c \quad (3.1)$$

$$Em(0) = Em_i \quad (3.2)$$

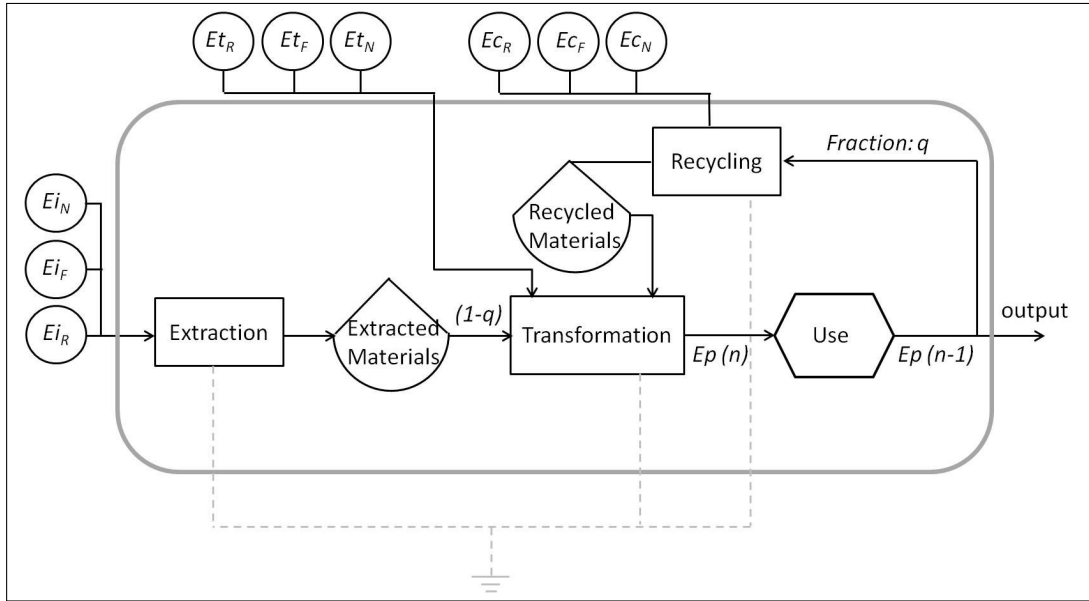


Figure 3.1: Multiple recycling accounting (adapted from [Amponsah 2011b])

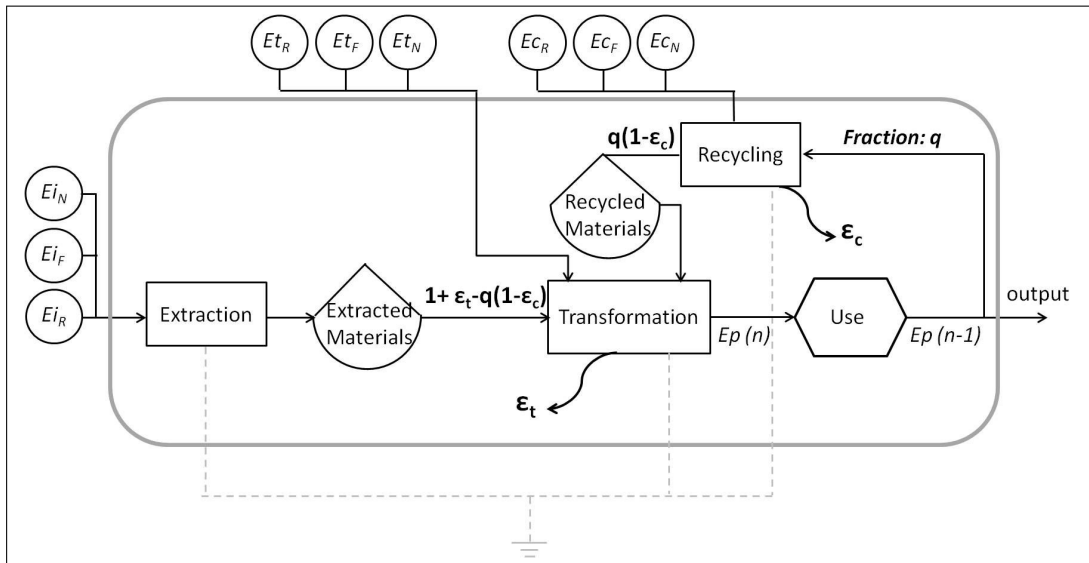


Figure 3.2: Closed-loop recycling with mass losses (single source)

$$Em(n) = Em_i + q \cdot \frac{q^n - 1}{q - 1} \cdot Em_c \quad (3.3)$$

These equations describe the case of closed-loop recycling only where Em_i , Em_c and q are assumed constant. The authors then showed the combined influence of the fraction of recycled material and the number of recycling cycles on the product

emergy and the Emergy Yield Ratio. As a case study, they used two metallic and non-metallic materials commonly used in the industry. A specific complementary work applies this approach to the building material [Amponsah 2012]. This recycling accounting is based on the assumption that the recycling pathway is ideal in a sense that no losses take place along the different steps of the material reuse (in the chain of the processes showed in Fig. 3.1). In real recycling processes, considering that the lack of pure material has to be compensated with the additional raw material input [Deutz 2014], losses must be taken into account.

Following the initial works from Amponsah et al. [Amponsah 2011b, Amponsah 2012], the aim of this study is to broaden the multi-recycling emergy accounting. In particular, the new developments proposed in this chapter take into account the material losses at each cycle, as well as the two possible types of closed-loop recycling (single-source and multi-source). Additionally an application to the case recycled aluminum is proposed.

3.2 Methodology

Mass losses take place during the different steps of a process each time when the cycle of the material is replayed. This introduces the idea of number of times in the theory which must not be confused with the time used in the dynamic accounting of emergy [Tilley 2010, Tilley 2006].

3.2.1 Closed-loop recycling (single-source)

The system described in Fig. 3.2 corresponds to a closed-loop recycling with a single source as the recycled material coming from the product is used to produce the same type of product, even if it is a long time after the end of the product use. Added to the fraction of material recycled q , introduced by Amponsah et al. [Amponsah 2012], the ratios ε_t and ε_c proposed in Fig. 3.2 correspond to the material losses occurring at the transformation step and the recycling step respectively. They are defined as the percentage of mass losses for their respective stage in the process. Thus the mass balance can be written accordingly to the three possible cases Table 3.1: mass losses at the recycling step only, mass losses at the transformation step only and mass losses at both steps. Furthermore, in the description proposed in this work the emergy of the transformation (Em_t) is separate from the emergy of the material coming from the mine (Em_i), which was not the considered by Amponsah et al. [Amponsah 2011b].

The mass balance of each case is described in the second column of the Table 3.1. Accordingly, the emergy of the product Em_p can be written as a function of ε_c and ε_t by writing the mass balance at each stage for each recycling cycle of the fraction q .

Combination of mass losses	
Case 1:	
Mass losses at the recycling step $\varepsilon_c > 0, \varepsilon_t = 0$	<ul style="list-style-type: none"> • q: inlet mass rate at the recycling step • q: outlet mass rate at the recycling step • $1 - q \cdot (1 + \varepsilon_c)$: inlet mass rate at the transformation step coming from the raw material
Case 2:	
Mass losses at the transformation step $\varepsilon_c = 0, \varepsilon_t > 0$	<ul style="list-style-type: none"> • q: inlet mass rate at the recycling step • $q \cdot (1 - \varepsilon_c)$: outlet mass rate at the recycling step • $1 - q + \varepsilon_t$: inlet mass rate at the transformation step coming from the raw material
Case 3:	
Mass losses at the recycling step $\varepsilon_c > 0, \varepsilon_t > 0$	<ul style="list-style-type: none"> • q: inlet mass rate at the recycling step • $q \cdot (1 - \varepsilon_c)$: outlet mass rate at the recycling step • $1 + \varepsilon_t - q \cdot (1 - \varepsilon_c)$: inlet mass rate at the transformation step coming from the raw material

Table 3.1: Combination of mass losses

For the general case (case 3), the emergy of the product can be written with the time discrete equations:

$$Em_p(n) = (1 - q + \varepsilon_t + q \cdot \varepsilon_c) \cdot Em_i + q \cdot (Em_p(n-1) + Em_c) + (1 + \varepsilon_t) \cdot Em_t \quad (3.4)$$

$$Em_p(0) = (1 + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t) \cdot Em_t \quad (3.5)$$

Where $Em_p(0)$ corresponds to the first time that the transformation is considered ($n = 0$), and thus without any additional emergy due to the recycling. After the first cycle of recycling, Em_p becomes:

$$Em_p(1) = (1 + \varepsilon_t + q \cdot (\varepsilon_c + \varepsilon_t)) \cdot Em_i + (1 + \varepsilon_t) \cdot (1 + q) \cdot Em_t + q \cdot Em_c \quad (3.6)$$

After the second cycle of recycling:

$$Em_p(2) = (1 + \varepsilon_t \cdot (1 + q + q^2) + q \cdot \varepsilon_c \cdot (1 + q)) \cdot Em_i + (1 + \varepsilon_t) \cdot (1 + q + q^2) \cdot Em_t + q \cdot (1 + q) \cdot Em_c \quad (3.7)$$

After the n^{th} cycle:

$$Em_p(n) = (1 + \varepsilon_t + q \cdot (\varepsilon_c + \varepsilon_t)) \cdot \frac{q^n - 1}{q - 1} \cdot Em_i + (1 + \varepsilon_t) \cdot \frac{q^{n+1} - 1}{q - 1} \cdot Em_t + q \cdot \frac{q^n - 1}{q - 1} \cdot Em_c \quad (3.8)$$

Table 3.2 summarizes the equation giving the energy of the product for the three possible cases defined in the Table 3.1.

Energy of the product for the different combination of mass losses	
Case 1:	$Em_p(n) = \left[1 + q \cdot \varepsilon_c \cdot \left(\frac{q^n - 1}{q - 1} \right) \right] \cdot Em_i + \left(\frac{q^{n+1} - 1}{q - 1} \right) \cdot Em_t + q \cdot \left(\frac{q^n - 1}{q - 1} \right) \cdot Em_c$
Case 2:	$Em_p(n) = \left[1 + \varepsilon_t + q \cdot \varepsilon_t \cdot \left(\frac{q^n - 1}{q - 1} \right) \right] \cdot Em_i + (1 + \varepsilon_t) \cdot \left(\frac{q^{n+1} - 1}{q - 1} \right) \cdot Em_t + q \cdot \left(\frac{q^n - 1}{q - 1} \right) \cdot Em_c$
Case 3:	$Em_p(n) = \left[1 + \varepsilon_t + q \cdot (\varepsilon_c + \varepsilon_t) \varepsilon_t \cdot \left(\frac{q^n - 1}{q - 1} \right) \right] \cdot Em_i + (1 + \varepsilon_t) \cdot \left(\frac{q^{n+1} - 1}{q - 1} \right) \cdot Em_t + q \cdot \left(\frac{q^n - 1}{q - 1} \right) \cdot Em_c$

Table 3.2: Energy of the product for the different combination of mass losses (Closed-loop recycling/single-source)

It can be noted that Eq. (3.8), which is the most general, includes the specific case ($\varepsilon_t = \varepsilon_c = 0$ and $E_t = 0$) studied by Amponsah et al. [Amponsah 2011b], described by Eq. (3.3).

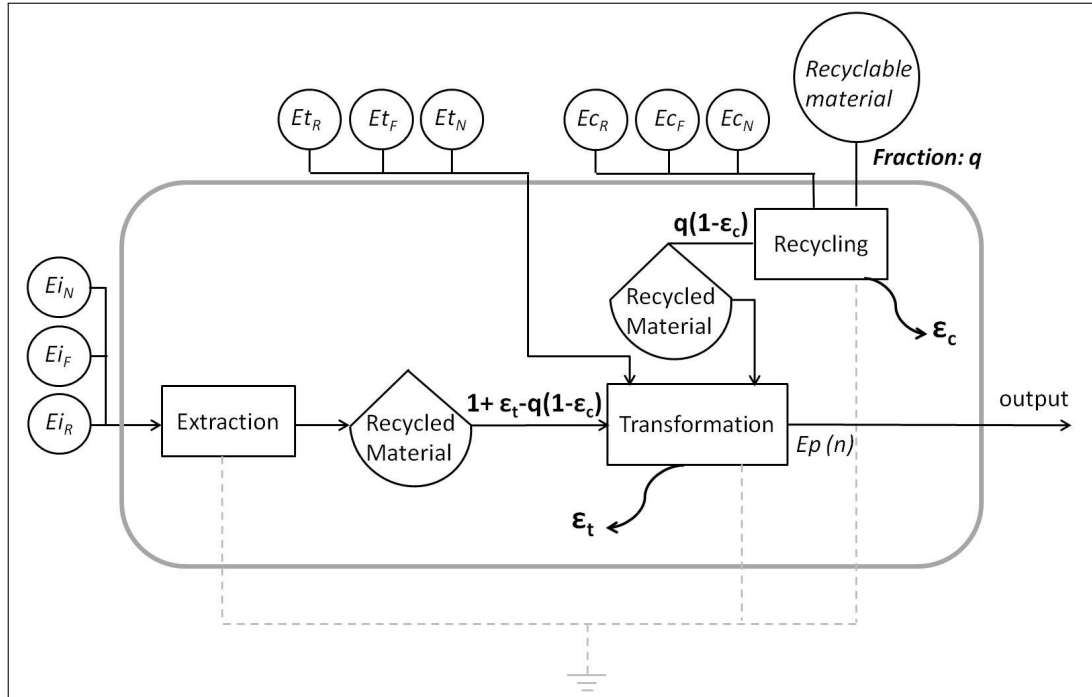


Figure 3.3: Closed-loop recycling with mass losses (reservoir made of mixed recycled material)

3.2.2 Closed-loop recycling (multi-source)

In this section closed-loop recycling with multiple sources is studied. It corresponds to the case when the recycled material comes from various sources, with the addition of raw material if necessary. Three cases are presented:

- Closed-loop recycling with the material coming from one reservoir made of mixed materials that were recycled different number of time but for which the representative percentage in mass in all reservoir is known (e.g 10% of the aluminum of the reservoir has been recycled 10 times, 50% has been recycled 5 times, and 40% only once).
- Closed-loop recycling with a discharge of a reservoir without addition of raw material.
- Closed-loop recycling with separate recycled material source reservoirs), for which the number of time that the material has been recycled is known.

3.2.2.1 Closed-loop recycling with a reservoir made of mixed recycled material

This case is purely theoretical as it seems difficult (even impossible) to be able to identify in a common reservoir the mass rate associated to a given number of times the material has been already recycled in the past. The demonstration done in this section aims to help to understand what is proposed for the other cases of closed-loop recycling (more realistic) and is not considered in the case study. In Fig. 3.3, the recycling material source is a composite one (made of material with different level of recycling). x_j is the mass fraction of recycled material (recycled for j times) and used for the transformation. This fraction after the n^{th} cycling can be written as $x_{j,n}$ with $j \in \{0 \dots n-1\}$. Then, for the general case (case 3, defined in the Table 3.1), the emergy of the product can be written with the time discrete equations:

$$\bar{E}m_p(n) = (1 + \varepsilon_t - q) \cdot Em_i + q \cdot (\bar{E}m_p(n-1) + Em_c) + (1 + \varepsilon_t) \cdot Em_t \quad (3.9)$$

$$\bar{E}m_p(0) = (1 + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t) \cdot Em_t \quad (3.10)$$

Where $\bar{E}m_p$ is defined as the average emergy from the material coming from the recycled reservoirs:

$$\bar{E}m_p(n-1) = \sum_{j=0}^{n-1} x_{j,n} \cdot Em_p(j) \quad (3.11)$$

After the n^{th} cycle, the average energy can be written (development similar to the one described in the Subsection 3.2.1) under its developed form:

$$\bar{E}m_p(n) = \bar{E}m_p(0) + \left(\sum_{k=0}^{n-1} \sum_{j=k}^{n-1} x_{j,n} \cdot q^{k+1} \right) \cdot ((\varepsilon_c + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t) \cdot Em_t + Em_c) \quad (3.12)$$

Similarly to the Table 3.2, the Table 3.3 summarizes the three possible cases of mass losses and the corresponding product energy.

Energy of the product for the different combination of mass losses	
Case 1:	$\bar{E}m_p(n) = \bar{E}m_p(0) + \left(\sum_{k=0}^{n-1} \sum_{j=k}^{n-1} x_{j,n} \cdot q^{k+1} \right) \cdot (\varepsilon_c \cdot Em_i + Em_t + Em_c)$
Case 2:	$\bar{E}m_p(n) = \bar{E}m_p(0) + \left(\sum_{k=0}^{n-1} \sum_{j=k}^{n-1} x_{j,n} \cdot q^{k+1} \right) \cdot (\varepsilon_t \cdot Em_i + (1 + \varepsilon_t)Em_t + Em_c)$
Case 3:	$\bar{E}m_p(n) = \bar{E}m_p(0) + \left(\sum_{k=0}^{n-1} \sum_{j=k}^{n-1} x_{j,n} \cdot q^{k+1} \right) \cdot ((\varepsilon_c + \varepsilon_t) \cdot Em_i + (1 + \varepsilon_t)Em_t + Em_c)$

Table 3.3: Energy of the product for the different combination of mass losses (Closed-loop recycling/reservoir made of mixed recycled material)

3.2.2.2 Closed-loop recycling with discharge of a reservoir without any addition of raw material

In this case, the raw material enters the process only the first time of the transformation; then, only recycled material is used and comes from a reservoir for which the number of time the material has been already recycled is homogeneous (see Fig. 3.4). This case is an intermediary one, and aims to explain the most general case of the next section. The simplifications chosen (raw material entering only once the process and a single homogeneous reservoir of recycled material) help to focus the equations governing the discharge of the reservoir.

The mass balance gives the mass of material (as defined in Eq. (3.13)), the energy of the product is given by Eq. (3.14) (both time discrete equations), whereas the specific energy (relatively to the mass defined in the Eq. (3.13)) is defined by Eq. (3.15).

$$m(n) = \frac{1 - \varepsilon_c}{1 + \varepsilon_t} \cdot q \cdot m(n - 1) \quad (3.13)$$

$$Em_p(n) = q \cdot m(n - 1) \cdot [em_p(n - 1) + em_c + (1 - \varepsilon_c) \cdot em_t] \quad (3.14)$$

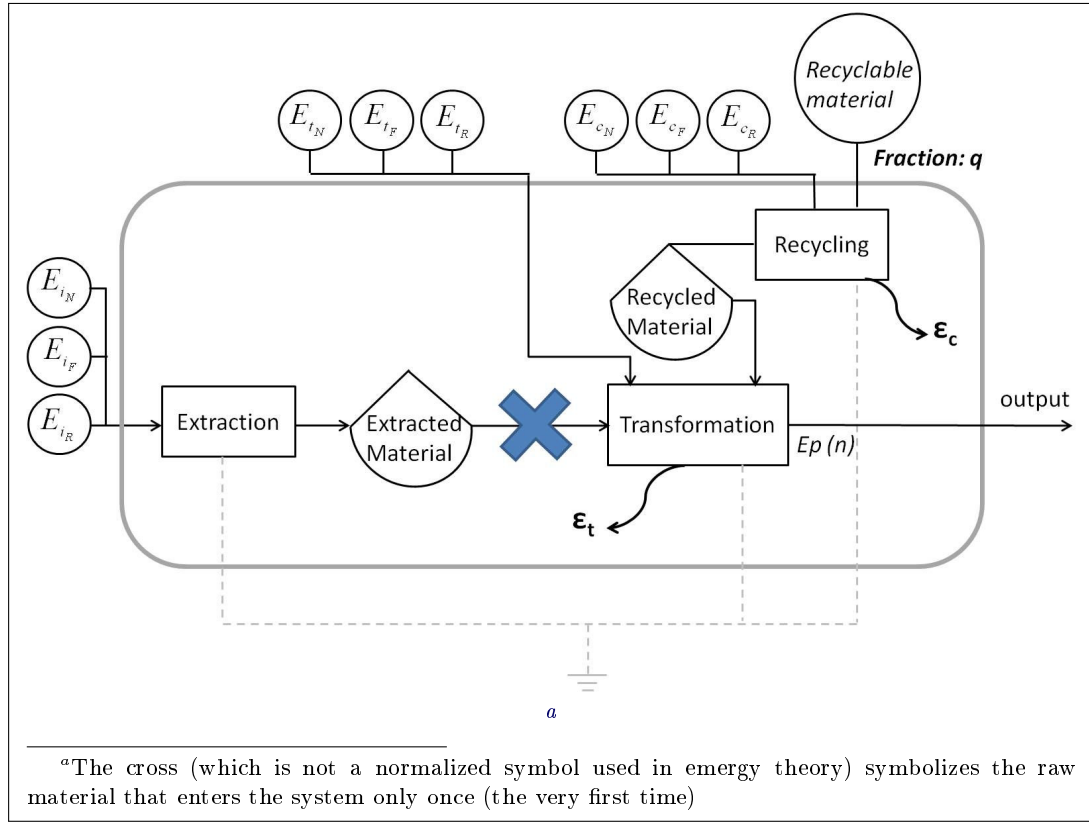


Figure 3.4: Closed-loop with mass losses (recycling with discharge of a reservoir without addition of raw material)

$$em_p(n) = \frac{Em_p(n)}{m(n)} \quad (3.15)$$

In these equations, the energy em_p , em_c and em_t correspond to the specific energy (see Table 3.5 for more details). Eqs. (3.16) to (3.18) correspond to the first time the raw material enters the process:

$$m(0) = 1 \quad (3.16)$$

$$Em_p(0) = (1 + \varepsilon_t) \cdot (Em_i + Em_t) \quad (3.17)$$

$$em_p(0) = (1 + \varepsilon_t)(em_i + em_t) \quad (3.18)$$

By developing these equations like in the section 1 (for each recycling stage), it

can be found:

$$m(n) = \left[\frac{1 - \varepsilon_c}{1 + \varepsilon_t} \cdot q \right]^n \quad (3.19)$$

$$Em_p(n) = q^n \cdot \left[(1 + \varepsilon_t) \cdot em_i + (1 + \varepsilon_t) \cdot em_t + ((1 - \varepsilon_c) \cdot em_t + em_c) \cdot \left(\frac{\left(\frac{1 - \varepsilon_c}{1 + \varepsilon_t} \right)^n - 1}{\frac{1 - \varepsilon_c}{1 + \varepsilon_t} - 1} \right) \right] \quad (3.20)$$

$$em_p(n) = \left[\frac{1 + \varepsilon_t}{1 - \varepsilon_c} \right]^n \cdot \left[(1 + \varepsilon_t) \cdot em_i + (1 + \varepsilon_t) \cdot em_t + ((1 - \varepsilon_c) \cdot em_t + em_c) \cdot \left(\frac{\left(\frac{1 - \varepsilon_c}{1 + \varepsilon_t} \right)^n - 1}{\frac{1 - \varepsilon_c}{1 + \varepsilon_t} - 1} \right) \right] \quad (3.21)$$

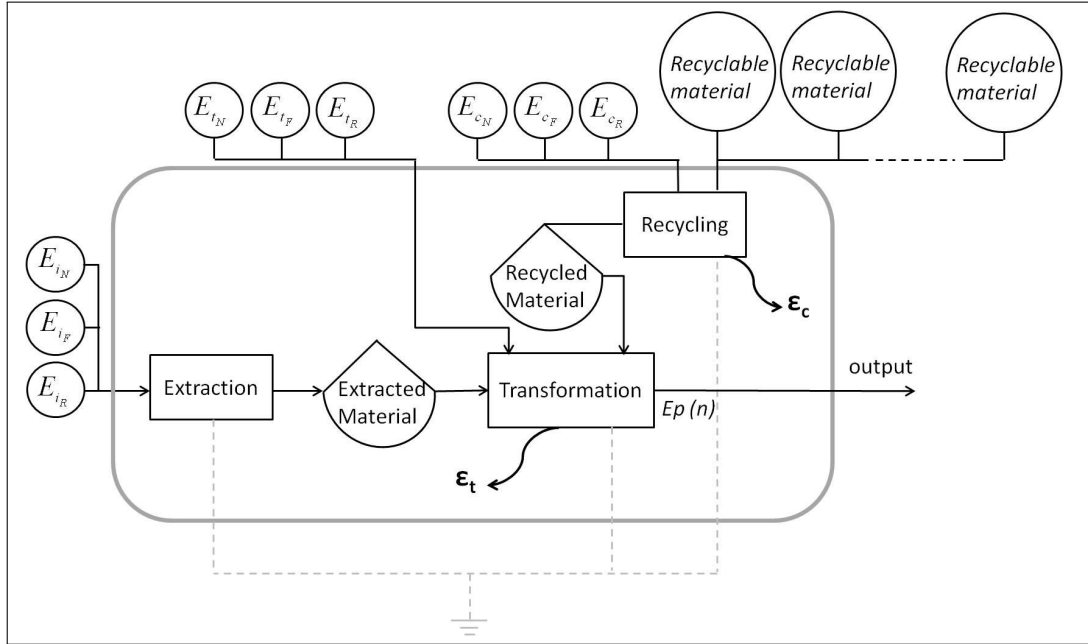


Figure 3.5: Closed-loop recycling with mass losses (separate recycled material sources)

3.2.2.3 Closed-loop recycling with separate recycled material sources - General case

This case of closed loop-recycling generalizes the previous one with multiple reservoirs (made of different level of recycled material) and the addition of raw materials when necessary (see Fig. 3.5).

$\bar{s}_p(n)$ is introduced as the mean specific additional energy of the storage. This

energy is given by the discharge description of a reservoir as it is done in the previous section. Its mathematical expression is obtained by solving the Eqs. (3.19) to (3.21). Thus, the mean specific energy of the product (in the general case) for closed-loop recycling can be written (for the case $\varepsilon_c > 0$, $\varepsilon_t > 0$) with the time discrete equation:

$$e\bar{m}_p(n) = (1 + \varepsilon_t - q \cdot \varepsilon_c) \cdot em_i + q \cdot \bar{s}_p(n) + em_c + (1 + \varepsilon_t) \cdot em_t \quad (3.22)$$

$$e\bar{m}_p(0) = em_i + em_t \quad (3.23)$$

The detailed form of \bar{s}_p can be used to rewrite the Eq. (3.22) as follow:

$$e\bar{m}_p(n) = (1 + \varepsilon_t - q - q \cdot \varepsilon_c) \cdot em_i + q \cdot \left(\sum_{j=0}^{n-1} x_{j,n} \cdot s_p(j) + em_c \right) + (1 + \varepsilon_t) \cdot em_t \quad (3.24)$$

Then, a development for each stage of recycling (as done previously) gives the specific energy of the product:

$$\begin{aligned} e\bar{m}_p(n) = & (1 + \varepsilon_t - q - q \cdot \varepsilon_c) \cdot em_i + q \cdot em_c + (1 + \varepsilon_t) \cdot em_t \\ & + q \cdot \left[(1 + \varepsilon_t) \cdot (em_i + em_t) \cdot \sum_{j=0}^{n-1} x_{j,n} \cdot \left(\frac{1 + \varepsilon_t}{1 - \varepsilon_c} \right)^j \right] \\ & + q \cdot \left[((1 - \varepsilon_t) \cdot em_t + em_c) \cdot \left(1 + \frac{1 - \varepsilon_c}{1 + \varepsilon_t} \right) \cdot \left(\sum_{j=0}^{n-1} x_{j,n} \cdot \frac{1 + \varepsilon_t}{1 - \varepsilon_c} \right)^j \right] \end{aligned} \quad (3.25)$$

The last equation is written under the assumption of a constant recycling rate q . In case of a variable recycling rate Eq. (3.22) must be used to determine the specific energy of the product at each cycle.

3.2.2.4 Energy indices

As it has been described in the first section, Brown and Buranakarn [Brown 2003] defined (using the energy theory) a set of indices dedicated to the assessment of recycling. The recycling accounting is not obvious and it is still under discussion in the literature [Ulgiati 2004, Amponsah 2011b, Agostinho 2013]. Thus, depending on the case studied, energy indices for recycling can be adapted like in the study of Agostinho et al. [Agostinho 2013], who defined a *Modified Recycle Yield Ratio*

(“modified“ to account the emergy of the refined material). In this article, a focus on the Recycling Benefit Ratio (*RBR*) is proposed. In its original definition, *RBR* is the ratio of emergy used in providing a material from raw resources to the emergy used in recycling [Brown 2003]. This definition is relevant for recycling accounting without variation of the recycled rate of the material at each cycle. To preserve the philosophy of *RBR*, and in the mean time to take into account the specific aspect of successive recycling, *RBR* is considered in this study as the ratio of emergy used in providing a material to the emergy used in recycling at each stage of recycling. Consequently both the numerator and the denominator are calculated at each cycle, by considering the fraction of recycled material q .

3.3 Case study

In this section, the equations described in previous sections are applied to the case of aluminum recycling. Considering both resource optimization and the economical point of view, aluminum recycling is considered to have a great potential. The efficiency of metal recycling depends on various parameters: purchasing cost of scrap, environmental regulations, metal recovery, metal yield and metal quality [Xiao 2002]. The different situations presented above are considered. The recycling rates for aluminum industry over the past years are deduced from the figures given by Bertram et al. [Bertram 2009] (Table 3.4). The specific emergy and the input resources for the conventional aluminum (Table 3.5) production are obtained from the work of Amponsah [Amponsah 2011b].

Aluminum recycling rates							
Year	1950	1960	1970	1980	1990	2000	2010
Recycling rate [%]	18	20	22	25	28	35	31

Table 3.4: Aluminum recycling rates [Bertram 2009]

Emergy evaluation of conventional aluminum production and reuse of aluminum				
Item	Unit/year	Input Resource	Specific Emergy [seJ/unit]	Emergy [seJ/year]
Conventiional aluminium sheet production				
1 Primary aluminium (ingot)	g	4.17E+11	1.17E+10	4.88E+21
2 Electricity	J	1.08E+15	1.74E+05	1.88E+20
3 Labour	\$	2.09E+07	1.15E+12	2.40E+19
4 Annual Yield	g	4.00E+11	1.27E+10	5.08E+21
Recycling Process				
5 Used aluminium can	g	2.29E+11	1.17E+10	2.68E+21
6 Primary aluminium (ingot)	g	1.25E+11	1.17E+10	1.46E+21
7 Aluminium scrap	g	6.25E+10	1.17E+10	7.31E+20

Continued on next page...

Item	Unit/year	Input Resource	Specific Emergy [seJ/unit]	Emergy [seJ/year]
8 Used Al. can collection	g	2.29E+11	2.51E+08	5.75E+19
9 Used Al. Can separation	g	2.29E+11	8.24E+06	1.89E+18
10 Electricity	J	1.08E+15	1.74E+05	1.88E+20
11 Transport (Truck)	ton-mile	2.82E+07	9.65E+11	2.72E+19
12 Labour	\$	2.90E+07	1.15E+12	3.34E+19
13 Annual Yield	g	4.00E+11	1.29E+10	5.18E+21
14 Specific emergy for recycling	seJ/g	$e_c = Em(8 + 9 + 11)/\text{Input}(13)$		
15 Specific emergy for transformation	seJ/g	$e_t = Em(2 + 3^*)/\text{Input}(4)$		
16 Specific emergy for raw material	seJ/g	$e_i = Em(1)/\text{Input}(4)$		

*Counted at the plant level

Table 3.5: Emergy evaluation of conventional aluminum production and reuse of aluminum [Amponsah 2011b]

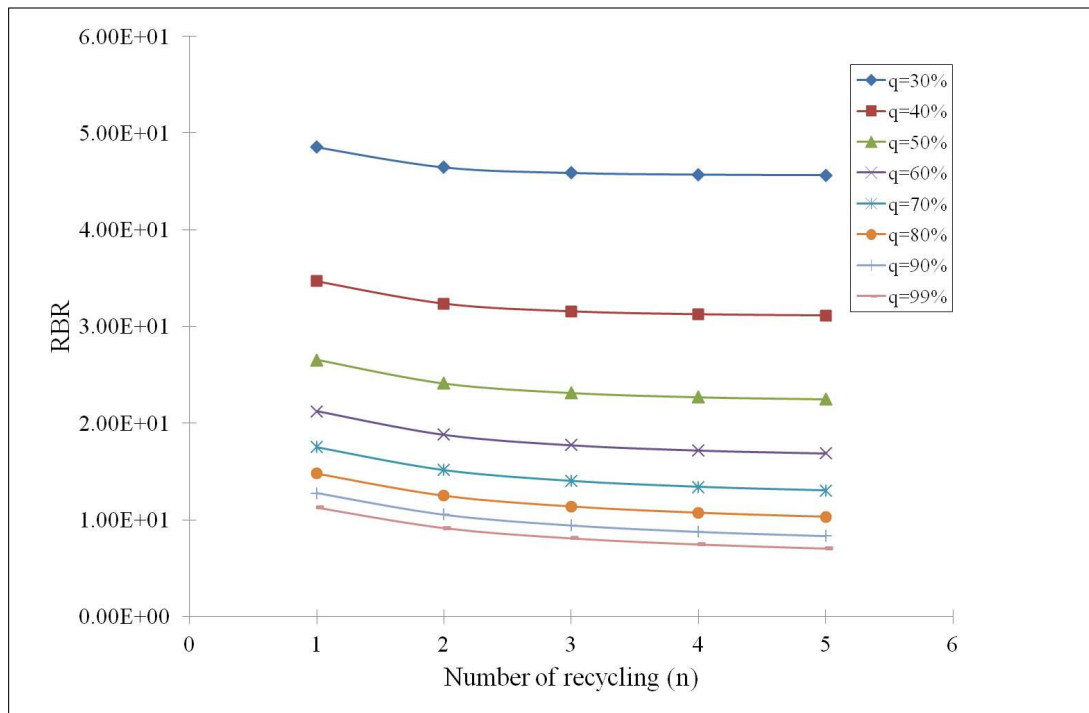


Figure 3.6: Influence of the recycling mass rate on RBR (Closed-loop recycling, case 3, $\varepsilon_c = \varepsilon_t = 10\%$)

3.4 Results

This case study is not used to illustrate the intermediary demonstration of *Closed-loop recycling with a reservoir of mixed recycled material* and *Closed-loop recycling*

with discharge of a reservoir without addition of raw material. These two case are intermediary steps to develop the theory associated to the general case of Closed-loop recycling. The focus is on the most realistic situations of closed-loop recycling: *Single-source recycling*, see Fig. 3.2 and *multi-sources recycling*, see Fig. 3.5.

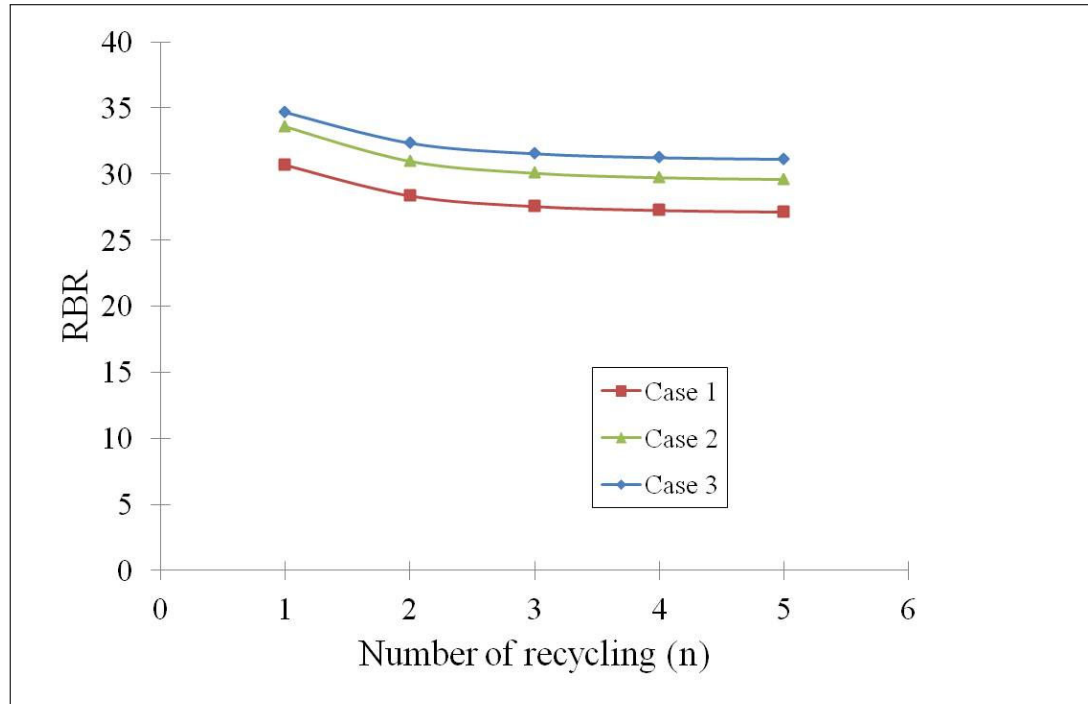


Figure 3.7: Influence of the different cases of mass losses on RBR (Closed-loop recycling $q = 40\%$)

3.4.1 Closed-loop recycling (single-source)

To illustrate the usefulness of the equations proposed in this work (see Eqs. (3.8) to (3.10)) the Recycling Benefit Ratio is used to identify the influence of the recycle rate q (see Fig. 3.6). In this figure, each curve corresponds to a fixed value of q which is used at each cycle n . The mass losses rates (ε_c and ε_t) are kept constant for all the cases in this figure. The values chosen for q are theoretical and cover a large range of variation. The general trend of RBR decreases similarly altogether with n (whatever the value for q) before reaching a horizontal asymptote. The benefit of recycling is constant after 4 cycles, but remains interesting as the lowest value for RBR is greater than 10 (see Deutz et al. and Agostinho et al. [Deutz 2014, Agostinho 2013]).

In Fig. 3.7, RBR is used to compare the three cases of mass losses described in the Table 3.1. In this case, ε_c and ε_t are set to 10% when they are not equal to zero, and the q is set to 40%. It can be observed that the advantage of using recycled material increases as the losses occur at the recycling step, the transformation step

and both. The RBR is decreasing until the number of cycles is equal to 4, after which the value almost reaches a horizontal asymptote. This trend is also visible in Fig. 3.8, which shows the influence of the mass losses on RBR . In this figure, for the three cases defined in Table 3.1, four different values are set to the mass losses rates ε_c and ε_t (when they are not equal to zero), and the recycling rate q is fixed at 40%. It is clear that for a selected case, the more losses occur in the process the lower global value for RBR is.

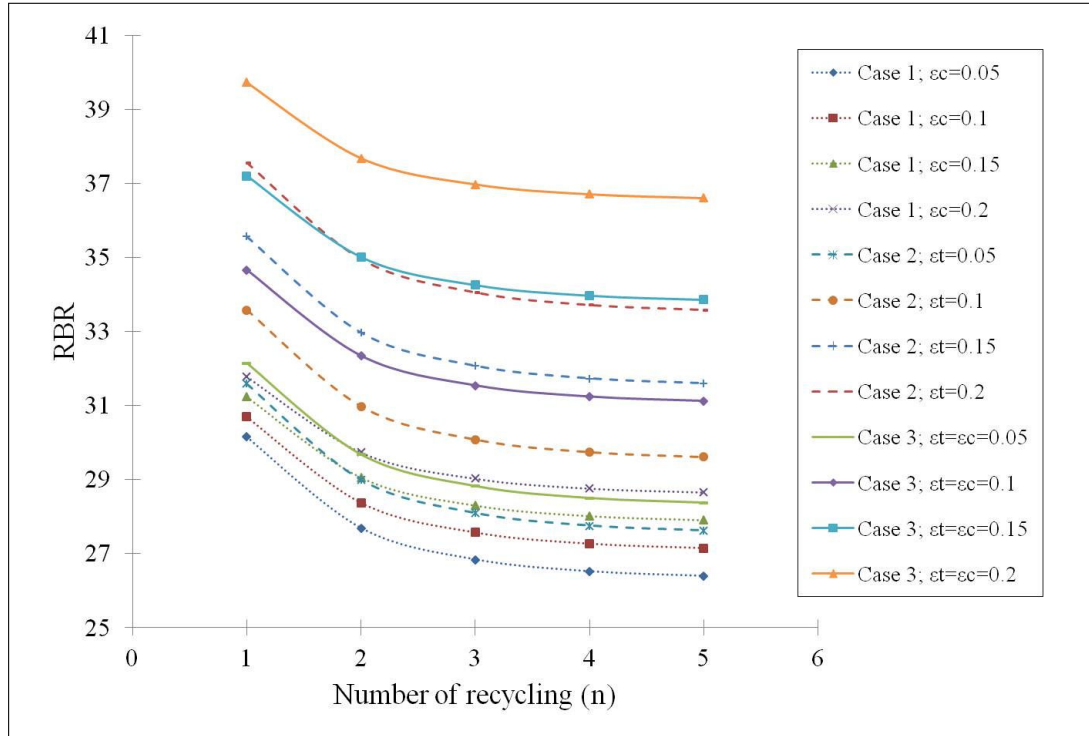


Figure 3.8: Influence of the mass losses on RBR (Closed-loop recycling, $q = \%$)

3.4.2 Closed-loop recycling (multi-sources)

Preliminary to the analysis of the case study results, Fig. 3.9 illustrates the accounting of the mass rates at the input and output of the process. In this figure, three cycles of recycling are presented to explain how the $x_{j,n}$ are calculated (see Eq. (3.25) $\bar{s}_p(n)$ (see Eq. (3.24))). It must be noted the extended form of Eq. (3.25) can be used only in the case of a constant recycling rate q . When this rate varies, Eq. (3.22) must be used.

This equation is used for the first time with a theoretical variation of the recycling rate (10%, 20%, 30%, 40%, 50%, 60%). The 10% must be understood as the rate of the output material after the first recycling is recycled, 20% as the rate of the output material of the second recycling is recycled, and 30% as the rate for the

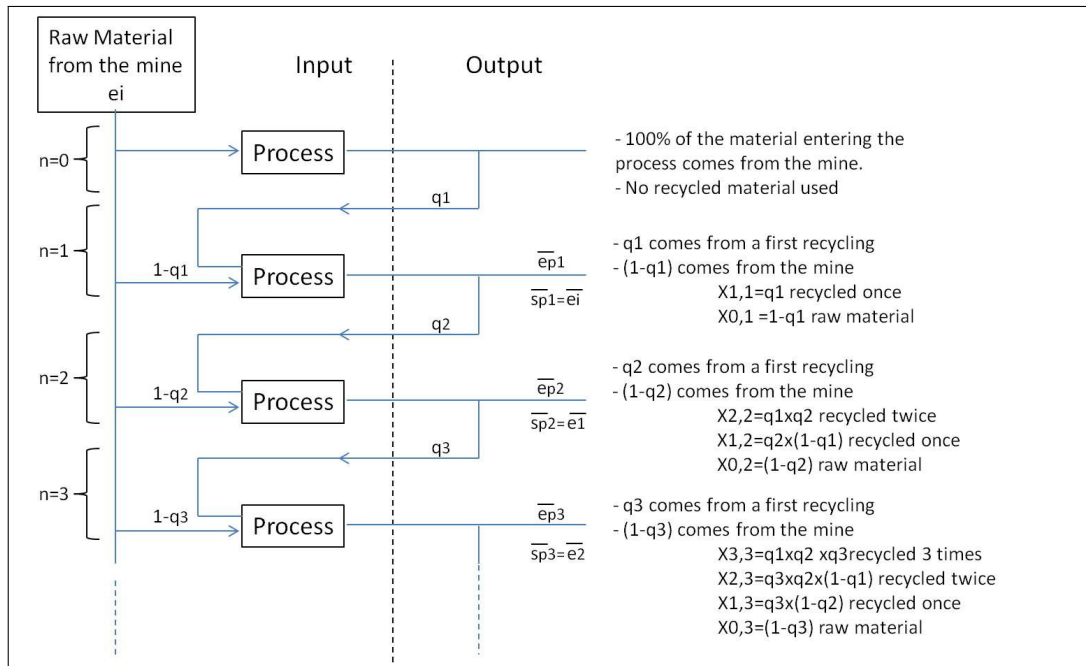


Figure 3.9: Material rates and energy accounting (Open-loop recycling)

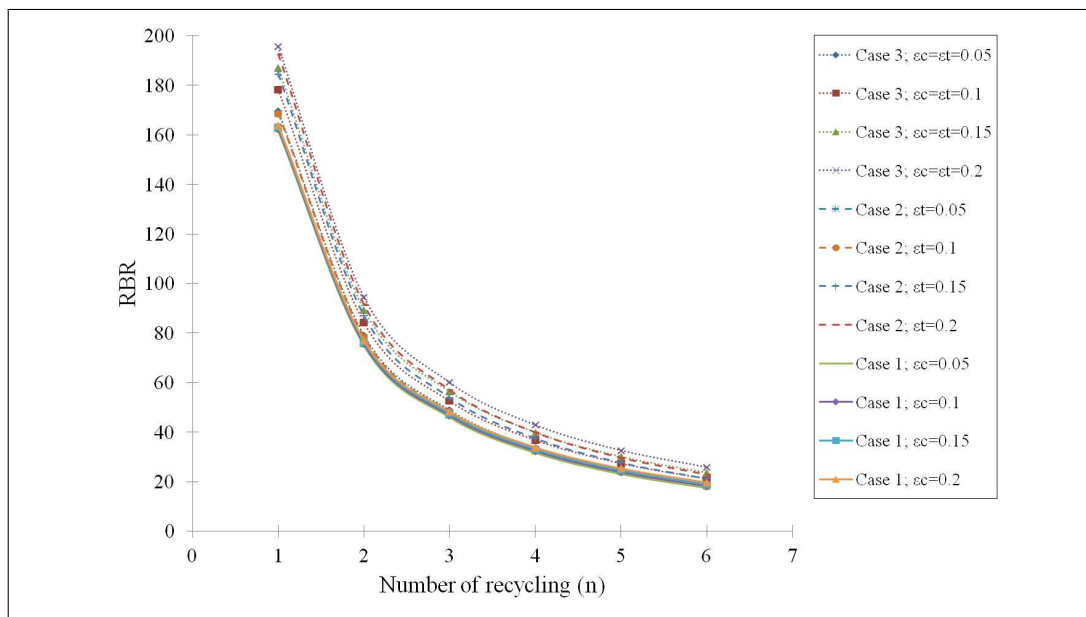


Figure 3.10: Influence of the mass losses on RBR (Closed-loop recycling/multi-source, theoretical case)

third recycling etc. It can be seen in Fig. 3.10 that the general shape and trend of the curves are similar to those obtained in the case of single-source recycling.

Furthermore, it can be noted that the horizontal asymptote is reached later than in the case of closed-loop recycling. Additionally, the values of RBR are also higher. This values suggest that the benefit of recycling in the case of closed-loop is always interesting even after many recycling cycles. The global ranking of RBR between the three cases (see Table 3.1) is also considered: the case of losses for both the recycling and the transformation step have a higher Recycling Benefit Ratio than in the case of the transformation step only (which has a higher RBR than the case of loses at the recycling step).

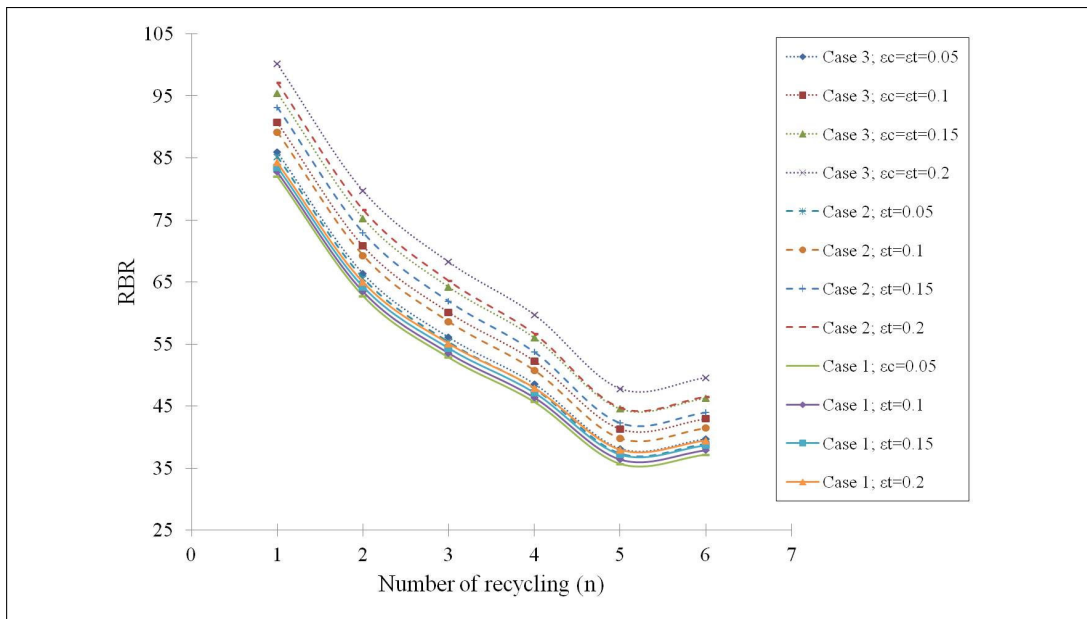


Figure 3.11: Influence of the mass losses on RBR (Closed-loop recycling/ multi-source, Case of Aluminum)

The same equations are applied to the case of the aluminum recycling rates over the past decades, as it is represented in the Table 3.4. In this table, the year 1950 is considered as the initial set of the reservoir of material, meaning this reservoir is assumed to be the mine. Then, for the next years the rates are used in Eq. (3.22) similarly to the previous case. In Fig. 3.11, the main conclusions assumed previously remain the same (concerning the global ranking of RBR between the different case and the existence of a horizontal asymptote). This figure also illustrates that the sensitivity of RBR to a non monotonous increase of q (as the decreasing rate for the year 2010 (31% of recycling)) can be detected as an increase of RBR . This behavior can be explained with the lower emergy for recycling.

3.5 Conclusion of the chapter

Recycling is commonly considered as suitable in term of sustainability. Numerous methods of assessment already exist in the literature, such as the life cycle analysis (a multi-criteria method or oriented user-side), or the emergy assessment (a mono-criteria method or oriented donor-side) and they are considered more in complementary than in competition. Closed-loop recycling can be done under two configurations, single-source or multi-sources. Applying the emergy assessment, discrete time emergy equations are set according to the recycling configuration. Specific emergy unit of the product, partially recycled, is increasing by definition. Therefore, the recycling ratio benefit *RBR* is redefined as the ratio of the emergy used in providing a material to the emergy used in recycling at each stage of the process. Thus, the *RBR* can be defined as a function of number of cycles. Under the assumptions of the study, the first values are the most important and that the asymptotic behavior after 5-6 cycles. As a case study on the global shared of recycled and primary materials aluminum is considered. Applying the discrete time emergy assessment, the effect of the shared material has the higher impact on *RBR* values.

Metallurgical recycling processes:
Sustainability ratios and
environmental performance
assessment

Metallurgical recycling processes: Sustainability ratios and environmental performance assessment

Abstract: Recycling is considered as core element of the sustainable development. In reality, however, due to the physical and chemical limits of current recycling technologies, material and quality losses occur that affect the efficiency of recycling. This chapter aims to assess the environmental performance of metallurgical recycling, from both a donor and user-side perspective, by using the emergy evaluation combined with exergetic life cycle assessment (*ELCA*). Two evaluation models have been developed. The first model is based on Odum's approach, it evaluates the environmental impacts of recycled materials taking into account all previous processes that generated the material. The second model is based on Ulgiati's approach, it erases the memory of the recovered material and accounts only for the current recycling cycle. Furthermore, the use of an average transformity is proposed, to measure the environmental performance of recycled materials. Contrary to classical transformities, it evaluates the material based on all previous processes that generated the material while avoiding the "double counting". Finally, three sustainability ratios have been defined: the resource efficiency ratio α , the performance ratio β and the eco-design ratio χ . Their functions have been described and clarified with provided examples.

Keywords: Emergy, LCA, ELCA, Metallurgical recycling, Material losses, Quality losses, Sustainability ratios

Nomenclature

Acronyms

<i>ELCA</i>	Exergetic Life Cycle Assessment
<i>EOL</i>	End-of-Life
<i>LCA</i>	Life Cycle Assessment
<i>PET</i>	Polyethylene terephthalate

Greek Symbols

ε	Molar losses [mol]
γ	Dilution ratio $\gamma = \frac{m_{DM}}{m^{\circ}}$ [-]
τ	Transformity [seJ/J]

Roman Symbols

<i>a</i>	Activity [-]
Δg_f	Specific Gibbs free energy of mineral formation [J/g]
<i>Em</i>	Absolute emergy [seJ]
<i>em</i>	Specific emergy [seJ/g]
<i>Ex</i>	Absolute exergy [J]
<i>ex</i>	Molar exergy [J/mol] or specific exergy [J/kg]
<i>m</i>	Mass [kg]
<i>n</i>	Number of moles [mol]
<i>R</i>	Universal gas constant [8.314 J/mol K]
<i>r</i>	Recycling cycles
<i>S</i>	Sources of energy
T°	Standard ambient temperature [298.15 K]
<i>x</i>	Mass fraction [g/g]
<i>y</i>	Molar fraction [mol/mol]

Superscripts

$^{\circ}$	Initial
\sim	Emergy based on Ulgiati's approach
\sim	Specific

Subscripts

<i>ch</i>	Chemical
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<i>D</i>	Dilution
<i>DM</i>	Dilution material
<i>i</i>	Component <i>i</i>
<i>j</i>	Component <i>j</i> of the final alloy
<i>k</i>	Component <i>k</i> of the diluting materials
<i>L</i>	Shredding and sorting (liberation)
<i>Mfg</i>	Manufacturing
<i>PM</i>	Primary material
<i>Q&M</i>	Quality and material
<i>Rcg</i>	Recycling
<i>RM</i>	Recycling material
<i>S</i>	Smelting
<i>T</i>	Thermal treatment
<i>W</i>	Collection and dismantling (waste)

4.1 Introduction

Since the late 20th century, the decreasing depletion of natural resources due to strong economic growth has become a particularly acute issue. To tackle this problem, recycling policies and legislation have been put in place to ensure a sustainable development. The recycling industry itself, however, requires inputs of primary resources, which makes its environmental performance depending on the chemical, physical and thermodynamical limits of the process [Reuter 2006].

A number of studies have been performed [Ignatenko 2007, Amini 2007] to assess (by using exergy analysis) the resource efficiency of metallurgical recycling. The results showed that high recycling rates do not necessarily ensure the preservation of natural resources, as it is not always possible to obtain, without considerable resource input, high-quality recyclates able to substitute virgin raw materials. End-of-life (*EOL*) products are often complex assemblies of different materials. During shredding the joints between the materials cannot be completely destroyed, causing the presence of foreign particles in the recovered stream [Castro 2007, Meskers 2007]. The contamination of these streams make the material lose its properties, downgraded to a lower quality the recycled material is no more suitable for its original use. Thus, the environmental benefit of recycled materials depends consequently on the composition and design of the product and on the physical separation efficiency during shredding .

Emergy spelled with an “m” refers to the embodied energy or energy memory and it represents the available energy previously used up (directly and indirectly) to generate a product or a service [Scienceman 1987]. The transformity is by definition the ratio between the emergy contribution and the exergy output [Brown 2004c]. In the case of recycled materials the emergy input represents all forms of energy invested by the environment, consumed or transformed, to make the material available and the exergy output the ability to do work (quality) of the material. The transformity allows then, to classify recycled materials according to the complexity of their production process and their quality (exergy). The emergy accounting procedure assumes that the transformity of the recycled material includes not only the emergy invested in the current recycling process but also the inputs of all previous processes (previous production or recycling processes) [Odum 1996]. This means that the transformity of the recovered material will increase with each recycling cycle as it engenders an emergy increase and an exergy degradation of the material. Under this aspect, recycling has no environmental benefit as the transformity of recycled materials would be higher than the transformity of virgin ones. Therefore it might be reasonably assumed that the integration of another accounting tool is necessary to adequately assess, in emergy terms, the resource efficiency of recycling.

The emergy approach has been used in several studies to evaluate the recycling processes. Almeida et al. [Almeida 2010] introduced emergy indices to determine the most advantageous recycling rate for *PET* (Polyethylene terephthalate) bottle and

aluminum can production in Brazil. Agostinho et al. [Agostinho 2013] assessed the energy performance of recovering materials from SCWTP (Sorting and Composting Waste Treatment Plant). Amponsah et al. [Amponsah 2012] and Brown and Buranakarn [Brown 2003] studied the reuse and recyclability of building materials on the basis of energy tools. A set of dynamic equations was proposed by Amponsah et al. [Amponsah 2011b] to calculate the energy of continuous recycling processes. Gianetti et al. [Gianetti 2013] adopted the energy ternary diagrams to evaluate a reverse logistics network for steel recycling. Jamali-Zghal et al. [Jamali-Zghal 2014] evaluated (in terms of energy) the effects of material losses in closed-loop recycling processes.

The aim of this work is to combine the exergetic life cycle assessment (*ELCA*) and the energy evaluation in order to study the environmental efficiency of metallurgical recycling. Linking these two approaches permits on the one hand to consider both the donor-side (energy) and the user-side (*ELCA*) of recycling and on the other hand to take into account for the quality loss (exergy loss) during the process.

4.2 Methodological approach

4.2.1 Exergetic Life Cycle Assessment of metallurgical recycling processes

4.2.1.1 Exergetic Life Cycle Assessment

Life cycle assessment (*LCA*) is an evaluation method that allows to measure the energy and environmental burden of a process or an activity by identifying and assessing the resources consumed and the waste released in the environment [Curran 2013, Finnveden 2014]. Based on the first and second law of thermodynamics, the exergetic life cycle assessment is an extension of the life cycle approach, including exergy analysis. This approach makes possible to measure the depletion of natural resources due to the irreversibility of life cycles. This tool enables not only to measure the thermodynamic imperfection of the process but also to find out where the exergy destruction occurs [Cornelissen 2002, Dincer 2007]. From the thermodynamic point of view, a material is useful when it is higher concentrated, structured and ordered than its surroundings, i.e. has a higher exergy and a lower entropy than its environment. The chemical exergy is defined as the maximum obtainable work of a material when it is brought into complete thermodynamic equilibrium with its reference environment at constant temperature and pressure [Szargut 2002]. This makes the choice of the latter crucial as the exergy analysis is based on its definition and thermodynamical properties. A reference environment presents a theoretical planet in thermodynamic equilibrium (mechanical thermal and chemical equilibrium) where all materials have reacted, dispersed and mixed [Szargut 1987]. The exergy of a mineral can be considered then, as its state of evolution, relative to its most degraded thermodynamic conditions. In literature,

many criteria have been established to define the reference environment. In general, it is composed of reference substances divided into gaseous, solid and liquid phases which represent respectively the gaseous components of the atmospheric air, the solid components of the external layer of the Earth's crust and the molecular components of seawater [Szargut 1989].

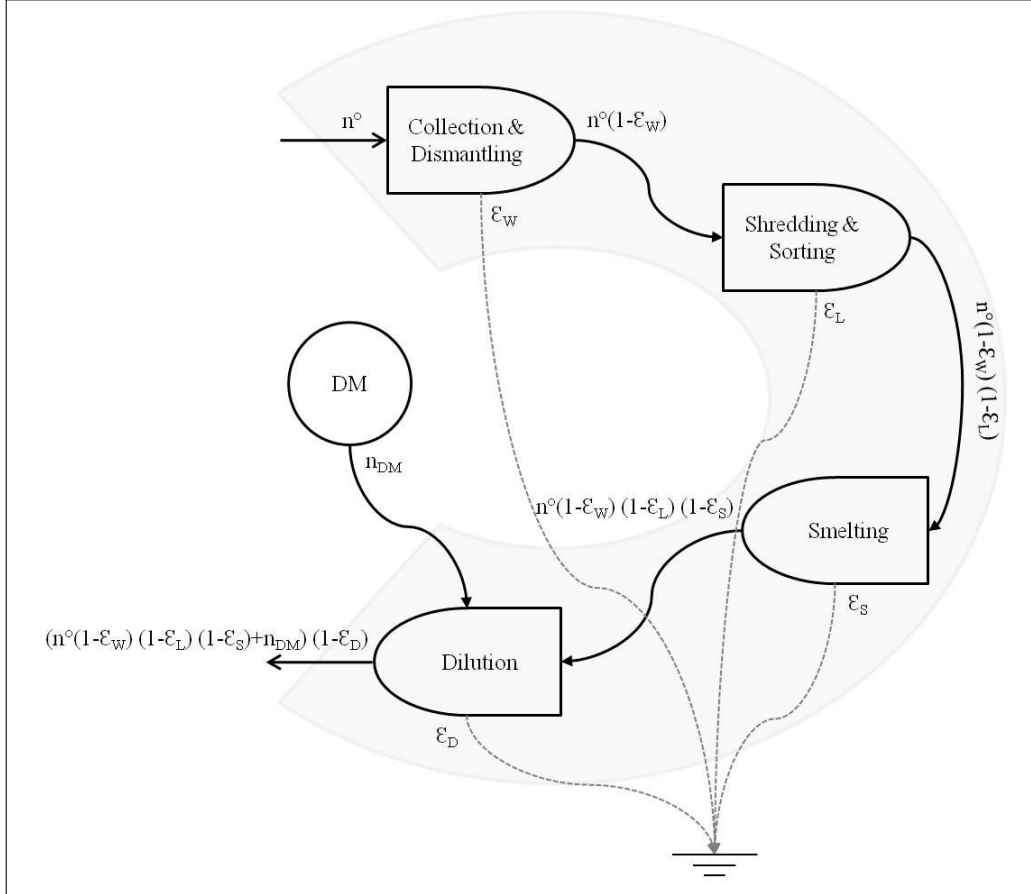


Figure 4.1: Flow chart of the metallurgical recycling

In this work, the chemical exergy is determined based on Szargut's reference environment methodology [Szargut 2005]. The reference environment is considered as a source of heat and reference substances. The molar chemical exergy of a material ex_{ch} can be calculated by using the exergy balance of a reversible reaction, as the reference substances are supposed to be at a standard ambient temperature, pressure and standard concentration in the natural environment, see Eq. (4.1).

$$ex_{ch} = \Delta g_f + \sum_i y_i \cdot ex_{chi} \quad (4.1)$$

where Δg_f represents the molar free Gibbs energy and y_i and ex_{chi} are respectively the molar fraction and the molar chemical exergy of component i .

The molar chemical exergy of a mixture $ex_{ch,mix}$ is then calculated as indicated in Equation (4.2):

$$ex_{ch,mix} = \sum_i y_i \cdot ex_{chi} + RT^\circ \sum_i y_i \ln(a_i) \quad (4.2)$$

where R represents the universal gas constant, T° the standard ambient temperature and a_i the activity of component i in the mixture. The first part of Equation 4.2 represents the components' chemical exergy i.e. the useful energy of the mixture whereas the second part reflects the entropy increase due to the interaction between the components i.e. internal quality (exergy) loss of the mixture.

The presence of contaminants in the recyclate increases the disorder of the system due to interactions between the components. The activity a_i permits to measure the deviation of the solution from ideal behavior: the stronger the interactions between the elements, the lower is the activity and the more the material loses its chemical potential [Castro 2004]. The activity is equal to one when there is no chemical interaction between the components see Eq. (4.3a), for an ideal solution the activity can be replaced by the mole fraction see Eq. (4.3b) [Finnveden 1997].

$$ex_{ch,mix} = \sum_i y_i \cdot ex_{chi} \quad (4.3a)$$

$$ex_{ch,mix} = \sum_i y_i \cdot ex_{chi} + RT^\circ \sum_i y_i \ln(y_i) \quad (4.3b)$$

4.2.1.2 Material and quality losses in metallurgical recycling processes

This study is focused on the fundamental limits of metallurgical recycling. As described in Fig. 4.1, the recycling process consists of following main steps: the collection and dismantling of *EOL* products, the shredding and sorting of the scrap to liberate trapped contamination, the re-melting of the scrap and potentially the dilution of contaminants with high purity resources to upgrade the quality of the recycled material. During the described process steps, material and quality losses occurs which significantly affect the environmental performance of the recycling procedure. In what follows, the external (material) and internal (quality) exergy losses have been calculated at each stage of the recycling process, by using Eqs. (4.2), (4.3a) and (4.3b).

- *Collection & Dismantling:*

During the recovery phase (collection and dismantling), ε_W represents the portion of recovered material discarded because it is unsuitable for use as a recycled input. The amount of exergy lost at this stage, ΔEx_W can be expressed as follows:

$$\Delta Ex_W = n^\circ \cdot \varepsilon_W \cdot ex_W \quad (4.4)$$

where ex_W is the molar chemical exergy of the rejected materials. This amount of exergy reflects not only the efficiency of the recovery phase but also the potential of the waste for causing harm to the environment, because the exergy embodied in the waste may disturb or even damage ecosystems [Ayres 1998].

- *Shredding & Sorting:*

During the liberation phase, the scrap is cut and crushed into small particles in order to ease the removal of contaminants from the material stream. The efficiency of the liberation process is fundamental in dictating the quality of the recycled stream, because the presence of impurities may deems the recovered stream unusable. In order to assess the quality degradation of the material due to incomplete liberation i.e. the entropy increase due to the presence of foreign substances, it is assumed that the recovered material after shredding and sorting is an ideal solid solution (hypothesis based on the work of Ignatenko et al. [Ignatenko 2007]). Thus Eq. (4.3a) and Eq. (4.3b) are used to calculate respectively the exergy content of the stream before and after the liberation phase. The external and internal exergy losses ΔEx_L throughout this phase can be calculated as follows:

$$\begin{aligned} \Delta Ex_L &= [Ex_L]_{in} - [Ex_L]_{out} \\ &= n^\circ(1 - \varepsilon_W) \cdot \left[\sum_i y_i \cdot ex_{chi} \right] \\ &\quad - n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L) \cdot \left[\sum_i y_i \cdot ex_{chi} + RT^\circ \sum_i y_i \ln(y_i) \right] \\ &= n^\circ(1 - \varepsilon_W)\varepsilon_L \cdot \left[\sum_i y_i \cdot ex_{chi} \right] \\ &\quad - n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L) \cdot \left[RT^\circ \sum_i y_i \ln(y_i) \right] \end{aligned} \quad (4.5)$$

where $[Ex_L]_{in}$ and $[Ex_L]_{out}$, are respectively the exergy content of the material before and after the liberation phase, n° the initial total number of moles in the recovered stream, ε_L the portion of recovered material lost during shredding and separation and y_i the components of the recycled stream (the composition of the stream does not change during the liberation phase as there is no foreign material added). It can be noted that the first term of the simplified equation represents the material loss, while the second term the exergy degradation due to entropy increase i.e. the quality degradation of the material.

- *Smelting:*

During smelting, chemical interaction between the entrapped contaminants and the material occurs, degrading the physical and chemical properties of the stream. Consequently, the contaminated material shifts from a low-entropy state to a high-entropy state. The efficiency of the refining process depends essentially on the potential of the contaminants to interfere with the material: the higher the degree of chemical interactions, the larger is the deviation from the ideal situation and the more internal exergy is destructed. Based on Eq. (4.2), the total exergy losses throughout this phase can be expressed as follows:

$$\begin{aligned}
 \Delta Ex_S &= [Ex_S]_{in} - [Ex_S]_{out} \\
 &= n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L) \cdot \left[\sum_i y_i \cdot ex_{chi} + RT^\circ \sum_i y_i \ln(y_i) \right] \\
 &\quad - n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L)(1 - \varepsilon_S) \cdot \left[\sum_i y_i \cdot ex_{chi} + RT^\circ \sum_i y_i \ln(a_i) \right] \\
 &= n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L)\varepsilon_S \cdot \left[\sum_i y_i \cdot ex_{chi} \right] \\
 &\quad + n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L) \cdot \left[RT^\circ \sum_i y_i \ln(y_i) \right] \\
 &\quad - n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L)(1 - \varepsilon_S) \cdot \left[RT^\circ \sum_i y_i \ln(a_i) \right]
 \end{aligned} \tag{4.6}$$

where $[Ex_R]_{in}$ and $[Ex_R]_{out}$, are respectively the exergy content of the material before and after the refining phase and ε_S is the amount of material lost in the furnace. It should be noted that low activity values point to strong interactions between the contaminants and the material, which implies a further quality degradation of the recycled stream. Similar to Eq. (4.5), the first term on the right hand side of this equation refers to the exergy degradation due to

material loss, while the second term represents the entropy decrease of the alloy due the presence of contaminants.

- *Dilution:*

The dilution with high purity materials is required when the obtained alloy after remelting does not satisfy the specification made by the industry. The efficiency of the dilution process depends not only on the material and quality losses during smelting, but also on the amount of raw materials required to adjust the recycled alloy. This is because the use of primary materials decreases the environmental performance of the recycling process as it contributes to natural resource depletion. For this reason, when primary materials are used it is proposed to consider their exergy content to be lost. It should be emphasized that this does not apply in the case of recycled materials. Hence, the exergy losses in the dilution phase can be defined as follows:

$$\Delta Ex_D = \Delta Ex_{PM} + \Delta Ex_{Q\&M} \quad (4.7)$$

where ΔEx_{PM} represents the exergy content of the primary materials (non recycled materials) added to upgrade the recycled alloy and $\Delta Ex_{Q\&M}$ the exergy losses during smelting, see respectively Eqs. (4.8) and (4.9).

$$\Delta Ex_{PM} = n_{PM} \cdot ex_{PM} \quad (4.8)$$

where n_{PM} and ex_{PM} are respectively the total number of moles and the molar chemical exergy of the primary materials.

$$\begin{aligned} \Delta Ex_{Q\&M} &= [Ex_{Q\&M}]_{in} - [Ex_{Q\&M}]_{out} \\ &= n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L)(1 - \varepsilon_S) \cdot \left[\sum_i y_i \cdot ex_{chi} + RT^\circ \sum_i y_i \ln(a_i) \right] \\ &\quad + n_{DM} \cdot \left(\sum_k y_k \cdot ex_{chk} \right) - (n^\circ(1 - \varepsilon_W)(1 - \varepsilon_L)(1 - \varepsilon_S) + n_{DM})(1 - \varepsilon_D) \\ &\quad \cdot \left[\sum_j y_j \cdot ex_{chj} + RT^\circ \sum_j y_j \ln(a_j) \right] \end{aligned} \quad (4.9)$$

where $[Ex_{Q\&M}]_{in}$ and $[Ex_{Q\&M}]_{out}$, are respectively the exergy input and output of the dilution phase, n_{DM} et y_k are respectively the total number of moles

and the components of the diluting materials, ε_D is the amount of material lost in the smelter and y_j represents the components of the final alloy.

It can be concluded that the *ELCA* is suitable for the calculation of the exergy amount lost during the metallurgical recycling process due to material losses, quality degradation and natural resource depletion, see Table 4.1. However, the environmental work required for coverage of these losses cannot be determined through this method. Therefore, the integration of the emergy approach is proposed in order to assess the environmental impacts of such recycling processes from both a donor and a user-side perspective.

Exergy losses throughout a metallurgical recycling process		
Process steps	Type of losses	ΔEx [J]
<i>Collection & Dismantling</i>	Material losses	ΔEx_W (Eq. (4.4))
<i>Shredding & Sorting</i>	Material losses, quality degradation	ΔEx_L (Eq. (4.5))
<i>Smelting</i>	Material losses, quality degradation	ΔEx_S (Eq. (4.6))
<i>Diluting</i>	Material losses, quality degradation natural resource depletion	ΔEx_D (Eqs. (4.7) to (4.9))

Table 4.1: *ELCA* of a metallurgical recycling process

4.2.2 Emergy evaluation of metallurgical recycling processes, according to Odum's approach

The emergy concept is a donor-orientated evaluation approach that accounts for the environmental work directly or indirectly involved to make a resource available [Brown 2004a]. In the case of recycled materials, each (recycling) cycle is considered as an energy transformation process (see Citation 4.1) that follows the *Energy hierarchy principle* developed by Odum (see Citation 4.2). The hierarchical position of the recycled material is indicated by its transformity which is defined as the emergy input per unit of exergy output [Brown 2004e]. According to this approach, consecutive cycles can be considered as an energy transformation chain, where every transformation process (in this case recycling cycle) generates an output (recycled material) at a higher energy level (i.e. higher transformity), see Fig. 4.2. This means that the transformity of recycled materials increases with every cycle.

Citation 4.1 (*Energy hierarchy and transformity in the universe*)

« An energy transformation is a work process that converts one or more kinds of available energy into a different type of available energy. » ([Brown 2004b])

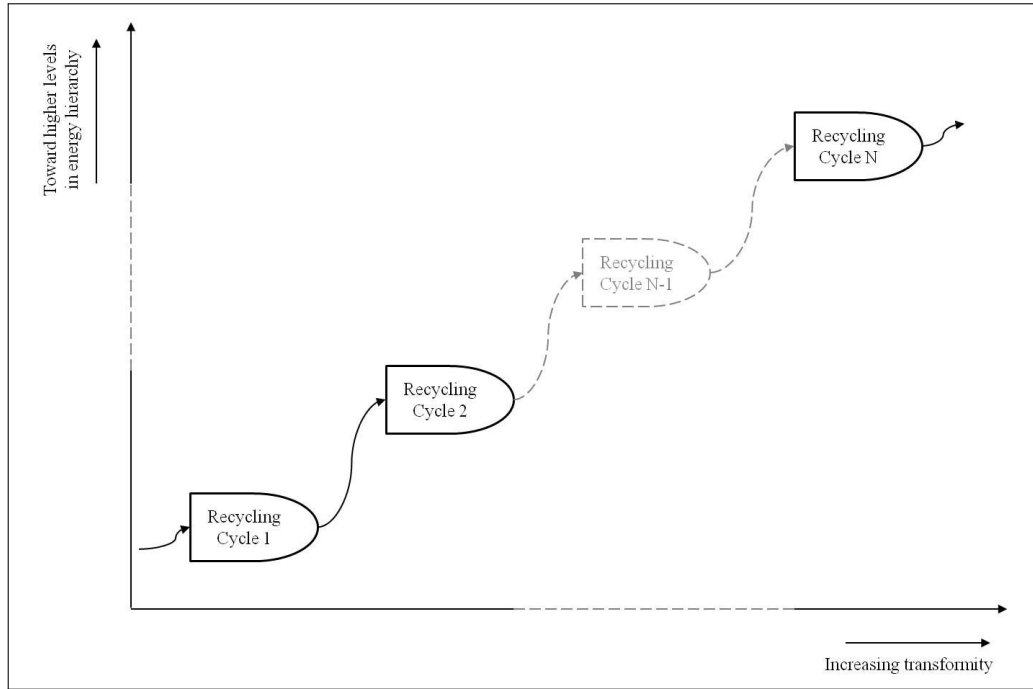


Figure 4.2: Hierarchical network of consecutive recycling cycles

Citation 4.2 (*Environmental accounting*)

« In any energy transformation, many joules of available energy of one kind are required in a transformation process to produce a unit of energy of another kind. The energy thus generated by the work of transformation constitutes a higher level in the series of transformation. » ([Odum 1996])

In what follows, the energy input and the exergy output of consecutive recycling processes are studied (Fig. 4.3). The energy flows of the process, that take into account the material and quality losses, are illustrated in Fig. 4.4. The calculation of the corresponding exergy output is based on the previous described *ELCA* approach, see Subsection 4.2.1. Thus, the first recycling cycle can be evaluated by using Table 4.2, with:

$$\begin{aligned}
 \gamma &\stackrel{\text{not}}{=} \frac{m_{DM}}{m^{\circ}} \\
 \varepsilon_{W\&L\&S} &\stackrel{\text{not}}{=} 1 - (1 - \varepsilon_W)(1 - \varepsilon_L)(1 - \varepsilon_S) \\
 \varepsilon_{Rcg} &\stackrel{\text{not}}{=} 1 - \frac{(1 - \varepsilon_{W\&L\&S} + \gamma)(1 - \varepsilon_D)}{(1 + \gamma)}
 \end{aligned} \tag{4.10}$$

Energy evaluation of a metallurgical recycling process			
Item	Amount	Specific energy [seJ/g]	Solar energy [seJ]
Material input			
Primary material	m°	em_{PM}	$m^\circ \cdot em_{PM}$
Manufacturing			
Transformation	m°	em_{Mfg}	$m^\circ \cdot em_{Mfg}$
Recycling			
Collection & Dismantling	m°	em_W	$m^\circ \cdot em_W$
Shredding & Sorting	$m^\circ(1 - \varepsilon_W)$	em_L	$m^\circ(1 - \varepsilon_W) \cdot em_L$
Smelting	$m^\circ(1 - \varepsilon_W)(1 - \varepsilon_L)$	em_S	$m^\circ(1 - \varepsilon_W)(1 - \varepsilon_L) \cdot em_S$
Dilution	$m^\circ(1 - \varepsilon_{W\&L\&S} + \gamma)$	em_D	$m^\circ(1 - \varepsilon_{W\&L\&S} + \gamma) \cdot em_D$
Total	$m^\circ(1 + \gamma)(1 - \varepsilon_{Rcg})$	em_{RM}	Em_{RM}

Table 4.2: Emergy evaluation of the first cycle, taking into account for material and quality losses

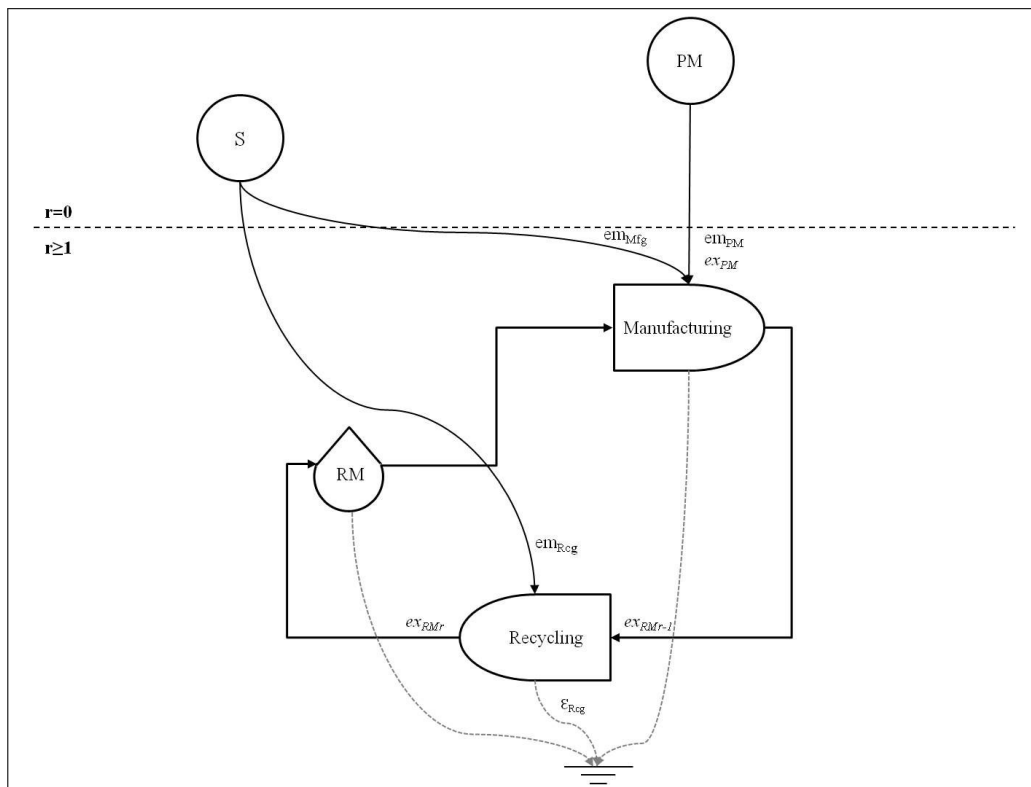


Figure 4.3: Emergy system diagram of consecutive metallurgical recycling

It should be noted that, contrarily to em_W , em_L and em_S , em_D is not constant due to the fact that it depends on the quantity of dilution material that was introduced to upgrade the recycled material, see Eqs. (4.11) and (4.12).

$$\begin{aligned} Em_D &= m^\circ(1 - \varepsilon_{W\&L\&S} + \gamma) \cdot em_D \\ &= m_{DM} \cdot em_{DM} + m^\circ(1 - \varepsilon_{W\&L\&S} + \gamma) \cdot em_T \end{aligned} \quad (4.11)$$

Consequently,

$$em_D = \frac{\gamma}{(1 - \varepsilon_{W\&L\&S} + \gamma)} \cdot em_{DM} + em_T \quad (4.12)$$

Where em_{DM} and m_{DM} are the specific energy and the mass of the dilution material (respectively) and em_T is the specific energy of the thermal treatment (melting) of the mixture.

According to Table 4.2, the energy of the material Em_{RM1} obtained from the first cycle is:

$$\begin{aligned} Em_{RM1} &= m^\circ(1 + \gamma_1)(1 - \varepsilon_{Rcg1}) \cdot em_{RM1} \\ &= m^\circ[em_{PM} + em_{Mfg} + em_W + (1 - \varepsilon_{W1}) \cdot em_L \\ &\quad + (1 - \varepsilon_{W1})(1 - \varepsilon_{L1}) \cdot em_S + (1 - \varepsilon_{W\&L\&S1} + \gamma) \cdot em_{D1}] \end{aligned} \quad (4.13)$$

Thus, the specific energy of the material em_{RM1} can be expressed as follows:

$$em_{RM1} = \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{PM} + \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{Mfg} + em_{Rcg1} \quad (4.14)$$

With:

$$\begin{aligned} em_{Rcg1} &= \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} [em_W + (1 - \varepsilon_{W1}) \cdot em_L + (1 - \varepsilon_{W1})(1 - \varepsilon_{L1}) \cdot em_S \\ &\quad + (1 - \varepsilon_{W\&L\&S1} + \gamma) \cdot em_{D1}] \end{aligned} \quad (4.15)$$

The transformity τ_{RM1} (that merges the energy investment and the exergy yield of the process) enables to assess the environmental impact from both user- and donor-side perspective. The specific exergy indicates the quality loss during the recycling

process, while the specific emergy accounts the environmental work that is necessary to compensate the quality and material losses during the process:

$$\tau_{RM1} = \frac{em_{RM1}}{\tilde{e}x_{RM1}} \quad (4.16)$$

where $\tilde{e}x_{RM1}$ is the specific exergy of the recycled material which can be calculated with the Eq. (4.2). It should be pointed out that the result of Eq. (4.2) is the molar chemical exergy ex_{RM} in $[J/mol]$. Thus, to obtain the specific chemical exergy $\tilde{e}x_{RM}$ in $[J/g]$, the result of Eq. (4.2) should be divided by the molar mass of the material M_{RM} in $[g/mol]$.

In general, for every recycling cycle r , em_{RMr} can be expressed as follows:

$$\left\{ \begin{array}{l} \text{For } r = 1, em_{RM1} = \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{PM} + \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{Mfg} + em_{Rcg1} \\ \text{For } r > 1, em_{RMr} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{RMr-1} + \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{Mfg} + em_{Rcgr} \end{array} \right. \quad (4.17)$$

With:

$$em_{Rcgr} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} [em_W + (1 - \varepsilon_{Wr}) \cdot em_L + (1 - \varepsilon_{Wr})(1 - \varepsilon_{Lr}) \cdot em_S + (1 - \varepsilon_{W\&L\&Sr} + \gamma_r) \cdot em_{Dr}], \forall r \geq 1 \quad (4.18)$$

The transformity τ_{RMr} is the ratio between the emergy input and exergy output of the cycle r :

$$\tau_{RMr} = \frac{em_{RMr}}{\tilde{e}x_{RMr}} \quad (4.19)$$

For example, based on the iteration in Eq. (4.17) , the specific emergy of the material em_{RM2} , obtained through the second cycle can be calculated as follows:

$$\begin{aligned}
em_{RM2} &= \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} \cdot em_{RM1} + \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} \cdot em_{Mfg} + em_{Rcg2} \\
&= \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} \cdot \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{PM} + \\
&\quad \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} \cdot \frac{1}{(1 + \gamma_1)(1 - \varepsilon_{Rcg1})} \cdot em_{Mfg} + \\
&\quad \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} \cdot em_{Mfg} + \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} \cdot em_{Rcg1} + em_{Rcg2}
\end{aligned} \tag{4.20}$$

With:

$$\begin{aligned}
em_{Rcg2} &= \frac{1}{(1 + \gamma_2)(1 - \varepsilon_{Rcg2})} [em_W + (1 - \varepsilon_{W2}) \cdot em_L + (1 - \varepsilon_{W2})(1 - \varepsilon_{L2}) \cdot em_S \\
&\quad + (1 - \varepsilon_{W\&L\&S2} + \gamma_2) \cdot em_{D2}]
\end{aligned} \tag{4.21}$$

Thus, by replacing the emergy of the material to be recycled by its value, the specific emergy at its N^{th} cycle can be defined as:

$$\begin{aligned}
em_{RMN} &= \prod_{r=1}^N \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{PM} + \\
&\quad \sum_{k=1}^N \prod_{r=k}^N \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{Mfg} + \\
&\quad \sum_{k=1}^{N-1} \prod_{r=k+1}^N \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot em_{Rcgk} + em_{RcgN}
\end{aligned} \tag{4.22}$$

With:

$$\begin{aligned}
em_{RcgN} &= \frac{1}{(1 + \gamma_N)(1 - \varepsilon_{RcgN})} [em_W + (1 - \varepsilon_{WN}) \cdot em_L + (1 - \varepsilon_{WN})(1 - \varepsilon_{LN}) \cdot em_S \\
&\quad + (1 - \varepsilon_{W\&L\&SN} + \gamma_N) \cdot em_{DN}]
\end{aligned} \tag{4.23}$$

The transformity of the material at the N^{th} cycle is then:

$$\tau_{RMN} = \frac{em_{RMN}}{\tilde{e}x_{RMN}} \tag{4.24}$$

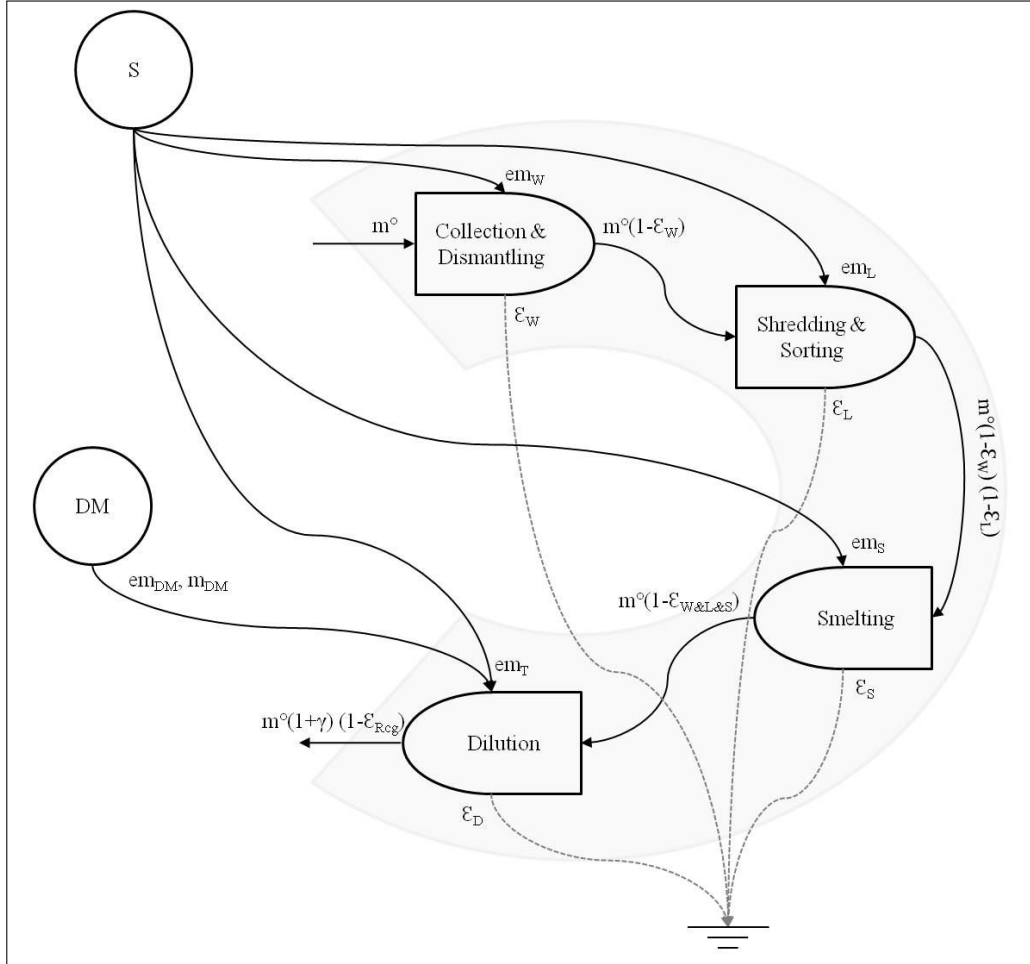


Figure 4.4: Energy flows in the metallurgical recycling

It is clear that for every cycle N , the transformity τ_{RMN} vary with $\epsilon_{W\&L\&SN}$, ϵ_{DN} and γ_N . These parameters reflect the performance of the recycling process since $\epsilon_{W\&L\&SN}$ and ϵ_{DN} represent the occurring material losses and γ_N the required dilution effort. Eqs. (4.22) to (4.24) show that the transformity increases with the loss of material ($\epsilon_{W\&L\&SN}$, ϵ_{DN}) and the destruction of exergy (ϵ_{DN}), which in turns means that the hierarchical position of the recovered material rises with the inefficiency of the process. In other words, more environmental work will be used up, causing more significant environmental impact.

It should be mentioned that in case of constant ϵ_w , ϵ_L , ϵ_D , γ and em_{DM} (i.e. constant loss ratios and the use of the same dilution material in every cycle), the following equation can be used:

$$\begin{aligned}
 em_{RMN} = & \left[\frac{1}{(1 + \gamma)(1 - \varepsilon_{Rcg})} \right]^N \cdot em_{PM} + \sum_{r=1}^N \left[\frac{1}{(1 + \gamma)(1 - \varepsilon_{Rcg})} \right]^r \cdot em_{Mfg} + \\
 & \sum_{k=1}^N \left[\frac{1}{(1 + \gamma)(1 - \varepsilon_{Rcg})} \right]^{N-r} \cdot em_{Rcg}
 \end{aligned}
 \tag{4.25}$$

In general, it can be concluded that the emergy approach is an adequate tool to assess the resource efficiency of the recycling processes. The developed model allows the comparison of different processes (for the same material) at several cycles, based on the occurring material and quality losses. It allows then to choose the most environmental friendly option (i.e. with the lower transformity). Nevertheless, and due to the fact that the transformity is always increasing with each recycling process, the emergy approach is not able to determine neither the benefits nor the limits of the recycling.

4.2.3 Emergy evaluation of metallurgical recycling processes, according to Ulgiati's approach

The transformity of a product is defined as the ratio between the emergy input of all previous processes that were directly or indirectly involved to generate the product and its exergy. In the case of recycled materials this means, that the transformity of the material increases with each recycling cycle. Consequently, the emergy approach could be unsuitable for such evaluations (see Subsection 4.2.2). In order to deal with this issue, Ulgiati suggests to reset the memory of all previous processes that generated the recovered material and to consider only the inputs required for the recycling and treatment of the latter. He argues that with a similarity to a detritus food chain, the recycling process degrades the recovered material and repress it to a lower energy level, see Citation 4.3. The authors of this study partially agree with this assumption. Additionally, we suggest that the chemical and physical treatments (that the recovered material has undergone during the manufacturing process) should be taken into account. Due to the fact that these alterations affect the outcome of the following recycling process. Therefore, adopting Ulgiati's approach could lead to the loss of information (in the evaluation process) that are embodied in the recycled material (for example, the presence of contaminants that result from the previous manufacturing process).

Citation 4.3 (*Third biennial emergy research conference*)

«[...] recycling has the same role in human productive systems as the detritus chain in natural systems. Both take a high

transformity input at the end of its life cycle, break it down to simpler components and feed them back to lower hierarchical levels. The recycled component then re-enter the same productive cycles through which it had already passed (may be many times), and therefore it would be "double counting" to assign to it the whole emergy it bore when it was still in the finished product form.[...] If wastes are treated and re-enter a production process as a substitute material or resource, only the emergy invested in the treatment and recycling process should be assigned to recycled resources. » ([Ulgiati 2004])

By erasing the memory of the path previously followed by the recovered material, the EOL product become the starting point for the evaluation process. Similarly to natural ores, EOL products could be considered as aggregates of matter which can be extracted and used for industrial applications. Thus, the emergy of the recovered material should include both, the effort that was invested to put the material into the chemical and physical conditions as it is found in the EOL product (by analogy with the ore creation) and the work required for the recycling process (by analogy with the extraction and refining of the mineral). According to this, $em_{RM_{r-1}}$ in Eq. (4.17) is reset to zero and the emergy of the recycled material $e\check{m}_{RM_r}$ can be expressed as follows:

$$e\check{m}_{RM_r} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} \cdot e_{Mfg} + em_{Rcgr} \quad (4.26)$$

With:

$$em_{Rcgr} = \frac{1}{(1 + \gamma_r)(1 - \varepsilon_{Rcgr})} [em_W + (1 - \varepsilon_{W_r}) \cdot em_L + (1 - \varepsilon_{W_r})(1 - \varepsilon_{L_r}) \cdot em_S + (1 - \varepsilon_{W\&L\&S_r} + \gamma_r) \cdot em_{Dr}] \quad (4.27)$$

The transformity of the material τ_{RM_r} can be calculated by dividing all the emergy inflows to the cycle r by the exergy yielded by the cycle, see Eq. (4.19).

Proposition 4.1 (Average transformity of recycled materials $\bar{\tau}_{RM}$)

The ratio between the emergy inflows of all previous processes and their exergy outputs. The average transformity of the recycled material at its N^{th} cycle is then:

$$\bar{\tau}_{RMN} = \frac{em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcgr})} \cdot em_{Mfg} + \sum_{r=1}^N em_{Rcgr}}{\tilde{e}x_{PM} + \sum_{r=1}^N \tilde{e}x_{RMr}} \quad (4.28)$$

where, em_{PM} is the emergy used for the ore creation, mineral extraction and refining of the primary material.

The recycled material, however, is the result of all previous (manufacturing and recycling) processes the material has been passed through. Thus, accounting only for the current recycling cycle to evaluate the material may not be in accordance with the emergy approach. The authors propose to use an average transformity (similar to the work of Bastianoni and Marchettini [Bastianoni 2000]) which can be calculated by dividing the emergy inflows of all previous processes by their exergy outputs, see Proposition 4.1. This allows to assess the environmental performance of consecutive recycling from both a donor and user-side perspective and to avoid the "double counting".

To further assess the benefits and limits of consecutive recycling processes, sustainability ratios are proposed:

Proposition 4.2 (Resource efficiency ratio α)

The ratio of the emergy used in the recycling process em_{Rcgr} to the emergy of the primary material em_{PM} . It is a measure of the resource efficiency of the recycling process. An α lower than 1 indicates that the recycling process saves natural resources.

$$\alpha_r = \frac{em_{Rcgr}}{em_{PM}} \quad (4.29)$$

Proposition 4.3 (Quality ratio β)

The ratio between the exergy (quality) of the recycled material obtained through cycle r and the exergy (quality) of the primary material. It measures the quality degradation of the recovered material during the recycling process. The performance ratio never exceeds 1, a β close to 1 indicates low quality losses.

$$\beta_r = \frac{\tilde{e}x_{RMr}}{\tilde{e}x_{PM}} \quad (4.30)$$

Proposition 4.4 (Eco-design ratio χ)

The ratio of the emergy used in the manufacturing process em_{Mfg} and the emergy of the primary material em_{PM} . The ability of the product to

be recycled at the end of its life cycle depends essentially on its design, on its production process and on the selected materials. The eco-design ratio measures the recyclability of the material, based on its properties and on the complexity of the manufacturing process.

$$\chi = \frac{em_{Mfg}}{em_{PM}} \quad (4.31)$$

By introducing the sustainability ratios α and β in Eq. (4.28), the average transformity of the recycled material at its N^{th} cycle can be expressed as follows:

$$\left\{ \begin{array}{l} \bar{\tau}_{RMN} = \frac{\sum_{r=0}^N \alpha_r \cdot em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Reg r})} \cdot em_{Mfg}}{\sum_{r=0}^N \beta_r \cdot ex_{PM}} \\ \text{with} \\ \alpha_0 = \beta_0 = 1 \end{array} \right. \quad (4.32)$$

In order to determine whether and to what extent consecutive recycling is sustainable in environmental terms, the average transformity $\bar{\tau}_{RMN}$ should be compared to the transformity of the primary material τ_{PM} , see Eq. (4.33). Recycling could be considered as an environmentally friendly option, only when the transformity of the recycled material is lower than the transformity of the primary material. Consequently, the lower τ_{RMr} is (compared to τ_{PM}) the higher is the environmental benefit.

$$\tau_{PM} = \frac{em_{PM}}{\tilde{ex}_{PM}} \quad (4.33)$$

The limit value of $\bar{\tau}_{RMN}$ is the transformity of the primary material τ_{PM} , thus:

$$\bar{\tau}_{RMN} \leq \tau_{PM} \quad (4.34)$$

According to Eq. (4.33), this implies that:

$$\frac{\sum_{r=0}^N \alpha_r \cdot em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcg_r})} \cdot em_{Mfg}}{\sum_{r=0}^N \beta_r \cdot \tilde{e}x_{PM}} \leq \frac{em_{PM}}{\tilde{e}x_{PM}}$$

Hence, (4.35)

$$\frac{\sum_{r=0}^N \alpha_r \cdot em_{PM} + \sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcg_r})} \cdot em_{Mfg}}{\sum_{r=0}^N \beta_r \cdot em_{PM}} \leq 1$$

The following inequalities can be deduced:

$$\frac{\sum_{r=0}^N \alpha_r}{\sum_{r=0}^N \beta_r} \leq 1 \quad (4.36a)$$

$$\chi \leq \frac{\sum_{r=0}^N \beta_r}{\sum_{r=1}^N \frac{1}{(1+\gamma_r)(1-\varepsilon_{Rcg_r})}} \quad (4.36b)$$

The Eqs. (4.36a) and (4.36b) indicate the recycling limits of the material, taking into account all the previous recycling cycles the material has passed through.

In the case of constant β , γ and ε_{Rcg} , the Eq. (4.36b) can be expressed as follows:

$$\chi \leq \frac{1 + N \cdot \beta}{(1+\gamma) \cdot (1-\varepsilon_{Rcg})} \quad (4.37)$$

This implies that:

$$\chi \leq \frac{(1+\gamma) \cdot (1-\varepsilon_{Rcg})}{N} + \beta \cdot (1+\gamma) \cdot (1-\varepsilon_{Rcg}) \quad (4.38)$$

Thus, a limit value of χ can be determined when N tends to infinity (i.e. infinite number of cycles):

$$\chi_{Limit} = \beta \cdot (1+\gamma) \cdot (1-\varepsilon_{Rcg}) \quad (4.39)$$

Otherwise, when χ is known the corresponding limit number of recycling can be determined by using Eq. (4.36b):

$$N \leq \frac{(1 + \gamma) \cdot (1 - \varepsilon_{Rcg})}{(\chi - \beta \cdot (1 + \gamma) \cdot (1 - \varepsilon_{Rcg}))} \quad (4.40)$$

Hence,

$$N_{Limit} = \frac{(1 + \gamma) \cdot (1 - \varepsilon_{Rcg})}{\chi - \chi_{Limit}} \quad (4.41)$$

The results show that the number of times the material can be recycled efficiently depends essentially on the eco-design ratio. This underpins that the recyclability of a product should be considered from the very beginning of the manufacturing process during the conception and design phase.

4.3 Case study

To demonstrate how the sustainability ratios can be used in practice, a concrete example is illustrated in what follows. In their paper entitled "*Exergy losses during recycling and the resource efficiency of product systems*", Castro et al. [Castro 2007] calculated the exergy degradation of a recovered aluminum alloy type 2036 (Al 96.6%, Cu 2.6%, Si 0.5%) containing steel residues. To upgrade the quality of the recovered stream, pure aluminum alloy type 2036 has been added to finally produce an aluminum alloy type 308 (Al 96.1%, Cu 2.6%, Fe 0.8%, Si 0.5%). The parameters of the study are displayed in Table 4.3.

Parameters of the study									
N	ex_{PM} [MJ/kg]	ex_{RM1} [MJ/kg]	m° [kg]	m_{D1} [kg]	γ	$\varepsilon_{W\&L\&S}$	ε_{D1}	ε_{Rcg1}	
1	32.105	31.893	121	17	0.14	0.1	0	0.087	

Table 4.3: Parameters of the study [Castro 2007]

Based on Table 4.3, and using the Eqs. (4.36a) and (4.36b) the value of β_1 and the limits of α_1 and χ can be determined:

$$\begin{cases} \beta_1 = 0.99; \\ \alpha_1 \leq 0.99 (\alpha_0 = \beta_0 = 1); \\ \chi \leq 2.07 \end{cases} \quad (4.42)$$

The results show that the quality ratio β_1 is near to 1. This reveals that the exergy losses are very small during the recycling process. The first inequality of

Eq. (4.42) indicates that resource efficiency ratio α_1 can take values very close to 1, due to the fact that the quality degradation of the recycled material is very low. Thus, even a recycling processes with a relatively high energy input (i.e. em_{Rcg1} close to em_{PM}) remains acceptable. According to the second inequality of Eq. (4.42), the eco-design ratio χ should be lower than 2. This implies that the energy of manufacturing em_{Mfg} should not exceed two times the energy of the primary material em_{PM} to ensure an efficient recycling of the material.

In the case of constant β , γ and ε_{Rcg} (according to Eq. (4.39)), χ_{Limit} is equal to 1.03. Thus, to ensure infinite recycling χ should be close 1. For example, for χ equal to 1.10, N_{Limit} is about 15 (according to Eq. (4.41)).

4.4 Conclusion of the chapter

The goal of this study was to assess, on the basis of an energy evaluation in combination with an *ELCA*, the environmental impacts of material and quality losses during consecutive metallurgical recycling processes. The following conclusions were developed:

1. The integration of the *ELCA* approach enables the energy evaluation to take into account the quality losses of the recycled material.
2. The proposed evaluation model based on Odum's approach is suitable for assessing the environmental burden of recycling processes. However, neither the limits nor the benefits of recycling can be determined through this method. Due to the fact that the transformity of the recycled material is always increasing with each recycling cycle.
3. The proposed average transformity allows to determine the environmental performance of the recycled materials, taking into account all previous recycling cycles the material has passed through.
4. A concrete example shows how the resource efficiency ratio α , the quality ratio β and the eco-design ratio χ can be used to assess the benefits and limits of recycling processes.

Carbon footprint and emergy
combination for eco-environmental
assessment of cleaner heat
production

Carbon footprint and emergy combination for eco-environmental assessment of cleaner heat production

Abstract:

The aim of this chapter is to study via environmental indicators to which extent, replacing fossil fuel with biomass for heating is an environmentally friendly solution. The environmental impact of using biomass depends mostly on the transportation process. Authors define the notion of maximum supply distance, beyond which biomass transportation becomes too environmentally intensive compared to a fossil fuel fired heating system.

In this work a carbon footprint analysis and an emergy evaluation, has been chosen to study the substitution of wood for natural gas. The comparative study seeks to examine, via the two approaches, two heating systems: one is fired with wood, transported by trucks and the other one is fired with natural gas transported by pipelines. The results are expressed in terms of maximum supply distance of wood. In the emergy evaluation it represents the maximum supply distance permitting wood to be more emergy saving than natural gas. In the carbon footprint analysis, it represents the maximum supply distance permitting wood to be a carbon saving alternative to natural gas. Furthermore, the unification of carbon footprint and emergy evaluation permits to define, for both approaches, the minimum theoretical wood burner efficiency that allows, CO_2 or emergy to be saved, when there is no wood transport. In order to identify the impacts of the main parameters of the study a sensitivity analysis has been carried out.

The case study investigated in this chapter shows that there is a large gap between the results. The maximum supply distances calculated via carbon footprint and emergy evaluation are respectively about 5000 km and 1000 km and the minimum theoretical wood burner efficiencies are respectively about 5% and 54%.

Keywords: Natural gas, Biomass, Emergy, Carbon footprint, Environment Criterion

Nomenclature

Acronyms

LHV Low Heating Value [J/kg]

Greek Symbols

α Ash content of wood [%]
 ε Oxidation factor of diesel
 η Efficiency
 γ Ratio of consumption [-]
 σ Relative error
 τ Transformity

Roman Symbols

C Load capacity [kg]
CO₂ Carbon dioxide emissions [kgCO₂]
D Distance [m]
d Distance crossed to remove ash
EF Emission factor [kgCO₂/J]
Ex Exergy [J]
FC Fuel consumption [l/km]
NC Number of ash collection
ND Number of wood deliveries
Q Energy consumption [J]
q Fuel consumption [kg]

Superscripts

a Ash collection
a₀ Ash supply without charge
a_{tr} Ash transportation
cf Carbon footprint approach
E Emergy approach
e_{tr} Home to work travel of the employees
ng_b Natural gas boiler
w_b Wood gas boiler
w Wood

w_0 Wood supply without charge
 w_b Wood boiler
 w_{tr} Wood transportation

Subscripts

a_{tr} Ash transportation
 b Boiler
 $comb_d$ Combustion emissions of diesel
 $comb_{ng}$ Combustion emissions of natural gas
 d Diesel
 e Employees
 e_{tr} Home to work travel of the employees
 f Fuel
 hl Human labor
 $l\&s$ Labor and services
 ng Natural gas
 ng_b Natural gas boiler
 w_b Wood gas boiler
 th Thermal
 up_d Upstream emissions of diesel
 up_{ng} Upstream emissions of natural gas
 v Passenger car
 w Wood
 up_w Upstream emissions of wood
 w_{tr} Wood transportation

5.1 Introduction

Global warming and declining fossil fuel reserves pushed many researchers to find out alternative sources of energy. Notions of *biofuel*, *bioenergy* and *biomass* are commonly used, but in reality they can be defined in different ways. In terms of microbiology, *biomass*, synonym of *bioorganisms*, is a source for methane production [Nallathambi Gunaseelan 1997], or hydrogen production [Ji 2010]. In this context, *biofuel* or *bioenergy* refers to *bioorganisms* digestion products. From energy point of view, biomass refers to contemporary plant matter formed by photosynthetic capture of solar energy and stored as chemical energy [Frank 1988]. As well as, Schmidt et al. [Schmidt 2011] consider biomass as forest biomass and agricultural biomass. Thus, *biofuel* or *bioenergy* can be considered as a renewable source of energy, only if the biomass harvest is replanted in the same period as it is combusted [Demirbas 2005, Cowi 2007]. This is to ensure on the one hand the maintain of biomass, and on the other hand that the new plants absorb, whilst growing, all CO₂ emitted by combustion to keep the carbon cycle in balance. Actually, only this kind of biomass ensures significant amounts of *bioenergy*, see [Al-Mansour 2010]. The review of Saidur et al. [Saidur 2011] details the different applications of biomass and identifies the efficiency of each technical conversion. The most expanded conversion of biomass is combustion, which is usually used for fossil fuel substitution such as natural gas, coal or oil.

It should be underlined, that fossil fuels cannot be accepted as *bioenergy* sources since it took millions of years to transform the original *biomatter*, near the terrestrial magma (under great pressure and constant heat). On one hand, it is not possible to produce fossil fuel as fast as it is consumed. On the other hand, the carbon released by fossil fuel has been stored millions of years ago and therefore present fossil fuel combustion is increasing the CO₂ content in the atmosphere.

That is why fossil fuel substitution became a great topic for research over the last years. The studies can be classified under five group headings:

- Technical aspect which involves the improvement of the conversion systems. Stehlik [Stehlik 2009] details a review on technologies which deal with bioenergy conversion. The cleaning of the exhaust gases is also under study [Skodras 2007].
- Economic aspect which evaluates the cost-effectiveness of using biomass. As such, De and Assadi [De 2009] and McIlveen-Wright et al. [McIlveen-Wright 2011] have studied the financial retrofit of a co-combustion plant (coal biomass).
- Policy actions that are required to intensify the development of biomass in energy applications. Schmidt et al. [Schmidt 2011] focused their work on forest biomass in association with CO₂ certifications. Mirata et al. [Mirata 2005] worked on the concept of distributed economy, notably in biomass sectors.

- Criteria of sustainable biomass production. A beneficial biomass production includes low fossil fuel use, sustainable management of agriculture soils and that the biomass crops are not in competition with food crops. Hence, Mizsey and Racz [Mizsey 2010] have challenged bio-ethanol production versus biomass (corn) combustion per hectare, on the basis of the fossil fuel required during the global process (from cradle to the grave).
- Analysis methodology such as LCA [Salazar 2009, Caserini 2010], carbon footprint [Holden 2005], greenhouse gases [Poudel 2012] and emergy (represents the embodied energy and can be considered as an energy footprint of a product). The fundamentals are explained by [Odum 1996]. Numerous studies have been carried out to compare these analytical methods [Sebastiàn 2011]. Carraretto et al. [Carraretto 2004] studied via emergy analysis and life cycle assessment, the environmental impact and the pros and cons of biodiesel as alternative fuel in boilers and diesel engines. Ju and Chen [Ju 2011] calculated the CO_2 emissions of a typical biodiesel production chain and assessed the ecological performance of the production chain by means of embodied energy analysis and emergy analysis. Ulgiati and Brown [Ulgiati 2002] evaluated the requirement for environmental services to dilute and abate process emissions of electricity production. Finally, Nilsson [Nilsson 1997] investigated the feasibility of using straw as a fuel in district heating plants by using energy, exergy and emergy approaches.

The substitution of biofuel for fossil fuels seems to be a great contribution to cleaner production. Particularly, because biofuels are considered as carbon-neutral, since burning biofuels only emit back to the environment the CO_2 that the plants absorbed whilst growing. The production and transportation process of biofuels, however, may not be carbon-neutral and that is why, it is very important to assess the limitation of biofuel to be a carbon-saving source of energy. Thus, a sustainable economic and environmental development of biomass is intrinsically linked to local collection area. Eriksson [Eriksson 2008] proposed a paper, highlighting the impact of biomass transport on the total cost and the associated CO_2 impact. A similar study has also been applied to biofuels [Von Blottnitz 2007]. In the same research area, the supply chain approach can contribute to the development of biomass applications [Lam 2010, Gold 2011]. The substitution potential of biofuels can be evaluated using footprint analysis, as they are effective methods to measure sustainability [Stöglehner 2003]. Definitions and units of environmental social and economic footprints as well as diverse tools for footprint evaluation are presented by Čuček et al. [Čuček 2012].

This work seeks to identify the environmental performance of using wood as a substitute for natural gas for producing thermal power of a small heating network. Contrary to natural gas the combustion of wood is considered as carbon neutral. So, the environmental performance of a wood fired heating system depends mostly on the mode and distance of wood transportation. An emergy evaluation and a carbon

footprint analysis [Meunier 2002] has been chosen to assess the maximum supply distance of wood. An original emergy versus carbon footprint diagram is defined to visualize the eco-environmental performance varying with the transport distance of wood. In the second part, a unification of the emergy evaluation and carbon footprint has been proposed. In the third and last part, a sensitivity analysis has been performed to determine the influence of different parameters on the maximum supply distances, calculated via the two approaches.

5.2 Methodology

A simplified heat production process includes heat production, fuel transportation, labor and services. To investigate properly the environmental impact and eco-efficiency of heat production, it is essential to specify the heat consumption, the performance of the heating system, the properties of the fuel, the modes of transport used for fuel supply (for example, coal can be transported by rail, wood by trucks and natural gas by pipelines, it is also possible to combine different modes of transport) and the labor and services required during the process.

The efficiency of the heating system has a significant impact on fuel use, since high efficiency reduces fuel consumption required to meet heating demand. A special care should be taken in choosing the type and quality of fuel, since the fuel consumption and the associated environmental impacts depend on the properties of the fuel. More especially renewable and fossil fuels must be clearly distinguished. It is also crucial to identify the means of transport, the sources of energy and the distance crossed to deliver the fuel. Finally, the environmental impairments of all labor and services needed during the process have to be taken into account.

A carbon footprint analysis and an emergy evaluation have been used to realize the eco-environmental quality assessment of two heating systems. These two environmental indicators have been chosen to cover all relevant aspects of the heat production process that may have an environmental impact. Carbon footprint analysis permits to measure the effect on the climate, in terms of the amount of CO_2 emitted during heat production, while the emergy evaluation accounts for all forms of energy and resources used in the process. Furthermore, the two approaches may be considered as complementing each other and a unification of the two indicators is envisaged. The results of the comparative study depend mainly on the following parameters (see Fig. 5.1):

- The heat consumption Q_{th}
- The efficiency of the heating system η_b
- The low heating value of the fuel LHV_f
- The fuel consumption Q_f

- The supply distance of fuel D
- The energy needed for fuel transportation Q_e
- And the energy consumed for labor and services $Q_{l\&s}$

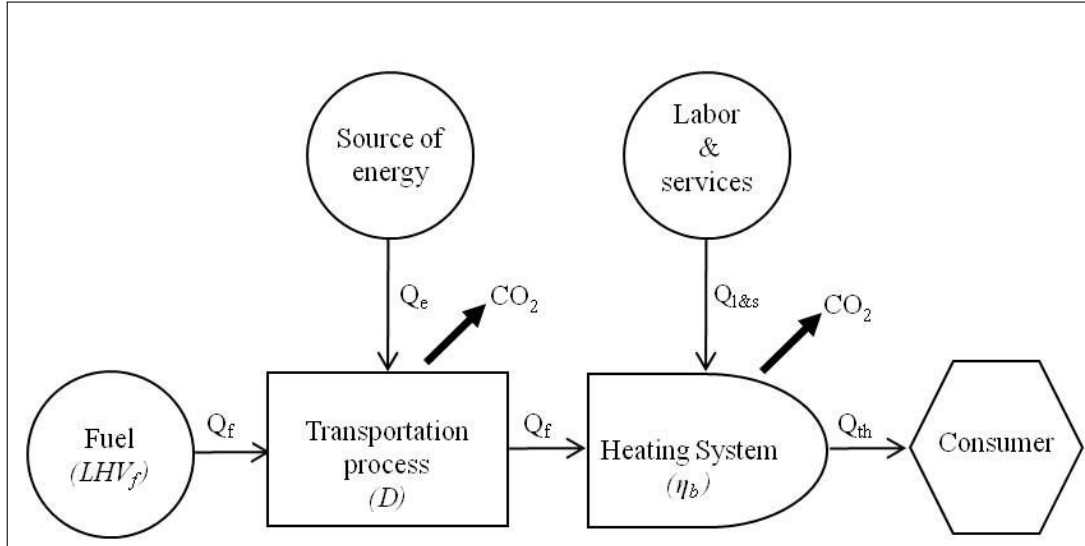


Figure 5.1: Simplified process diagram of heat production

For obtaining meaningful and significant results, it is very important to define the framework of the comparative study such as the time horizon and the boundaries of the heat production process.

5.3 Case study

This chapter proposes a comparative study between a wood fired heating system and a natural gas fired heating system. The aim is to identify the environmental performance and eco-efficiency of using biomass as a substitute for fossil fuels for heat production. As a concrete example, the ecological sustainability of a project launched in 2010 has been analyzed, which consists of building a central wood-fired heating plant in the district of Chantrerie (Nantes-France). The aim is to replace local natural gas heating units, in total, 25 natural gas boilers providing the space heating of 5 establishments (4 institutions of higher education and a laboratory for veterinary tests) covering an area of $120\,000\text{m}^2$, which corresponds to an annual thermal consumption of about $Q_{th} = 42\,800\text{GJth}$ (average annual heat consumption of the campus over the past five years).

To provide a consistent basis for comparing the two heating systems, the same steps of heat production have been considered to assess the eco-environmental performance of each of them. In the calculations, the construction of the two plants and

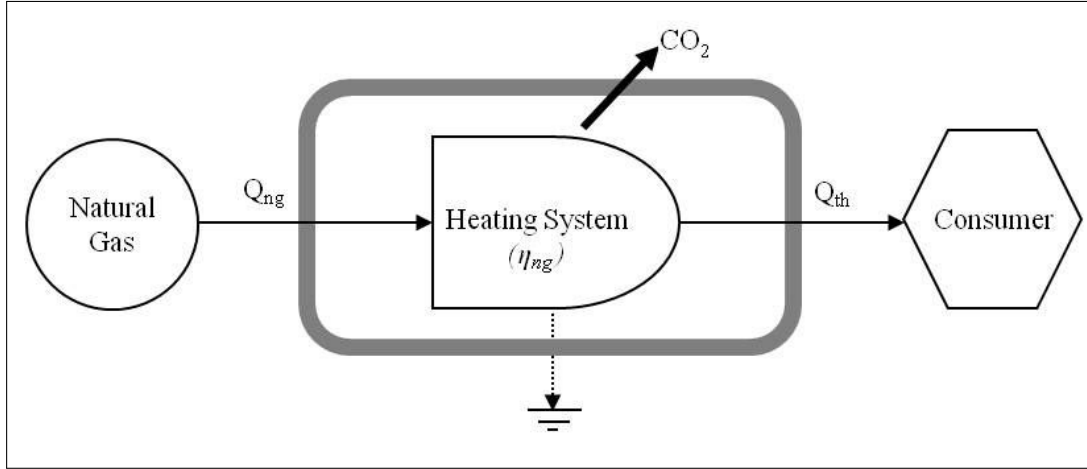


Figure 5.2: System diagram of heat production via a natural gas heating system

maintenance work on the two heating systems are not taken into account. However the fuel production and transportation, labor and services required to operate each of the two heating systems have been accounted for. In the case of the natural gas fired heating system, the boiler is directly supplied by pipelines and there is no significant labor or services required to make the automatic system work. In the case of the wood fired heating system, the wood is transported by trucks. Human labor is needed for wood supply, ash collection and functioning of the boiler. The system diagram and the CO_2 emissions of heat production via both a natural gas heating unit and a wood-fired heating plant are detailed respectively in Figs. 5.2 and 5.3.

It has to be mentioned that upstream emission factors have been used to estimate the CO_2 emissions of production and transportation for both diesel and natural gas. Wood combustion cannot be considered as carbon neutral unless the overall stock of forest is maintained. Thus an upstream emission factor of wood has been used to calculate the CO_2 emissions of producing controlled forest biomass. The same approach has been applied in choosing the transformities for the emergy evaluation.

5.3.1 Model

In the general case, the annual fuel consumption q_f [kg] of a boiler is given by:

$$q_f = \frac{Q_{th}}{LHV_f \cdot \eta_b} \quad (5.1)$$

Where, Q_{th} [MJ] is the average annual heat consumption, LHV_b [MJ/kg] is the low heating value of the fuel and η_b is the efficiency of the boiler.

In the case of a wood boiler, the low heating value of wood at constant pressure

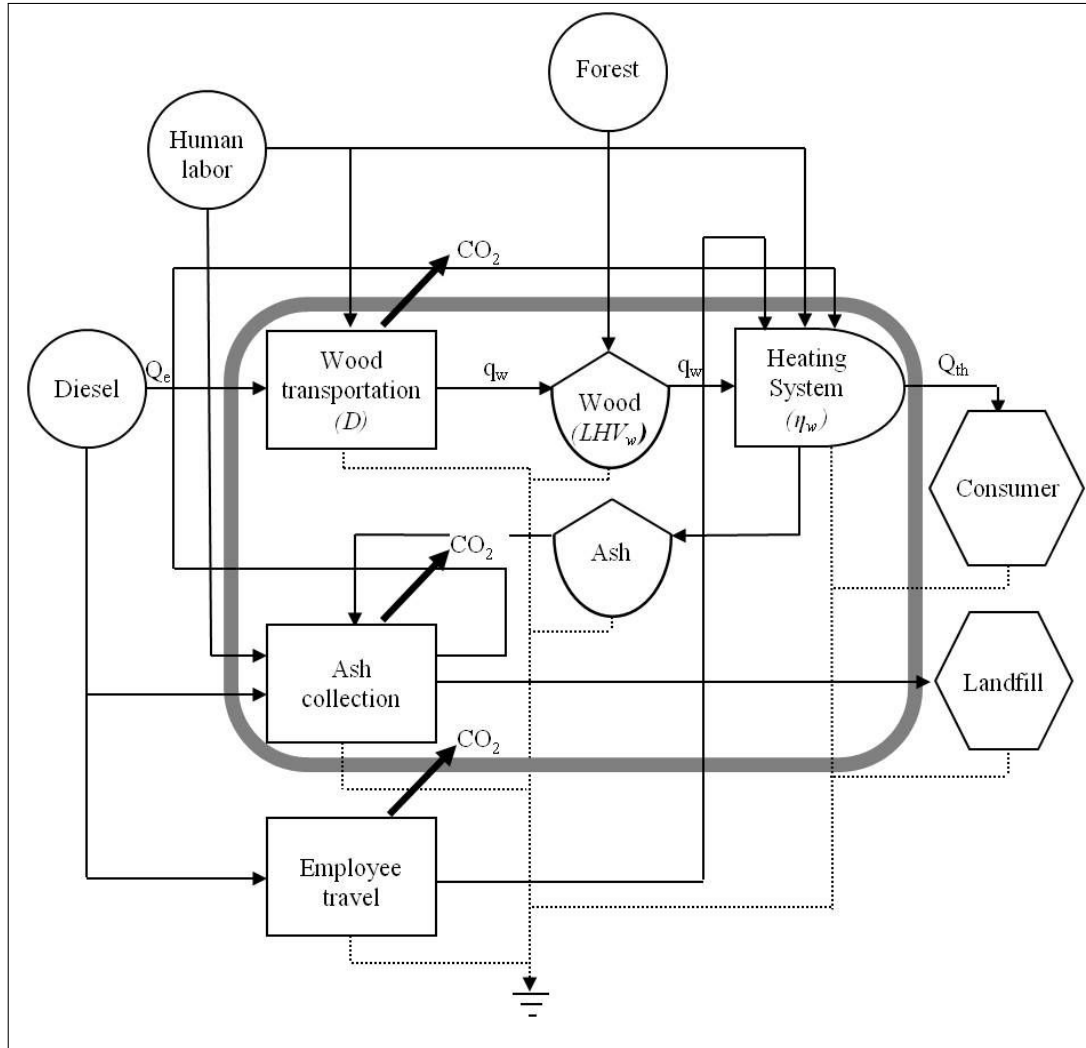


Figure 5.3: System diagram of heat production via a wood fired heating system

LHV_w is given by the Equation [Telmo 2011]:

$$LHV_w = \frac{LHV_w(0\%) \cdot (100 - M)}{100} - 0.02443 \cdot M \quad (5.2)$$

Where, $LHV_w(0\%)$ is the low heating value of dry wood (moisture-free) and M is the moisture content of wood.

Thus, the annual wood consumption of the boiler q_w [kg] is:

$$q_w = \frac{100 \cdot Q_{th}}{(LHV_w(0\%) \cdot (100 - M) - 0.02443 \cdot M) \cdot \eta_w} \quad (5.3)$$

Where, η_w is the efficiency of the wood boiler.

In the case of natural gas boiler, the annual natural gas consumption Q_{ng} [MJ] is given by:

$$Q_{ng} = \frac{Q_{th}}{\eta_{ng}} \quad (5.4)$$

Where, η_{ng} is the efficiency of the natural gas boiler.

Parameters of the study				
Definition	Item	Unit	Amount	Ref.
Load capacity of truck (ash collection)	$C_{max}^{a\ tr}$	kg	7E+3	[Shunping 2010]
Load capacity of truck (wood delivery)	$C_{max}^{w\ tr}$	kg	2E+3-50E+3	[Shunping 2010]
Annual distance traveled by the employees ^a	D_e	km	13.2E+3	[-]
Crossed distance to remove ash	d	km	50	[-]
Fuel consumption of passenger car	FC^v	l/km	0.092	[Shunping 2010]
Fuel consumption of truck (wood delivery)	FC^w	l/km	0.168-0.318	[Shunping 2010]
Fuel consumption of truck (ash collection)	FC^a	l/km	0.242	[Shunping 2010]
Average annual heat consumption	Q_{th}	MJ	42.8E+6	Appendix A
Exergy of the produced heat	Ex_{th}	MJ	8.25E+6	Appendix A
Low heating value of diesel	LHV_d	MJ/l	36.5	[Yao 2010]
Low heating value of dry wood	$LHV_w(0\%)$	MJ/kg	19	[EPA 2005]
Low heating value of wood	LHV_w	MJ/kg	9.3-13.6	Appendix A
Moisture content of wood	M	w%	0.25-0.45	Appendix A
Ratio of molecular weight of CO_2 to the molecular weight of carbon	$\frac{M_{CO_2}}{M_C}$	[-]	$\frac{44}{12}$	[EPA 2011]
Annual consumption of natural gas	Q_{ng}	J	5.2E+13	Appendix A
Ash content of wood	α	[-]	0.02	Appendix A
Ratio of fuel consumption of empty truck to loaded truck (ash collection)	γ^a	[-]	0.75	[-]
Ratio of fuel consumption of empty truck to loaded truck (wood delivery)	γ^w	[-]	0.75	[-]
Oxidation factor of diesel	ε	[-]	0.99	[EPA 2005]
Efficiency of the wood boiler	η_w	[-]	0.5-0.75	Appendix A
Efficiency of the natural gas boiler	η_{ng}	[-]	0.82	Appendix A
Number of hours worked by the employees ^b	h_w	h	5280	[-]

^a 5.5 Full Time Employees, 6 months heating period, average daily work commute of 20km:

$$D_e = 5.5 * 6 * 20 * 20 = 13.2E+3 \text{ km}$$

^b 5.5 Full Time Employees, 6 months heating period, the number of hours worked by the employees:

$$h_w = 5.5 * 6 * 20 * 8 = 5270 \text{ h}$$

Table 5.1: Parameters of the study

5.3.1.1 Carbon footprint analysis:

The carbon footprint analysis permits to quantify all the CO_2 emissions of the natural gas and wood fueled heating systems.

- The annual CO_2 emission of the natural gas fueled heating system CO_2^{ng-b} [kg CO_2] is given by:

$$CO_2^{ng-b} = Q_{ng} \cdot (EF_{up_ng} + EF_{comb_ng}) \quad (5.5)$$

Where, EF_{up_ng} is the upstream emission factor and EF_{comb_ng} is the combustion emission factor of natural gas and Q_{ng} [MJ] is the annual consumption of natural gas.

- The annual CO_2 emission of the wood fueled heating system CO_2^{w-b} [kg CO_2] is given by:

$$CO_2^{w-b} = CO_2^{w-tr} + CO_2^{a-tr} + CO_2^{e-tr} + CO_2^{w-up} \quad (5.6)$$

Where, CO_2^{w-tr} [kg CO_2] is the CO_2 emissions of wood transportation, CO_2^{a-tr} [kg CO_2] is the CO_2 emissions of ash collection, CO_2^{e-tr} [kg CO_2] is the CO_2 emissions of the home-to-work travel of the employees and CO_2^{w-up} [kg CO_2] is the upstream emissions of wood.

$$CO_2^{w-tr} = ND \cdot D \cdot (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC^w \cdot (1 + \gamma^w) \quad (5.7)$$

$$CO_2^{a-tr} = NC \cdot d \cdot (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC^a \cdot (1 + \gamma^a) \quad (5.8)$$

$$CO_2^{e-tr} = D_e \cdot (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC^v \quad (5.9)$$

$$CO_2^{w-up} = q_w \cdot LHV_w \cdot EF_{w-up} \quad (5.10)$$

Where, ND is the number of wood deliveries during the heating period ($ND = \frac{q_w}{C_{max}^{w-tr}}$, C_{max}^{w-tr} is the load capacity of the truck used for wood delivery), D [km] is the transport distance of wood, EF_{up_d} is the upstream emission factor of diesel, EF_{comb_d} is the combustion emission factor of diesel, ε is the oxidation factor, $\frac{M_{CO_2}}{M_C}$ is the ratio of the molecular weight of CO_2 to the molecular weight of carbon, the ratio of average fuel consumption of the truck used for wood supply without charge to average fuel consumption of the truck with charge is FC^{w0} , NC is the number of ash collection ($NC = \frac{\alpha \cdot q_w}{C_{max}^{a-tr}}$, α is the ash content and C_{max}^{a-tr} is the load capacity of the truck used for ash collection), d is the distance crossed by the trucks to remove ash, FC^a is the fuel consumption of the truck used for ash collection, $\gamma^a = \frac{FC^{a0}}{FC^a}$ is the ratio of average fuel consumption of the truck used for ash collection with

charge FC^{a_0} to average fuel consumption of the truck charge FC^a , D_e is the annual distance traveled by the employees to get to work and back again, FC^v is the fuel consumption of a passenger car and EF_{w_up} is the upstream emission factor of wood. The upstream and combustion emission factors of natural gas, diesel and wood are given in Table 5.2.

The carbon saving performance of the wood fueled heating system depends on the supply distance of wood and the load capacity of the truck. Hence, for a fixed load capacity, $C_{m\bar{a}x}^{w_tr}$ the maximum transport distance D_{max}^{cf} allowing wood to be a carbon saving alternative to natural gas is given by:

$$CO_2^{ng-b} = CO_2^{w-b} \cdot (D_{max}^{cf}) \quad (5.11)$$

Thus, according to Eqs. (5.5) and (5.6)

$$D_{max}^{cf} = \frac{CO_2^{ng-b} - CO_2^{a-tr} - CO_2^{e-tr} - CO_2^{w-up}}{ND \cdot (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{MC} \cdot FC^w \cdot (1 + \gamma^w)} \quad (5.12)$$

Emission factors			
Item	Unit	Amount	Ref.
EF_{up_ng}	kgCO ₂ /MJ	0.01	[ADEME 2010]
EF_{comb_ng}	kgCO ₂ /MJ	0.05	[ADEME 2010]
EF_{up_d}	kgC/l	0.08	[ADEME 2010]
EF_{comb_d}	kgC/l	0.73	[ADEME 2010]
EF_{w_up}	kgCO ₂ /MJ	0.0036	[ADEME 2010]

Table 5.2: Emission factors

5.3.1.2 Energy evaluation:

The energy evaluation permits to assess the energy flow of the natural gas and wood fueled heating systems.

- The annual energy flow of the natural gas fueled heating system Em_{ng_b} [seJ] is given by:

$$E_{ng_b} = Q_{ng} \cdot (\tau_{ng} + \tau_{ng_tr}) \quad (5.13)$$

Where, τ_{ng} is the solar transformity of natural gas, τ_{ng_tr} is the solar transformity of natural gas transport.

Solar transformities			
Item	Unit	Solar transformity [seJ/unit] ^a Baseline 15.2E+24seJ/yr	Ref.
Wood biomass	J	5.62E+4	[Odum 1996]
Natural gas	J	7.73E+4	[Odum 1996]
Transport of natural gas	J	1.74E+4	[Romitelli 1999]
Diesel	J	1.07E+05	[Odum 2000c]
Human labor ^{b,c}	h	8.58E+13	[Odum 1996]

^a Baseline calculated by Brown and Ulgiati [Brown 2010]

^b Different methods exist to calculate transformities of labor and services, notably by using the energy/money ratio [Sweeney 2007].

In this work, authors used transformities of labor and services which refer to Brazil and the United States because they consider that their economic and technological levels are not so different from France.

^c Human labor: $((1 \cdot 131E+16 \text{ seJ/ind/yr} + 4.5 \cdot 28E+16 \text{ seJ/ind/yr})/5.5)/(24 \cdot 365) = 5,33E+13 \text{ seJ/h}$, 5.5 Full Time Employees: 1 Post college+ 4,5 College grad.

Table 5.3: Solar transformities

- The annual energy flow of the wood fueled heating system Em_{w_b} [seJ] is given by:

$$Em_{w_b} = Em_w + Em_{w_tr} + Em_{a_tr} + Em_{e_tr} + Em_{hl} \quad (5.14)$$

Where, Em_w [seJ] is the emergy flow of wood, Em_{w_tr} [seJ] is the emergy flow of wood transportation, Em_{a_tr} [seJ] is the emergy flow of ash collection, Em_{e_tr} [seJ] is the emergy flow of the home-to-work travel of the employees and Em_{hl} is the emergy flow of human labor [seJ].

$$Em_w = q_w \cdot LHV_w \cdot \tau_w \quad (5.15)$$

$$Em_{w_tr} = ND \cdot D \cdot LHV_d \cdot \tau_d \cdot FC^w \cdot (1 + \gamma^w) \quad (5.16)$$

$$Em_{a_tr} = NC \cdot d \cdot LHV_d \cdot \tau_d \cdot FC^a \cdot (1 + \gamma^a) \quad (5.17)$$

$$Em_{e_tr} = D_e \cdot LHV_d \cdot \tau_d \cdot FC^v \quad (5.18)$$

$$Em_{hl} = h_w \cdot \tau_{hl} \quad (5.19)$$

Where, τ_w is the solar transformity of wood, LHV_d is the low heating value of diesel, τ_d is the solar transformity of diesel, τ_{hl} is the solar transformity of human

labor and h_w is the number of hours worked by the employees. The solar transformities of natural gas, natural gas transportation, wood, diesel and human labor are listed in Table 5.3.

From the emergy point of view, using wood as fuel is less environmentally intensive than natural gas when the emergy flow of the natural gas fueled heating system Em_{ng_b} is greater than the emergy flow of the wood fueled heating system Em_{w_b} . As Em_{w_b} depends on the distance crossed by the trucks which supply the boiler with wood, for a fixed load capacity $C_{max}^{w_tr}$, the maximum possible supply distance D_{max}^E permitting wood fuel to be emergy saving compared to natural gas is given by:

$$Em_{ng_b} = Em_{w_b}(D_{max}^E) \quad (5.20)$$

Thus, according to Equation Eqs. (5.13) and (5.14):

$$D_{max}^E = \frac{Em_{ng_b} - Em_w - Em_{a_tr} - Em_{e_tr} - Em_{hl}}{ND \cdot LHV_d \cdot \tau_d \cdot FC^w \cdot (1 + \gamma^w)} \quad (5.21)$$

Emergy flows of the natural gas fired heating system					
Note	Item	Unit	Input	Transformity [seJ/unit]	Solar Emergy [seJ]
Nonrenewable Inputs					
1	Natural gas	J	5.2E+13	7.73E+4 ^a	4.02E+18
Good and services					
2	Transport of natural gas	J	5.2E+13	1.74E+4 ^b	9.04E+17
Annual product yield (exergy)		J	8.25E+12	5.96E+05 ^c	4.92E+18

^a Transformity of natural gas (see Table 5.3)

^b Transformity of natural gas transport (see Table 5.3)

^c Deducted transformity of the heat produced by the heating system.

Table 5.4: Emergy flows of the natural gas fired heating system (parameters are given in Table 5.1)

5.3.1.3 Carbon footprint versus emergy evaluation:

Comparing the results of the two approaches, it must be noted that, as illustrated in Fig. 5.4, the maximum transport distance of wood calculated via carbon footprint D_{max}^c is nearly five times longer than the maximum transport distance calculated via emergy evaluation. These results indicate that the environmental impact of using wood fuel for heating cannot be effectively evaluated based solely on its CO_2 emissions. Many other factors affect the environmental performance of the process and that is why an emergy evaluation is much more appropriate because emergy measures all forms of energy which has been used or transformed to make a product

or service. The corresponding energy flows of the two heating systems are given in Tables 5.4 and 5.5. The CO_2 emissions are calculated in Tables 5.6 and 5.7.

Emergy flows of the wood fired heating system					
Note	Item	Unit	Input	Transformity [seJ/unit]	Solar Emery [seJ]
Nonrenewable Inputs					
1 ^d	Wood transportation (0km)	J	0	1.07E+5 ^a	0
1 ^d	Wood transportation (50km)	J	3.6E+11	1.07E+5	3.84E+16
1 ^d	Wood transportation (D_{max}^E)	J	7.14E+12	1.07E+5	7.61E+17
1 ^d	Wood transportation (D_{max}^{cf})	J	3.57E+13	1.07E+5	3.8E+18
2	Ash collection	J	1.03E+10	1.07E+5	1.09E+15
3	Commute of the employees	J	4.43E+10	1.07E+5	4.72E+15
Renewable Inputs					
4	Wood biomass	J	6.59E+13	5.62E+4 ^b	3.7E+18
	Good and services				
5	Human labor	h	5280	8.58E+13 ^c	4.53E+17
	Annual product yield (0km) (exergy)	J	8.25E+12	5.04E+05 ^e	4.16E+18
	Annual product yield (50km) (exergy)	J	8.25E+12	5.09E+05 ^e	4.2E+18
	Annual product yield (D_{max}^E) (exergy)	J	8.25E+12	5.96E+05 ^e	4.92E+18
	Annual product yield (D_{max}^{cf}) (exergy)	J	8.25E+12	9.65E+05 ^e	7.97E+18

^a Transformity of diesel (see Table 5.3)

^b Transformity of wood biomass (see Table 5.3)

^c Transformity of human labor (see Table 5.3)

^d The emery flow of wood transportation depends on the supply distance of wood, the values represent the emery flows of wood transportation for a supply distance of respectively 0km (direct supply), 50km, $D_{max}^E = 990$ km and $D_{max}^{cf} = 4950$ km.

^e Deducted transformity of the heat, produced by the heating system, for a supply distance of respectively 0km (direct supply), 50km, $D_{max}^E = 990$ km and $D_{max}^{cf} = 4950$ km.

Table 5.5: Emery flows of the wood fired heating system ($LHV_w = 11.49$ MJ, $\eta_w = 0.65$ and $C_{max}^{w-tr} = 14$ t)

5.3.2 Discussion

In Table 5.1, C_{max}^{a-tr} , C_{max}^{w-tr} , LHV_w , FC^w , M and η_w have been defined in value ranges, which permits to realize the sensitivity analysis of these parameters (for more details see Subsection 5.3.5). In addition, it should be pointed out that LHV_w , M and η_w are related in Eq. (5.3) and that the fuel consumption varies with the load capacity of the truck.

In order to compare and visualize the distance limitations of emery evaluation and carbon footprint, a specific graph has been used, in which (see Fig. 5.5):

- The x-axis indicates the difference between the emery flows of the natural

gas fired heating system and the wood fired heating system.

- The y-axis represents the difference between the emissions of the natural gas fired heating system and the wood fired heating system.

The graph is divided into four quadrants. The first one represents supply distances permitting and energy savings, the second one represents supply distances which permits savings but are too energy intensive, the third one represents supply distances which are and energy intensive and finally the fourth one represents supply distances which are energy saving but intensive.

In the case illustrated in Fig. 5.5, the x- and y-axis are respectively defined as follows:

$$\Delta Em(D)[\text{seJ}] = Em_{ng_b} - Em_{w_b}(D)$$

$$\Delta CO_2(D)[\text{kgCO}_2] = CO_2^{ng_b} - CO_2^{w_b}(D)$$

Three different categories of supply distances can be observed: those accepted by energy evaluation and carbon footprint, those exceeding distance limitation of energy evaluation but accepted by carbon footprint and finally those which exceed the distance limitation of the two approaches. The intersections of the straight line with the x-axis and the y-axis correspond, respectively, to D_{max}^E and D_{max}^{cf} , illustrated in Fig. 5.4.

CO ₂ emission of the natural gas fired heating system					
Note	Item	Unit	Input	Emission factor [kgCO ₂ /unit]	CO ₂ emission [kgCO ₂]
Nonrenewable Inputs					
1	Natural gas	J	5.2E+13	5E-8 ^a	2.60E+06
Good and services					
2	Transport of natural gas	J	5.2E+13	1E-8 ^b	5.20E+05
Annual product yield (exergy)			8.25E+12	3.78E-07 ^c	3.12E+06

^a Emission factor of natural gas combustion (see Table 5.2)

^b Upstream emission factor of natural gas (see Table 5.2)

^c Deducted emission factor of the heating system.

Table 5.6: CO₂ emission of the natural gas fired heating system (parameters are given in Table 5.1)

CO₂ emission of the natural gas fired heating system					
Note	Item	Unit	Input	Emission factor [kgCO ₂ /unit]	CO ₂ emission [kgCO ₂]
Nonrenewable Inputs					
1 ^c	Wood transportation (0km)	l	0	2.94 ^a	0
1 ^c	Wood transportation (50km)	l	9.88E+03	2.94	2.91E+04
1 ^c	Wood transportation (D_{max}^E)	l	1.96E+05	2.94	5.75E+05
1 ^c	Wood transportation (D_{max}^{cf})	l	9.79E+05	2.94	2.88E+06
2	Ash collection	l	2.82E+02	2.94	8.28E+02
3	Commute of the employees	l	1.21E+03	2.94	3.57E+03
Renewable Inputs					
4	Wood biomass	J	6.59E+13	3.6E-9 ^b	2.37E+05
	^c Annual product yield (0km) (exergy)	J	8.25E+12	2.93E-08 ^d	2.41E+05
	^c Annual product yield (50km) (exergy)	J	8.25E+12	3.28E-08 ^d	2.71E+05
	^c Annual product yield (D_{max}^E) (exergy)	J	8.25E+12	9.90E-08 ^d	8.17E+05
	^c Annual product yield (D_{max}^{cf}) (exergy)	J	8.25E+12	3.78E-07 ^d	3.12E+06

^a Emission factor of diesel per [kgCO₂/l]

^b Upstream emission factor of wood biomass (see Table 5.2)

^c The CO₂ emissions of wood transportation depend on the supply distance of wood, the values represent the CO₂ emissions of wood transportation for a supply distance of respectively 0 km (direct supply), 50km, $D_{max}^E = 990$ km and $D_{max}^{cf} = 4950$ km.

^d Deducted emission factor of the heating system, for a supply distance of respectively 0km (direct supply), 50km, $D_{max}^E = 990$ km and $D_{max}^{cf} = 4950$ km.

Table 5.7: CO₂ emission of the natural gas fired heating system (parameters are given in Table 5.1)

5.3.3 Unification of carbon footprint and emergy evaluation

For a better understanding and interpretation of the large discrepancy between the results of the emergy evaluation and the carbon footprint, the possibility of a relationship between the two approaches has been investigated. According to Eqs. (5.12) and (5.22) the distance ratio $\frac{D_{max}^E}{D_{max}^{cf}}$ can be expressed as:

$$\frac{D_{max}^E}{D_{max}^{cf}} = K \cdot \left(\frac{\eta_w - \eta_{min}^E}{\eta_w - \eta_{min}^{cf}} \right) \quad (5.22)$$

Where, K , η_{min}^E and η_{min}^{cf} are defined as follows:

$$K = \frac{(EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C}}{LHV_d \cdot \tau_d} \cdot \frac{Em_{ng_b} - Em_{e_tr} - Em_{hl}}{CO_2^{ng_b} - CO_2^{e_tr}}$$

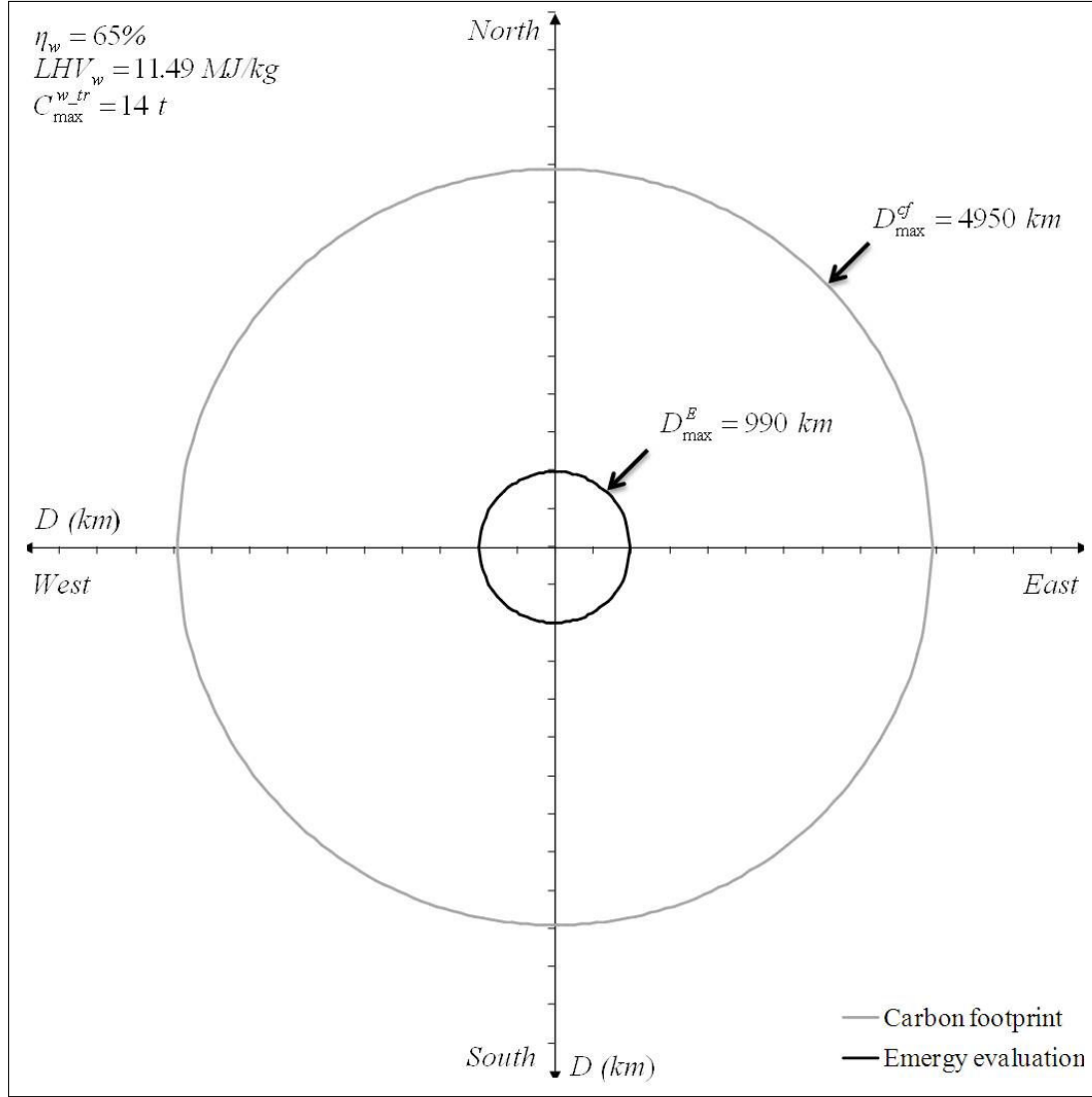


Figure 5.4: Maximum distance calculated via energy evaluation and carbon footprint

$$\eta_{min}^E = \frac{Q_{th} \cdot \left(\frac{\alpha}{C_{max}^{a-tr} \cdot LHV_w} \cdot d \cdot LHV_d \cdot \tau_d \cdot FC^a \cdot (1 + \gamma^a) + \tau_w \right)}{Em_{ng_b} - Em_{e_tr} - Em_{hl}}$$

$$\eta_{min}^{cf} = \frac{Q_{th} \cdot \left(\frac{\alpha}{C_{max}^{a-tr} \cdot LHV_w} \cdot d \cdot (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_c} \cdot FC^a (1 + \gamma^a) + EF_{w_up} \right)}{CO_2^{ng_b} - CO_2^{e_tr}}$$

It can be seen that, in the case of this study, the ratio $\frac{D_{max}^E}{D_{max}^{cf}}$ varies only with the

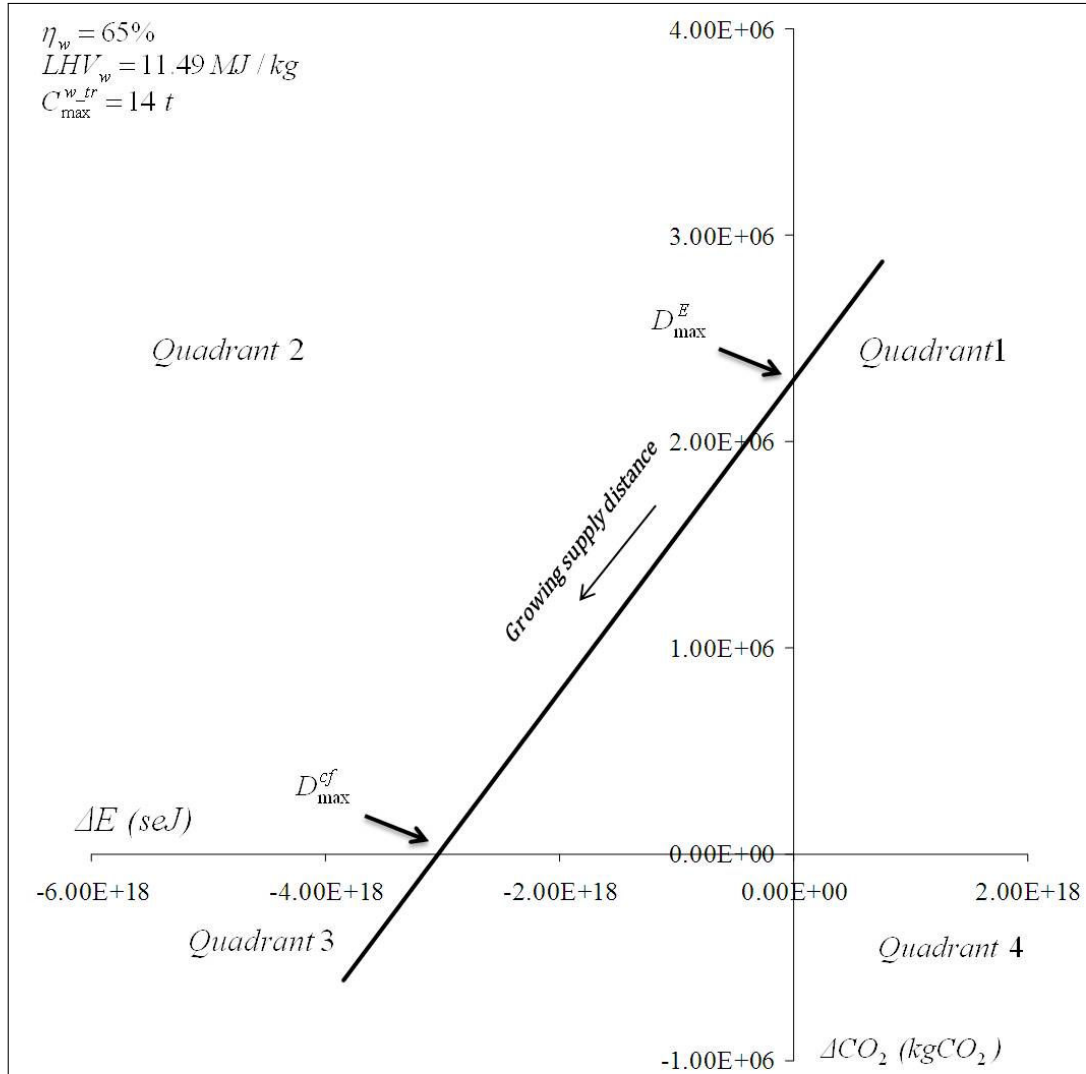


Figure 5.5: Eco-environmental performance varying with supply distances

low heating value of wood and the efficiency of the wood boiler, since all the other parameters are fixed. But as LHV_w varies only between 9 and 13MJ (by definition), its effects can be neglected. Hence, the ratio $\frac{D_{\max}^E}{D_{\max}^{cf}}$ varies only with the efficiency of the wood boiler η_w (see Fig. 5.6). This means that for a fixed wood boiler efficiency η_w , the ratio $\frac{D_{\max}^E}{D_{\max}^{cf}}$ is constant and thus it is possible to deduce directly D_{\max}^{cf} from D_{\max}^E and vice versa. This points to the fact that the carbon footprint method can be considered as a part of energy evaluation method, since it only measures the CO₂ emissions of the system while energy evaluation considers all the energy required directly and indirectly by the system. Furthermore, it should be noticed that for a wood boiler efficiency η_w lower than η_{\min}^E , D_{\max}^E becomes negative. It means that from an energy point of view, substitution of wood for natural gas is

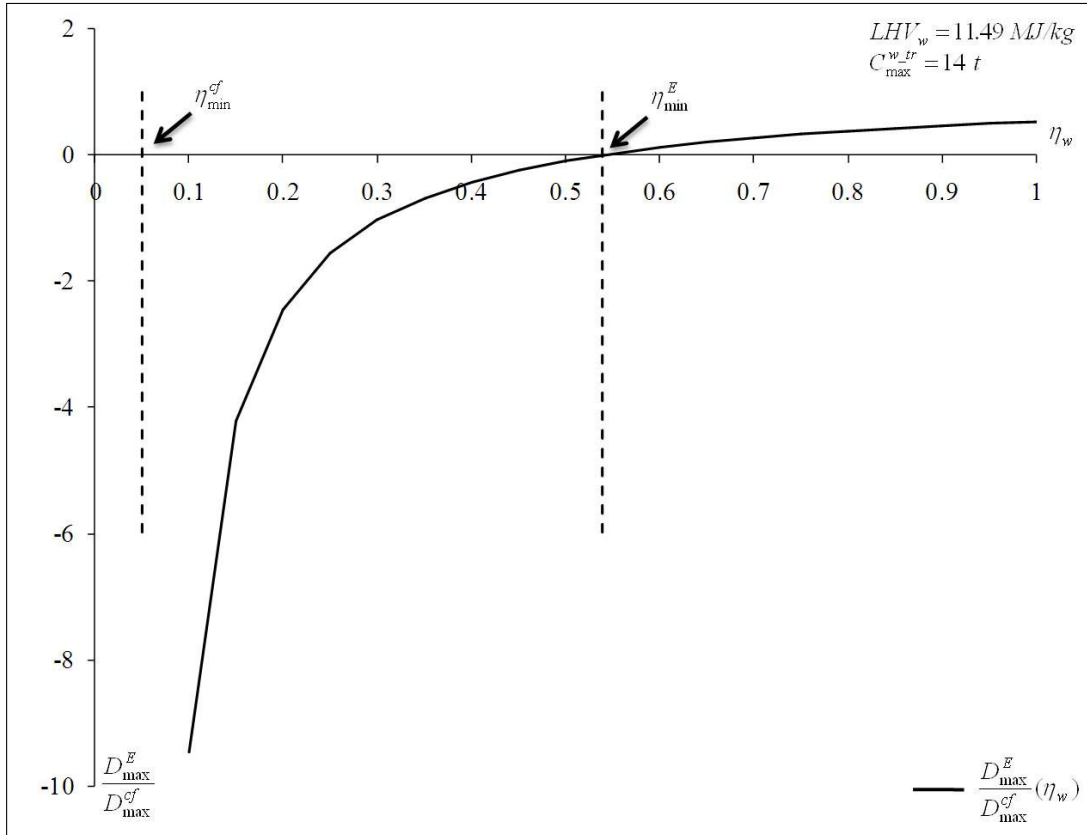


Figure 5.6: The distance ratio varying with the efficiency of the wood boiler

no longer sustainable. Similarly, for a wood boiler efficiency η_w lower than η_{min}^{cf} , D_{max}^{cf} becomes negative and hence, substitution of wood for natural gas is no longer carbon saving.

5.3.4 Sensitivity analysis

The following sensitivity analysis consists of identifying the impacts of different parameters such as the efficiency of the wood boiler, the low heating value of wood, the load capacity of trucks used to transport wood and finally the distance crossed to remove ash.

5.3.4.1 Impact of wood boiler efficiency:

According to Eqs. (5.12) and (5.21), for a fixed load capacity $C_{max}^{w_{tr}}$ and low heating value of wood LHV_w the variation of D_{max}^{cf} and D_{max}^E with the wood boiler efficiency

are given by:

$$\frac{\partial D_{max}^{cf}}{\partial \eta_w} = \frac{CO_2^{ng_b} - CO_2^{e_tr}}{\frac{Q_{th}}{C_{max}^{w_tr} \cdot LHV_w} \cdot (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_c} \cdot FC^w \cdot (1 + \gamma^w)} \quad (5.23)$$

$$\frac{\partial D_{max}^E}{\partial \eta_w} = \frac{E_{ng_b} - E_{e_tr} - E_{hl}}{\frac{Q_{th}}{C_{max}^{w_tr} \cdot LHV_w} \cdot LHV_d \cdot \tau_d \cdot FC^w \cdot (1 + \gamma^w)} \quad (5.24)$$

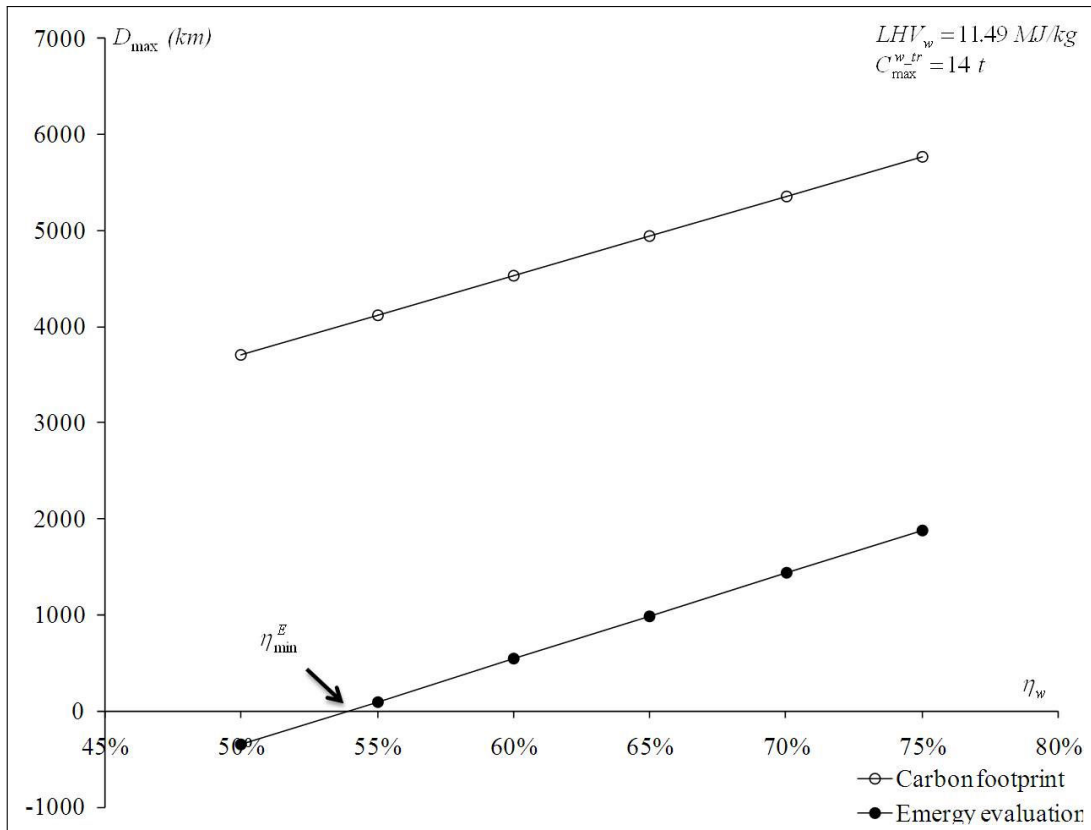


Figure 5.7: Maximum distances varying with efficiency of wood burner

Since $\frac{\partial D_{max}^{cf}}{\partial \eta_w}$ and $\frac{\partial D_{max}^E}{\partial \eta_w}$ are positive constants, the maximum distances D_{max}^{cf} and D_{max}^E are, as illustrated in Fig. 5.6, linear increasing functions of wood burner efficiency. According to Eq. (5.24), the higher the efficiency of the burner the lower the wood consumption to provide heat demands for the campus and therewith greater distances are acceptable for wood supply. The intersection of the x-axis with the line of maximum supply distances calculated via energy evaluation represents the minimum theoretical wood burner efficiency that allows energy to be saved.

5.3.4.2 Impacts of low heating value of wood:

According to Eqs. (5.12) and (5.21), for a fixed load capacity $C_{max}^{w_tr}$ and wood boiler efficiency η_w the variation of D_{max}^{cf} and D_{max}^E as a function of low heating value of wood are given by:

$$\frac{\partial D_{max}^{cf}}{\partial LHV_w} = \frac{CO_2^{ng_b} - CO_2^{e_tr} - \frac{Q_{th} \cdot EF_{w_up}}{\eta_w}}{\frac{Q_{th}}{C_{max}^{a_tr} \cdot \eta_w} (EF_{up_d} + EF_{comb_d}) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_c} \cdot FC^w \cdot (1 + \gamma^w)} \quad (5.25)$$

$$\frac{\partial D_{max}^E}{\partial LHV_w} = \frac{Em_{ng_b} - Em_{e_tr} - Em_{hl} - \frac{Q_{th} \cdot \tau_w}{\eta_w}}{\frac{Q_{th}}{C_{max}^{a_tr} \cdot \eta_w} \cdot LHV_d \cdot \tau_d \cdot FC^w \cdot (1 + \gamma^w)} \quad (5.26)$$

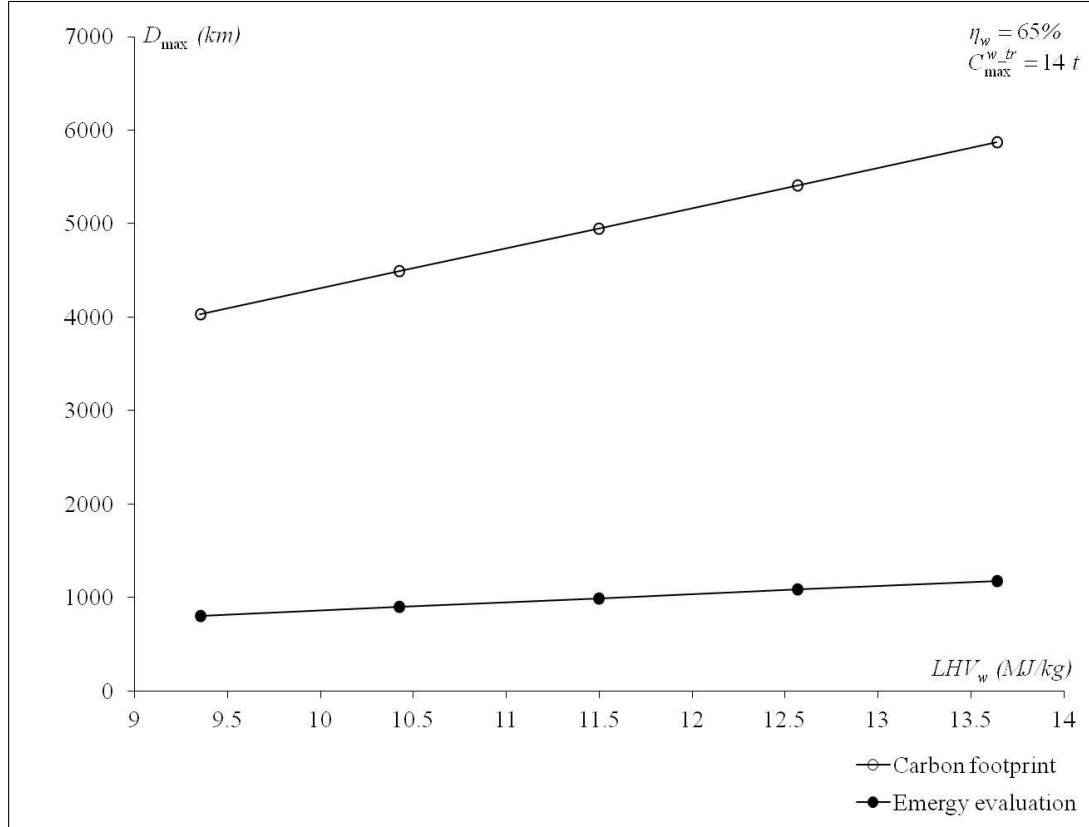


Figure 5.8: Maximum distances varying with low heating value of wood

Since $\frac{\partial D_{max}^{cf}}{\partial LHV_w}$ and $\frac{\partial D_{max}^E}{\partial LHV_w}$ are positive constants, the maximum distances D_{max}^{cf} and D_{max}^E are, as shown in Fig. 5.8, linear increasing functions of low heating value of wood. In reality, as shown in Eq. (5.26), high moisture content of wood M lowers the heat value LHV_w and hence a higher quantity of wood is needed to provide

the heat demand. The rise of wood consumption implies a higher number of wood deliveries ND and shorter acceptable supply distances of wood.

5.3.4.3 Impacts of load capacity of trucks:

For a given wood consumption, the increase of C_{max}^{a-tr} reduces the number of wood deliveries ND and according to Eqs. (5.12) and (5.21), greater distances for supplying the burner with wood are possible. Thus, as shown in Fig. 5.9, the maximum accepted supply distances of wood, D_{max}^{cf} and D_{max}^E increase with the load capacity of truck C_{max}^{a-tr} .

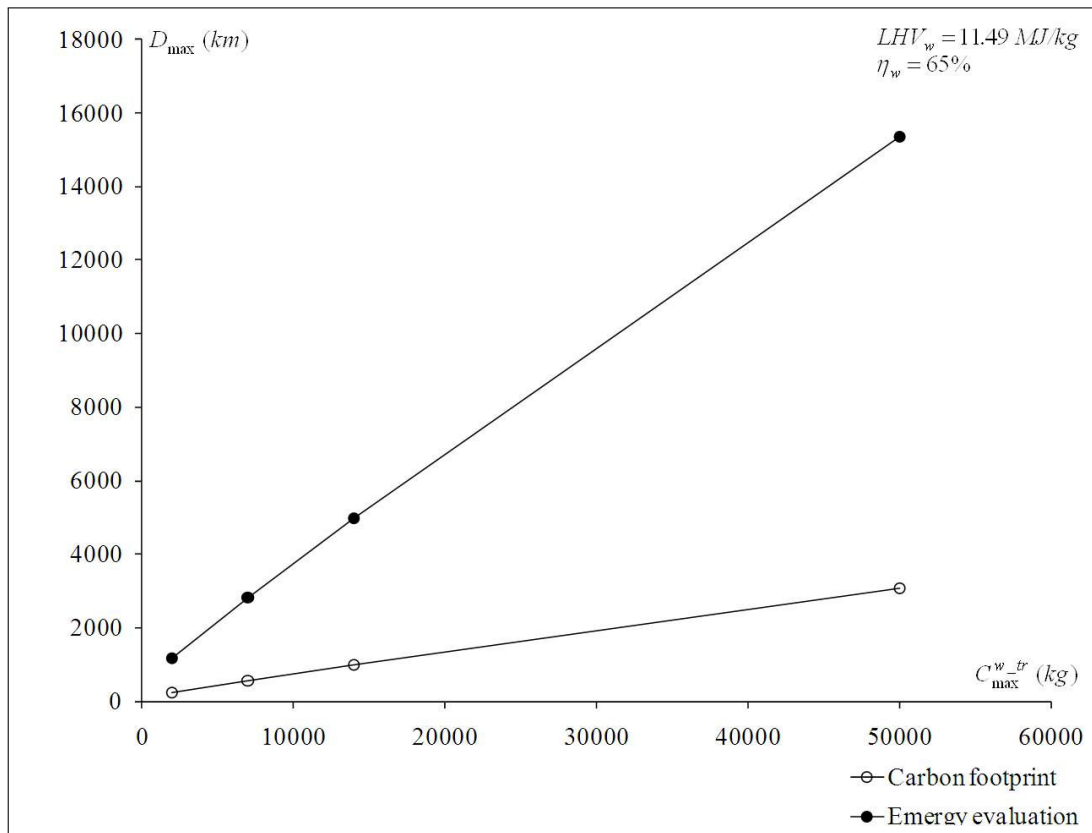


Figure 5.9: Maximum distances varying with load capacity of trucks

5.3.4.4 Impact of distance crossed to remove ash:

The ash quantity during the heating period is negligible compared to the wood consumption Q_w of the burner (α is about 2%), that is why the distance crossed to remove ash does not affect considerably the calculation of acceptable wood supply distances D_{max}^{cf} and D_{max}^E .

5.3.4.5 Uncertainty analysis of emission factors and transformities:

Emission factors and transformities are very sensitive to several factors (time, region, resources, production process, utilization. . .) and it is quite difficult to find out the appropriate value that has to be used. That is why the relative error for 10% of change of all the emission factors and transformities, used in this work, has been calculated, see Tables 5.8 and 5.9.

Relative errors of emission factors	
Relative error	Value
$\sigma_{EF_{ng}}$	1.08E-01
σ_{EF_d}	9.10E-02
σ_{EF_w}	8.24E-03

Table 5.8: Relative errors of emission factors

Relative errors of transformities	
Relative error	Value
$\sigma_{\tau_{ng}}$	6.46E-01
σ_{τ_d}	9.16E-02
σ_{τ_w}	4.86E-01
$\sigma_{\tau_{hl}}$	5.95E-02

Table 5.9: Relative errors of transformities

The relative error is defined as:

$$\sigma_x = \frac{\Delta D}{D_0} = \frac{|\frac{\partial D}{\partial x}(x - x_0)|}{D_0}$$

With:

$$\begin{cases} x \in \{EF_i; \tau_j\}; i = \{\text{Natural gas, wood, diesel}\}; j = \{\text{Natural gas, wood, diesel, human labor}\} \\ x - x_0 = 10\% x_0 \end{cases}$$

It can be noticed that for coherent results of carbon footprint analysis the emission factors of fossil fuel should be carefully chosen, as they are important CO_2 creators. To realize a meaningful energy evaluation special care must be taken in choosing the transformities of the fuel used for heat production, whether fossil fuel or biomass.

5.3.5 Conclusion of the chapter

This chapter discusses the feasibility conditions of using biomass as a substitute for fossil fuel. Authors used a carbon footprint analysis and energy evaluation to assess

the maximum supply distance of biomass that permits biomass to be, according to the approach, a CO_2 or emergy saving alternative to fossil fuel.

As the emergy evaluation takes into account both the impact of fossil fuel as well as carbon footprint, the unification of the two approaches has been applied. This permits to define, for each of the two approaches, the minimum theoretical wood burner efficiency that allow, according to the approach, CO_2 or emergy saving, when there is no wood transport (the wood burner is constructed in the forest).

In the case study, a project launched in 2010 has been analyzed, which consists of building a central wood fired heating plant in the zone of Chantrerie (Nantes-France), to replace local natural gas heating units. The results show that the maximum supply distance and the minimum theoretical wood burner efficiency calculated via carbon footprint are respectively about 5000km and 5%. Whereas the maximum supply distance and the minimum theoretical wood burner efficiency calculated via emergy evaluation, are about 1000km and 54%. These results do not surprise because contrary to carbon footprint, which measures only the CO_2 emissions of the process. The emergy concept is based on the principle of memorizing all the available energy that has been required directly or indirectly to make a product or service.

The sensitivity analysis reveals that the eco-environmental efficiency of wood as a substitute for natural gas depends mainly on the performance of the heating system (efficiency of the wood boiler), the quality of wood (moisture content of wood) and the fuel consumption of the trucks transporting the wood. The uncertainty analysis of the emission factors and transformities indicates that special care should be taken in choosing the emission factors of fossil fuels (in this case natural gas and diesel) and the transformities of the fuels used to fire the heating system (whether it is fossil fuel or biomass).

The methodology proposed in this chapter is appropriate to study all types of fossil fuel substitution by biomass.

Appendix 5A

The following figure describes the average thermal need of the 5 establishments varying with seasons. It represents an annual thermal consumption of about $Q_{th} = 42\,800\text{GJ}_{th}$. These results are based on the real heat consumption of the 5 establishments over the past five years.

Natural gas fired heating system:

The heating of the 5 establishments is provided by 25 natural gas boilers with a thermal capacity of 13 MW_{th}, distributed over 13 boiler rooms. For each establishment, the annual heating need and the natural gas consumption of the last five years have been studied to identify the average heat consumption and the global efficiency of the heating system (see Table 5.11).

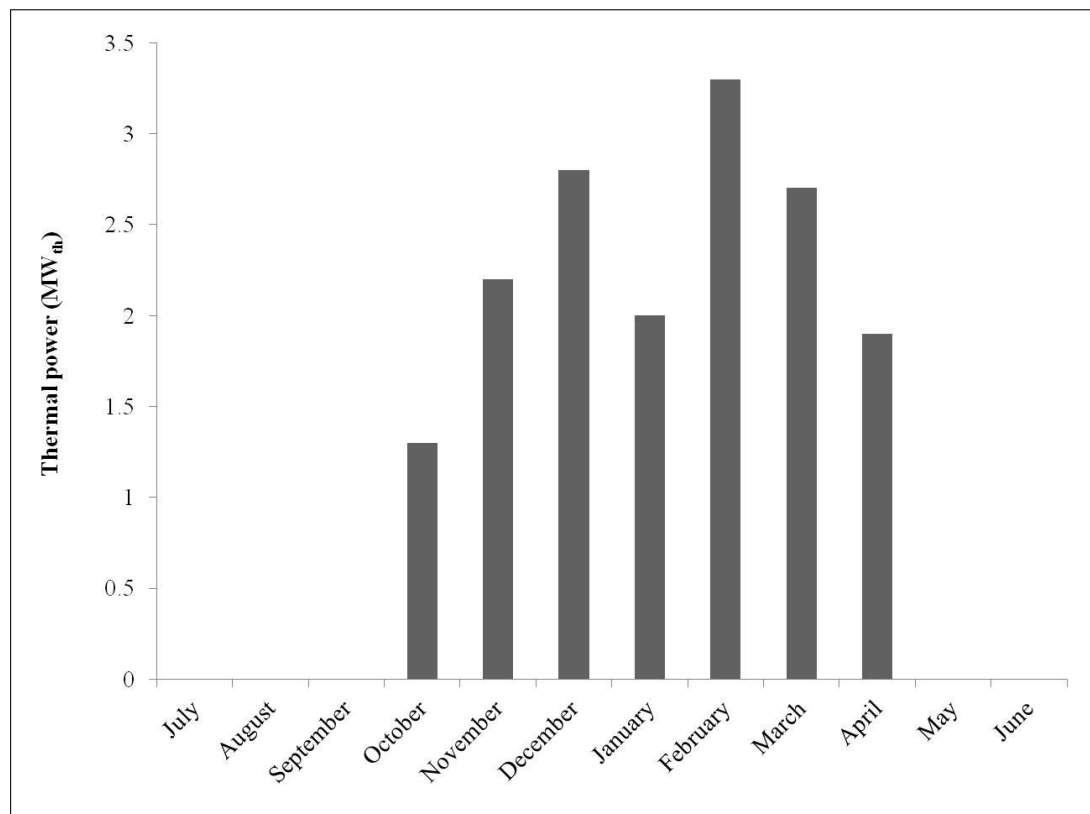


Figure 5.10: Average thermal need

Wood fired heating system:

A wood fueled boiler was installed to replace the natural gas heating system. The boiler is connected to a heating network, which transports the heat to the buildings by 3 km long pipes and 13 distribution stations. The boiler consumes about 3 900 tons of wood per year (50% wood waste from sawmills and 50% wood chips). The

characteristics of the boiler and the used fuel (see Table 5.10) have been the basis for the sensitivity analysis of this chapter.

Parameters of the wood fired heating system			
Definition	Item	Unit	Amount
Low heating value of wood	LHV_w	MJ/kg	11.5
Moisture content of wood	M	w%	35
Ash content of wood	α	-	0.02
Global efficiency of the heating system	η_w	-	0.65
Social impact	-	-	5.5 Full Time Employee ^a

^a 1 Post college+ 4,5 College grad.

Table 5.10: Parameters of the wood fired heating system

Parameters of the natural gas fired heating system			
Definition	Item	Unit	Amount
Average annual heat consumption	Q_{th}	MJ	42.8E+6
Exergy of produced heat ^a	Ex_{th}	MJ	8.25E+6
Average annual natural gas consumption	Q_{ng}	MJ	5.2E+7
Global efficiency of the heating system	η_{ng}	-	0.82

^a The total heat production of the system is about 4.28E+13J, using a Carnot efficiency of 0.19 (ambient temperature is 20°C and temperature of hot water is 90°C) the exergy of the produced heat is 8.25E+12J.

Table 5.11: Parameters of the natural gas fired heating system

Environmental impact assessment
of retrofitting existing coal fired
power plants to co-firing with
biomass: carbon footprint and
energy approach

Environmental impact assessment of retrofitting existing coal fired power plants to co-firing with biomass: carbon footprint and emergy approach

Abstract: To reduce the emission of greenhouse gases, developed countries tend to increase the use of environmentally friendly renewable energy sources. Retrofitting of existing coal fired condensing power plants to co-firing with biomass is a generally accepted method for decreasing the dependency on fossil fuels and carbon-dioxide emission reductions. To determine if the co-firing is an environmentally friendly solution, two methods are used to cover all significant aspects of electricity production process that may influence the environment: carbon footprint and emergy evaluation. These environmentally accounting approaches were chosen to determine the maximum supply distance of biomass that allows the co-firing of coal and biomass to be more environmentally efficient than the pure coal combustion. Furthermore, geological origin of the coal combusted is taken into account, considering that the environmental inputs for feedstock creation varied throughout the history. The results of the study showed that the addition of approximately 20% biomass to the mass of the combustion mixture causes the decrease in carbon-dioxide emissions for nearly 11-25% and total emergy flow for 8-15%. However, further results indicate that the co-firing process is environmentally acceptable if the biomass supply stocks are within the area determined by maximum supply distances. Nevertheless, the supply area radius resulting from the emergy evaluation is 49-62% shorter depending on the coal type combusted. Furthermore, the emergy loading ratio of co-firing was lower than for the pure coal firing (10.65 compared to 12.39, respectively) indicating that the co-firing process causes less pressure on the ecosystem.

Keywords: Coal, Biomass, Co-firing, Emergy, Carbon footprint

Nomenclature

Acronyms

<i>CCS</i>	Carbon Capture and sequestration
<i>CHP</i>	Combined Heat and Power
<i>EIR</i>	Emergy Investment Ratio
<i>ELR</i>	Emergy Load Ratio
<i>EYR</i>	Emergy Yield Ratio
<i>HHV</i>	High Heating Value [J/kg]
<i>LCA</i>	Life Cycle Assessment
<i>LHV</i>	Low Heating Value [J/kg]
<i>STPP</i>	Small Thermal Power

Greek Symbols

α	Weight percentage [-]
ε	Oxydation ratio of diesel
η	Efficiency of the boiler [-]
γ	Fuel consumption ratio [-]
ρ	Density [kg/m^3]
τ	Transformity [seJ/J]
θ	Employment factor [emp./W]

Roman Symbols

<i>A</i>	Area [m^3]
<i>A</i> _%	Weight percentage of Ash [-]
<i>C</i>	Capacity
<i>C</i> _%	Weight percentage of Carbon [-]
<i>CO</i> ₂	Carbon dioxide emission [kgCO_2/yr]
<i>D</i>	Transport distances[km]
<i>d</i>	Daily delivery distance [km]
<i>E</i>	Energy [J]
<i>EF</i>	Emission factor [kgCO_2/J]
<i>El</i>	Electricity production [W/yr]
<i>F</i>	Purchased inputs
<i>FC</i>	Fuel consumption [l/km]

h	Height [km]
$H_{\%}$	Weight percentage of Hydrogen [-]
I	Working hours [h]
L	Length [m]
M	Molar mass [kg/mol]
m	Stoichiometric weight [kg/kg]
$M_{\%}$	Weight percentage of Moisture [-]
N	Non-renewable inputs
$N_{\%}$	Weight percentage of Nitrogen [-]
ND	Annual number of deliveries
$O_{\%}$	Weight percentage of Oxygen [-]
P	Power [W]
Q	Emission rate [kg/s]
q	Annual fuel consumption [kg/yr]
R	Renewable inputs
$S_{\%}$	Weight percentage of Sulfur [-]
t	Time [s]
V	Stoichiometric volume [m^3 /kg]
v	Speed [m/s]
W	Annual energy production [J/yr]

Superscripts

c	Coal
cfp	Carbon footprint
d	Diesel
E	Emergy
pc	Pure coal firing

Subscripts

aa	Air access
a	Ash
an	Annual
atk	Ash transportation by truck
atr	Ash transportation
b	Biomass
b, i	i type of biomass

<i>bm</i>	Biomass mixture
<i>btk</i>	Biomass transportation by truck
<i>btr</i>	Biomass transportation
<i>c</i>	Coal
<i>cf</i>	Carbon footprint
<i>co</i>	Combustion
<i>ctr</i>	Coal transportation
<i>cw</i>	Cooling water
<i>d</i>	Diesel
<i>dl</i>	Dilution
<i>dust</i>	Dust
<i>eac</i>	Equivalent annual cost
<i>el</i>	Electricity
<i>em</i>	Employees
<i>fl</i>	Full load
<i>h</i>	Working hours
<i>hl</i>	Human labor
<i>k</i>	Kinetic [m]
<i>m</i>	Fuel mixture
<i>O2</i>	Oxygen
<i>p</i>	Pollutant
<i>pr</i>	Electricity production
<i>t</i>	Total
<i>tr</i>	Transportation by train
<i>up</i>	Upstream
<i>w</i>	Water
<i>wd</i>	Working day
<i>wl</i>	Without a load

6.1 Introduction

Global warming presents increasing and certain threat for the future with physical, social, ecological and large scale impacts. Analysis conducted by EPA [EPA 2009] predicted that without switching to renewable energy resources, carbon-dioxide concentration will reach 500 *ppm* by 2030. About 41% of global carbon-dioxide emissions are from electricity and heat production, with 43% emitted from coal combustion in thermal power plants [IEA 2012]. Taking into account emission factors and impact on global warming process, with rapidly decreasing reserves of fossil fuels, one of the primary goals for securing environmentally friendly future is decreasing the dependency on fossil fuels and incorporating renewable sources for energy production.

Refurbishment of the existing power plants to adapt to new emission regulations has become one of the major concerns in the electricity production sector. As suggested by Geisbrecht and Dipietro [Geisbrecht 2009], current options for refurbishment are: retrofitting with carbon capture and sequestration (*CCS*), re-powering with advanced coal combustion technologies, measures for improving the overall efficiency of the plant or switching to co-firing with (or pure firing) renewable fuels with low carbon content. Gerbelova et al. [Gerbelová 2013] evaluated the effect of retrofitting Portuguese fossil fuel power plants with *CCS*, and the study showed that this technology can significantly reduce carbon-dioxide emissions, but with the overall efficiency decrease of average 19-33% and with additional capital costs. However, the results also suggested that *CCS* investment is feasible if the emission taxes are high (85-140\$/*tCO*₂). Additionally, co-firing of coal and biomass in traditional pure coal-fired boilers for electricity and heat production presents a promising cost-effective and efficient technology for increasing the participation of renewable sources in this sector. This system allows extensive combustion of biomass with higher efficiency than the one currently achieved in pure biomass combustion systems. Considering that biomass usually has higher moisture and oxygen content in its composition (and lower density than coal), for efficient and safe co-firing process to be achieved, an in-depth understanding of the process properties under a wide range of conditions is required. Many different biomass types can be used for co-combustion with coal. Wood, residues from forestry and related industry sectors, and agricultural residues are all widely available and suitable for this process. For biomass combustion, it is considered that the total amount of carbon-dioxide emitted from its combustion is absorbed by the new plants whilst growing, keeping the carbon cycle in balance. Considering these benefits, new EU regulations such as Large Combustion Plant Directive [European Commission 2001] and Integrated Pollution Prevention and Control Directive [European Commission 2008] imply increased usage of biomass.

Taking into account previously explained benefits, retrofitting existing power plants instead of closing them, and building new carbon efficient ones, is a possible and attractive solution. A techno-economical assessment of retrofitting existing

coal power plant to co-firing with biomass has been conducted by De and Assadi [De 2009]. Their conclusions were that emissions are significantly decreased, but the cost of retrofitting increases with the installed capacity of the plant. Additionally, the cost decreases for the plants with higher capacity (over 250 MW). Furthermore, for co-firing mixture with high levels of biomass, specific and initial costs are increased. Consequently, the price of produced electricity also increases. Another techno-economical analysis for coal and biomass co-firing was presented in the work of Gomes et al. [Gomes 2013]. The study considered the possibility of implementation of decentralized Small Thermal Power Plants (*STPP*) in the Brazilian state Rio Grande de Sul with the co-combustion of different biomass waste and local coal in fluidized beds. The 0.25 MW_{th} pilot plant was used for combustion tests and the integrated system for energy generation, carbon crediting and sand lime bricks manufacturing was considered. The authors concluded that the proposed integrated system coupled with economical availability presents a cleaner production approach for *STPPs*.

However, considering just greenhouse emissions from fuel combustion is not sufficient to assess the impact of co-firing system on the environment. All amounts of energy consumed during the process and the environmental impact of the product (in this particular case, electricity and heat) during its whole life needs to be considered. Life cycle assessment (LCA) accounts for all the emissions released by all the systems involved in the life cycle of a product, and it contributes on standardization of impact assessment of a broad variety of emissions. The LCA analysis of biomass and coal co-firing in CHP plant was conducted by Zuwala [Zuwala 2012]. The results showed that the material requirements for the construction of co-firing installation are significantly lower comparing to the whole construction and decommissioning energy consumption for the plant. Furthermore, partial substitution of coal with biomass leads to decline of the total life-cycle non-renewable energy resources depletion. This study considered several sources of environmental impact (fuel, collection and transportation, plant operation), through coefficients of cumulative energy consumption and greenhouse gasses burdening the production of electricity. Martín et al. [Martín 2006] used exergy analysis to prove technical feasibility of co-firing. Exergy analysis is suitable for tracing the energy losses through the process, so it is beneficial for process improvements and for gauging ecosystem health and stability. The results revealed that between 48.4% and 56.2% of the exergy input is lost due to the irreversibility of the process.

To determine the environmental impact of complete co-firing system, two methods are used in this study:

1. *The carbon footprint*: this approach has become widely used concept in carbon-dioxide emissions assessments. This method has been applied to determine emission factors at different levels, such as industrial parks [Dong 2013], national parks [Villalba 2013], cities [Lin 2013] and the whole countries [Larsen 2011]. It is a measure of total amount of carbon-dioxide released into

the atmosphere in the given time frame that is directly or indirectly caused by an activity to provide service or a product. Consequently, aside from fuel combustion emissions of co-firing process, all the other emission sources are taken into account: fuel transportation, ash collecting and employees travel to work. The methodology used in this chapter was devolved following the five main process steps for life cycle emissions calculations, outlined in the PAS 2050:

- Process map creation (see Fig. 6.1)
 - Selecting boundaries and prioritization (see Fig. 6.1 and Section 6.2)
 - Data collection (see Section 6.3)
 - Footprint calculation (see Sections 6.3 and 6.4)
 - Uncertainty (see Subsection 6.4.1)
2. *The emergy approach*: this method accounts for, and in effect, measures quality differences between diverse types of energy. The emergy concept and the emergy accounting have been firstly introduced by H.T. Odum during the 1970s. He defined the emergy as the available energy of one kind of previously used up directly or indirectly to make a service or product [Odum 1996]. The unit of emergy is the emjoule. Using emergy concept, fuel, electricity, human labor and all other environmental resources can be expressed in the same unit. Solar emergy of a product is the emergy of the product expressed in the equivalent solar energy required to generate it [Brown 2004d]. The Unit Emergy Value (UEV) is calculated based on the emergy required to generate one unit of output from a process. Solar transformity of the product, one type of UEV, is equal to the ratio of the emergy that was used in a process and the exergy yielded by the process and it is expressed as solar emergy Joules per Joule. Therefore, the lower transformity is, the smaller the emergy amount is required to produce the service or a product. Once all the types of energy inputs are on the same basis, they can be compared. After calculations of the indigenous renewable, non-renewable and purchased resources emergy flows, sustainability of the system can be evaluated through several emergy-based indices and ratios (emergy yield ratio, emergy investment ratio and emergy loading ratio). This approach has been used to assess environmental performance in various areas, such as geo-biosphere [Brown 2010], agricultural systems [Ghisellini 2014], and diverse industry processes [Yang 2013, Ulgiati 2002].

The aim of this chapter is to assess the environmental performance of co-firing, considering all the inputs for plant operation (fuels, transportation, human labor, renewable environmental resources such as air and water) and combustion fuel creation (for the creation of different coal types during geological periods and dilution of carbon dioxide). All inputs are considered through two different approaches, used to calculate and compare the performance of this process with pure coal firing,

and to determine the benefits for the environment. Environmental performances of co-firing are identified for various types of coal with different geological origins and compositions, and biomass consisted of wood and diverse agricultural residues (straw, barley and willow). The unification of the methods is conducted to define the maximum supply distance for biomass, after which co-firing becomes too environmentally intensive.

6.2 Methodology

The environmental impact of co-firing power plant is evaluated in three steps: energy analysis, carbon footprint analysis and emergy analysis. Energy analysis defines the amount of fuel, as a main resource, required for the power plant operation during a year. Through the carbon footprint analysis, total annual emissions of the whole system from the relevant sources (combustion, transportation, etc.) are investigated. Finally, all the renewable, non-renewable inputs and services are considered through the emergy evaluation. With all the inputs defined and classified, emergy indices are used to assess the impact and sustainability of the system. Emergy loading ratio is a measure of the ecosystem stress due to the production activity, emergy yield ratio is an indicator of the ability of the process to exploit local resources and emergy investment ratio gives an evaluation if the process is a good user of the emergy that is invested, in comparison with the alternatives [Brown 1997b]. Comparing both emergy and carbon footprint analysis of co-combustion system with pure coal combustion system, limitations of biomass transportation are given through the maximal supply distances allowed. It should be noted that in this study, inputs during the power plant construction period were not taken into account, due to the assumption that the emergy flow of the construction phase would be constant, no matter which type of coal and biomass is combusted. It is also considered that the properties and composition of the fuels are constant during the year. The overall efficiency of the boilers is assumed to be constant and equal to the average efficiency of the boilers in nominal operating conditions. In the emergy analysis, heat production is considered as a by-product of electricity production and thus it is not taken into account. Furthermore, the pure coal firing and co-firing alternative processes are calibrated to produce the same amount of electricity. The authors suggest that the following method can be used for the coal condensing type of power plants, regardless of the power plant capacity and geographical location.

6.2.1 Energy analysis

Primarily, compositions, properties and consumption of fuels used in combustion process must be determined. One of the essential fuel properties is the low heating value. It is defined as the net heat production during combustion per one unit of fuel combusted (it is assumed that water leaves with the combustion products without

being fully condensed). Low heating value is the direct consequence of the fuel composition, and it is determined through the data from ultimate analysis that gives the composition in weight percentage of carbon, hydrogen, oxygen, nitrogen, sulfur, ash and moisture. The low heating value of the coal (LHV_c [MJ/kg]) is calculated with the following equation [Brkic 2010]:

$$LHV_c = (0.34 \cdot C_{\%} + 1.2 \cdot (H_{\%} - \frac{O_{\%}}{0.008}) + 0.105 \cdot S_{\%} - 0.025 \cdot M_{\%}) \quad (6.1)$$

where $C_{\%}$, $H_{\%}$, $O_{\%}$, $S_{\%}$, $M_{\%}$ are percentages of carbon, hydrogen, oxygen, sulphur and moisture, respectively. Higher heating value of biomass, HHV_b [MJ/kg] (that assumes that all vapor produced during the combustion process is fully condensed) is given by [U.S. Department of Energy 2011]:

$$HHV_b = 0.35 \cdot C_{\%} + 1.18 \cdot H_{\%} + 0.1 \cdot S_{\%} - 0.02 \cdot N_{\%} - 0.1 \cdot O_{\%} - 0.02 \cdot A_{\%} \quad (6.2)$$

Where $A_{\%}$ is the ash mass percentage in regarded fuel. Taking into consideration the moisture content, low heating value of biomass is defined as [U.S. Department of Energy 2011]:

$$LHV_b = HHV_b \cdot (1 - M_{\%}) - 2.447 \cdot M_{\%} \quad (6.3)$$

Low heating value of the biomass mixture (LHV_{bm} [MJ/kg]) is directly related to weight percentages of biomass types from which the mixture is consisted:

$$LHV_{bm} = \sum_{i=1}^n \alpha_{b,i} \cdot LHV_{b,i} \quad (6.4)$$

where $\alpha_{b,i}$ and $LHV_{b,i}$ are the mass percentage and low heating value for the i type of biomass, respectively (for example, i = wood, straw, willow etc.). Furthermore, LHV_m [MJ/kg] of co-firing mixture of coal and biomass is:

$$LHV_m = \alpha_c \cdot LHV_c + \alpha_{bm} \cdot LHV_{bm} \quad (6.5)$$

α_c and α_{bm} are weight percentages of coal and biomass mixture, respectively. The annual power plant consumption of such a fuel mix (q_m [kg/yr]) is:

$$q_m = \frac{W_{an}}{\eta \cdot LHV_m} \quad (6.6)$$

where W_{an} [MJ/yr] is annual energy produced and Δ is the average efficiency of the boilers. Therefore, the annual consumptions of coal (q_c) and biomass (q_{bm}) in

[kg/yr] are:

$$q_c = \alpha_c \cdot q_m \quad (6.7)$$

and

$$q_{bm} = \alpha_{bm} \cdot q_m \quad (6.8)$$

Amounts of oxygen used for combustion process is given by:

$$m_{O_2} = \alpha_{aa} \cdot m_{O_2,t} \quad (6.9)$$

$$m_{O_2,t} = m_{O_2,c} \cdot q_c + m_{O_2,bm} \cdot q_{bm} \quad (6.10)$$

where m_{O_2} [kg/yr] is the actual total amount of air used, α_{aa} [-] is the air access coefficient, $m_{O_2,t}$ [kg/yr] is the total stoichiometric amount of oxygen used for combustion, $m_{O_2,c}$ [kg/kg] is the specific stoichiometric amount of oxygen used for the combustion of 1kg of coal (see Eq. (6.11)), and $m_{O_2,bm}$ [kg/kg] is the specific stoichiometric amount of oxygen used for the combustion of 1kg of biomass mixture (see Eq. (6.14)). For the coal, specific oxygen consumption is given by [Mazumdar 2000]:

$$m_{c,O_2} = 0.08 \cdot \left(\frac{C\%}{3} + H\% \right) + 0.01 \cdot S\% - 0.01 \cdot O\% \quad (6.11)$$

and for the biomass [Brkic 2010]:

$$V_{b,O_2} = \frac{1}{100} \cdot \left(1.866 \cdot C\% + 5.6 \cdot \left(H\% - \frac{O\%}{8} \right) + 0.7 \cdot S\% \right) \quad (6.12)$$

$$V_{bm,O_2} = \sum_{i=1}^n \alpha_{b,i} \cdot V_{b,O_2,i} \quad (6.13)$$

$$m_{bm,O_2} = V_{bm,O_2} \cdot \rho_{O_2} \quad (6.14)$$

where $V_{b,O_2,i}$ [m^3 /kg] is the stoichiometric volume of oxygen required for combustion of 1kg of respected biomass type, V_{bm,O_2} [m^3 /kg] is the stoichiometric volume of oxygen required for combustion of 1kg of biomass mixture, and ρ_{O_2} [kg/ m^3] is the air density.

6.2.2 Carbon footprint analysis

For the carbon footprint analysis, all the sources of emissions in the system have to be primarily defined. In the observed power plant co-firing system Fig. 6.1, it is clear that emissions are caused by the coal combustion ($CO_{2,co}$ [kgCO₂/yr]) and various transportation processes. As mentioned previously, it is considered that all the carbon-dioxide emitted from biomass combustion is used by growing plants to replenish the biomass stock. Therefore, authors assume that emissions from that source are not considered. Fuel transportation requires combustion of diesel fuel for inner combustion engines in transport vehicles, resulting in emissions from coal and biomass transportation ($CO_{2,ctr}$ [kgCO₂/yr] and $CO_{2,btr}$ [kgCO₂/yr], respectively). Considering that ash from the combustion process must be transported to the landfill or the cement industry, the emission from ash transportation should be taken into account ($CO_{2,atr}$ [kgCO₂/yr]). Furthermore, additional amount of diesel is combusted during the employees home-to-work traveling ($CO_{2,em}$ [kgCO₂/yr]). Consequently, the annual emission from the system ($CO_{2,cf}$ [kgCO₂/yr]) is defined by:

$$CO_{2,cf} = CO_{2,co} + CO_{2,ctr} + CO_{2,btr} + CO_{2,atr} + CO_{2,em} \quad (6.15)$$

The emission from coal combustion ($CO_{2,co}$) is given by the equation:

$$CO_{2,co} = q_c \cdot LHV_c \cdot EF_C \quad (6.16)$$

EF_C [kgCO₂/MJ] is the emission from coal combustion. The emission from coal train transportation ($CO_{2,ctr}$) can be expressed as:

$$CO_{2,ctr} = ND_c \cdot D_c \cdot (EF_{up}^d + EF_{co}^d) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC_{tr,fl} \cdot (1 + \gamma_{tr}) \quad (6.17)$$

where ND_c is the annual number of coal deliveries (see Eq. (6.18)), D_c [km] is the coal transport distance (from the mine to the power plant and back), EF_{up}^d [kgC/l] is the upstream emission of diesel fuel, EF_{co}^d [kgC/l] is the combustion emission factor for diesel fuel, ε [-] is the diesel oxidation factor, M_{CO_2} [g/mol] is the molecular mass of carbon-dioxide, M_C [g/mol] is the molecular mass of carbon, $FC_{tr,fl}$ [l/km] is the train fuel consumption with full load, γ_{tr} [-] is the train fuel consumption ratio (see Eq. (6.19)).

$$ND_c = \frac{q_c}{C_{tr,max}} \quad (6.18)$$

$$\gamma_{tr} = \frac{FC_{tr,wl}}{FC_{tr,fl}} \quad (6.19)$$

$C_{tr,max}$ [kg] is the maximum train capacity and $FC_{tr,wl}$ [l/km] is the train fuel consumption without a load.

$$CO_{2,btr} = ND_{bm} \cdot D_{bm} \cdot (EF_{up}^d + EF_{co}^d) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC_{btk,fl} \cdot (1 + \gamma_{btk}) \quad (6.20)$$

$$ND_{bm} = \frac{q_{bm}}{C_{btk,max}} \quad (6.21)$$

$$\gamma_{btk} = \frac{FC_{btk,wl}}{FC_{btk,fl}} \quad (6.22)$$

where ND_{bm} is the annual number of biomass deliveries, D_{bm} [km] is the biomass delivery distance, γ_{btk} [-] is the truck fuel consumption ratio, $FC_{btk,wl}$ [l/km] and $FC_{btk,fl}$ [l/km] are the truck fuel consumptions without and with the full load, respectively.

The emissions from ash collecting and transportation processes $CO_{2,atr}$ are given by Jamali-Zghal et al. [Jamali-Zghal 2013]:

$$CO_{2,atr} = ND_a \cdot D_a \cdot (EF_{up}^d + EF_{co}^d) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC_{atk,fl} \cdot (1 + \gamma_{atk}) \quad (6.23)$$

$$ND_a = \frac{A_{\%,c} \cdot q_c + A_{\%,bm} \cdot q_{bm}}{C_{atk,max}} \quad (6.24)$$

$$A_{bm} = \sum_{i=1}^n \alpha_{b,i} \cdot A_{\%,i} \quad (6.25)$$

$$\gamma_{atk} = \frac{FC_{atk,wl}}{FC_{atk,fl}} \quad (6.26)$$

where ND_a is the annual number of ash collections, D_a [km] is the delivery distance crossed (from power plant to the landfill or cement industry), $FC_{atk,fl}$ [l/km] is the ash collecting truck fuel consumption with the full load, γ_{atk} [-] is the truck fuel consumption ratio, $FC_{atk,wl}$ [l/km] is the truck fuel consumption without load, $A_{\%,c}$ and $A_{\%,bm}$ are the ash content percentages in coal and biomass mixture, respectively.

$$CO_{2,em} = D_{em} \cdot (EF_{up}^d + EF_{co}^d) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC_c \quad (6.27)$$

$$D_{em} = d_{em} \cdot n_{em} \cdot n_{wd} \quad (6.28)$$

$$n_{em} = \theta \cdot P \quad (6.29)$$

D_{em} [km/yr] is the annual distance crossed by the employees during the home-to-work traveling, FC_c [l/km] is the average car fuel consumption, d_{em} [km] is the daily distance crossed, n_{em} [emp.] is the number of employees, n_{wd} [days/yr] is the number of working days in a year, θ [emp./MW] is the power plant employment factor, and P [MW] is the installed power.

6.2.3 Emery evaluation

In this evaluation, inputs of all resources and services are examined. All the inputs are represented on Fig. 6.1. The emery flows of the fuel combustion in power plant are from the coal combustion (E_c [seJ/yr]) and biomass combustion (Em_{bm} [seJ/yr]). Transportation processes include coal (E_{ctr} [seJ/yr]) and biomass (Em_{btr} [seJ/yr]) transportation, ash transportation (Em_{atr} [seJ/yr]) and employees home-to-work traveling (Em_{em} [seJ/yr]). Considering that oxygen is necessary for the combustion process, and that significant amounts of fuel are combusted, emery flow of oxygen (Em_{O_2} [seJ/yr]) should be taken into account. The cooling system in the condenser requires water from the river for cooling, with annual emery flow Em_{cw} [seJ/yr]. The carbon-dioxide emitted from the power plant is diluted in the atmosphere, resulting in emery flow Em_{dl} [seJ/yr]. Furthermore, human labor as an important service input is considered through the emery flow Em_{hl} [seJ/yr]. Additionally, the equivalence annual cost (maintenance and investment) of the power plant elements (construction, turbine, pumps, mills etc.) emery flow is considered through E_{eac} [seJ/yr]. Therefore, the total annual emery flow of the system (E_{cf} [seJ/yr]) is given by:

$$Em_{cf} = E_c + Em_{bm} + E_{ctr} + Em_{btr} + Em_{atr} + Em_{em} + Em_{hl} + Em_{dl} + Em_{O_2} + Em_{cw} + E_{eac} \quad (6.30)$$

$$Em_c = LHV_c \cdot q_c \cdot \tau_c \quad (6.31)$$

$$Em_{bm} = q_{bm} \cdot \tau_{bm} \quad (6.32)$$

$$Em_{ctr} = ND_c \cdot D_c \cdot LHV_d \cdot \tau_d \cdot FC_{tr,fl} \cdot (1 + \gamma_{tr}) \quad (6.33)$$

$$Em_{btr} = ND_{bm} \cdot D_{bm} \cdot LHV_d \cdot \tau_d \cdot FC_{btk,fl} \cdot (1 + \gamma_{btk}) \quad (6.34)$$

$$Em_{atr} = ND_a \cdot D_a \cdot LHV_d \cdot \tau_d \cdot FC_{atk,fl} \cdot (1 + \gamma_{atk}) \quad (6.35)$$

$$Em_{em} = D_{em} \cdot LHV_d \cdot \tau_d \cdot FC_c \quad (6.36)$$

$$Em_{em} = I_{hl} \cdot \tau_{hl} \quad (6.37)$$

$$I_{hl} = n_{em} \cdot n_{wd} \cdot n_h \quad (6.38)$$

where τ_c [seJ/J], τ_{bm} [seJ/kg], τ_d [seJ/J], τ_{hl} [seJ/h] are the *UEVs* of coal, biomass, diesel fuel and human labor (respectively), and n_h [h/day] is the number of working hours during the day for one employee.

For calculating the emergy flow of air dilution process, simplified box model is used. In the box model theory, it is assumed that pollutant is instantly mixed throughout the planetary boundary limit and it is "flushed" through this layer by the boundary layer mean wind with a certain speed [Rigby 2007]. Planetary boundary limit is the layer of the atmosphere directly influenced by the Earth's surface, since it is the layer into which the pollutants are emitted. The box dimensions are determined by the length of the area upwind of a receptor and the height of the boundary layer. The referent concentration of the pollutant (C_{ref}) is defined as [Rigby 2007]:

$$C_{ref} = \frac{Q_p \cdot L}{v_{air} \cdot h} \quad (6.39)$$

where Q_p [kg/s] is the emission rate of pollutant, L [m] is the length of the area, v_{air} [m/s] is the wind speed and h [m] is the height of the boundary layer. It is assumed that the width of the box is equal to 1. The kinetic energy of dilution ($E_{k,d}$) [J/yr] is:

$$E_{k,d} = \frac{1}{2} \cdot \rho_{air} \cdot A \cdot t \cdot v_{air}^3 = \frac{1}{2} \cdot \rho_{air} \cdot h \cdot t \cdot v_{air}^3 \quad (6.40)$$

Where t [s] is the time interval and A [m³] is the flux surface area. Combining the Eqs. (6.39) and (6.40), it is clear that:

$$Em_{k,d} = \frac{1}{2} \cdot \rho_{air} \cdot \frac{Q_p}{C_{ref}} \cdot t \cdot v_{air}^3 \quad (6.41)$$

The steady state box model has been applied in several air quality evaluations. United Kingdom Meteorological office used this model to forecast the operational air quality [Middleton 1998]. De Leeuw et al. [de Leeuw 2002] used it to assess the influence of meteorology on urban pollutant concentrations measured across the Europe. Another example of application is the comparison of the air pollution ventilation climates of different areas [Gassmann 2000].

Therefore, the annual emery flow of dilution (Em_{dl}) is given by:

$$Em_{dl} = Em_{k,dl} \cdot \tau_{dl} \quad (6.42)$$

where τ_{dl} [seJ/J] is the solar transformity of dilution.

$$Em_{O_2} = m_{O_2} \cdot \tau_{O_2} \quad (6.43)$$

$$Em_{cw} = m_{cw} \cdot \tau_{cw} \quad (6.44)$$

$$m_{cw} = V_{cw} \cdot \rho_w \quad (6.45)$$

$$V_{cw} = V_w \cdot El_{pr} \quad (6.46)$$

τ_{O_2} [seJ/g] is the *UEV* of oxygen, m_{cw} [kg/yr] is the annual mass of the water used for cooling, τ_{cw} [seJ/g] is the *UEV* of the cooling water, V_{cw} [m^3 /yr] is the volume of the water used annually, ρ_w [kg/m^3] is the water density, V_w [m^3 /kWh] is the volume of water required for cooling per kWh of electricity produced (for open-flow cooling system), and El_{pr} [kWh/year] is the annual electricity produced.

$$Em_{eac} = El_{pr} \cdot \zeta \cdot \tau_{eac} \quad (6.47)$$

where ζ [\$/kWh] is the equivalence annual cost (maintenance and investment) and τ_{eac} [seJ/\$] is the solar transformity of this cost. With the annual emery flow defined, solar transformity of the electricity produced by co-firing system is given by:

$$\tau_{el} = \frac{E_{cf}}{W_{an}} \quad (6.48)$$

Moreover, to assess the sustainability of the process, all previously defined flows should be classified to indigenous non-renewable, renewable sources and purchased

inputs and determine aforementioned emergy indices:

$$EYR = \frac{Y}{F} \quad (6.49)$$

$$EIR = \frac{F}{R + N} \quad (6.50)$$

$$ELR = \frac{F + N}{R} \quad (6.51)$$

The equations for the indices were thoroughly explained and given in the work of Odum [Odum 1996] and Brown and Ulgiati [Brown 1997b]. EYR is the emergy yield ratio, calculated as the ratio between the yield (Y , sum of all inputs) and purchased inputs (F) from outside the system. Emergy investment ratio (EIR) is the ratio of purchased inputs and the sum of indigenous renewable (R) and non-renewable (N) inputs. ELR is the emergy loading ratio, the ratio between the sum of the purchased and indigenous non-renewable inputs and the indigenous renewable inputs. Taking into account that the actual source of energy should be considered as an integral part of the system for the indices calculation, coal is classified as non-renewable and biomass as a renewable input. All emergy flows from the transportation processes are considered as purchased resources, considering that the calculation of these flows is based on the diesel fuel consumption. Emergy flow of human labor is classified as purchased resource due to the fact that the employees receive paycheck for their work. The emergy flow of the maintenance is considered as purchased, since it represents the additional labor and material used during the process. The indigenous renewable input furthermore takes into account the dilution, oxygen used for combustion and cooling water emergy flows, due to the assumption that these resources are located within the system. Thus, the inputs are classified as:

$$N = Em_c \quad (6.52)$$

$$R = Em_{bm} + Em_{dl} + Em_{O_2} + Em_{cw} \quad (6.53)$$

$$F = Em_{ctr} + Em_{btr} + Em_{atr} + Em_{em} + Em_{hl} + Em_{eac} \quad (6.54)$$

$$Y = R + N + F \quad (6.55)$$

For the complete environmental assessment, it is not recommended to bring a conclusion based on the results of solely carbon footprint. Therefore, maximum biomass transportation distances are chosen for the comparison of the results from the two applied methods. In the carbon footprint analysis, it represents the max-

imum supply distance of biomass, that allows the co-firing system to be carbon saving compared to the pure coal firing system power plant. In other words, it is the maximum distance defined by the carbon footprint approach for the considered biomass transportation process that allows the co-firing to be beneficial compared to pure coal firing. In the emergy evaluation, maximal transportation distance defines the supply distance of biomass that grants the co-firing to be emergy saving in comparison with the pure coal firing process. Thus, every biomass transport distance longer than the suggested maximum one is less environmentally friendly than the pure coal firing process. Maximum supply distances are given by (using the same principle as Jamali-Zghal et al. [Jamali-Zghal 2013].):

$$D_{bmax}^{cfp} = \frac{CO_2^{pc} - CO_{2,co} - CO_{2,ctr} - CO_{2,atr} - CO_{2,em}}{ND_{bm} \cdot (EF_{up}^d + EF_{co}^d) \cdot \varepsilon \cdot \frac{M_{CO_2}}{M_C} \cdot FC_{btk,fl} \cdot (1 + \gamma_{btk})} \quad (6.56)$$

$$D_{bmax}^E = \frac{Em^{pc} - Em_C - Em_{bm} - Em_{ctr} - Em_{atr} - Em_{em} - Em_{hl} - Em_{dl} - Em_{O_2} - Em_{cw} - Em_{eac}}{ND_{bm} \cdot \tau_d \cdot LHV_d \cdot FC_{btk,fl} \cdot (1 + \gamma_{btk})} \quad (6.57)$$

Where D_{bmax}^{cfp} [km] is the maximum biomass distance allowed by carbon footprint, D_{bmax}^E [km] is the maximum supply distance permitted by emergy evaluation, while CO_2^{pc} [kgCO₂/yr] and Em^{pc} [seJ/yr] are the annual carbon-dioxide emission and emergy flow of pure coal firing in studied power plant, with the same parameters (except $\alpha_{bm} = 0$).

6.3 Case study

In this chapter, comparative study has been undertaken between the pure coal firing and co-firing of coal and biomass for electricity and heat production in power plant located in Poznan, Poland. The first line in power plant is equipped with two OP-140 natural circulation steam boilers, and in the second line one OP-430 boiler is installed. Main properties of installed boilers are given in Table 6.1.

Properties of the installed boilers					
Boiler type	Steam flow [kg/s]	Pressure [10 ⁵ Pa]	Temperature [°C]	Power [MW]	Efficiency [%]
OP- 140	39	150	540	105	90.8
OP- 430	120	151	540	315	90.0

Table 6.1: Properties of the installed boilers

The whole system is consisted of co-firing boilers for electricity and heat production with additional equipment, fuel and ash transport, and employee's home-to-work travel (Fig. 6.1). As a fuel, mixture of coal and biomass is used. Coal

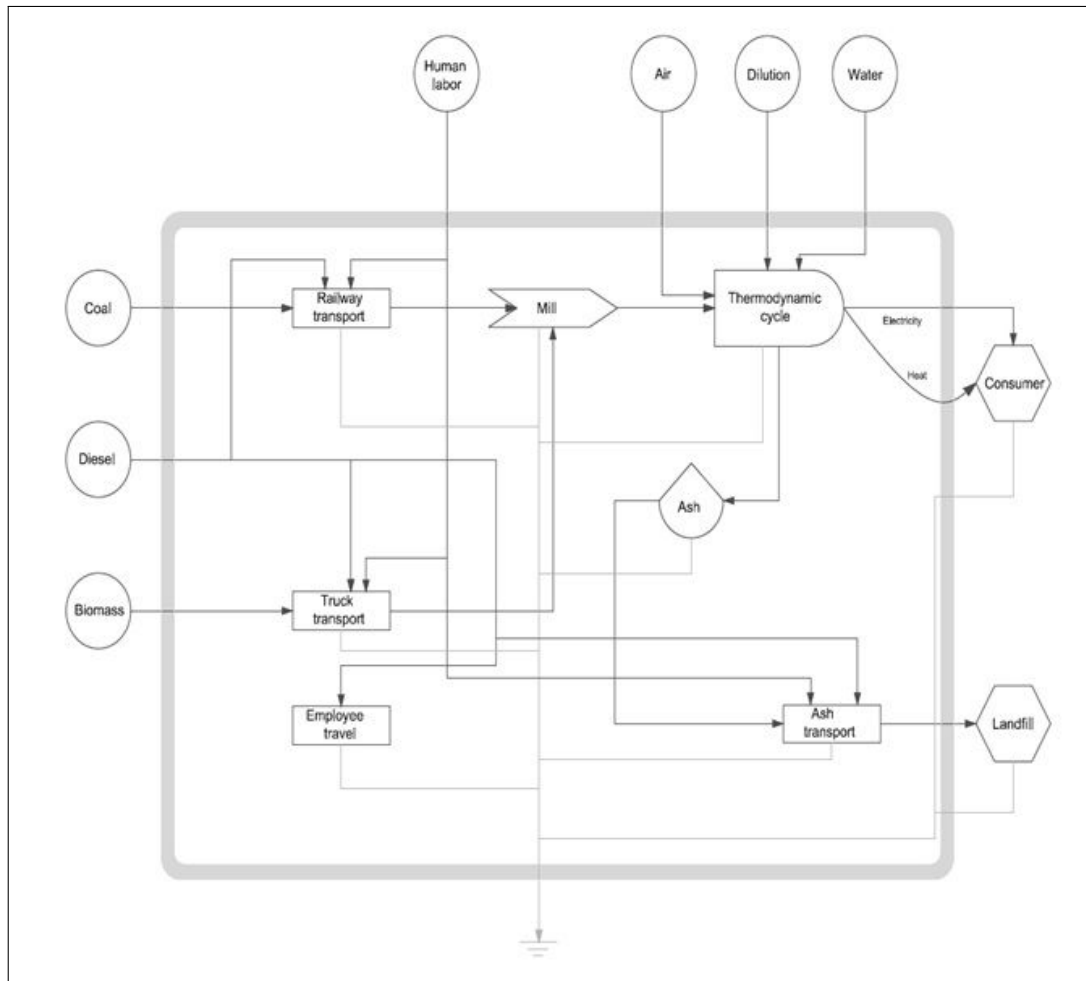


Figure 6.1: Biomass and coal co-firing power plant system

is transported from the mines of Silesia which are located in south-western area of Poland. Semi-covered wagons pulled by the Class 66 locomotives with maximal load of 3600t and average speed of 100 km/h [FRTP 2013] are used for coal transport, covering the distance of 400km from the mines to the power plant. Biomass consisted of wood and various agricultural crops (straw, willow and barley) is transported by trucks with the capacity of 7t. Considering the biomass stock, the distance for supplying is 120 km. Coal and biomass are transported from power plant stocks to mills by conveyers. After the milling and drying process in the mill, fuel mixture is combusted in boilers with tangential firing method. Ash from combustion process is transported to a landfill and cement industries, with 14t freight transport trucks, covering the distance of 200 km. Properties of the considered coal and biomass types are given in Table 6.2 and Table 6.3, respectively. All parameters used in carbon footprint and energy analysis are given in Table 6.4. For the case study, anthracite is chosen as a coal type combusted.

Coal ultimate analysis, as received (including ash and moisture)							
Coal	Carbon [%]	Hydrogen [%]	Oxygen [%]	Nitrogen [%]	Sulfur [%]	Ash [%]	Moisture [%]
Anthracite	82.16	3.22	2.24	1.25	0.63	6.00	4.50
Bituminous	74.93	4.62	9.14	1.27	0.54	4.20	5.30
Sub-bituminous	59.82	4.38	11.67	1.33	1.10	11.20	10.50
Lignite	37.42	2.27	12.23	0.58	0.21	10.40	36.90

Table 6.2: Coal ultimate analysis, source: [Hingman 2008]

Biomass ultimate analysis, as received (including ash and moisture)							
Coal	Carbon [%]	Hydrogen [%]	Oxygen [%]	Nitrogen [%]	Sulfur [%]	Ash [%]	Moisture [%]
Wood	49.50	6.08	44.01	0.12	0.06	0.20	7.80
Willow	49.10	6.01	42.79	0.59	0.05	1.40	10.10
Barley	49.08	5.90	41.55	0.66	0.12	4.70	11.50
Straw	44.16	5.07	40.27	0.90	0.12	9.50	12.40

Table 6.3: Biomass ultimate analysis, source: [Vassilev 2013]

6.4 Results and discussion

The results of conducted carbon footprint analysis and emergy evaluation are represented in Tables 6.5 and 6.6, respectively. From Table 6.5, it is clear that the main source of emissions is the coal combustion process, with almost 99 % of the share, as a consequence of the high carbon content in coal, especially in anthracite. The second source by the quantity of the emissions is the biomass transportation process. Considering that the same type of fuel is used by train and biomass transportation trucks, and taking into account that average fuel consumption of the train is notably higher, the conclusion is that capacity of the mean of transport is the dominant factor for fuel transportation process emissions. With the load capacity of trucks significantly lower than the train load capacity, number of the deliveries for the biomass combusted is extensive, resulting in more diesel fuel consumed, and thus increasing the carbon-dioxide emissions. Furthermore, using railway transport for biomass is unpractical because of the storing capacity issues in power plant (large volume of load defined by low density of biomass) and conditions (temperature and humidity). Compared to aforementioned emission sources, emissions from ash transportation and employees home-to-work traveling are noticeably lower, due to relatively high ash density (average $1500\text{kg}/\text{m}^3$ [INCAB 2013] compared to average $18\text{ kg}/\text{m}^3$ [Reisinger 2006] for straw and $340\text{ kg}/\text{m}^3$ for wood [Preto 2007] and low car fuel consumption).

Parameters of the study				
Definition	Item	Unit	Value	Reference
Weight percentage of wood in biomass mixture	$\alpha_{b,w}$	-	0.25	[-]
Weight percentage of willow in biomass mixture	$\alpha_{b,wl}$	-	0.25	[-]
Weight percentage of barley in biomass mixture	$\alpha_{b,ba}$	-	0.25	[-]
Weight percentage of straw in biomass mixture	$\alpha_{b,s}$	-	0.25	[-]
Weight percentage of biomass mixture in co-firing blend	α_{bm}	-	0.20	[-]
Weight percentage of coal in co-firing blend	α_c	-	0.80	[-]
Air access coefficient	α_{aa}	-	1.4	[-]
Air density	ρ_a	kg/m ³	1.25 ^a	[WS 2013]
Installed power	P	MW	525	[-]
Coal delivery distance	D_c	km	800	[-]
Biomass delivery distance	D_{bm}	km	240	[-]
Ash transportation distance	D_a	km	200	[-]
Daily distance for employee home-to-work travel	d_{em}	km	20	[-]
Emission from coal combustion	EF_C	kgCO ₂ /MJ	0.095	[ADEME 2010]
Upstream emission of the diesel fuel	EF_{up}^d	kgC/l	0.08	[ADEME 2010]
Combustion emission factor for diesel	EF_{co}^d	kgC/l	0.73	[ADEME 2010]
Oxidation factor for diesel	ε	-	0.99	[EPA 2005]
Molecular weight of carbon-dioxide	M_{CO_2}	g/mol	44.01	[EPA 2005]
Molecular weight of carbon	M_C	g/mol	12.01	[EPA 2005]
Maximum train capacity	$C_{tr,max}$	t	3600	[FRTP 2013]
Maximum capacity of biomass transport trucks	$C_{btk,max}$	t	7	[Shunping 2010]
Maximum capacity of ash coll. trucks	$C_{atk,max}$	t	14	[Shunping 2010]
Average train fuel cons. with full load	$FC_{tr,fl}$	l/km	5.33 ^b	[AECOM 2011]
Average train fuel cons. without a load	$FC_{tr,wl}$	l/km	2.21 ^c	[AECOM 2011]
Average biomass transport truck fuel cons. with full load	$FC_{btk,fl}$	l/km	0.242	[Shunping 2010]
Average biomass transport truck fuel cons. without a load	$FC_{btk,wl}$	l/km	0.181	[Shunping 2010]
Average ash coll. truck fuel cons. with full load	$FC_{atk,fl}$	l/km	0.267	[Shunping 2010]
Average ash coll. truck fuel cons. without a load	$FC_{atk,wl}$	l/km	0.207	[Shunping 2010]
Percentage of coal load released during the rail transport	δ	%	0.001	[Ferreira 2003]
Power plant employment factor	θ	emp./MW	0.18	[Singh 2001]
Average wind speed in Poznan	v_a	m/s	3.35	[WS 2013]
Water density	ρ_w	kg/m ³	1000	[Macknick 2012]
Volume of water required for cooling	V_w	m ³ /kWh	0.094	[Macknick 2012]
Annual electricity production	E_{pr}	kWh/yr	1.89E+09	[-]
Background concentration of carbon-dioxide in Poznan	c_{ref}	kg/m ³	7.91E-04	[Chmura 2005]
Low heating value of the diesel fuel	LHV_d	J/l	3.65E+07	[Yao 2010]
Average number days worked annually per employee	n_{wd}	days/yr	260	[EFLW 2011]
Hours worked daily by one employee	n_h	h/yr	8	[-]
Annual investment and maintenance costs	ζ	[/kWh]	0.085 ^d	[DECC 2014]

^a Air density for 10°C which is the average air temperature during a year in Poznan

^b It is considered that during a full load, train is using throttle position 8

^c It is considered that without a load, train is using throttle position 4

^d The price was converted to dollars following the exchange cours on the day of the calculation

Table 6.4: All parameters used in carbon footprint and emergy analysis

From Table 6.6, it is noticeable that the most significant energy flow is from the coal combustion. This is a direct consequence of the fact that extensive environmental inputs were required for creation of the coal (growing the required biomass and then its carbonization under high pressure and temperature) during a long

time period. The most influential input is the maintenance that uses high energy materials and processes for the heavy machinery repairs. In the open power plant cooling system, water from the river that is used for cooling process in the condenser, is pumped back to the river with higher temperature (due to the amount of heat received), creating the large-scale impact on the river eco-system. Next most influential environmental input is the oxygen required for combustion due to the oxidation process. Oxygen from air reacts with the carbon from the fuel, resulting in carbon-dioxide, and thus creating the major source of emissions (see Table 6.5). Moreover, energy flow of the biomass is the fifth highest value, as a result of various inputs (agricultural farming, chemical pesticides etc.) for creating the biomass stock. Compared to aforementioned energy flows, other inputs have a minor impact on the environment.

Analyzing the energy indices from Table 6.7, it is clear that use of the non-renewable resources (i.e. coal) have the highest impact on the environmental performance. The values of *EYR* and *EIR* decrease and increase (respectively) with the addition of the biomass due to the fact that specific energy of the biomass is lower than the one for coal and the system was calibrated to produce the same amount of energy in all cases regarded. Furthermore, it can be concluded that the pressure on the local ecosystem is lower for the co-combustion due to the lower values of the energy loading ratio. Finally, increased inputs result in higher solar transformity value, suggesting that for producing the same quantity of electricity, the environmental performance is lower in the case of the pure coal combustion.

Results of carbon footprint analysis			
Definition	Item	Unit	Value
Annual emissions from coal combustion process	$CO_{2,co}$	[kgCO ₂ /yr]	1.53E+09
Annual emissions from coal transportation process	$CO_{2,ctr}$	[kgCO ₂ /yr]	6.76E+06
Annual emissions from biomass transportation process	$CO_{2,btr}$	[kgCO ₂ /yr]	1.46E+07
Annual emissions from ash transportation process	$CO_{2,atr}$	[kgCO ₂ /yr]	1.94E+06
Annual emissions from employees home-to-work travel	$CO_{2,em}$	[kgCO ₂ /yr]	3.56E+05
Total annual emissions from co-firing system	$CO_{2,cf}$	[kgCO ₂ /yr]	1.55E+09

Table 6.5: Results of carbon footprint analysis

Energy evaluation results						
Item	Input type	Unit	Input	UEV^* [seJ/unit]	Solar energy [seJ/yr]	Reference
Coal	N	J	1.61E+16	1.09E+05 ^a	1.76E+21	[Brown 2010]
Biomass	R	kg	1.28E+08	9.96E+10 ^b	1.28E+19	[Sha 2012]
Coal transportation	F	J	3.15E+13	1.72E+05 ^c	5.42E+18	[Odum 1996]
Biomass transportation	F	J	6.78E+13	1.72E+05	1.17E+19	[Odum 1996]

Continued on next page...

Item	Input type	Unit	Input	UEV* [seJ/unit]	Solar emergy [seJ/yr]	Reference
Ash transportation	<i>F</i>	J	9.02E+12	1.72E+05	1.55E+18	[Odum 1996]
Employees traveling	<i>F</i>	J	1.66E+12	1.72E+05	2.85E+17	[Odum 1996]
Human labor	<i>F</i>	h	1.98E+05	6.25E+13 ^d	1.24E+19	[Odum 1996]
Dilution	<i>R</i>	J	1.37E+13	1.44E+03	1.97E+16	[Ulgiati 2002]
Oxygen for combustion ^e	<i>R</i>	g	1.67E+12	5.16E+07	8.64E+19	[Bargigli 2009]
Cooling water	<i>R</i>	g	1.78E+14	6.38E+05	1.13E+20	[Sha 2012]
Annual equivalence cost	<i>F</i>	\$	3.91E+8	1.20E+12	4.77E+20	[Ulgiati 2002]

^a Solar transformity for weighted mass anthracite, with drilling/milling accounted

^b UEV of biomass mixture

^c UEV of diesel fuel

^d UEV of human labor is calculated taking into account individual emergy flows of employees

with different level of education: 25 with high-school, 60 with college and 10 employees with post-college education.

Solar transformity is given by:

$$\tau_{hl} = \frac{n_{em,pc} \cdot Em_{epc} + n_{em,c} \cdot Em_{ec} + n_{em,hc} \cdot Em_{ehc}}{n_{em,pc} + n_{em,c} + n_{em,hc}} \cdot \frac{1}{8760}$$

where $n_{em,pc}$, $n_{em,c}$ and $n_{em,hc}$ are the numbers of employees with post-college, college and high school education, and Em_{epc} , Em_{ec} and Em_{ehc} [seJ/ind/yr] their individual emergy, given by Odum [Odum 1996]

^e Some researcher recommend to not take into account for the oxygen of combustion in the calculation

* The baseline of Brown and Ulgiati [Brown 2010] has been used to calculate the UEVs

Table 6.6: Emergy evaluation results

Emergy indices				
Definition	Item	Unit	Co-combustion	Pure coal combustion
Renewable inputs	<i>R</i>	[seJ/yr]	2.13E+20	2.01E+20
Non-renewable inputs	<i>N</i>	[seJ/yr]	1.76E+21	1.99E+21
Purchased inputs	<i>F</i>	[seJ/yr]	5.08E+20	4.97E+20
Yield	<i>Y</i>	[seJ/yr]	2.48E+21	2.69E+21
Emergy yield ratio	<i>EYR</i>	[-]	4.87	5.41
Emergy investment ratio	<i>EIR</i>	[-]	0.26	0.23
Emergy loading ratio	<i>ELR</i>	[-]	10.65	12.39
Solar transformity of electricity	τ_{el}	[seJ/J]	1.50E+05	1.63E+05

Table 6.7: Emergy indices

For better understanding of the maximum biomass supply distance, the study is conducted for two different types of coal with most diverse composition: lignite and anthracite. Comparing the maximal allowed distances, it is noticeable that the distances permitted by the carbon footprint are longer than the ones permitted by emergy evaluation (9121km compared to 3494km for lignite and 9142km compared to 4668km for the anthracite, see Fig. 6.2). To produce the same amount of electricity with the lignite as with the anthracite, larger quantities of coal are required due to significantly lower heating value of lignite (see Eqs. (6.6) and (6.7)).

Therefore, combustion of larger quantities of lignite ($1.07\text{E}+09\text{kg}$) which has lower carbon content (37.42%) have a similar trend in total emissions as the combustion of smaller quantities of anthracite ($5.11\text{E}+08\text{kg}$) with higher carbon content (82.16%). The distances granted by the energy evaluation imply that combusting the higher amounts of lignite has more pressure on the environment than the combustion of smaller quantities of anthracite, since the difference between distances allowed by energy evaluation differ for 1174km.

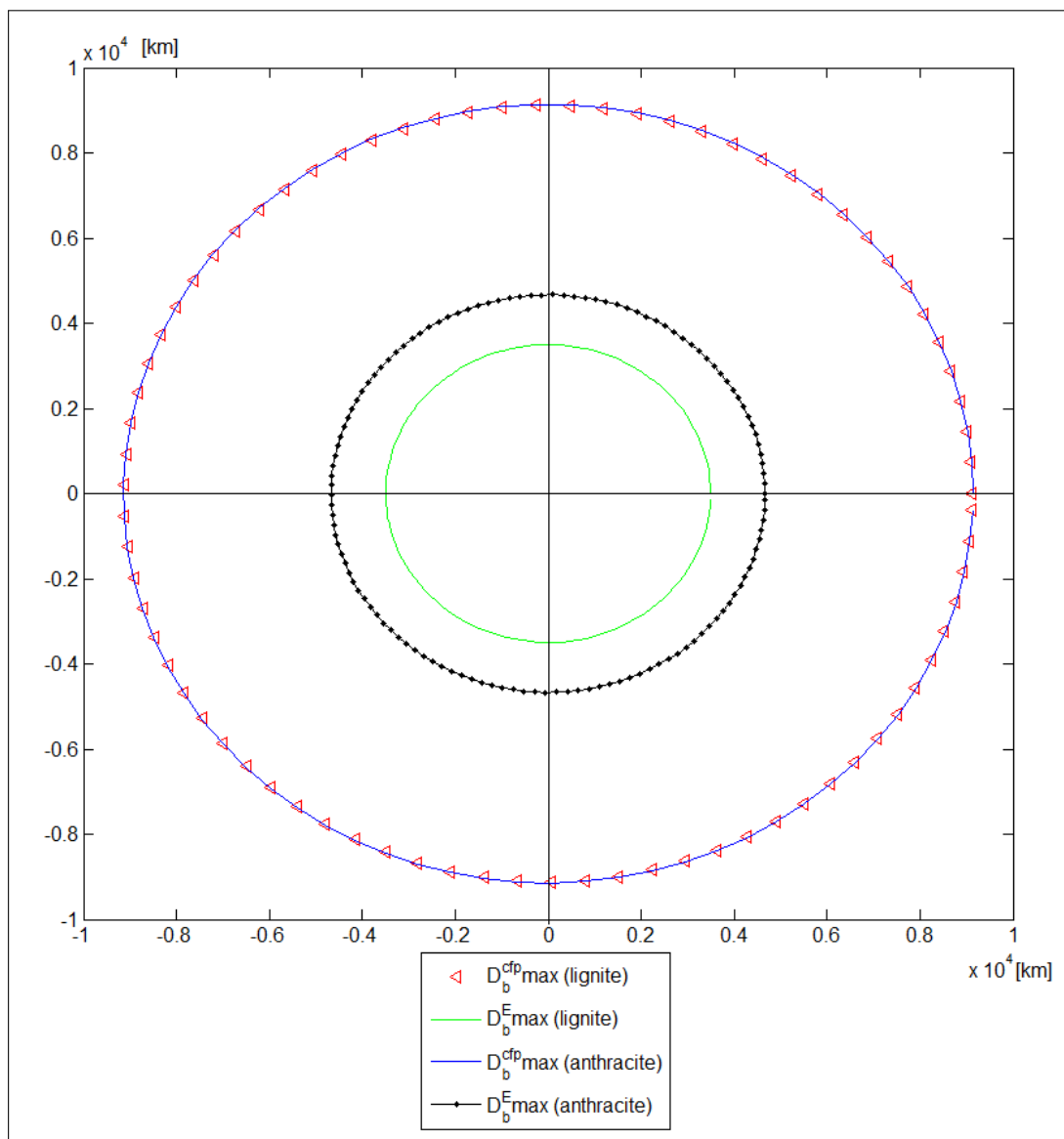


Figure 6.2: Maximum biomass distances permitted by carbon footprint and energy evaluation

6.4.1 Sensitivity analysis

To examine the influence of various parameters on the results of the study, the sensitivity analysis is conducted. This analysis takes into account possible changes in fuel types and their respective proportions in the combustion mixture, as well as capacities of means of transportation and distances of the power plant from the fuel stocks. As mentioned in the Subsection 6.2.1, the key parameter of this study are the properties of the fuel mixture used for combustion process, especially the low heating value. Low heating value of the mixture is a direct consequence of the compositions and proportions of coal and biomass types from which the combustion mixture is consisted.

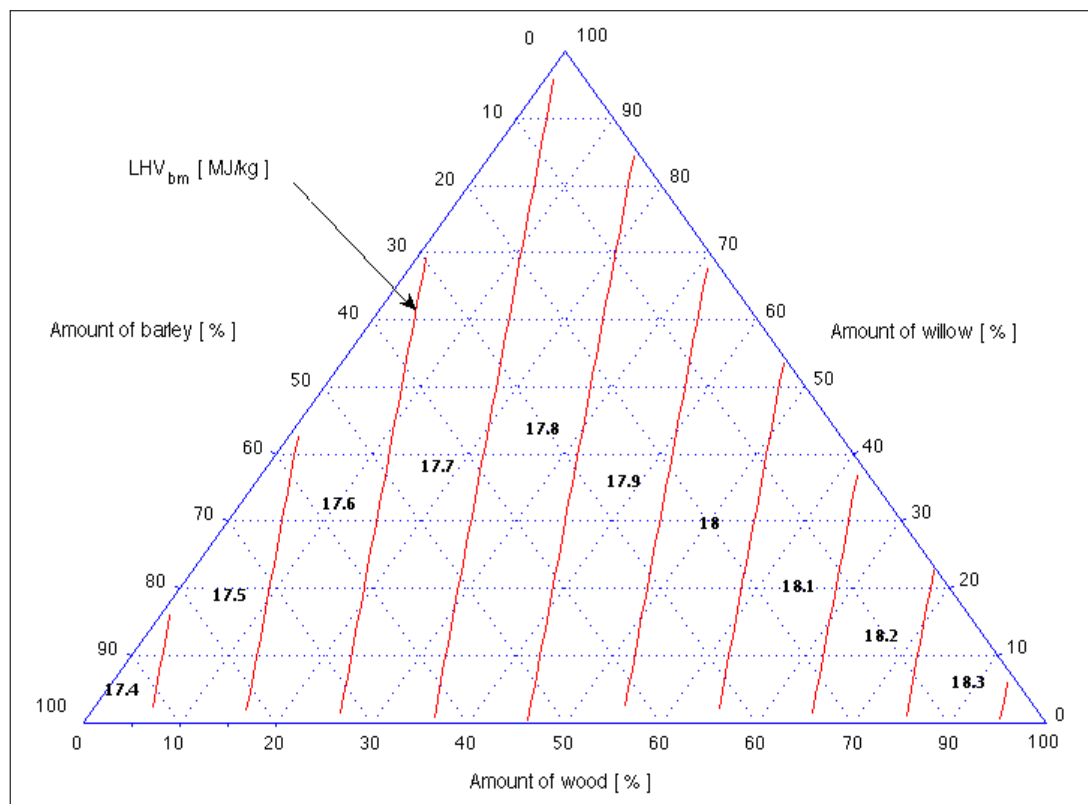


Figure 6.3: Ternary diagram for biomass mixture low heating value depending on a composition

Concerning the biomass, which is consisted from four different types, the proportions of those types in mixture can continuously vary, due to different feedstock availability levels during the year. The influence of biomass composition change mixture's low heating value is represented with the ternary diagram on Fig. 6.3. With the increase of biomass with higher carbon content (in this particular case wood), the low heating value of the biomass mixture will proportionally increase. Therefore mixture consisted of 95% wood has the maximal low heating value, 18.3MJ/kg. The

variation of the low heating value due to the storing conditions and pre-treatment method are not taken into account in this study, due to the fact that in the regarded power plant there is no pre-treatment facility, and it is assumed that the storing conditions are constant.

Taking into account that the main source of carbon-dioxide emissions comes from the coal combustion, the total emissions increases with firing coal types that consist higher amounts of carbon. Considering that the level of carbon in fuel is the main parameter for its low heating value, it is possible to express the low heating value-carbon emissions dependency, see Fig. 6.4. As shown, the highest emissions are from the anthracite combustion, and the lowest from the lignite combustion. Mixing the several types of coal for the combustion can also influence the emission efficiency. For example, mixture of approximately 60% of lignite and 40% of bituminous coal or 40% of lignite and 60% of anthracite will result in the same emissions as the one from pure sub-bituminous coal combustion.

Furthermore, the geological origin of the coal must be considered, as the environmental inputs for creating the coal were different throughout the history [Brown 2010]. For instance, Triassic-Jurassic extinction event created harsh environment for the biosphere [Hodych 1992], making the production of biomass stock obscure during the Jurassic period. Thus, the environment inputs for creating the coal during that period were significant, resulting in high energy value. Moreover, the appearance of bark-bearing threes and lower sea levels (compared to Devonian period) in Carboniferous created conditions for creation of large coal deposits [Stanley 1999], effecting the high energy flow. Coal from the Devonian period has a high energy value as a consequence of the incomplete separation of the continents that resulted in low amounts of terrestrial biomass.

Solar transformities for coal by geological age		
Geologic age	Transformities of hard coals ^a [seJ/J]	Transformities of soft coals ^b [seJ/J]
Devonian	1.06E+05	7.33E+04
Carboniferous	1.07E+05	7.96E+04
Permian	9.02E+04	6.56E+04
Triassic	9.11E+04	6.63E+04
Jurassic	2.57E+05	1.83E+05
Cretaceous	4.96E+04	3.67E+04
Tertiary	5.08E+04	3.75E+04
Weighted mean	1.09E+05	3.75E+04

^a, ^b values for milling/drilling processes are included

Table 6.8: Solar transformities for coal by geological age

The annual emergy flow for combusting lignite or anthracite with diverse amounts of biomass is represented on Fig. 6.5, using the emergy transformities for

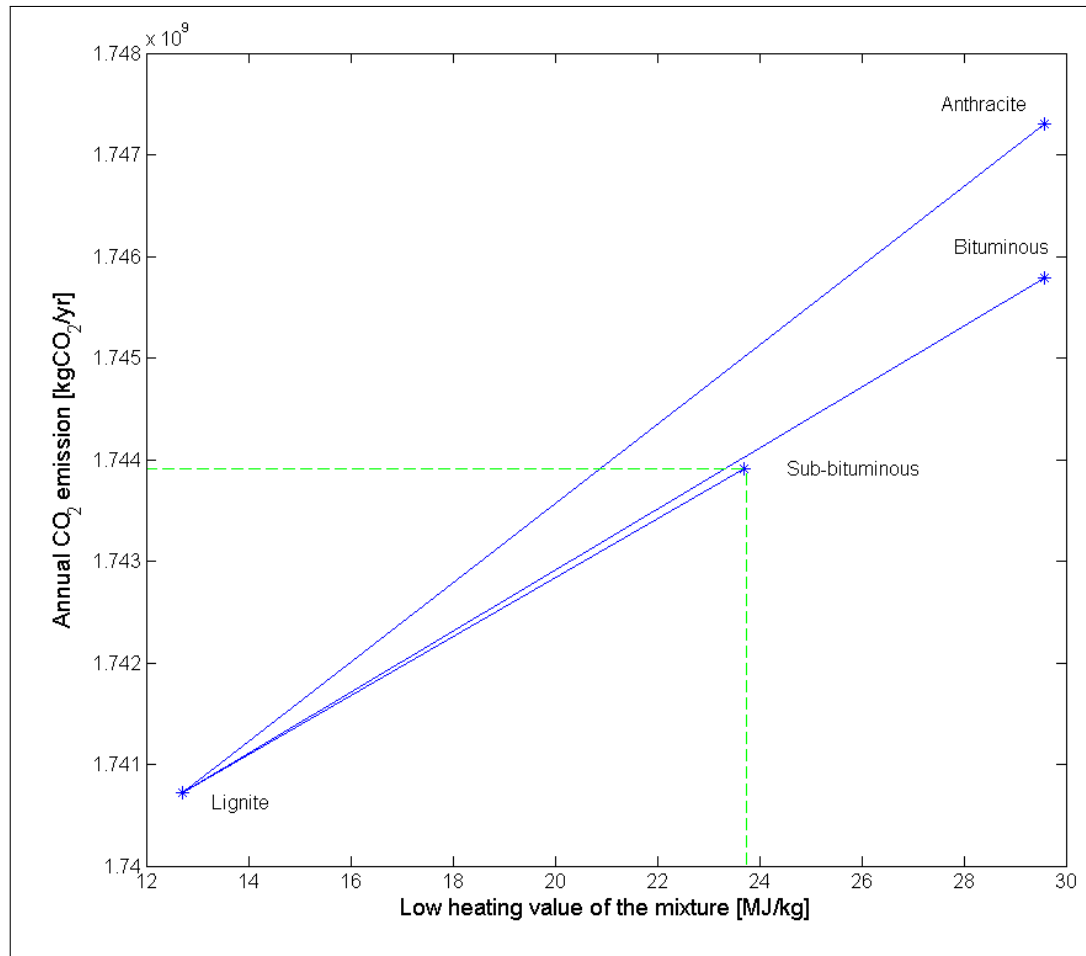


Figure 6.4: Influence of coal low heating value on annual carbon-dioxide emissions from co-combustion system ($\alpha_{aa} = 1.4$, $\alpha_b = 0$, $D_c = 800km$, $D_a = 200km$, $D_b = 240km$, $d_{em} = 20km$)

soft coal (lignite) and hard coal (anthracite) calculated by Brown et al.[Brown 2010], with added values for the coal drilling/milling from the mine, see Table 6.8. Values for the Jurassic period are not showed on the diagram for the reason of better scaling. The required ratios of biomass with different coal types and their geological origin for achieving the same annual emergy flow can be determined for the diagram. For example, combustion of 47% of biomass with 53% of the anthracite from the Carboniferous period has the same emergy flow as the pure combustion of lignite from the Devonian period (as showed with the dashed line on the diagram).

To compare the impact of coal type combusted on annual emergy flow, it is more suitable to use weighted mean values for soft coals and hard coals. Results for lignite and anthracite are shown on Fig. 6.6, obtained by using the weighted mean transformities [Brown 2010]. Again, emergy flows of the drilling/milling the coal from the mine are taken into account. Results revealed that co-combustion of the

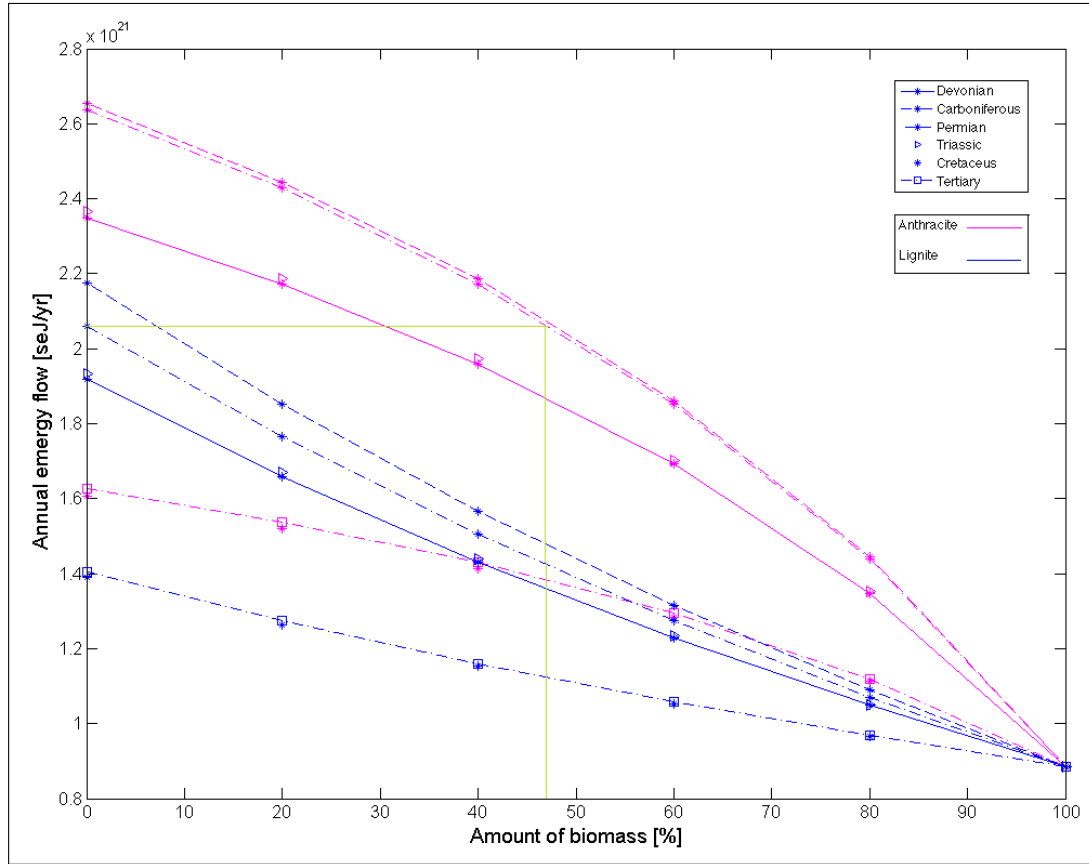


Figure 6.5: Comparison of co-combustion system energy flows for lignite and anthracite with different geological origin ($\alpha_{aa} = 1.4$, $\alpha_{bw} = 0.25$, $\alpha_{bwl} = 0.25$, $\alpha_{bba} = 0.25$, $\alpha_{bs} = 0.25$, $D_c = 800km$, $D_a = 200km$, $D_b = 240km$, $d_{em} = 20km$)

mixture consisted from 40% of biomass and 60% of anthracite has the same energy flow as pure lignite combustion (dashed line on the diagram).

The main factor that influences the energy flow of oxygen used for combustion is the level of oxygen in fuel composition. Combustion of the coal that has small amounts of oxygen in the composition (approximately 2-13%, see Table 6.2) requires considerable amounts of air during the process. Biomass consists high levels of oxygen compared to coal (approximately 40-45%) resulting in low quantities of oxygen used in combustion process. Consequently, increasing the proportion of the biomass in the fuel mixture results in low air consumption, decreasing the energy flow of the air, as shown on Fig. 6.7. Results indicate that energy flow of air drops for about 2% with the 20% increase of biomass proportion.

To assess the stress to the environment caused by aforementioned factors, their influence on the environmental loading ratio is examined. As mentioned in Subsection 6.2.3, the higher the ELR indicates the higher environmental pressure. Furthermore, impact of the coal geological origin is observed. From the results illustrated

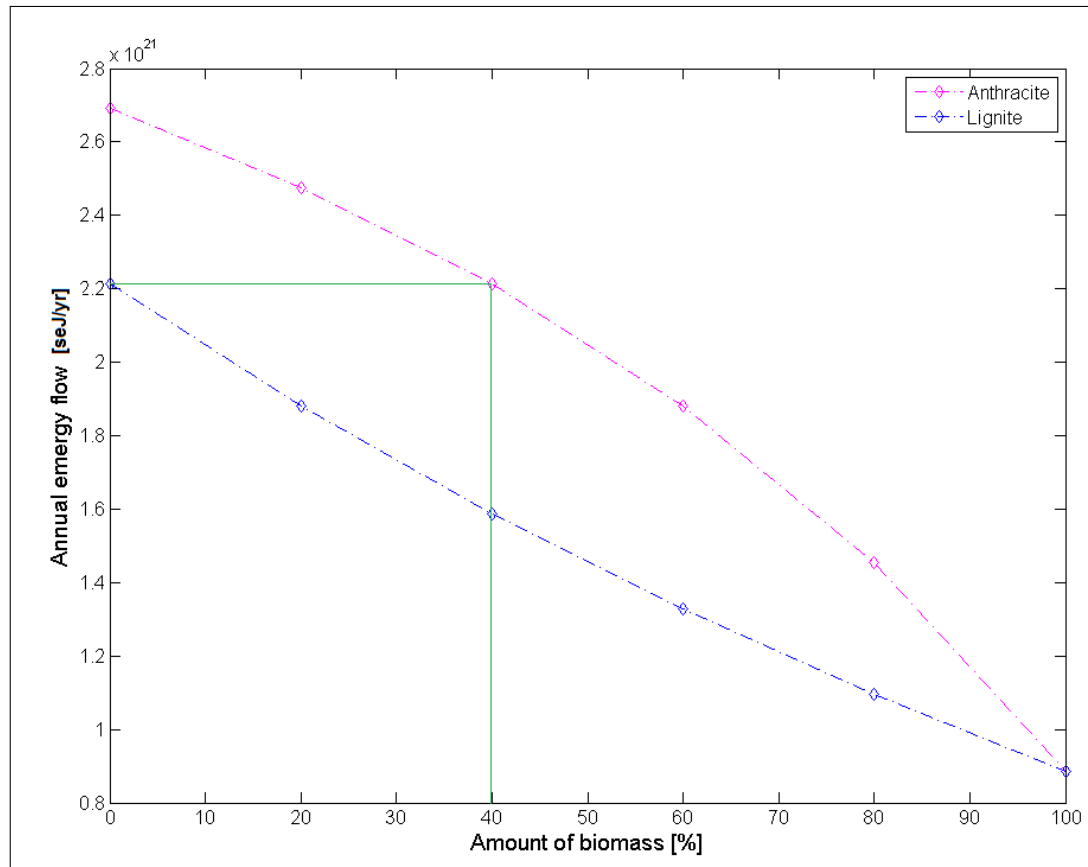


Figure 6.6: Comparison of co-combustion system energy flows for lignite and anthracite based on weighted mean ($\alpha_{aa} = 1.4$, $\alpha_{bw} = 0.25$, $\alpha_{bwl} = 0.25$, $\alpha_{bba} = 0.25$, $\alpha_{bs} = 0.25$, $D_c = 800km$, $D_a = 200km$, $D_b = 240km$, $d_{em} = 20km$)

on Fig. 6.8, it is clear that the most substantial stress on the environment is caused by the combustion of the coals from the Jurassic and the Carboniferous period. The environmental loading ratio of the system that uses the coal from these periods is high, due to the significant purchased high-energy input. Furthermore, pressure on the environment is always higher for combustion system that uses anthracite than lignite, for all geological period origins.

On Fig. 6.9, the change of *ELR* depending on low heating value of the fuel mixture is represented. Furthermore, due to the strong connection between the low heating value and the mixture's composition, the *ELR*-composition dependency can also be represented on the same diagram. In this case, results demonstrated on the diagram are for anthracite and biomass mixture. Increasing the amount of biomass decreases the input of purchased energy resources (coal) that required more environmental inputs to be produced in the first place. Taking into account the results from this study, the pressure on the environment is lowered for approximately 14% (for crossing from 0% to 20% biomass) and even 45% (for crossing from 80%

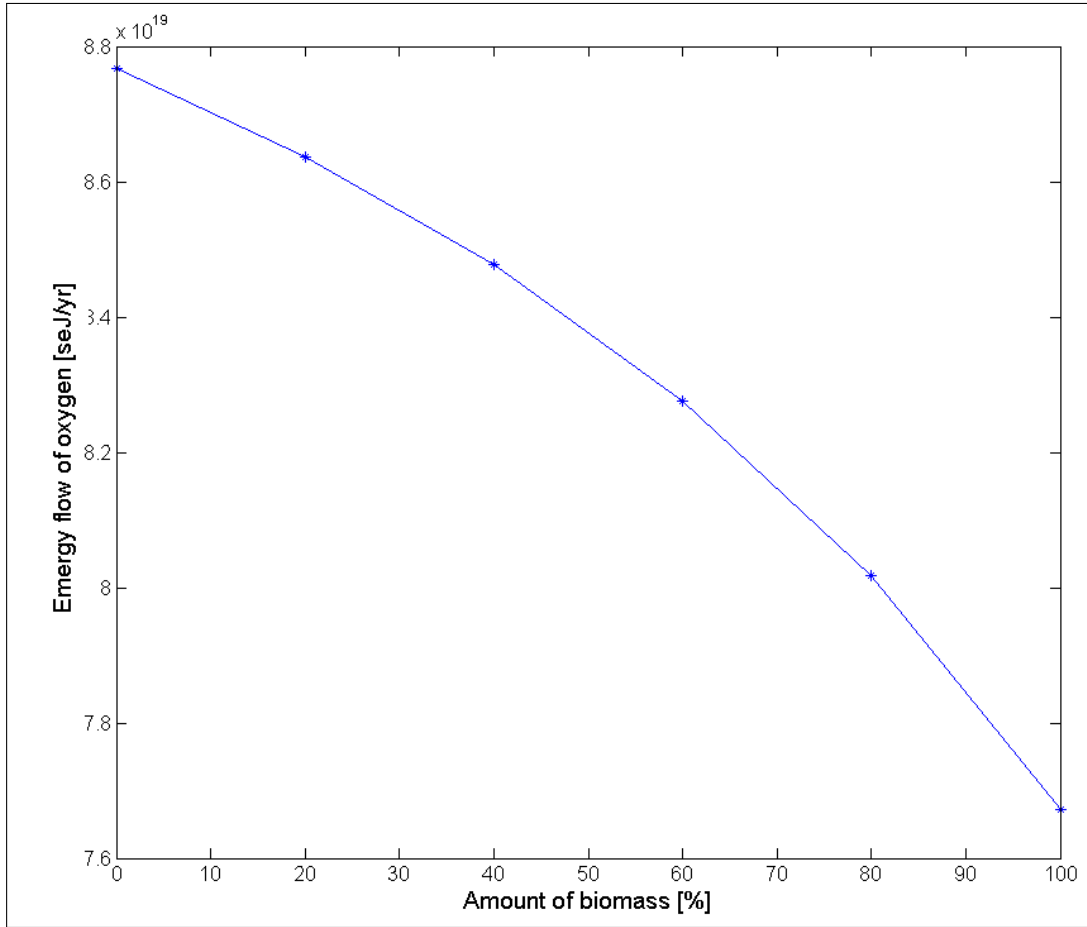


Figure 6.7: Influence of biomass proportion in fuel mixture on emergy flow of air used for combustion ($\alpha_{aa} = 1.4$, $\alpha_{bw} = 0.25$, $\alpha_{bwt} = 0.25$, $\alpha_{bba} = 0.25$, $\alpha_{bs} = 0.25$, $D_c = 800km$, $D_a = 200km$, $D_b = 240km$, $d_{em} = 20km$)

to 100% biomass) by adding 20% of the biomass to the combustion mixture.

Finally, the impact of distances and transportations means capacities on the results is investigated. From Table 6.9, it is clear that represented parameters have the minor impact on the results of the study (less than 1%), compared to the other factors. These results indicate the importance of fuel compositions and the low heating values in the studied system. Authors also note that the increase in the storage capacity of the biomass transportation mean (for example, transporting biomass with train instead of trucks) would cause two major problems in the biomass storage in the power plant. The first one is that considering the low density of biomass, significant increase in storage capacity would be required. The second problem is that maintaining the storage conditions (temperature, humidity etc.) requires additional investment and operating costs.

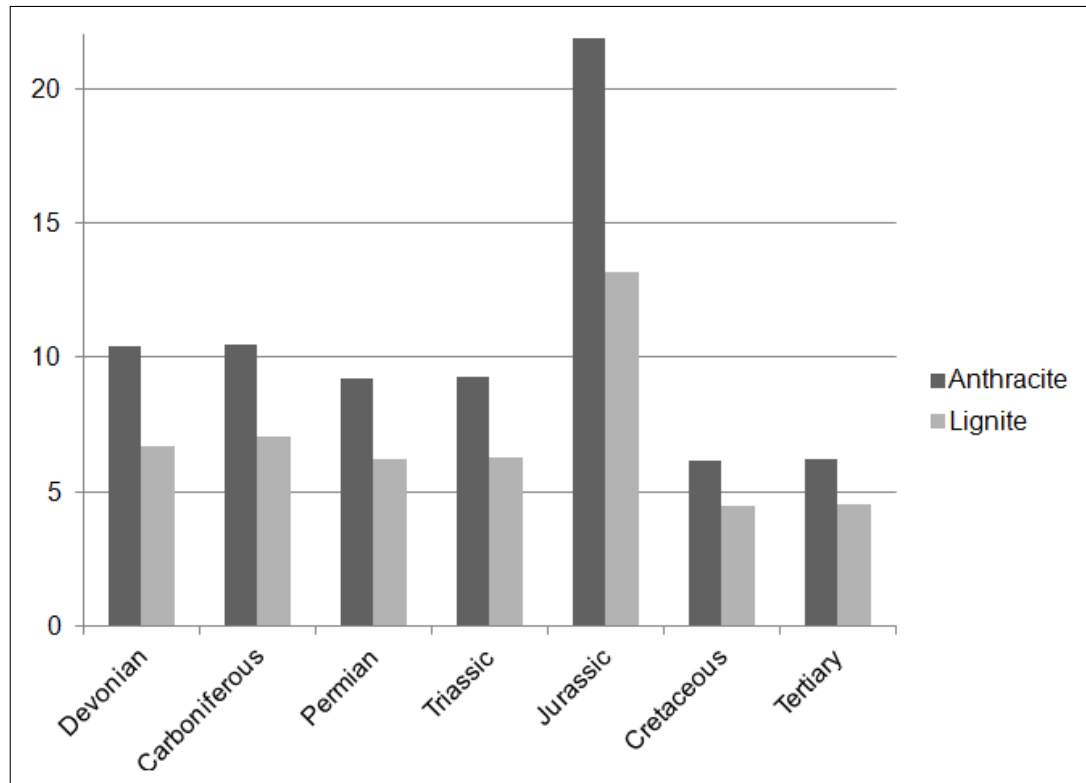


Figure 6.8: Influence of the geological origin of the coal on the environmental loading ratio of the system

Impacts on the results of the study		
Change of parameter	Change of annual emission $\Delta CO_{2,cf} [\%]$	Change of annual energy flow $\Delta Em_{cf} [\%]$
$\Delta D_c [25\%]$	0.04	0.04
$\Delta D_b [25\%]$	0.09	0.08
$\Delta D_a [25\%]$	0.01	0.01
$\Delta d_{em} [25\%]$	0.002	0.001
$\Delta C_{tr,max} [25\%]$	0.05	0.05
$\Delta C_{btk,max} [25\%]$	0.07	0.06
$\Delta C_{atr,max} [25\%]$	0.08	0.07

Table 6.9: Impact of transport distances and capacities on the results of the study

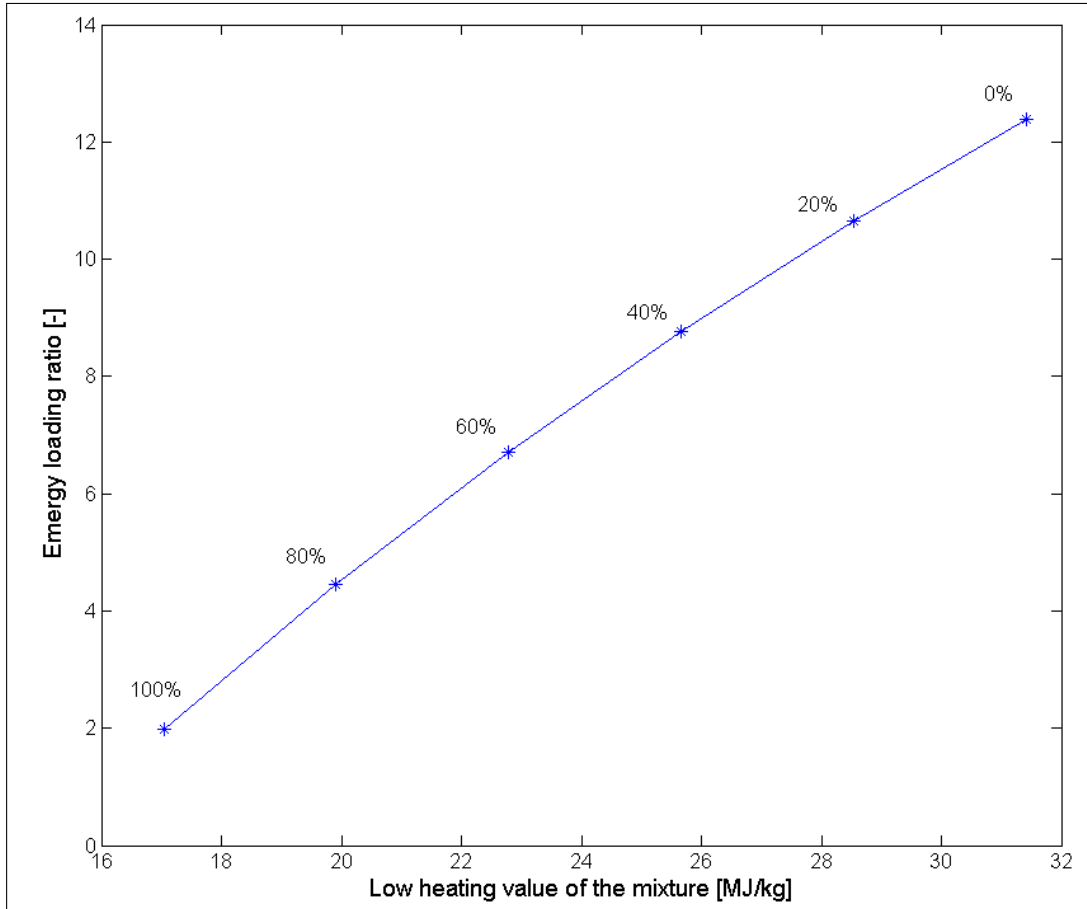


Figure 6.9: The influence of low heating value and composition of the mixture on ELR ($\alpha_{aa} = 1.4$, $\alpha_{bw} = 0.25$, $\alpha_{bwl} = 0.25$, $\alpha_{bba} = 0.25$, $\alpha_{bs} = 0.25$, $D_c = 800km$, $D_a = 200km$, $D_b = 240km$, $d_{em} = 20km$)

6.5 Conclusion of the chapter

This chapter presents a comprehensive comparison between the pure coal combustion and co-combustion of the biomass and coal for electricity production from the environmental point of view. Composition of the fuel types used and their low heating values are the main factors that define the impact on the environment considering that fuel combustion is the main source of emissions and has the most significant energy flow. However, using only low heating value of the fuel type is not suitable, due to the composition influence on the other environmental inputs, especially oxygen used for combustion, cooling water and dilution. Furthermore, geological origin of different coal types should be taken into account, considering that the resources for creating the fossil fuels had different availability throughout the history. Accordingly, the fuels that required considerable environmental inputs to

be created in the first place, increase the emergy flow of the whole system (especially fuels created during Carboniferous and Jurassic period).

The maximum biomass transportation distances suggest that the environmental impact of co-firing cannot be efficiently assessed by taking into account only carbon-dioxide emissions. The emergy evaluation counts inputs of the indigenous renewable, non-renewable resources and purchased inputs, giving more reliable information about the environmental performance of the studied system. Consequently, the distance that is permitted by the emergy evaluation is 49-62% shorter (depending on the coal type and geological origin). The sensitivity analysis showed that co-firing has the better environmental performance than the pure coal combustion in all cases examined. Adding approximately 20% of the biomass decreases the carbon-dioxide emissions for 11-25% and the emergy flow for 8-15%. The analysis of emergy indices showed that the co-firing is more environmentally friendly compared to pure co-firing. The lower value of the emergy investment ratio (10.65 compared to 12.39) suggests lower pressure on the ecosystem for the co-firing.

However, the technical challenges of co-firing and both advantages and disadvantages of using biomass should be considered for clear final decision. The technical challenges of co-combustion are the negative impact of the biomass increase in the fuel mixture on the efficiency, fouling and corrosion of the boiler and utilization of fly ash. Additionally, economic aspects of retrofitting should be taken into account. For the power plants with high capacity, the effect on the initial and operating costs are not so significant as for the plants with the capacity under 50MW, but the increase in the price of produced electricity and effect on the market should be considered. Biomass is widely available throughout the world (except in the areas with extreme climate) and theoretically inexhaustible fuel source with no harmful emissions and can decrease the current dependency on fossil fuels. However, due to a lower heating value, the significant amounts are required to substitute the fossil fuels. Consequently, more land would be required for biomass growth to satisfy the increasing demand, resulting in major topological changes.

Conclusion and perspectives

This chapter describes the conclusions that were reached by answering the research questions of this thesis.

RQ1: Is it possible, and if so how, to assess the environmental impacts resulting from the exploitation of mineral resources, taking into account their abundance, their chemical and physical properties and the effects of their extraction?

In Chapter 1, emergy and exergy assessment tools have been combined to evaluate the environmental impact of mining, considering only the natural exergy of the mineral. Based on the assumption that every group of dispersed mineral is a co-product of the Earth's crust, an evaluation model was proposed that permits to calculate the specific emergy of mineral reserves based on the chemical and concentration exergy of the mineral, its abundance and concentration in the mine. To assess the impact of mining on the ecosystem, a methodology is introduced that permits to quantify the theoretical minimum emergy that Nature should invest to restore the post-mining land. Although different methods could be envisaged to calculate the emergy of the Earth's crust, the proposed evaluation model remains valid whatever numerical value of the latter is chosen. The specific emergy of about 40 main commercially used minerals have been calculated, respecting the material hierarchy as the specific emergy rise with scarcity (see Citations 2.2 and 2.3). The application to some Australian mineral reserves shows that the specific emergy of the reserve decreases with its ore grade. Theoretically, when all the reserve is exhausted its specific emergy tends to the crustal specific emergy of the mineral, representing the lowest position that the reserve can ever reach in the material hierarchy (see Citations 2.6 and 2.7). Finally, the application to the US copper mines reveals that the ecosystem will loose about $7.26 \text{ E}+20 \text{ seJ}$ when all the copper reserves have been extracted and that Nature should invest at least about $1.81 \text{ E}+16 \text{ seJ}$ to restore the post-mining land.

Citation 2.2 (*Environmental accounting*)

« *Emergy per unit mass (seJ/g) indicates the position a mineral has on the scale of Earth scarcity and unit value.* »
(Odum [Odum 1996], p.121)

Citation 2.3 (*Environmental accounting*)

« *In general, the scarce products from the Earth are those that required more work for their formation and concentration. Therefore they tend to have higher Emergy contents. Burnett [Burnett 1981] found that materials with more emergy contribution were less abundant.* » (Odum [Odum 1996], p.117)

Citation 2.6 (An energy hierarchy law for biochemical cycles)

«... any increase in concentration of material requires an increase in the energy per mass. When concentration increase in some part of a biogeochemical cycle, the emergy per mass increases.» (Odum [Odum 2000a])

Citation 2.7 (An energy hierarchy law for biochemical cycles)

«When material disperses, the stored emergy decreases.» (Odum [Odum 2000a])

RQ2: Is it possible, and if so how, to evaluate the environmental performance of recycling, taking into account the chemical, physical and thermodynamic limits of the process?

The emergy evaluation combined with an exergetic life cycle assessment has been used to assess the environmental impacts of material and quality losses during consecutive metallurgical recycling processes. The integration of the *ELCA* approach enables the emergy evaluation to take into account the quality losses of the recycled material. Due to the fact that the transformity of the recycled material is always increasing with each recycling cycle, the classic evaluation model based on Odum's approach (see Citation 4.2) is not suitable for assessing neither the limits nor the benefits of recycling. Therefore, an average transformity based on Ulgiati's approach (see Citation 4.3) is proposed that allows to determine the environmental performance of the recycled materials, taking into account all previous recycling cycles the material has passed through. Three sustainability ratios have been defined to evaluate the environmental performance of recycling cycles:

- *Resource efficiency ratio* α : The ratio of the emergy used in the recycling process to the emergy of the primary material. It is a measure of the resource efficiency of the recycling process.
- *Quality ratio* β : The ratio between the exergy (quality) of the recycled material obtained through cycle r and the exergy (quality) of the primary material. It measures the quality degradation of the recovered material during the recycling process.
- *Eco-design ratio* χ : The ratio of the emergy used in the manufacturing process and the emergy of the primary material. The ability of the product to be recycled at the end of its life cycle depends essentially on its design, on its production process and on the selected materials. The eco-design ratio measures the recyclability of the material, based on its properties and on the complexity of the manufacturing process.

Furthermore, the proposed evaluation model shows that for constant quality degradation and material losses, a limit value of the number of recycling and the eco-design ratio can be calculated.

Citation 4.2 (*Environmental accounting*)

« *In any energy transformation, many joules of available energy of one kind are required in a transformation process to produce a unit of energy of another kind. The energy thus generated by the work of transformation constitutes a higher level in the series of transformation.* » ([Odum 1996])

Citation 4.3 (*Third biennial energy research conference*)

« [...] *recycling has the same role in human productive systems as the detritus chain in natural systems. Both take a high transformity input at the end of its life cycle, break it down to simpler components and feed them back to lower hierarchical levels. The recycled component then re-enter the same productive cycles through which it had already passed (may be many times), and therefore it would be "double counting" to assign to it the whole emergy it bore when it was still in the finished product form. [...] If wastes are treated and re-enter a production process as a substitute material or resource, only the emergy invested in the treatment and recycling process should be assigned to recycled resources.* » ([Ulgiati 2004])

RQ3: To which extent a partial or complete substitution of fossil fuels with biomass is an environmentally friendly solution?

To answer this question, two concrete examples have been studied. The first example provides a comparative study between two heating systems: one is fired with wood, transported by trucks and the other one is fired with natural gas transported by pipelines (Chapter 5). While the second example provides a comparative study between the pure coal firing and co-firing of coal and biomass for electricity and heat production (Chapter 6). The carbon footprint analysis and emergy evaluation have been used to assess the maximum supply distance of biomass that permits biomass to be, according to the approach, a CO₂ or emergy saving alternative to fossil fuel. For both case studies the following conclusions were developed:

- The maximum biomass transportation distances suggest that the environmental performance of fossil fuel substitution cannot be efficiently assessed by taking into account only carbon-dioxide emissions. The emergy evaluation counts

inputs of the indigenous renewable, non-renewable resources and purchased inputs, giving more reliable information about the environmental performance of the studied system. Consequently, the distance that is permitted by the emergy evaluation is considerably shorter (about 50% in the first case study and about 15-35% in the second case study).

- The eco-environmental efficiency of biomass as a substitute for fossil fuels depends mainly on the efficiency of the boiler, the low heating value of the biomass and the fuel consumption of the transportation of the biomass.
- Considering that the resources for creating the fossil fuels had different availability throughout the history, the geological origin of different fuel types should be taken into account. Accordingly, the fuels that required considerable environmental inputs to be created in the first place, increase the emergy flow of the whole system (especially fuels created during Carboniferous and Jurassic period).

APPENDIX A

**Impact of building material
recycle or reuse on selected
energy ratios**

Impact of building material recycle or reuse on selected energy ratios

Abstract: While the energy evaluation method has been used successfully in recycling processes, this area of application still requires further development. One of such is developing energy ratios or indices that reflect changes depending on the number of times a material is recycled. Some of these materials may either have been recycled or reused continuously as inputs to a building, for example, and thus could have various impacts on the energy evaluation of the building. The paper focuses on reuse building materials in the context of environmental protection and sustainable development. It presents the results of an energy evaluation of a low-energy building (*LEB*) in which a percentage of input materials are from recycled sources. The corresponding impacts on the energy yield ratio (*EYR_B*) and the environmental loading ratio (*ELR_B*) are studied. The *EYR* which is the total energy used up per unit of energy invested, is a measure of how much an investment enables a process to exploit local resources in order to further contribute to the economy. The *ELR* however, is the total nonrenewable and imported energy used up per unit of local renewable resource and indicates the stress a process exhibits on the environment. The evaluation provides values for the selected ratios based on different recycle times. Results show that values of the energy indices vary, even more, when greater amounts of material is recycled with higher amount of additional energy required for recycling. This provides relevant information prioritizing the selection of materials for recycling or reuse in a building, and the optimum number of reuse or recycle times of a specific material.

Keywords: Energy, Recycle, Low-energy building

A.1 Introduction

Almost 40% of the world's consumption of materials converts to the built environment, and about 30% of energy use is due to housing [Pulselli 2007]. The building sector is the biggest consumption sector, before transports sector. As a result, there are ongoing research works to investigate how to significantly reduce the consumption of energy and material flows in the building industry. In effect, terms such as low-energy and passive house are used more frequently all over Europe.

Reuse and recycling of building material is a growing area of interest and concern in many parts of the world. Current practices and trends in the building material waste management are examined from a building life cycle standpoint or cradle to grave concept. To evaluate buildings and their environmental impacts more effectively, several tools and methods are adopted. These methods provide a list of indicators, based on objective values that compare buildings' performances and impacts to their environmental constraints. Some examples of these are the life cycle analysis [Guinée 2001], the emergy analysis [Odum 1996], the ecological footprint [Rees 1994], and the exergy analysis [Szargut 1987]. All of these assessments are needed to develop a comprehensive waste management plan for specific projects.

The use of construction waste management techniques which rely on recycle and reuse of materials have proven to have economic benefits for the construction industry [Kralj 2007]. Reuse is a means to prevent solid waste from entering the landfill, and increase the material, educational and occupational well being of citizens by taking useful products discarded by those who no longer want them and providing them as inputs to the construction of buildings. In many cases, reuse reduces raw material inputs to a very large extent. This is important since a significant percentage of the total natural resources that are used in industrialized countries are exploited by the building industry [Peuportier 1996]. High quantities of raw material inputs for building construction results in high energy required for the extraction and processing of these materials.

Emergy evaluation has been widely applied in the evaluation of ecological systems, energy systems, and environmental impacts of processes, generating a large number of studies. Yet, despite such a wide debate, only a few studies have been produced concerning applications of emergy evaluation to building construction and to building materials. In most of these studies, emergy evaluation is employed as an environmental indicator for construction activities, building materials production and recycling [Buranakarn 1998, Odum 2002, Brown 2003, Huang 2003, Meillaud 2005, Pulselli 2007]. Odum [Odum 2002] presents a broad approach to the relationships of building construction with materials circulation and energy hierarchy.

In the emergy approach, buildings are a storage of materials that is the sum of the inputs during the construction process. This storage loses energy as building materials depreciate along time and become dispersed in the environment. New inputs by means of maintenance and repair actions keep the emergy flow into the

building system.

Buranakarn [Buranakarn 1998] and Brown [Brown 2003] proposed a set of energy indices to evaluate recycling patterns and recyclability of building materials. These energy indices are suggested to measure the environmental benefits of three recycling trajectories: material recycle, by-product use, and adaptive reuse, i.e. recycling the material for a different purpose. The reuse option in the sense of reusing a product elsewhere was not considered in these studies. Energy per mass is also pointed as a good indicator for recyclability. Buranakarn [Buranakarn 1998] and Brown and Buranakarn [Brown 2003] also recognize that materials with higher energy per mass are more suitable for being recycled by human systems due to their 'quality', and have more environmental impacts when released to the environment. In the context of an environmental approach, Huang and Hsu [Huang 2003] proposed a set of indicators based on energy to measure the effects of construction in Taipei's sustainability: (a) intensity of resource consumption; (b) inflow/outflow ratio; (c) urban livability; (d) efficiency of urban metabolism; and (e) energy evaluation of urban metabolism. The relevance of energy analysis for that study was in the fact that it enabled the consideration of biophysical value of resources to the economic system. Evaluation of main energy flows of materials used due to urban construction provided both an understanding of their relative value and contribution to the ecological-economic system (urban construction is equivalent to 44% of the Energy used in Taipei), and a measure of the ecological interface of rapid urban development (environmental load of construction waste generation and recycling opportunities).

Meillaud et al. [Meillaud 2005] applied energy analysis to evaluate an experimental building of three stories containing faculty and students' offices and a workshop, built in 1981, by including environmental, economical, and information flows. By including information flows generated by building occupants to the analysis of the whole building system, it was possible to calculate the outputs generated by the building usage: energy per educated student, energy per publication, energy per course and energy per 'service'. The significance of energy per unit was highlighted by Meillaud et al. [Meillaud 2005], since there were few available energy per unit references for most commodities as inputs to a building.

Another application of energy to building construction was published by Pulselli et al. [Pulselli 2007]. The authors proposed a set of environmental indices to provide a basic approach to environmental impacts of buildings by accounting for the main energy and materials inflows within the building construction process, maintenance, and use:

- (i) Building energy per volume (E_m -building volume): this represents the 'environmental cost' of the building;
- (ii) Building energy to money ratio (E_m -building/money ratio): this represents the ratio of total Energy used to money (seJ/€);
- (iii) Building energy per person (E_m -buildings per person): this represents the

rate of Energy use of human systems with relation to buildings.

The proposed indices based on energy accounting provide a framework for evaluating and comparing different building typologies, technologies and materials, regarding different manufacturing processes, maintenance, use, thermal efficiency and energy consumption. Pulselli et al. [Pulselli 2007] argue that buildings are like full energy reservoirs (storage) that persists in time, and that energy evaluation of a building highlights the durability of materials as a factor for sustainability. With reference to building materials, the most extensive Energy study was developed by Buranakarn [Buranakarn 1998] in order to identify recycling patterns. The author analyses several common materials.

The main aim of this paper is to extend the energy based methodology to continuous matter reuse as devised by Amponsah et al. [Amponsah 2011b] to a process. In fact, authors consider that the additional energy (coming from each recycle matter) can be aggregated to the “classical” energy evaluation which does not include any recycling. The different impacts this continuous reuse might have on the energy yield ratio (*EYR*) and the environmental loading ratio (*ELR*) on the whole process require new definitions.

The rest of this paper is organized as follows: in Appendix A.2, relevant literature on energy evaluation and its application in buildings are reviewed. The methodology developed by Amponsah et al. [Amponsah 2011b] is outlined and defined in its specific context. In Appendix A.3, a case study is presented on a low energy building that corresponds to the present construction standards in France. Appendix A.4 presents a discussion and finally, Appendix A.5 concludes the paper.

A.2 Materials and methods

With reference to the work and formulae developed by Buranakarn [Buranakarn 1998] and Amponsah et al. [Amponsah 2011b] respectively, the output energy of a system involving recycle inputs differs marginally from a similar system with 100% raw material inputs. Amponsah et al. [Amponsah 2011b] further explained that the continuous recycling of a specific material due to the additional energy required at each stage of recycle, impacts on the final output energy of the system usually increasing the output energy after each additional recycle.

As such, authors of the said paper pointed out that the specific energy of any material e_m , containing a recycled part (or reused part) q_m , has a dynamic equation at discrete time, see Eq. (A.1), according to the specific total energy inputs e_{mi} (energy of raw material, fuel, goods and services etc.) without recycle, and the specific additional energy needed for recycling (for reusing) e_{mc} . The sampling time for recycling is noted Te and the recycling number is noted n_m . As such the discrete time t is just equal to the product Te by n_m . For unitary amount of matter,

one gets:

$$e_m(t) = (1 - q_m(t)) e_{mi}(t) + q_m(t) e_{mc}(t) + q_m(t) e_m(t - 1) \quad (\text{A.1})$$

The specific energy of any matter at the n^{th} recycling is the sum of three terms: the specific energy of raw material adjusted to its raw mass, the specific additional energy adjusted to its recycled part and the part coming from the past within the matter itself adjusted to its recycled part. Amponsah et al. [Amponsah 2011b] detailed that there is no double-counting in this decomposition and the pathway of the recycled matter is followed.

Eq. (A.1) is in a general form. Assuming that the specific energy inputs e_{mi} and the specific additional energy needed for recycling e_{mc} and the recycled part q_m are independent of the discrete time, the specific energy of matter containing a recycled part can be easily calculated by underlying the sum of a geometric series, noted ψ :

- for the 1st Recycle, where the factor $\psi = q_m$

$$e_m(1) = e_{mi} + e_{mc} q_m \quad (\text{A.2})$$

- for the 2nd Recycle, where $\psi = q_m + q_m^2$

$$e_m(2) = e_{mi} + e_{mc} (q_m + q_m^2) \quad (\text{A.3})$$

- for the 3rd Recycle, $\psi = q_m + q_m^2 + q_m^3$

$$e_m(3) = e_{mi} + e_{mc} (q_m + q_m^2 + q_m^3) \quad (\text{A.4})$$

- for the 4th , $\psi = q_m + q_m^2 + q_m^3 + q_m^4$

$$e_m(4) = e_{mi} + e_{mc} (q_m + q_m^2 + q_m^3 + q_m^4) \quad (\text{A.5})$$

- and so on...

Energy evaluation classifies inputs into three categories: purchased, renewable, and non renewable. On the basis of these classes, some indicators can be computed in order to assess the sustainability of the use of resources [Lagerberg 1999]:

- the energy yield ratio (*EYR*) is the energy of an output divided by the energy of those inputs to the process that are purchased from the economy;
- the energy investment ratio (*EIR*) is the purchased energy from the economy (services and other resources) divided by the free energy inflow from the environment.

- the environmental loading ratio (ELR) is the ratio of purchased and non-renewable indigenous emergy to free environmental emergy.

On this basis, Amponsah et al. [Amponsah 2011b] extended these ratios to some dimensionless emergy indices for a single recycled material. Assuming that the emergy inputs e_{mi} and e_{cm} and the recycled part q_m are constant, these ratios are in connection with the pathway of the recycled material by the number of recycle times. Thus, by means of the geometric series:

$$EYR_m(q_m, n_m) = \frac{e_{mi} + \psi e_{mc}}{e_{miF} + \psi e_{mcF}} \quad (\text{A.6})$$

$$EIR_m(q_m, n_m) = \frac{e_{miF} + \psi e_{mcF}}{(e_{miN} + \psi e_{mcN}) + (e_{miR} + \psi e_{mcR})} \quad (\text{A.7})$$

$$ELR_m(q_m, n_m) = \frac{(e_{miF} + \psi e_{mcF}) + (e_{miN} + \psi e_{mcN})}{e_{miR} + \psi e_{mcR}} \quad (\text{A.8})$$

Where e_{mi} is the specific emergy of raw material use without recycle, and e_{mc} is the additional emergy needed for recycling. Their renewable part is indexed by R , the non renewable part by N and the purchased part by F , so $e_{mi} = e_{miF} + e_{miR} + e_{miN}$, see Fig. A.1, where emergy source is noted SE.

If only one single matter with its associated pathway is considered, the total emergy for processing is increased by its additional emergy $\Delta E_{mc}(q_m, n_m)$:

$$\Delta E_{mc}(q_m, n_m) = m_m e_{mc} q_m \left(\frac{q_m^{n_m} - 1}{q_m - 1} \right) \quad (\text{A.9})$$

where m is the mass of the considered material, q_m is its mass fraction of recycle, n_m is its number of recycle, e_{mc} is the specific emergy required for 100% recycle.

For M recycled materials in a process indexed by P , such as building manufacturing, dimensionless ratios for the entire process can be defined as:

$$EYR_P = \frac{E_P^0 + \sum_{j=1}^M \Delta E_{jc}(q_j, n_j)}{E_{PF}^0 + \sum_{j=1}^M \Delta E_{jcF}(q_j, n_j)} \quad (\text{A.10})$$

$$EIR_P = \frac{E_{PF}^0 + \sum_{j=1}^M \Delta E_{jcF}(q_j, n_j)}{E_{PN}^0 + E_{PR}^0 + \sum_{j=1}^M (\Delta E_{jcN}(q_j, n_j) + \Delta E_{jcR}(q_j, n_j))} \quad (\text{A.11})$$

$$ELR_P = \frac{E_{PF}^0 + E_{PN}^0 + \sum_{j=1}^M (\Delta E_{jcF}(q_j, n_j) + \Delta E_{jcN}(q_j, n_j))}{E_{PR}^0 + \sum_{j=1}^M \Delta E_{jcR}(q_j, n_j)} \quad (\text{A.12})$$

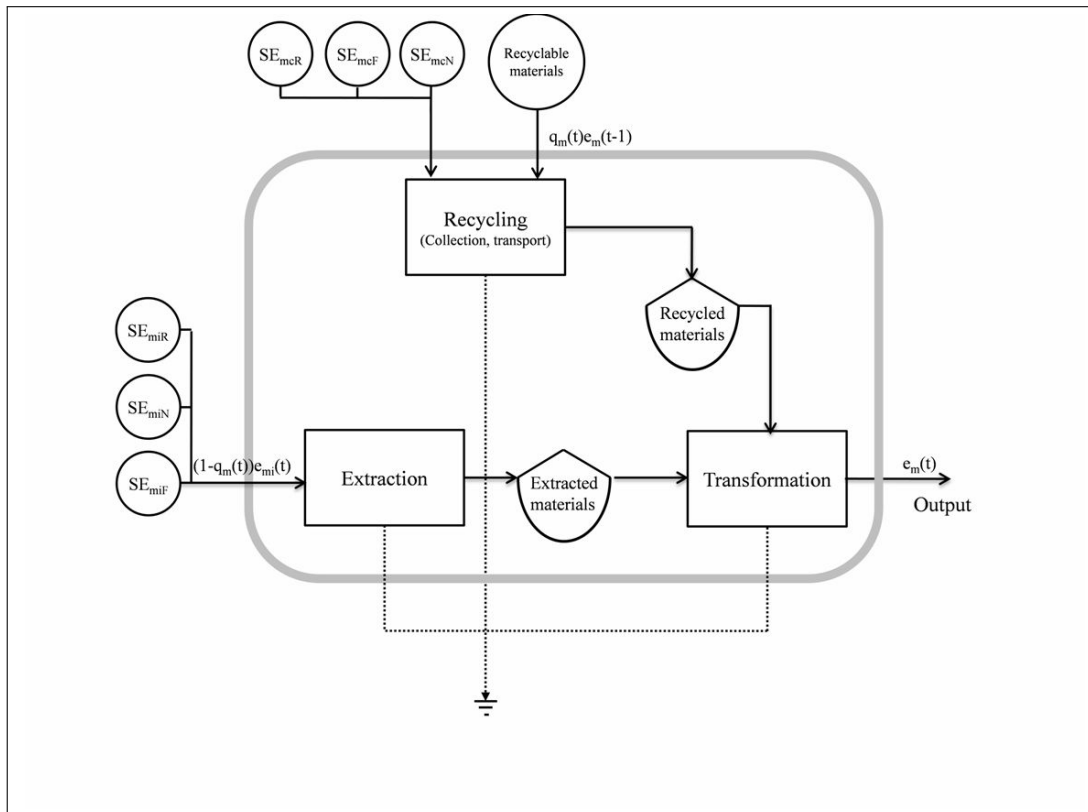


Figure A.1: Energy flows with additional energy for recycling

Where E_P^0 is the total emergy of the process without any recycle matter. E_{PF}^0 , E_{PR}^0 and E_{PN}^0 are respectively its purchased, renewable and non renewable part. The additional emergy of the j^{th} matter ΔE_{jc} is also decomposed into its three parts (purchased, renewable, and non renewable).

Buranakarn [Buranakarn 1998] obtained the value for the main materials likely to be recycled in building construction:

- bricks: $e_{bi}(100\%) = 3.68E+09$ seJ/g, when reused $e_{bc}(100\%) = 2.6E+05$ seJ/g and when recycled $e_{bc}(100\%) = 4.8E+05$ seJ/g, see Amponsah [Amponsah 2011b, p. 158-160]
- steel via the electric arc furnace process:
 $e_{si}(100\%) = 4.15E+09$ seJ/g, $e_{sc}(100\%) = 9.0E+07$ seJ/g, see [Buranakarn 1998, p. 76]
- aluminium: $e_{ai}(100\%) = 1.27E+10$ seJ/g,
 $e_{ac}(100\%) = 6.4E+08$ seJ/g, see Buranakarn (1998, p60)
- plastic lumber: $e_{pi}(100\%) = 5.75E+09$ seJ/g, $e_{pc}(100\%) = 5.8E+08$ seJ/g, see [Buranakarn 1998, p. 52]

A.3 Case Study

Low energy buildings involve the reduction of fossil fuel use such as oil, gas and coal, which enhances sustainable building and development. There are many ways to make a building energy-efficient: by high insulation, using building components resulting in less thermal bridges, buildings with good air tightness or by technical installations such as mechanical heat recovery ventilation, which also benefits the indoor climate [Anderson 2006, Wargocki 2007].

The building studied is located in Theys (Isère) which is a small town 30 km far from Grenoble. It is defined by a net area of $155 m^2$ calculated as the sum of the living area plus the garage area. It is intended for residential use. It comprises a basement, a ground floor and one other floor. The structure consists of a reinforced concrete frame with pillars and beams. The walls are made of concrete blocks with an internal insulation layer and gypsum plastering. The external wrapping is formed by two side walls (adjoining blocks), two facades (brickwork with cavities), an insulated basement. The upper ceiling is covered with mineral wool, under clay tiles roof. The house is heated by a natural gas boiler. The aluminum glass windows are double glazed with an overall heat transfer coefficient of $1.1 W/m^2K$. The annual heating consumption is of $50 kWh/m^2$, corresponding to the upper limit for the French label low-energy building.

An inventory of inputs to the construction process with relative raw data has been drawn and the quantity of materials and their compositions are reported in

a succession of steps that cover from the first to the last brick settled. Raw data (mass quantities) in the building metric computation has been reported in Table A.1, and has been processed through the relative transformities and expressed in terms of solar energy joules. References for transformities used in the table are from: Odum et al. [Odum 2000c]; Brown and Buranakarn [Brown 2003]; Meillaud et al. [Meillaud 2005] and Odum [Odum 1996].

Energy evaluation Table								
Note	Item	Density [kg/m ³]	Volume [m ³]	Raw Data	Unit	Transformity [seJ/unit]	Ref.	Energy [seJ]
Renewable inputs								
1	Sun			6,19E+11	J	1,00E+00	a	6,19E+11
2	Water	1000	614,52	6,15E+05	kg	4,80E+04	a	2,95E+10
Non renewable inputs								
<i>Basement (floor)</i>								
3	Concrete	1500	5,1	7718	kg	1,81E+12	b	1,40E+16
4	Soft limestone	1500	1,0	1544	kg	1,68E+09	f	2,59E+12
5	Heavy concrete	2300	0,5	1183	kg	1,81E+12	b	2,14E+15
<i>Ground floor</i>								
6	Concrete	1500	0,8	7718	kg	1,81E+12	b	1,94E+15
7	Heavy concrete	2300	0,2	474	kg	1,81E+12	b	8,58E+14
8	Polyurethane effisol	35	0,3	11	kg	8,85E+12	c	9,57E+13
9	Mortar	2000	0,3	618	kg	3,31E+12	c	2,05E+15
10	Tiles	2300	0,1	118	kg	3,68E+12	c	4,36E+14
<i>Underground Wall</i>								
11	Concrete	1500	5,2	7803	kg	1,81E+12	b	1,1E+16
12	Heavy concrete	2300	1,0	2393	kg	1,81E+12	b	4,33E+15
<i>Wall (on the west)</i>								
13	Light wood	500	0,2	110	kg	2,40E+12	f	2,64E+14
14	Wooden fibre	40	0,6	23	kg	2,40E+12	f	5,64E+13
15	Bricks	741	2,8	2040	kg	3,68E+12	c	7,51E+15
16	Plaster	1400	0,1	206	kg	3,29E+12	d	6,76E+14
17	Wooden panel	120	0,02	2	kg	2,40E+12	f	5,74E+12
18	Plaster	1200	0,02	24	kg	3,29E+12	d	7,87E+13
<i>Wall coating</i>								
19	Lime plaster	1400	0,1	73	kg	3,29E+12	d	2,41E+14
20	Bricks	741	1,0	727	kg	3,68E+12	c	2,67E+15
21	Plaster	1400	0,1	73	kg	3,29E+12	d	2,41E+14
<i>Plastering</i>								
22	Plaster	1400	0,01	14	kg	3,29E+12	d	4,68E+13
23	Concrete blocks	1300	0,10	132	kg	1,81E+12	b	2,39E+14
24	Lime plaster	1400	0,01	14	kg	3,29E+12	d	4,68E+13
<i>Wall (east)</i>								
25	Porotherm bicks 30	762	0,3	196	kg	3,68E+12	c	7,21E+14

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Note	Item	Density [kg/m ³]	Volume [m ³]	Raw Data	Unit	Transformity [seJ/unit]	Ref.	Emergy [seJ]
26	Bricks 10.7cm	1700	0,1	153	kg	3,68E+12	c	5,63E+14
27	Bricks 10.5cm	1700	0,1	153	kg	3,68E+12	c	5,63E+14
<i>Wall (North)</i>								
28	Concrete	1500	1,8	2694	kg	1,81E+12	b	4,88E+15
29	Bricks	741	0,7	499	kg	3,68E+12	c	1,84E+15
30	Wooden fibre	40	0,1	3	kg	2,40E+12	f	6,90E+12
31	Light wood	500	0,1	27	kg	2,40E+12	f	6,47E+13
<i>Intermediate floor</i>								
32	Plaster	1500	0,1	154	kg	3,29E+12	d	5,07E+14
33	Concrete	1300	0,6	802	kg	1,81E+12	b	1,45E+15
34	Heavy concrete	2300	0,2	473	kg	1,81E+12	b	8,56E+14
35	Extruded Polystyrene	35	0,3	11	kg	8,85E+12	c	9,55E+13
36	Mortar	2000	0,3	514	kg	3,31E+12	c	1,70E+15
37	Tiles	2300	0,1	118	kg	3,68E+12	c	4,35E+14
<i>Room partitioning</i>								
38	Plaster	1200	0,1	74	kg	3,29E+12	d	2,44E+14
39	Wooden fibre	40	0,5	20	kg	2,40E+12	b	4,75E+13
40	Plaster+cellulose	1200	0,1	74	kg	3,29E+12	d	2,44E+14
41	Concrete	600	0,1	73	kg	1,81E+12	b	1,33E+14
<i>Roof rafters</i>								
42	Teerracotta	1900	0,1	153	kg	1,68E+09	b	2,57E+11
43	Air space	1	-	0,04	kg	6,97E+12	a	2,80E+11
44	Wooden fibre	40	0,5	19	kg	2,40E+12	b	4,63E+13
45	Wooden board	800	0,1	43	kg	2,40E+12	b	1,03E+14
<i>Upsatairs roofing</i>								
46	Terracotta	1900	0,1	165	kg	1,68E+09	b	2,78E+11
47	Air space >1,3cm	1	-	0,04	kg	6,97E+12	a	3,03E+11
48	Wooden fibre	40	0,5	21	kg	2,40E+12	b	5,01E+13
49	Light wood	800	0,1	46	kg	2,40E+12	b	1,11E+14
50	Interior wooden door	750	0,06	48	kg	2,40E+12	b	1,15E+14
60	Double glass windows for external door 4,16,4 argon	2700	0,03	82	kg	2,13E+13	c	1,74E+15
61	Glass windows	2700	0,02	44	kg	1,41E+12	e	6,18E+13
62	External wooden door	750	0,06	41	kg	2,40E+12	b	9,91E+13
63	Metallic gate	7874	-	48	kg	8,55E+08	a	4,12E+10
64	Drainage system (PVC)			171	kg	9,86E+12	c	1,69E+15
65	Staircase (wood)			300	kg	2,40E12	b	7,20E+14
Purchased inputs								
66	Fuel (transports)			1,74E+08	J	1,13E+05	h	1,96E+13
<i>Energy consumed (electricity use on site)</i>								
67	Nuclear (78%)			8,85E+05	J	2,00E+05	g	1,78E+11
68	Hydro (14%)			1,59E+05	J	8,00E+04	a	1,28E+10
69	Natural gas (4%)			4,56E+04	J	4,80E+04	a	2,19E+09

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Appendix A. Impact of building material recycle or reuse on selected energy ratios

Note	Item	Density [kg/m ³]	Volume [m ³]	Raw Data	Unit	Transformity [seJ/unit]	Ref.	Emergy [seJ]
70	Coal (4%)			4,56E+04	J	4,00E04	a	1,82E+09
Total emergy for building manufacturing								7,11E+16
[a]: [Odum 2000c]; [b]: [Simoncini 2006]; [c]: [Brown 2003]; [d]: [Meillaud 2005]								
[e]: [Odum 1987]; [f]: [Odum 1996]; [h]: [Bastianoni 2005]								

Table A.1: Emergy evaluation results

Emergy flows have been reported relative to the materials used to build each component and structural part. In this case, human labor is not considered. The composition and the percentage of the main building materials used, assists in knowing the main material inputs for the construction of the building. The subsequent emergy results enable us to make a list of building materials based on their 'environmental cost' (in terms of seJ) that depends on both their quantity and their transformity (quality).

Major comments on Table A.1 are the following:

- Line 1, the sun primarily serves as a source of light for site workers during the daytime of work. The sun also helps in drying material used in construction (such as, concrete, mortar, paints, etc...), see Pulselli et al. [Pulselli 2007] and Meillaud et al. [Meillaud 2005].
- The electricity breakdown used, come from the energy mix in France, see [U.E. 2007]. Since electric energy is purchased to national grid, authors chose to make no distinction from the source.
- The renewable emergy part of whole building construction is considered as the sum of sun and water emergy. Its purchased emergy part is considered as the sum of fuel and electricity emergy.
- In Table A.1, the value of transformities corresponds to a process with no recycling. Without any recycled material, the total emergy for building manufacturing, noted E_B , is $7.11E+16$ seJ, sharing in its renewable inputs (line 1 and 2) E_{B0} , in its non renewable inputs (line 3-65) E_{B1} and in its purchased inputs (line 66-70) E_{B2} . The index B refers to building construction, the process studied in the case study, and the exponent 0 refers to any recycled material.
- It is observed that concrete takes about 74% in mass of the entire material inputs of the building followed by bricks.

Emergy values of the main individual materials are also presented in Fig. A.2. It can again be observed that concrete still remains a significant material not only in quantity use but also in terms of its emergy input to the building. This is because although concrete does not have a too high transformity value, it is used in a very large proportion in the construction and thus it becomes responsible for a large share of the total emergy (65%) of the total material input.

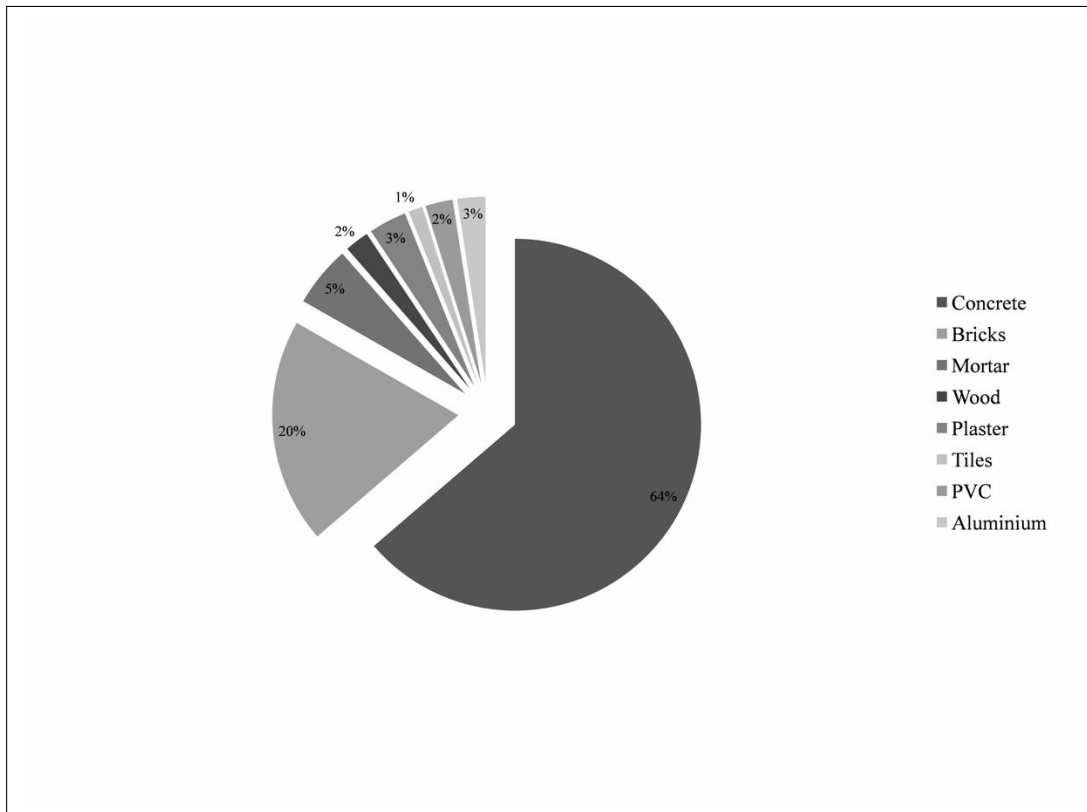


Figure A.2: Emery inputs of main raw materials in constructing the building

Fig. A.2 shows, however, that limestone (which has the third largest input quantitatively) falls out when emeries are considered. This is explained by the low transformity value ($1.68\text{E}+09$ seJ/kg) of limestone. Inversely, PVC, though slightly low in consumption, have a high value of transformity ($9.86\text{E}+12$ seJ/kg). This makes PVC a good choice for recycling or reuse, since it has a high embodied energy per unit mass. Nevertheless, PVC cannot have a significant effect on the emery of the building construction.

A.4 Discussion

First, authors consider only one matter, the bricks, since they were found to be the second most used material in the construction of the building (after concrete), accounting for about 19% of the total material input. Though it might not be the best example of a reusable or recyclable material in building, compared to PVC, steel etc, the idea is to illustrate the developed procedure of emery evaluation. The emery of the building is thus re-evaluated, taking into account different scenarios. As such, emery for sorting, collection and transportation to the recycling plant is considered, in addition to the emery for the plant process. This emery adds

up to give the additional energy of bricks recycling (ΔE_{bc}). For this building, the specific energy of bricks (with a total mass of 3767 kg) is $e_{bc} = 2.6E + 05$ seJ/g if 100% reused and $e_{bc} = 2.648E + 05$ seJ/g if 100% recycled. Numerical application gives an energy of 9.9E+11 seJ when reused and 1.81E+12 seJ when recycled. This is then multiplied by the quantity ($q_b = 30\%$ in this case) of recycled (or reused) bricks. Authors assume that this additional energy $\Delta E_{bc}(q_m, n_m)$, corresponds mainly to collection and separation, and is incorporated only in purchased inputs $\Delta E_{bcF}(q_m, n_m)$. Eq. (A.10) begins:

$$EY R_B = \frac{E_B^0 + \Delta E_{bcF}(q_m, n_m)}{E_{BF}^0 + \Delta E_{bcF}(q_m, n_m)} \quad (\text{A.13})$$

- The result for the first reuse ($q_b e_{bc}$) is added up to the initial energy of the building (Table A.1) 7.1E+16 seJ giving an energy difference of 5.4E+11 seJ. Results for recycled bricks are proposed in Table A.2, in the case of 30% recycle rate of bricks (q_b) and for different number of times of recycling.
- For the first reused bricks, the numerical application gives the energy difference of 2.99 E+11 seJ. Results for reused bricks are proposed in Table A.3 always in the case of 30% reuse part and for different number of times of reuse.

Energy results for bricks recycling for different recycling times	
	ψE_c [seJ]
Recycling	
1st	5.4E+11
2nd	7.1E+11
3rd	7.6E+11
4th	7.7E+11
5th	7.8E+11

Table A.2: Energy results for bricks recycling for different recycling times

Results of new energy of building for reuse of bricks (e.g. in concrete mix)	
	ψE_c [seJ]
1st	2.99E+11
2nd	3.89E+11
3rd	4.15E+11
4th	4.24E+11
5th	4.26E+11

Table A.3: Results of new energy of building for reuse of bricks (e.g. in concrete mix)

This is continued for different number of times of recycle and for different quantities to assess the various impacts on the energy analysis of the building (refer to equations Eqs. (A.2) to (A.5)).

The same scenario is used to analyze the various effects on the emergy yield ratio. It is seen from the results presented that the EYR decreases with respectively an increase of recycling time in Fig. A.3a and reusing time in Fig. A.3b. This is explained by the increase of additional goods and services purchased to aid in the recycling process. Fig. A.4a et Fig. A.4b show respectively the potential impact of recycled bricks (Fig. A.4a) and reused bricks (Fig. A.4b) on the emergy yield ratio (EYR_B) of the building. Without any recycling is the ratio of the total energy for building construction ($7.11 \text{ E}+16 \text{ seJ}$) to the emergy part purchased from economy ($1.98 \text{ E}+13 \text{ seJ}$). Numerical application gives $3.59\text{E}+3$. This value means that the purchased emergy part is low. As presented in Table A.2 for recycling or Table A.3 for reusing, the additional emergy $\Delta E_{bc}(q_m, n_m)$ is about 1% of E_{BF}^0 so the bricks recycling, or the bricks reusing, has a low impact on the ratio EYR_B for the building construction, see Fig. A.3a and Fig. A.3b. Since bricks reusing energy is approximately half the one for recycling, the impact of reusing one is lower than the one for recycling. The greater the number of recycling (or reusing) is, the lower the EYR_B is and consequently the proportional part of purchased economy increases, see Fig. A.4a and Fig. A.4b.

Common sense has it that both recycling and reusing tend toward sustainability. Hence, Ulgiati et al. [Ulgiati 2004] proposed a path of emergy allocation in which the emergy rules are not violated. In this, the emergy invested in the treatment and recycling process should be assigned to the recycled resource. As such, the proposal suggests that wastes only bear the additional emergy inputs needed for their further processing. Ulgiati et al. [Ulgiati 2004] then amounted to 'resetting' the emergy content in recycling processes to eliminate the problem of cumulative emergy.

Authors consider one additional material, the plastic, its mass is 171 kg and its specific recycle emergy is $5.8 \text{ E}+08 \text{ seJ/g}$. For 30% of recycled part, the value of the first recycling ($2.98 \text{ E}+13 \text{ seJ}$ corresponding to the product of specific transformity $5.8\text{E}+13 \text{ seJ/kg}$ by its mass 171 kg and by its recycle part 30%) is greater than the purchased emergy for the building construction ($1.98 \text{ E}+13 \text{ seJ}$). So the impact of plastic recycling is very significant on EYR_B , see Fig. A.5. Fig. A.6 shows the impact of recycled plastic on the emergy yield ratio (EYR_B) of the building.

As can be seen in the results of the EYR_B , ignoring the impact of material reuse or recycling leads to the loss of significant information. Extending the traditional EYR_B to include the recyclable values from the additional emergy needed for recycling, increases the value associated to the purchased goods and services and thus reduces the EYR_B . It is observed that EYR_B s are lower in higher recycling times. For instance, the difference between EYR_B for a 1st recycle and a 5th recycle is quite significant ($3.92\text{E}+01$). This is due to the significant changes in the additional emergy amounts needed for the cycle of material recycling or reuse.

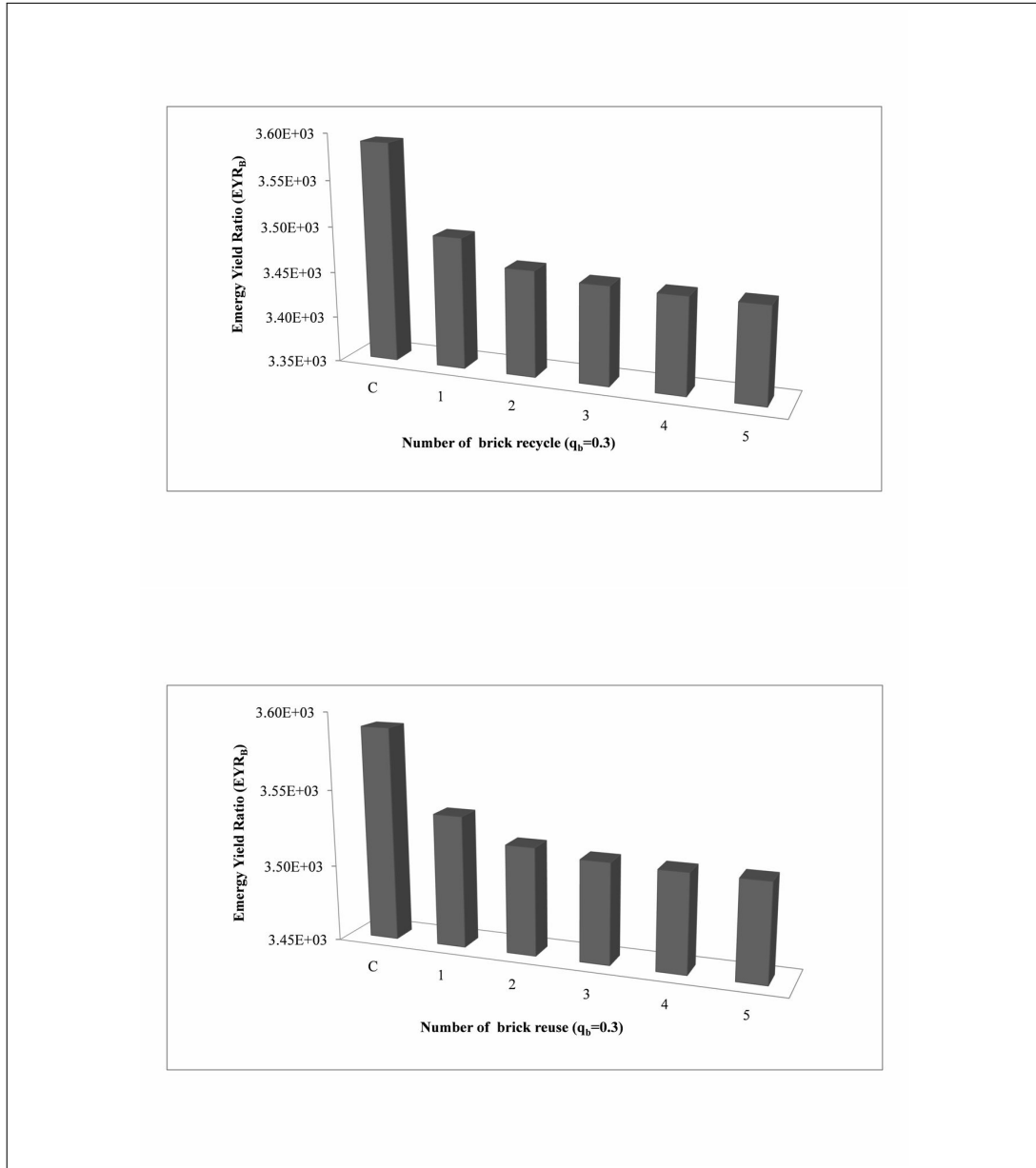


Figure A.3: Impact of 30% (constant rate) continuous bricks recycle (a) and reuse (b) on EYR_B of the building

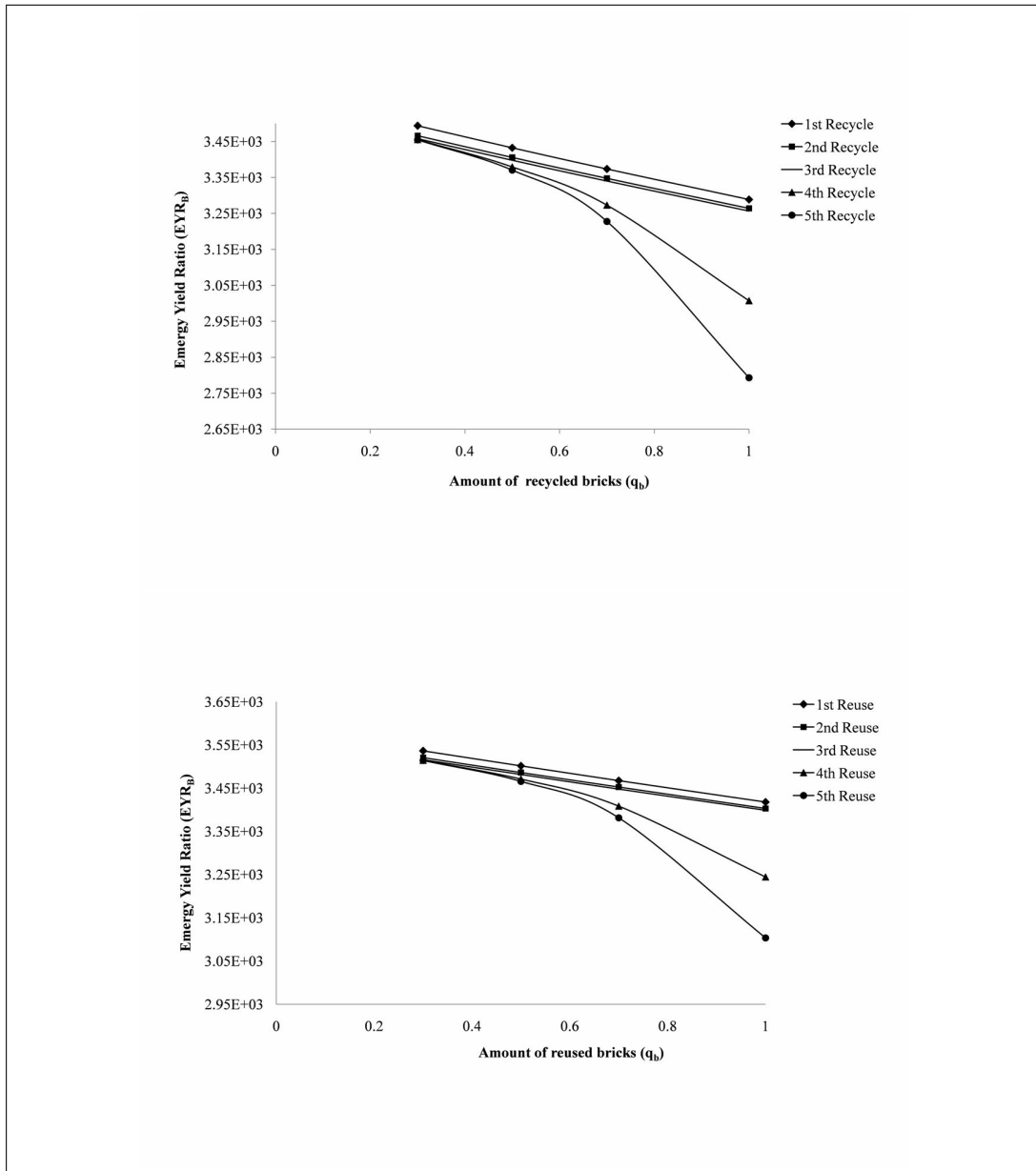


Figure A.4: Impact of different recycling rates for continuous bricks recycle (a) and reuse (b) on EYR_B of the building

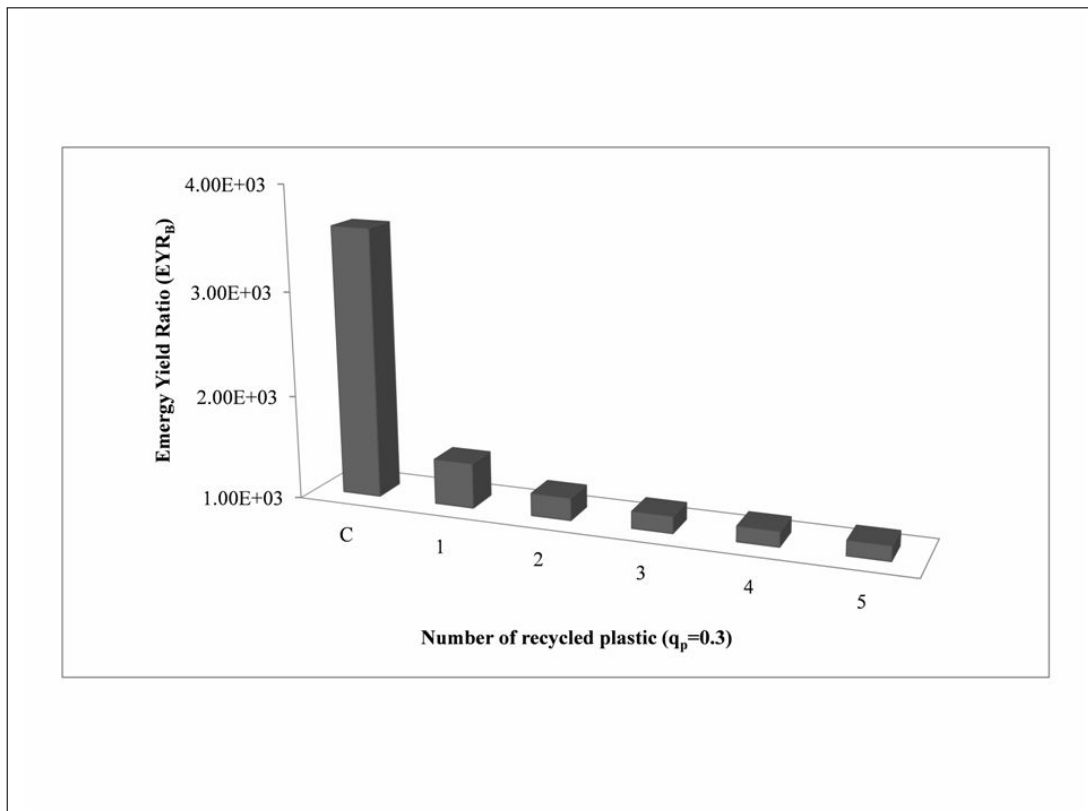


Figure A.5: Impact of 30% (constant rate) continuous plastic recycle on EYR_B of the building

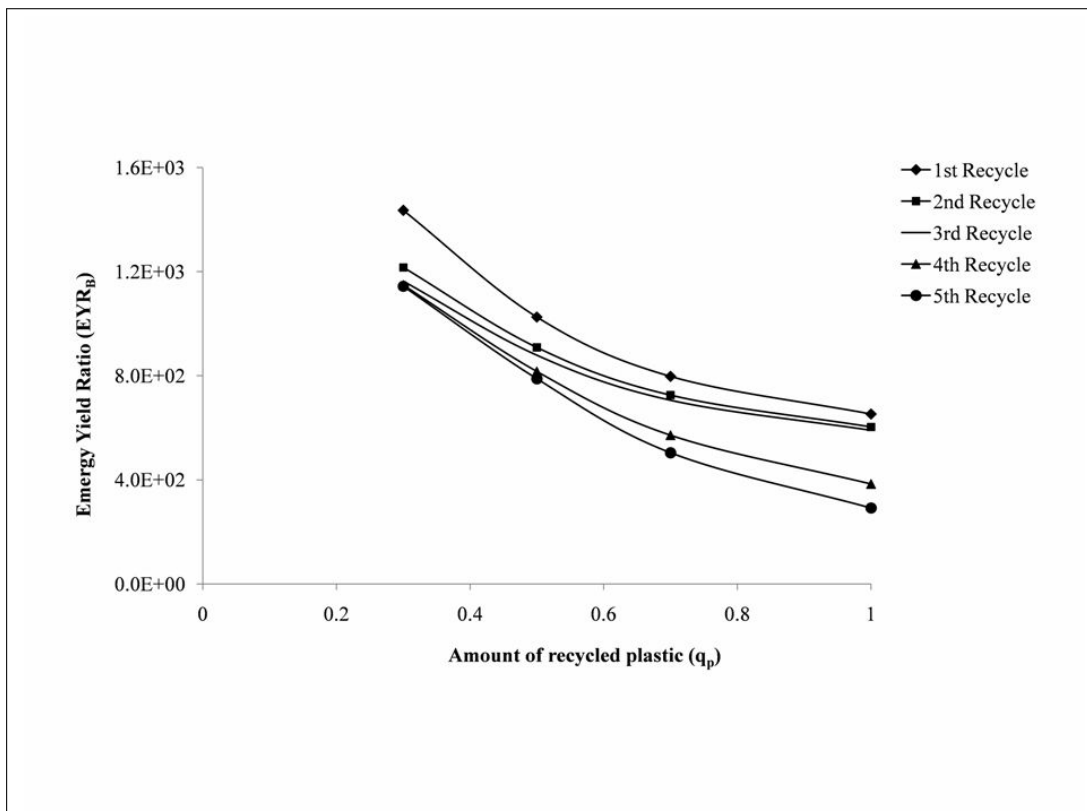


Figure A.6: Impact of different recycling rates for continuous plastic recycle on EYR_B of the building

In the case only one material is recycled (or reused), bricks for example, the energy loading ratio for building construction is defined as:

$$ELR_B = \frac{E_{BF}^0 + E_{BN}^0 + \Delta E_{bcF}(q, b, n_b)}{E_{BR}^0} \quad (\text{A.14})$$

ELR_B is increasing with both the recycle part (or reuse part), and the number of cycles. A higher ELR_B suggests that investing in waste management causes more environmental stress. This is due to the fact that the purchased inputs from the economy needed for recycling, or reusing, increase.

Fig. A.7a and Fig. A.7b show that the developed methods if utilized would serve as an extension to quantify and interpret the attributes of systems with percentages of respectively recycled inputs and reused inputs, with important implications in comparative decision making.

Before conclusion, authors would like to emphasize on two major points

- Eqs. (A.10) to (A.12) have been introduced to study the impact of several recycled materials (or reused) with different parts and at different numbers of recycling (or reusing) on energy assessment of a process. In this paper, it does not worth it to multiply numerical applications. It is possible to mix the assessment of bricks and plastic recycling, and so on... This paper provides the method.
- It is very important to know the industrial process for recycling (or reusing), in other words the pathway of the recycled (or reused) material. In this paper, authors have considered that this industrial process is based on collection and separation, and have allocated this additional energy as a purchased energy. If one wants to allocate it to the product itself, by increasing its transformity in emergy table (as Table A.1), then the additional energy is considered in the non renewable part in the emergy assessment of a process. In this case of building construction, recycling and reusing would not have any impact on the ratios EYR_B and ELR_B because the value E_B^0 is so significant that the additional energy is negligible.

A.5 Conclusion

Emergy can be used successfully to evaluate systems with a fraction of its input materials derived from recycle sources, by effectively following the pathway of the material during the entire process (avoiding double counting). In this paper the methodology proposed by Amponsah et al. [Amponsah 2011b] is applied and exemplified in the emergy evaluation of a low energy building in France. The evaluation results reveal significant impacts on the emergy yield ratio (EYR_B) and the emergy loading ratio (ELR_B) of the building having a fraction of its input materials from re-

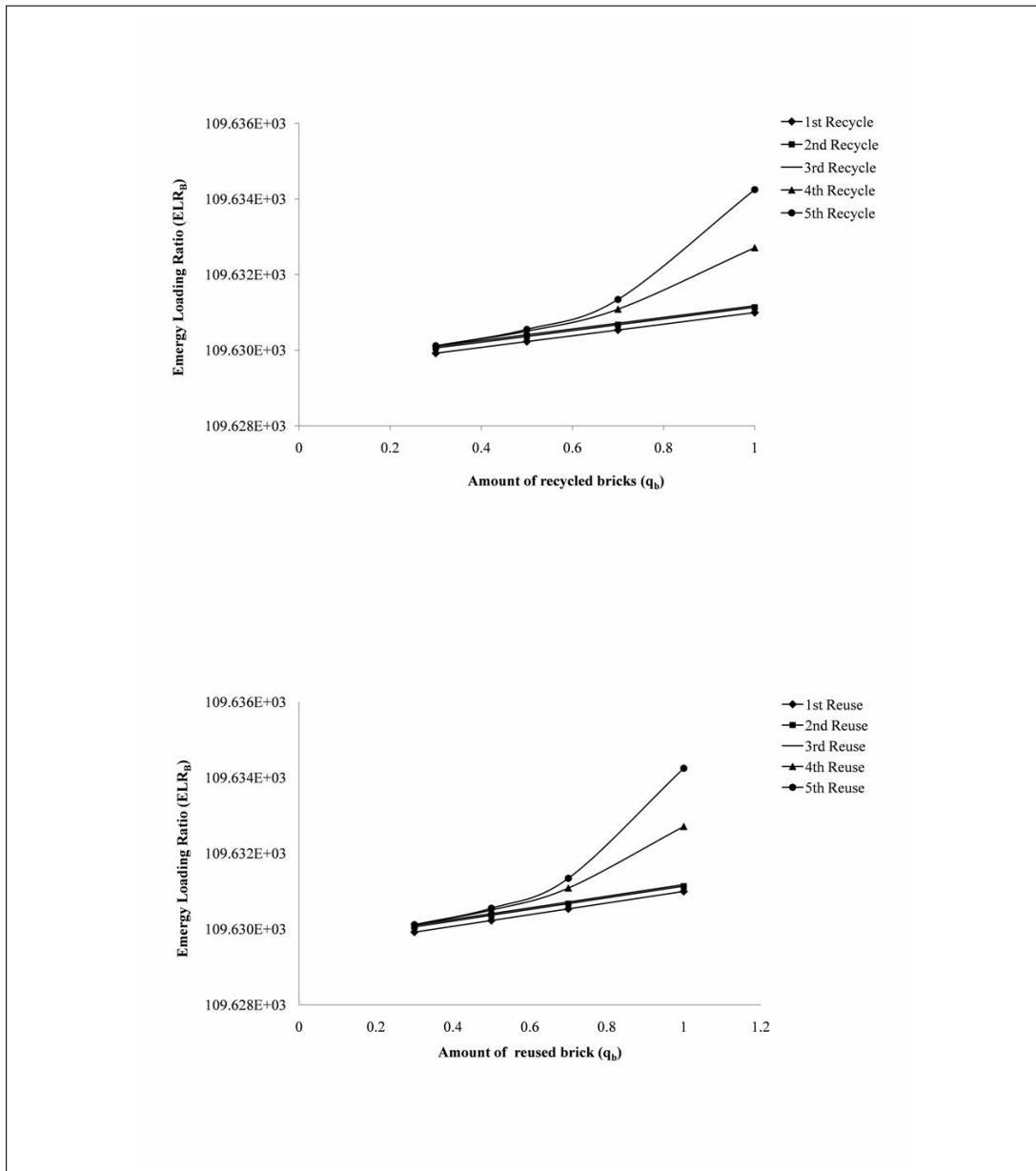


Figure A.7: Impact of different recycle rates (a) and reuse rates (b) for continuous bricks recycle on ELR_B of the building

cycled sources. The proposed methodology is important to provide the link between the emergy evaluation method and the hidden information in recycling materials severally. This is very useful for evaluating and improving systems which often have recycled inputs, to compare the usefulness of using raw material inputs or recycled inputs. Moreover, it enables an investigator to select optimum levels of recycling (amount to recycle and number of times of recycle) to achieve greater results towards sustainability. From the case study, every process in which a fraction of inputs can be traced to recycle sources, can be evaluated simply by applying the factor α . In this way the difficulty of recalculations is somehow reduced, since the factor could easily be selected depending on the time of recycling (1st, 2nd, 3rd etc. recycling). The results of EYR_B and ELR_B substantiate the need for the continuous development of emergy as a useful analytical tool, due to its ability to account for the contribution of ecosystems to economic activity. Furthermore, emergy provides useful indicators for evaluating the ecological feasibility as well as sustainability of construction processes and buildings. The improved indicators proposed in this work provide a conceptually sound basis to quantify the impacts of recycling or reuse of materials in a typical low energy building. The calculated indicators were shown to be consistent with the notion that investing in waste management must be expected to lead to less environmental stress largely dependent on the input materials either from renewable, non renewable or purchased sources. A good balance of these would enhance sustainability.

In future works, it could be interesting to consider the emergy assessment for automotive since the part of recycling is rather important in this sector (up to 90%). The consumer goods sector should also be studied through the emergy assessment as it is a non-negligible natural-resources consumption (e.g. packaging: metal cans, glass cans, paper, cardboard...).

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Thèse de Doctorat

Nadia Jamali-Zghal

Outils d'analyse environnementale pour un usage durable des ressources naturelles

Environmental assessment tools for sustainable resource management

Résumé

En 1987, la commission sur l'environnement et le développement des Nations-Unies définissait le développement soutenable/durable par "un développement qui répond aux besoins actuels sans compromettre les capacités des générations futures à répondre au leur". Cette définition vise à améliorer/maintenir la qualité de vie de l'humanité avec le temps en perspective. Le développement durable met en exergue trois actions: la diminution des besoins, l'utilisation d'énergies propres et renouvelables et le recyclage.

Cette thèse vise à proposer des éléments de réponses à trois questions scientifiques :

RQ1: Comment évaluer l'impact environnemental résultant de l'exploitation des ressources minérales, en tenant en compte de leur abondance, de leur composition chimique, de leurs propriétés physiques et des effets de leur extraction?

RQ2: Comment évaluer la performance du recyclage, en prenant en compte les différentes pertes (de quantité et de qualité)?

RQ3: Substituer de l'énergie fossile par de la biomasse s'inscrit-il toujours dans le cadre du développement durable?

La méthode *émergétique* est principalement utilisée pour cette recherche. Elle est complétée par *l'exergético-écologie*, *l'empreinte carbone* ou *l'analyse exergétique du cycle de vie*.

L'énergie spécifique initiale (avant exploitation) des 42 minéraux les plus utilisés dans l'industrie est proposée, tout en respectant le principe de hiérarchisation des matériaux formulé par Odum. La performance environnementale du recyclage métallurgique a été étudiée tout en tenant compte des pertes de matière et de qualité. Une transformité moyenne et trois ratios sont proposés, permettant de quantifier une solution qualifiable de "éco-conception". Finalement, l'intérêt d'une substitution d'un combustible fossile par de la biomasse a été analysé à l'aide de deux exemples concrets.

Mots clés

Énergie, Exergie, Gestion des ressources naturelles, Recyclage, AECV.

Abstract

In 1987, the United Nations World Commission on Environment and Development defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The aim is to continuously improve the quality of life for both current and future generation without increasing the use of natural resources beyond the Earth's carrying capacity. The entire life-cycle of natural resources, from their extraction to their final disposal as waste, engenders negative environmental impacts. Waste recycling and the substitution of excessively polluting resources with alternatives are considered as the key components of sustainable resource management. The flow of the thesis is formalized in the following three research questions:

RQ1: Is it possible, and if so how, to assess the environmental impacts resulting from the exploitation of mineral resources, taking into account their abundance, their chemical and physical properties and the effects of their extraction?

RQ2: Is it possible, and if so how, to evaluate the environmental performance of recycling, taking into account the chemical, physical and thermodynamic limits of the process?

RQ3: To which extent a partial or complete substitution of fossil fuels with biomass is an environmentally friendly solution?

The work is essentially based on the *emergy approach*, but also other environmental assessment tools has been used such as the *exergoecology approach*, the *exergetic life cycle* assessment and the *carbon footprint*. The specific energy of about 42 main commercially used minerals has been calculated, respecting the material hierarchy developed by Odum. The environmental performance of metallurgical recycling has been studied, taking into account for the material and quality losses during the process. The use of an average transformity is proposed and three sustainability ratios have been defined to assess the benefits and limits of recycling processes. Finally, in order to determine the environmental impact of using biomass as substitute for fossil fuels, two concrete examples has been studied.

Key Words

Energy, Exergy, Resource management, Recycling, ELCA.