THE ROLE OF CIRCULAR ECONOMY, CONSUMPTION REDUCTION, AND MATERIAL EFFICIENCY IN PEAK WASTE

PENG WANG*, SAMI KARA*, MICHAEL Z. HAUSCHILD**

** Sustainable Manufacturing and Life Cycle Engineering Research Group, School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, 2052, Australia*
*** Division for Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark*

SUMMARY: Over recent decades, demand for various materials has increased at an unprecedented rate to underpin human well-being. However, our current material use is problematic and generates massive waste, which is approaching the carrying capacity of our planet and requires a spin on its growth, namely the peak waste. Hence, the current waste generation trend must be fully understood and adjusted. In particular, (iron and) steel is considered as a benchmark case for peak waste studies, since it is the world's most used and recycled metals with various applications to support our daily lives. This study proposes a dynamic material cycle model and applies it to waste management. The trend of waste generation from steel use (from 1900 to 2100) is simulated through year by year calculation from the dynamic material cycle model. To facilitate future waste management, four scenarios are built to predict the future trend from 2016 to 2100, namely the business as usual scenario, Circular Economy scenario, Material Efficiency scenario, and Lifestyle Compromise scenario. These results indicate (a) Steel faces a severe waste issue despite being the most recycled metal; (b) Optimization of waste management requires a whole life cycle investigation; (c) Circular economy is not enough to peak waste; (d) Compromising lifestyle has limited effect; (e) Peak Waste requires comprehensive solution accompanied by Material Efficiency.

1. INTRODUCTION

Waste is one of the major challenges for environmental sustainability worldwide (Goodland, 1995). Over the latest decades, the consumption of various resources has increased at an unprecedented rate accompanying growth in global population and material standard of living in many regions. However, our current material use pattern is problematic and generates massive amounts of waste. The trend of waste generation and its consequences is acknowledged widely (UNEP, 2015): solid waste, for instance, has increased tenfold in the past century and causes severe impacts to humans and environment. Furthermore, the per capita waste will double by 2025 according to some estimation (Hoornweg et al., 2015; World Bank, 2012), which will pose great threats to the earth's life support system. Accordingly, in the latest United Nation's sustainable goals, it is required to "substantially reduce waste generation through prevention, reduction, recycling and reuse by 2030". Meanwhile, some studies like (Hoornweg et al., 2013) demonstrate the necessity to bend this trend by peaking the generation of waste within this

Proceedings Sardinia 2017 / Sixteenth International Waste Management and Landfill Symposium/ 2 - 6 October 2017
S. Margherita di Pula, Cagliari, Italy /

century. Similar to peak energy (Bardi, 2009) or peak mineral (Prior et al., 2012) concepts, some studies (Bardi et al., 2014; Hoornweg et al., 2015; World Bank, 2012) proposed the idea of "peak waste". Targets set by those studies clarify the limitations of our waste generation. According to those studies, the waste needs to peak by 2075, otherwise, it will be far more than the earth can manage. However, the core questions are if the waste reduction is feasible through a peak waste approach, and if so, how it can be achieved.

Most of the previous waste management studies have focused on end-of-life solutions, which are considered to be a straight-forward strategy to cope with the waste issue. In particular, circular economy (CE) is most widely promoted strategy in many industries and governments. The core concept of CE is to improve the circularity of material use through turning materials at the end of their service life into resources for others (Winans et al., 2017). As this concept indicates, the circularity of materials underlines the end-of-life activities (i.e. recycling, reuse, remanufacturing, and repair), which not only reduces the waste generation but also decreases the raw material demand. Hence, numerous studies have been conducted to investigate the end-of-life solutions and issues like generation, recyclability, treatment, and disposal of various End-of-Life (EOL) wastes (Ferreira et al., 2016; Hoornweg et al., 2013; Reck and Graedel, 2012).

However, the circular economy has been criticized by some recent research results. Allwood (2014) stated that the circular economy is not always desirable or feasible due to the complexity and effort in dealing with end-of-life products. Sometimes, higher impacts will be generated to separate the complicated wastes rather than choosing the raw material. Meanwhile, Wang et al.(2017) pointed out that the market dynamics between the primary and secondary production would suppress the benefits of closing the loop. Furthermore, Zink and Geyer (2017) argued that there would be a rebound effect of the circular economy, which would increase overall production and offset the expected benefits.

Therefore, a systemic view is required on the dynamics of material consumption rather than at the end-of-life stage, and more specifically, there is a need to focus on the total waste of steel use along its life cycle rather than just in the end-of-life stage. Herein, material efficiency, proposed by (Allwood et al., 2011), is a novel concept to focus on the entire material consumption and its impact with the ultimate goal to "meet human needs while minimizing the impacts of material use". Meanwhile, detailed strategies to related material efficiency have been recently proposed and applied to the steel case (Milford et al., 2013), which includes a series strategies along the metal cycle (i.e. less metal for same service, more intense use, life extension, fabrication scrap diversion, reuse of end-of-life scrap, and fabrication yield improvements). The material efficiency should receive more attention to guide our resource consumption and related activities from a more holistic view. As urged by (Allwood, 2014), we should adjust the aim from closing material loop or promoting the circular economy to minimizing the impacts of material use. Unfortunately, the studies on material efficiency (Allwood, 2013; Milford et al., 2013; Wang et al., 2017) are quite limited compared to the studies on circular economy, especially from the waste management perspective.

Similarly, the waste management calls for a holistic understanding of its dynamics as well as a solid forecast on future trends. There are many ways to investigate the waste generation, mainly based on the input and output analysis of social metabolism (Beigl et al., 2008; Dyson and Chang, 2005). However, the waste generation is not only linked to these inputs and outputs, but also calls for a more holistic investigation of the whole life cycle, especially of its inherent dynamics inside social metabolism. Herein the stock and flow model is a widely used method to depict this dynamics in the build-up, renewal, maintenance, and obsolescence of in-use stocks (Müller et al., 2014) with related social-economic factors like population, affluence, etc. Hence, the stock dynamics can provide a comprehensive view on the waste generation by incorporating important social and technological factors within the whole cycle quantification.

This study aims at implementing a stock and flow model to construct the full cycle of material use with a specific investigation of the waste generation. Combined with a full life cycle perspective based on material flow analysis (MFA), this model provides a robust long-term estimation on the extraction, production, use, and end-of-life for material use.

Steel is considered a good case for a material peak waste study since it is the world's most used metal with various applications to underpin our daily lives. Hence, it is of great interest to investigate whether steel scrap will peak in this century and what are the important factors determining this trend. This study will primarily focus on steel and quantify the full cycle of steel use from 1900 to 2100. Based on a peak waste study on steel, this work aims at providing a more holistic view on waste management by comparing two main strategies (i.e. circular economy and material efficiency) and one novel option of consumption reduction. It is important to consider these strategies concurrently to test whether they are sufficient to peak the waste in this century as required by peak waste studies. Meanwhile, this study aims to improve our current understanding of material consumption and promote the shift from current waste management to creating a circular economy to minimize the total impact of material use.

The work is organized into three major parts: in section 2, our proposed framework will be described, especially for the stock and flow model and full material cycle. To build the scenarios for future projection, the strategies of circular economy and material efficiency will be analyzed in detail. Meanwhile, the data sources and the future scenarios to quantify the steel cycle from 1900 to 2100 will be also included in this study. Section 3 will not only focus on the results of steel use, but will also discuss the formation of peak waste and the key factors behind it. Based on these results, this study will (a) discuss the feasibility of peak waste, and (b) highlight the shortcomings and challenges of the circular economy, together with (c) the benefits and importance of material efficiency. The final part will present conclusions on the work.

2. METHODOLOGY

To quantify the waste generation from steel use and its potential trends, this section describes the model construction as well as the scenario settings to trace the waste from 1900 to 2100.

2.1 Framework for stock and flows of material use

The boundary of this study covers all waste related to steel use, which is not solely generated by the end-of-life stage, but also from a material perspective to trace all the losses in the whole life cycle of steel use. It is also noted the waste in this study only presents the mass losses from material use rather than covering channels and impacts to environmenta. In line with this recognition, this study adopts the dynamic material cycle framework to quantify all the flows and stocks over the life cycle of steel use (shown in Figure 1a). Meanwhile, there are three layers (i.e. biosphere, manufacturing layer, and consumption layer) in this framework to clarify the interaction of social metabolism and environment regarding the issue of waste.

The biosphere and lithosphere is uniquely proposed to follow the today's necessity to reduce the life cycle impacts of material use to avoid disastrous consequences to a stable Earth's life-support system (Griggs et al., 2013). In other words, this layer forms the boundary to regulate the material use, thus it is located in the outer ring of our framework. In this work, the waste is the proxy for the impact of anthropogenic material use, and of great interest to find the suitable use pattern to minimize the waste. As noted in Figure 1, the waste of anthropogenic material use specially contains all the waste from the stages of its life cycle.

The technical layer is in the middle of this framework as a bridge to link consumption and environment. Although the consumption layer also contributes to the environmental impacts, it is neglected in this framework as these impacts are always allocated to the whole end-use sectors (like building, transportation, etc.) rather than one specific material (Liu et al., 2012). Herein, this layer introduces a full life cycle model covering five main stages (i.e. mining, primary production, secondary production, product fabrication and recycling) and the exchange of product use. This model follows the typical substance or material flow analysis (MFA), which is commonly used to characterize the transfer of material flows through a series of processes within boundaries on the basis of material balance principle (Brunner and Rechberger, 2004). Hence, this principle applies to the five life cycle stages in this layer, and it is assumed that no stock remaining in these stages: the mass input to each stage must equal the mass loss (waste) to the environment and mass output to next stage. Resource efficiency is proposed to measure the mass ratio of output to input to measure the efficiency of each stage from the resource perspective. In particular, the resource efficiency of recycling is termed as recycling rate to follow the common terminology (Reck and Graedel, 2012).

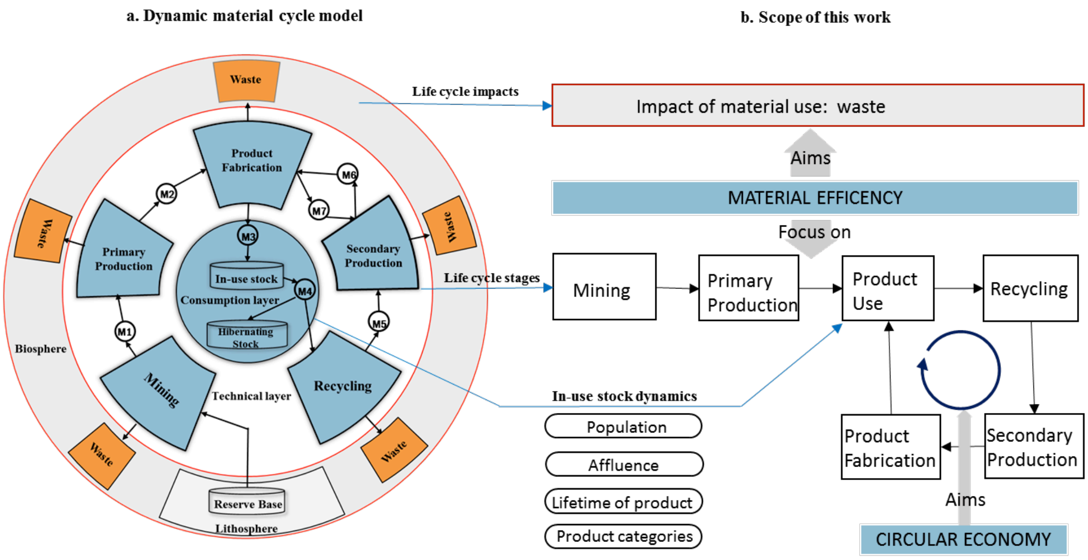

Figure 1. The framework and scope of this study (The left figure gives details of the life cycle stages and their exchange, M*n* means the material flow; The right figure shows the differences on the scopes of material efficiency and circular economy. The linkages between framework and scope are shown through their connection arrows)

Consumption layer locates in the center of this framework as the material consumption pattern is the critical driver to manufacturing activities and environmental impacts. Although previous studies in industrial ecology have viewed the scrap market as the center of the material cycle (Chen and Graedel, 2012; Pauliuk and Müller, 2014) with the emphasis of closing material loops, this framework put the consumption layer in this position to highlight material efficiency: how to improve the material use to mitigate environmental impacts. This layer is modeled as in-use stock, which contains all the products and their key materials which provide service to the society. Stock dynamics, which is widely used to study the social metabolism in industrial ecology (Müller et al., 2014), is also used in this paper on the in-use stock of materials or products and the mechanism behind it. The stock dynamics is in focus in this framework since it helps to (a) reflect direct material service level and lifestyle directly through in-use stock level (Graedel et al., 2010; Müller et al., 2011), (b) reveal the dynamics of material in-use stage and its role in determining consumption and end-of-life products (Pauliuk and Müller, 2014), and (c) produces robust long-term prediction of future change of metal cycles (B. Müller, 2006; Gerst, 2009).

The lifetime distribution function is widely used to obtain the outflow (end-of-life flow) from the in-use stage:

$$Outflow(t,n) = \int_{t-2\tau}^{t} Inflow(n,tt) \times f(tt,\tau,\theta)dt \quad (1)$$

where $f(tt,\tau,\theta)$ is the probability densities (normally Weibull distribution) of the lifetime distribution function, τ is the lifetime of this product category, t is current time, and θ is the lifetime distribution parameter.

The historical quantification starts from the technical layer and the outflow based on equation (1), seeing it as production driven (Liu et al., 2012). For the future estimation, the whole quantification is based on the projection of in-use stock level, which can be obtained from an adjusted Logistics function (Pauliuk et al., 2012), assuming a stock-driven approach (Liu et al., 2012). As indicated in Figure 1, the key parameters for stock dynamics are population, affluence (the benchmark of in-use stock from mature countries), the lifetime of products, and performance of the product end-use categories.

2.2 Retrospective estimation

The retrospective estimation is a preparation for future projection and is conducted to quantify the steel cycle from 1990 to 2014. The quantification process starts from the primary route and obtains the in-use stock and secondary route based on MFA, namely the production-driven. The main inputs are the mining production, primary production, the resource efficiency of each process, etc. Meanwhile, the end-use products are divided into four major groups: Transportation, Machinery, Construction, and (other consumer) Products.

As for the data source, the mining production and primary production is based on data from United States Geological Survey (USGS, 2013). The data sources for end-use products (i.e. market share, lifetime, recycling rate, etc.) are adopted from (Pauliuk et al., 2013b). However, as for resource efficiency of each process, a linear growth is assumed to combine the current level and the historical level (Pauliuk et al., 2013b). Based on these inputs, the historical trends for the whole material cycle can be obtained through the production-driven method.

2.3 Scenario settings and Prospective estimation

The prospective estimation covers 2015–2100 with 2015 as the baseline year. The whole estimation starts from the saturation level of steel in-use stock. Then the whole cycle is quantified following stock dynamics and material flow analysis. This study aims to investigate the future trend of waste generation, and to clarify and compare two key strategies (i.e. circular economy and material efficiency) and the influence of other related social-economical factors like population, affluence, etc. Meanwhile, it is of great interest to investigate a potential pattern towards low steel use lifestyle. Hence, four scenarios are built for prospective estimation, namely the Baseline Scenario (Scenario 1), the Circular Economy Scenario (Scenario 2), Material Efficiency Scenario (Scenario 3), and Consumption Control Scenario (Scenario 4). The differences for these scenarios are mainly attributed to consumption and manufacturing layers, namely future steel use level, the resource efficiency of production stages, recycling rate, and lifetime of in-use products. The detailed settings for each scenario are shown in Table 1. The following gives the basic background for these scenarios.

Scenario 1 is the baseline scenario, which gives a business as usual estimation on future trend without additional policy intervention. Based on stock saturation hypothesis (Müller et al., 2011), per capita stock level will saturate with the increase of living standard. Through investigation on mature countries (Pauliuk et al., 2013b), this saturation level is around 13.4 ± 2 tons per capita. Many studies adopt the western lifestyle (mainly the USA) as the benchmark for steel's prospective estimation (Milford et al., 2013; Pauliuk et al., 2013a). In this scenario, this level (13.4 tons) and its division into four end-use categories are used as the saturation level for the global trend, and its growth pattern follows the combined logistic and Gompertz model (Milford et al., 2013; Pauliuk et al., 2013a). The other parameters are obtained based on an extension of the previous trend.

Table 1. Parameter setting for four future scenarios

	Key parameters	Transportation	Machinery	Construction	Products
S1	In-use stock saturation per capita (t)	1.9	1.6	9.2	0.7
	Lifetime (years)	20	30	70	15
	Recycling rate	0.82	0.87	0.82	0.58
	Resource efficiency of Fabrication	0.83	0.93	0.922	0.77
	Resource efficiency of other stages	Mining: 0.75; Primary Production: 0.94; Secondary Production:0.945			
S2	In-use stock saturation per capita (t)	1.9	1.6	9.2	0.7
	Lifetime (years)	20	30	70	15
	Recycling rate	0.90	0.95	0.90	0.70
	Resource efficiency of Fabrication	0.83	0.93	0.922	0.77
	Resource efficiency of other stages	Mining: 0.75; Primary Production: 0.94; Secondary Production:0.945			
S3	In-use stock saturation per capita (t)	1.045	1.072	7.452	0.511
	Lifetime (years)	23	33	70	47
	Recycling rate	0.90	0.95	0.90	0.70
	Resource efficiency of Fabrication	0.90	0.95	0.94	0.82
	Resource efficiency of other stages	Mining: 0.80; Primary Production: 0.97; Secondary Production: 0.97			
S4	In-use stock saturation per capita (t)	0.95	0.8	4.6	0.35
	Lifetime (years)	20	30	70	15
	Recycling rate	0.82	0.87	0.82	0.58
	Resource efficiency of Fabrication	0.83	0.93	0.922	0.77
	Resource efficiency of other stages	Mining: 0.75; Primary Production: 0.94; Secondary Production:0.945			

Over the years, the package of the circular economy has been broadened to include many other elements like use minimisation and dematerialisation (Geissdoerfer et al., 2017). In this study, the concept of circular economy is used as its initial idea of closing the loop in contrast to the linear economy (Walter R. Stahel, 2015). From a whole cycle (in Figure 1b), the circular economy focuses on the end-of-life solutions like recycling, remanufacturing, reuse, etc., which are included as the secondary route in this study. Hence, the design of a circular economy strategy as the future scenario is mainly about improving the recycling rate and expanding the secondary route. We assumed a linear growth of recycling rate from the current level to the designed level in 2050 (see Table 1), followed by a constant rate till the end of this century.

Material efficiency focuses on the life cycle impacts of material use from the material perspective (Allwood et al., 2011). To optimize resource efficiency, the solutions are specialized by (Allwood et al., 2011; Milford et al., 2013) on the entire cycle, including resource efficiency improvement for each stage, recycling rate improvement, less material for the same service, more intense use, life extension, etc. It is noted that a material efficiency strategy aims for the same improvement of end-of-life stage performance as a circular economy strategy. The data for each parameter in the basket of material efficiency change are obtained from material efficiency studies as the theoretical maximum limits (Milford et al., 2013; Wang et al., 2017). These strategies are designed not to comprise the lifestyle but to provide the same service level as benchmark level in scenario 1. Hence, the reduction for per capita in-use stock saturation level in Table 1 is not because of consumption reduction but to provide the same service through solutions like better design, dematerialization, light weighting, etc. In addition, it is also in this scenario assumed that there will be a linear growth of recycling rate from current level to the designed level in 2050 and keep the same afterward.

Scenario 4 provides an alternative option for future steel consumption, namely Lifestyle Compromise Scenario, in which the steel in-use stock saturation level will be compromised for each person globally. Although almost all previous studies (Milford et al., 2013; Pauliuk et al., 2013a) have assumed that global steel use will follow the western lifestyle to reach the saturation level of 13.4 tons, this study constructs this novel scenario of steel use reduction to half the consumption of the western lifestyle. For instance, the global population will only own the half the dwelling area, vehicles, consumer steel products etc. on average compared to the level in western countries. The parameter setting for the four scenarios is summarized in Table 1.

3. RESULTS AND DISCUSSION

The anthropogenic iron and steel cycle has been estimated from 1900 to 2100. This section will firstly present these results and the trends of flows and stocks. Based on these findings, this section will discuss the critical issue regarding challenges regarding waste management and the necessity of material efficiency

3.1 Whole steel cycle investigation based on the aggregative results from 1900 to 2100

This study estimates the steel flows and stocks along its life cycle in four scenarios from 1900 to 2100. To give an overview of the steel cycle, the flows and stocks are aggregated in the “clock diagram” of steel cycle as shown in Figure 2.

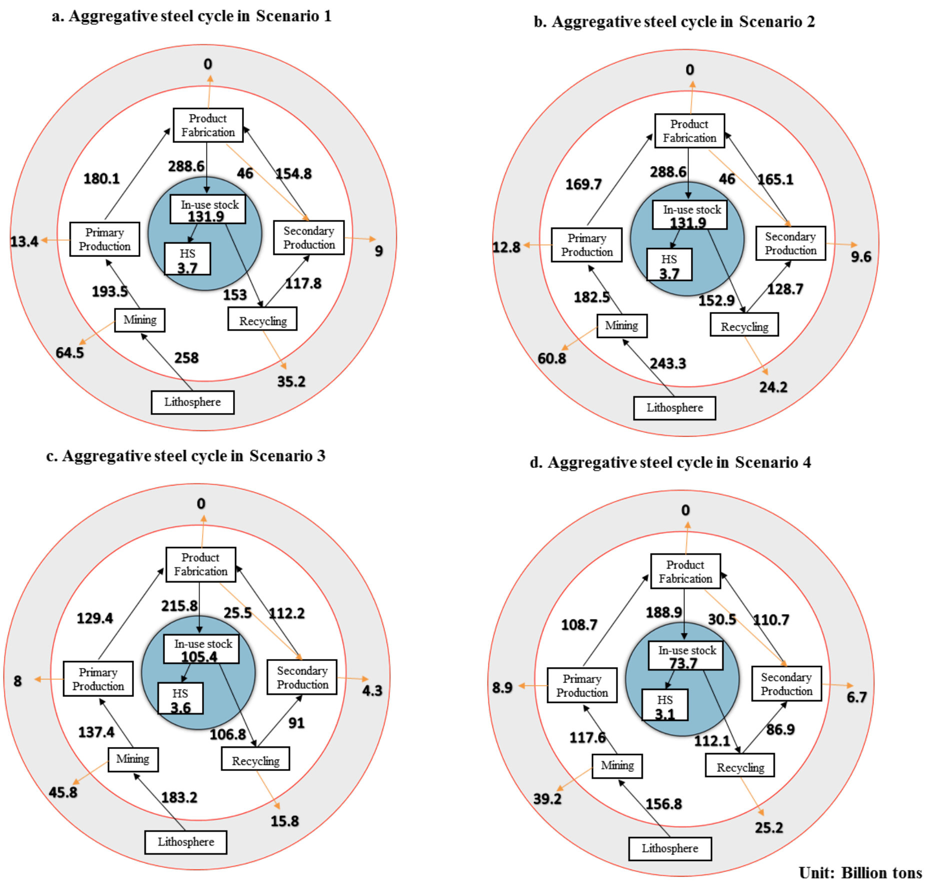

Figure 2. The steel cycle in aggregative format from the year 1900 to 2100 for four scenarios and the units is billion tons.

(1) Total in-use stock level. As a representative for living standard, the in-use stocks play a critical role in determining the whole material cycle. In scenario 1 as the business as usual scenario, the in-use stock has reached to 131.9 Billion tons (Bt) in the year 2100, which is identical to the scenario 2 as the same lifestyle (the Circular Economy scenario). Due to the technical improvement for steel in-use products, the in-use stock of the Material efficiency scenario (scenario 3) would be around 105.4 Bt. The steel in-use stock in the Lifestyle Compromise Scenario (Scenario 4) would be 73.7 Bt in 2100, which is 58.2 Bt less than the Scenario 1. Although the standard for the saturation level in Scenario 4 is a half of Scenario 1, the in-use stock in Scenario 4 is more than the half of Scenario 4 since the in-use stock has not been saturated in Scenario 1.

(2) Natural resource demand. From a whole cycle perspective, the total input to the anthropogenic cycle is extraction amount from lithosphere as the inflow to the mining stage. As shown from Figure 2, Scenario 1 would consume 258 Bt ore resource in total from 1900 to 2100. The Scenario 2, 3, 4 would consume 243.3 Bt, 183.2 Bt, and 156.8 Bt of natural resources, respectively. These results illustrate how improvement on any part of the metal's anthropogenic cycle (the recycling, whole stages, and in-use stage for these three scenarios) will reduce the natural resource extraction.

(3) The change of production routes. Secondary production route is an alternative production route depending on the recycled End-of-Life flow, which is more material and energy efficient compared with the primary one for steel (Wang et al., 2014). In any scenario, the secondary route will become a significant supply to help meet steel demand with the ratio of

46.2%, 49.3%, 46.4%, and 50.5% for scenario 1 to 4, respectively. Compared with the business as usual scenario, the Circular Economy scenario provides the same inflow to meet the demand with less natural resource extraction and primary production. In other words, the recycling improvement can help to reduce the dependence on the natural resource. Although the Circular Economy could improve the secondary production ratio compared with the Material Efficiency scenario, the absolute outflow of secondary production in the Material Efficiency scenario (112.2 Bt) is 52.9 Bt less than the Circular Economy scenario. Hence, the impact of material use in the Material Efficiency scenario would be less than in the Circular Economy scenario.

(4) Total waste generation. The waste of anthropogenic steel use comes from 5 stages, namely the mining, primary production, secondary production, products fabrication, and recycling. The total waste is 122 Bt, 107 Bt, 73.9 Bt, and 80 Bt for scenario 1 to 4, respectively. Comparing the total waste of the anthropologic cycle to the extracted resource (which is the input to the system), around 47.3%, 44.2%, 40.3%, and 51% of the extracted resource would be wasted during the whole cycle of steel use for scenario 1 to 4, respectively. Steel is considered as the most recycled metal by the World Steel Association (WSA, 2010). Figure 2 confirms this observation as the waste of recycling is only 28.8%, 22.5%, 21.3%, and 31.5% of total waste in scenario 1 to 4, respectively. The significance of waste from other stages has not been investigated in most of the previous studies. This study shows that the waste from other stages is not only significant but also dominates the total waste for steel use, which calls for the whole life cycle investigation. It is noted that the waste from mining dominates the total waste with a ratio of 52.8%, 56.6%, 62%, and 49% in scenario 1 to 4, respectively. This type of waste is attributed to the decreasing ore grade (Prior et al., 2013), which also brings difficulties for future improvement and recovery. Hence, there is a strong need to reduce the supply of primary production as an effort to improve the overall resource efficiency.

3.2 Trends of waste generation in four scenarios

The waste generation trend is the core research scope in this study. The following section will compare the total waste generation trend and its trends in different stages (i.e. mining, production, and recycling).

(1) Total waste trend. Figure 3 presents the total waste generation trend for steel use from 1900 to 2100 based on year by year estimation. In the retrospective estimation, the total waste rises at an increasing rate to 698.5 Mt per year in 2015, which is equivalent to around 37% of extracted natural resource (1885 Mt per year) in that year. As for the future, four different trends are observed in different scenarios. In the Business as Usual Scenario, the waste keeps rising to 1263 Mt/yr by the end of this century, which is almost twice the level in 2015. However, the waste generation in this scenario keeps stable in the second half of this century. The tendency of the future trend shows peak waste behavior for the other three scenarios (i.e. Circular Economy Scenario, Material Efficiency Scenario, and Lifestyle Compromise Scenario) occurring at different points in time.

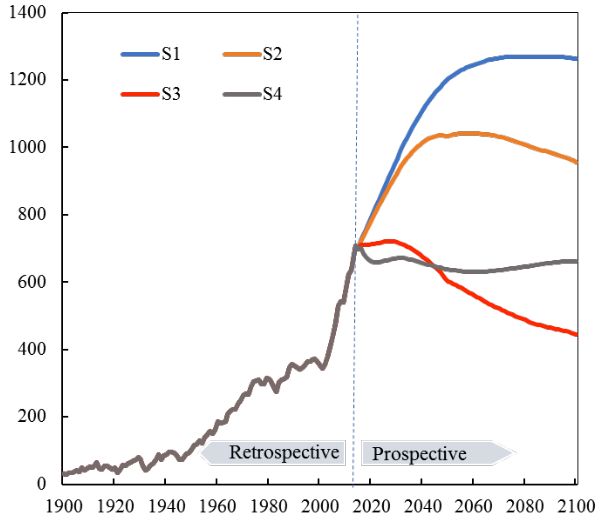

Figure 3. Total waste trend of steel use from 1900 to 2100 (S means Scenario, Unit: Million ton per year (yr))

In absolute terms, the Circular Economy Scenario generates the second most waste, peaking at around 1042 Mt/yr in 2057 and decreasing to 957 Mt/yr in 2100, which is still 259 Mt/yr more than the 2015 level. Compared with the BAU Scenario, the impact of the circular economy reduces not only the end-of-life waste but also the needs of the primary route. Hence, a significant reduction (14664 Mt) of total waste is obtained during the period from 2016 to 2100. The Lifestyle Compromise Scenario ranks the third in the total waste generation. After a peak in 2016, the waste in this Scenario declines remarkably afterwards and stabilizes at around 650 Mt/yr till 2100, which demonstrates that a scenario that implies stabilization at half the in-use saturation stock per capita that mature countries currently have would bring significate short-term but limited long-term impact on the waste generation (the reason is mainly attributed to the demand of the construction sector as discussed below). In contrast, the Material Efficiency Scenario shows quite robust and substantial reduction of total waste generation, which peaks at around 721 Mt/yr in 2027 and then declines to 445 Mt/yr, which is 216 Mt/yr less than the Lifestyle Compromise Scenario. Hence, the Material Efficiency Scenario is the best strategy among the four scenarios to reduce the waste generation. In general, the Material Efficiency strategy could not only maintain the lifestyle at the level of the mature countries, but it also generates the least waste which is even less than the Lifestyle Compromise Scenario.

(2) Waste trend in different stages. Figure 4 presents the trends of waste generation from mining (Figure 3a), primary production (Figure 3b), recycling stage (Figure 3c), and secondary production (Figure 3d). Generally speaking, there is a significant transition of production route from primary route to secondary route.

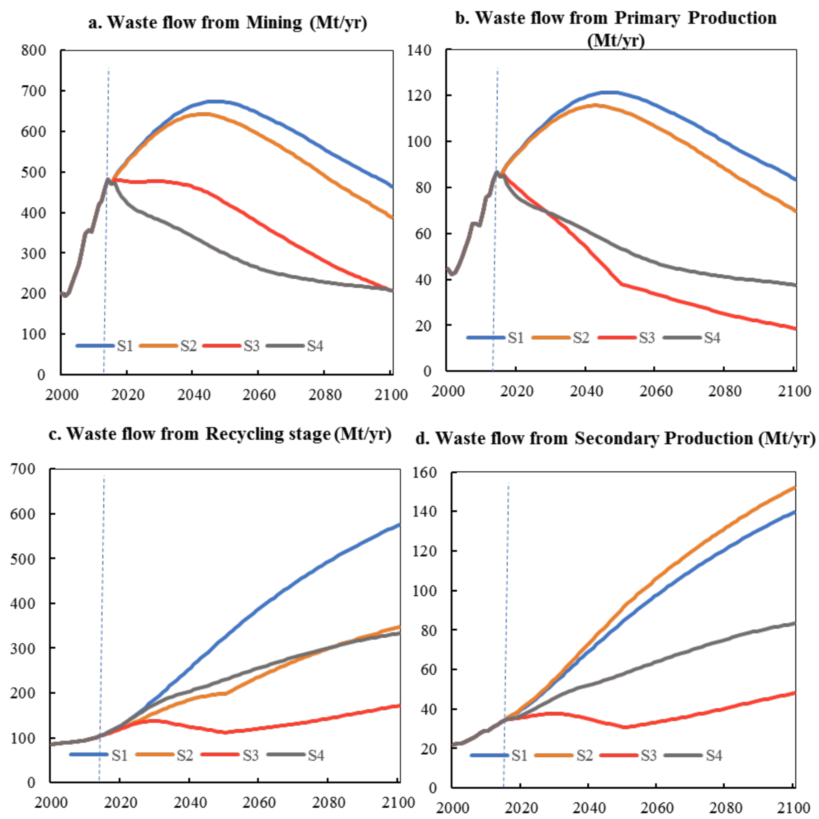

Figure 4. Waste trend from different life stages from 2000 to 2100 (S means Scenario)

Taken together, Figure 4a and 4b present the waste trend in the primary route. In these two figures, all four scenarios show a peak in the waste generation. Comparing Scenario 1 and 2, the overall trend of waste generation is similar but with the difference in the absolute amount, which implies that the circular economy can reduce the primary production through improving the resource from recycling but with limited impact. Scenario 3 and 4 in comparison show a substantial reduction relative to the circular economy. The in-use stock reduction ranks the least waste generation of mining in Figure 4a. However, the Material Efficiency scenario can reach a similar level in 2100 with maintaining the lifestyle. As for the waste trend in primary production, Material Efficiency ranks the least due to its effort to improve the resource efficiency of this stage.

Figure 4c and 4d present the waste trend in the secondary route. As shown in these figures, there is no peak trend to be seen during the period from 2016 to 2100. In the recycling stage, the impact of demand growth exceeds the effort of circular economy significantly as shown for Scenario 2 in Figure 4c and 4d. Meanwhile, the reduction of consumption (Lifestyle Compromise Scenario) cannot peak the waste either. Hence, it is not feasible to reach peak waste with the strategies of circular economy and consumption reduction for steel use solely. However, as shown in Figure 4c and 4d, Material Efficiency can restrain the growth of waste generation in both the end-of-life stage and secondary production with least waste generation in those stages. Overall, Material Efficiency is the only solution for waste management to reach the target of peak waste within the end-of-life stage.

(3) Waste trend from end-use product groups. The trend of waste generation in end-of-life stage is the main scope of waste management. In this study, we present the end-of-life waste from different end-use product groups in different scenarios in Figure 5. In terms of cumulative end-of-life waste in this century, the consumer products sector would generate the most end-of-life waste (around 40%) in Scenario 1,2, and 4 despite that its share in in-use stock is around 5%. The second largest waste comes from the transportation sector with around 30%. However, the Building sector only generates around 20% of waste with more than 65% in-use stock. This result implies that end-of-life waste generation is more dependent on the recycling rate, lifetime, and historical inflow than on the in-use stock share. The sector of consumer products and transportation can generate more waste due to its short lifetime compared with the building sector. In other words, prolonging the lifetime of products in-use can reduce the waste generation.

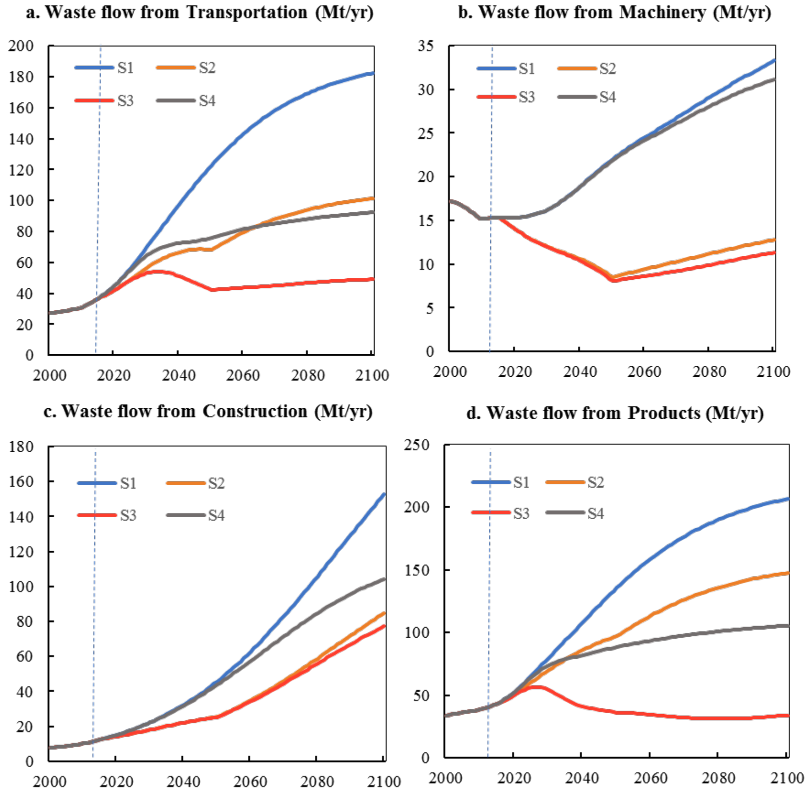

Figure 1 Waste trend from end-of-life stage from 2000 to 2100 (S means Scenario)

In terms of the tendency, there is no peak waste trend in the construction sector for any of the four scenarios due to its long use lifetime and fast-growing future inflow to meet more than three times the current in-use stock level per capita. There is also no peak waste observed for any of the other product sectors in Scenario 1. Comparing the trends of Scenario 1 and 4, the consumption reduction can reduce the amount of waste generation but not the trend, which is still increasing to the end of this century. The circular economy can help generate a peak waste but only in the machinery sector. However, the material efficiency generates the least waste across all scenarios and sectors and can at the same time facilitate transportation, machinery, and products sector to peak their end-of-life waste.

4. CONCLUSIONS

Anthropogenic material use generates massive waste, not only in the end-of-life stage but in its whole life cycle from extraction to end-of-life. This study models the waste generation from steel use, from 1900 to 2100, with a focus on its whole life cycle. The trend of waste generation is simulated through year by year calculation from the dynamic material cycle model. To analyze possible trends in future waste management, four scenarios are built to predict the future trend from 2016 to 2100, namely the business as usual scenario, Circular Economy scenario, Material Efficiency scenario, and Lifestyle Compromise scenario. The differences between the waste generation in these four scenarios are mainly attributed to the in-use stock saturation level, lifetime of products within different sectors, the recycling rate of in-use products, and the resource efficiency of other life stages. Several findings are obtained based on the results:

(1) Steel faces a severe waste issue despite being the most recycled metal. Steel has been well recycled and managed under the guidance of circular economy. Without further improvements, the waste from steel use (in the business as usual scenario) would double the current level in 2016 by the end of this century. Since other materials are generally more poorly managed than steel, the waste issue of anthropogenic material use would be worse and call for more effective solutions.

(2) Waste management requires a whole life cycle investigation. Over time, the waste management has been mainly focused on the end-of-life stage. However, in many cases like steel, the end-of-life stage is not the hotspot of waste generation. Other life stages, especially the mining, generate much more waste than the end-of-life stage for steel. Hence, this study calls for a whole cycle investigation on waste management of material use.

(3) Circular economy is not enough to peak waste. Although circular economy has been widely promoted worldwide, our result indicates that this strategy alone at the end-of-life stage could not peak the total waste amount.

(4) Compromising lifestyle has limited effect. This study analyses a novel scenario where the saturation steel use level is halved by compromising lifestyle as the western countries. The result of this scenario indicates a sudden decrease of waste generation (mainly in the primary route) and would stay in this amount afterward. However, this scenario has a quite limited effect on the recycling and secondary production not to mention that compromising lifestyle in this way entails a severe equality issue.

(5) Peak Waste requires comprehensive solution served by Material Efficiency. Through a whole life cycle investigation, this study improves our current understanding on waste, which is not only determined by the end-of-life solution but closely linked to more complicated mechanisms influenced by parameters like population growth, changed pattern of material living standard (measured by in-use stock pattern), in-use behavior for different products (e.g. lifetime), historical consumption, and the efficiency of the production and processing stages. The Material Efficiency strategy builds on a more comprehensive understanding and recognition of the total impact of material use, which leads to a better management of the material-related waste issue. The detailed strategy of Material Efficiency seems not only to be able to maintain the lifestyle expressed as per capita in use stocks at the level of the mature countries, but also to generate the least waste of all scenarios, in the long term even less than the Lifestyle Compromise Scenario.

REFERENCES

Allwood, J.M., 2014. Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies, in: Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists, Elsevier Publisher, Amsterdam, 445–477.

Allwood, J.M., 2013. Transitions to material efficiency in the UK steel economy. Philos. Trans. A. Math. Phys. Eng. Sci. 371, 20110577-20110577.

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper.

Resour. Conserv. Recycl. 55, 362–381.

B. Müller, D., 2006. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. Ecol. Econ. 59, 142–156.

Bardi, U., 2009. Peak oil: The four stages of a new idea. Energy 34, 323–326.

Bardi, U., Pierini, V., Lavacchi, A., Mangeant, C., 2014. Peak Waste? The Other Side of the Industrial Cycle. Sustainability 6, 4119–4132.

Beigl, P., Lebersorger, S., Salhofer, S., 2008. Modelling municipal solid waste generation: A review. Waste Manag. 28, 200–214.

Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers, Florida, USA.

Chen, W.-Q., Graedel, T.E., 2012. Anthropogenic cycles of the elements: a critical review. Environ. Sci. Technol. 46, 8574–86.

Dyson, B., Chang, N. Bin, 2005. Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling. Waste Manag. 25, 669–679.

Ferreira, F., Avelino, C., Bentes, I., Matos, C., Teixeira, C.A., 2016. Assessment strategies for municipal selective waste collection schemes. Waste Manag. 59, 3–13.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? J. Clean. Prod. 143, 757–768.

Gerst, M.D., 2009. Linking material flow analysis and resource policy via future scenarios of in-use stock: An example for copper. Environ. Sci. Technol. 43, 6320–6325.

Goodland, R., 1995. The concept of environmental sustainability. Annu. Rev. Ecol. Syst. 26, 1–24.

Graedel, T.E., Dubreuil, A., Gerst, M., Hashimoto, S., Moriguchi, Y., Müller, D., Pena, C., Rauch, J., Sinkala, T., Sonnemann, G., 2010. Metal stocks in society: scientific synthesis. United Nations Environment Programme (UNEP), Paris.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Ohman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., Noble, I., 2013. Policy: Sustainable development goals for people and planet. Nature 495, 305–307.

Hoornweg, D., Bhada-tata, P., Kennedy, C., 2013. Waste production must peak this century. Nature 502, 615–617.

Hoornweg, D., Bhada-Tata, P., Kennedy, C., 2015. Peak Waste: When Is It Likely to Occur? J. Ind. Ecol. 19, 117–128.

Liu, G., Bangs, C.E., Müller, D.B., 2012. Stock dynamics and emission pathways of the global aluminium cycle. Nat. Clim. Chang. 3, 338–342.

Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The roles of energy and material efficiency in meeting steel industry CO2 targets. Environ. Sci. Technol. 47, 3455–3462.

Müller, D.B., Wang, T., Duval, B., 2011. Patterns of iron use in societal evolution. Environ. Sci. Technol. 45, 182–188.

Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. Technol. 48, 2102–2113.

Pauliuk, S., Milford, R.L., Müller, D.B., Allwood, J.M., 2013a. The steel scrap age. Environ. Sci. Technol. 47, 3448–3454.

Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Chang. 24, 132–142.

Pauliuk, S., Wang, T., Müller, D.B., 2013b. Steel all over the world: Estimating in-use stocks of iron for 200 countries. Resour. Conserv. Recycl. 71, 22–30.

Pauliuk, S., Wang, T., Müller, D.B., 2012. Moving toward the circular economy: The role of stocks in the Chinese steel cycle. Environ. Sci. Technol. 46, 148–154.

Prior, T., Daly, J., Mason, L., Giurco, D., 2013. Resourcing the future: Using foresight in resource governance. Geoforum 44, 316–328.

Prior, T., Giurco, D., Mudd, G., Mason, L., Behrisch, J., 2012. Resource depletion, peak minerals and the implications for sustainable resource management. Glob. Environ. Chang. 22, 577–587.

Reck, B.K., Graedel, T.E., 2012. Challenges in metal recycling. Science. 337, 690–695.

UNEP, 2015. Global Waste Management Outlook. United Nations Environment Programme (UNEP), Paris.

USGS, 2013. Historical statistics for mineral and material commodities in the United States (2013 version). United States Geological Survey, Virginia.

Walter R. Stahel, 2015. The circular economy. Nature 531, 435–438.

Wang, P., Jiang, Z., Geng, X., Hao, S., Zhang, X., 2014. Quantification of Chinese steel cycle flow: Historical status and future options. Resour. Conserv. Recycl. 87, 191–199.

Wang, P., Li, W., Kara, S., 2017. Cradle-to-Cradle Modeling of the Future Steel Flow in China. Resour. Conserv. Recycl. 117, 45–57.

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev. 68, 825–833.

World Bank, 2012. What a Waste: A Global Review of Solid Waste Management. World Bank, Washington, DC.

WSA, 2010. The three Rs of sustainable steel, World Steel Association. Search Results

World Steel Association, Brussels/Beijing.

Zink, T., Geyer, R., 2017. Circular Economy Rebound. J. Ind. Ecol. In Press, 1–10.