Is recycling the solution for the reduction of our raw materials demand?

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Abstract

In this study, a first attempt was made to quantify effects of recycling on the long term supply of raw materials. The research question was: how important is the role of recycling for a sustainable use of materials in a production chain? Important variables in this production and recycling chain are the growth rate in the production of goods, the lifetime of products in the use phase and the percentage of the waste that can be effectively recycled.

Material flow analyses (MFA) was used to calculate material flows in a system where raw materials are used to make products with a given lifetime. The products are subsequently partly recycled when reaching their end of life phase. The recycled materials are then available as 'secondary' raw materials to make new products. The rejects of used products that are not recycled are assumed to be landfilled. Several scenarios with varying recycling rates, production growth rates and product lifetimes are described in the report.

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Summary

Many different raw materials (resources) are used for the production of consumer goods. Some of these raw materials are very abundant, for example sand or limestone. Other resources (for instance certain metals, phosphate or rare earth elements) are already scarce or will become scarce in the coming decades.

Recycling of materials to produce new products is seen as an important step to fulfil the long term material demand. However, the influence of waste management strategies (for example re-use and recycling) on the total raw (primary) material demand is not well studied.

In this study, a first attempt was made to quantify effects of recycling on the long term supply of raw materials. The research question was: how important is the role of recycling for a sustainable use of materials in a production chain? Important variables in this production and recycling chain are the growth rate in the production of goods, the lifetime of products in the use phase and the percentage of the waste that can be effectively recycled.

Material flow analyses (MFA) was used to calculate material flows in a system where raw materials are used to make products with a given lifetime. The products are subsequently partly recycled when reaching their end of life phase. The recycled materials are then available as ‘secondary’ raw materials to make new products. The rejects of used products that are not recycled are assumed to be landfilled. Several scenarios with varying recycling rates, production growth rates and product lifetimes are described in the report.

The MFA models provide insight in effects of policy choices on the whole chain from production to the waste management phase and can be applied for scenario calculations. The developments and results reported here can be seen as a first step towards application to real-world scenarios. However, the outcome of this study already provides insight in the main mechanisms that influence the long-term raw materials need and waste production: production growth rate, recycling rate and the product lifetime.

The results show that the recycling rate, product lifetime and the production growth rate are important factors that determine the long term waste production and the raw material need for production. In summary, when a production growth rate of 3% is assumed with a recycling rate of 60%, the yearly raw material need would grow with a factor 9 over a period of 100 years compared to the starting amount to keep up with the production growth rate of 3%. In other words, recycling alone would not be enough to prevent the use of primary raw materials. When

the production growth rate is 1% and the recycling rate is 60%, the raw material need would effectively not grow over a period of 100 years. Such a scenario would lead to a more sustainable and circular production chain.

Only when a recycling rate of 99% is assumed in combination with a 1% production growth rate, the yearly raw material need would drop to around 10% of the starting amount. In that case, a substantial reduction of the primary raw material amounts is realised and the products would in the longer term consist largely of secondary raw materials. However, it is important to note that these calculations do not take the environmental impacts into account that are needed for a 99% recycling rate, such as the energy and water use that could be unacceptably high.

The MFA modelling results were also used to make estimations on the expected time frame at which the raw material stock becomes depleted and/or exhausted. Results showed that recycling lowers the total amount of raw materials needed for production and can, therefore, postpone the moment of material exhaustion. Depending on the assumed scenario, the material exhaustion could be postponed for periods in the order of a century or only by one or several decades. These results were also consistent with findings from other authors. In real life, also other factors can positively influence the long term material availability, that is prolonging the lifetime of products, repairing products or re-using products. More detailed analyses of real-world cases would be needed to quantify such scenarios. Material flow analyses can help to quantify these effects for different production chains.

In addition, the results of the study obviously indicate that substantial amounts of waste (that cannot be recycled) will continue to be generated over the long term when realistic recycling rates (±60%) are achieved. These observations do also provide useful input for the long term policy decisions on waste management.

An interesting and so far quite unexplored area is the assessment of the optimum recycling rate for several waste materials. It is likely that a recycling rate of nearly 100% is often not feasible from an economic point of view and also not from an ecological point of view. Research indicates that an optimum has to be found for the technical, economic and ecological aspects of recycling and this optimum might be substantially lower than 100% (Staubli et al., 2016).

1. Introduction

Many different raw materials (resources) are used for the manufacturing of consumer goods (products). Some of these raw materials are very abundant, for instance sand or limestone. Others are already scarce or will become scarce in the coming decades (for example certain metals, phosphate or rare earth elements). The concerns around these relatively scarce resources are partly related to their absolute amounts as well as the geopolitical risks for supply. More information about the backgrounds and the identified critical metals can be found elsewhere (Henckens, 2016; Moss et al., 2011). These studies and several other publications have gained insight in the long term availability of resources and make projections on the time periods in which potential problems in supply could arise. These studies do also recognize the current increasing material demand that is still coupled substantially to our economic growth (historically around 3% increase per year). The increasing growth of material demand leads to an exponential growth in the need for raw materials.

Although the availability and projected material demand has been investigated for the primary materials (from mining to raw materials), much less attention has been given so far to the dynamics of raw material use and to those factors that could positively influence their long-term availability. The influence of waste management strategies (for example re-using and recycling) on the total raw (primary) material demand is not well studied. This statement is particularly true when an increasing production rate for materials is taken into account.

In this study, a first attempt was made to quantify effects of recycling on the long term supply of raw materials. The research question was: how important is the role of recycling for a sustainable use of materials in a production chain? Important variables in this production and recycling chain are the growth rate in the production of goods, the lifetime of products in the use phase and the percentage of the waste that can be effectively recycled.

Material flow analyses was used to set up a generic model for the calculation of dynamic material flows in a system where raw materials are used to make products with a given lifetime. Subsequently, the products are partly recycled when reaching their end of life phase. The recycled products are then available as secondary raw materials to make new products. The rejects of used products that are not recycled are assumed to be landfilled. Several scenarios with varying recycling rates, production growth rates and product lifetimes are described in the report.

2. Material flow analyses

Material flow analyses (MFA) is an important tool to study the amounts of material flows in installations, regions, countries or continents as a consequence of technologies or policies. MFA is used to model defined systems and to create more insight in amounts of materials (or even substances in materials) that move through a system and also takes into account the 'build-up' of materials in for example products in use or landfills. Software has been developed to calculate the material flows and stocks in systems and these tools can be used for a wide range of applications.

In this report, the software package STAN2.5 (http://www.stan2web.net/) was used to perform the model calculations. STAN2.5 has been developed by the Technische Universität Wien (TUW) and has been used since its development in 2004 as computing tool in more than 100 publications (http://www.stan2web.net/infos/publications). Therefore, this modelling tool can be considered to be the most advanced and user friendly program for MFA. The description of the modelled system and assumptions is given in Chapter 3.

3. Material production and recycling scenarios

The material flow diagram used in this report is shown in Figure 1. The flow diagram represents a hypothetical production and recycling scenario of a product (for instance steel, plastics or concrete) that is used to illustrate long term effects of production growth and the effects of recycling on the raw material demand. A product (or good) is here assumed as a sum of more materials. The scenario is representative for many product chains in that the flow diagram takes the most important life cycle stages of materials and products into account: raw materials, production, use, recycling and landfilling or another waste management option such as incineration.

On the left side of Figure 1, the input flow (I) represents the raw material need that is used in a production process to obtain a product. The product is subsequently sold and used by consumers: the use phase of the product. The inserted square in the use phase represents the stock of materials. This can be seen as the amount of material in the products that are used by consumers and, hence have not yet reached their end of life (EoL) phase. At some point in time (see below), the products reach their EoL phase and will move to the recycling stage. The materials that can be recycled (secondary raw materials), assuming a certain recycling rate, go back to the production to produce new products again. Because not all of the material can be recycled (and/or not all of the used products might reach the recycling plant due to other disposal routes), a certain recycling rate is assumed for the whole flow of used products (EoL). The part of materials which is not recycled will be waste and goes to landfill. Please note that the landfill process might also be a composting or incineration process depending on a specific material. The main aim here is to indicate that the materials do not enter the production anymore. Again, the inserted square in the landfill phase represents the stock of materials. The landfill process has no outflow and, therefore, all materials go to the Landfill stock.

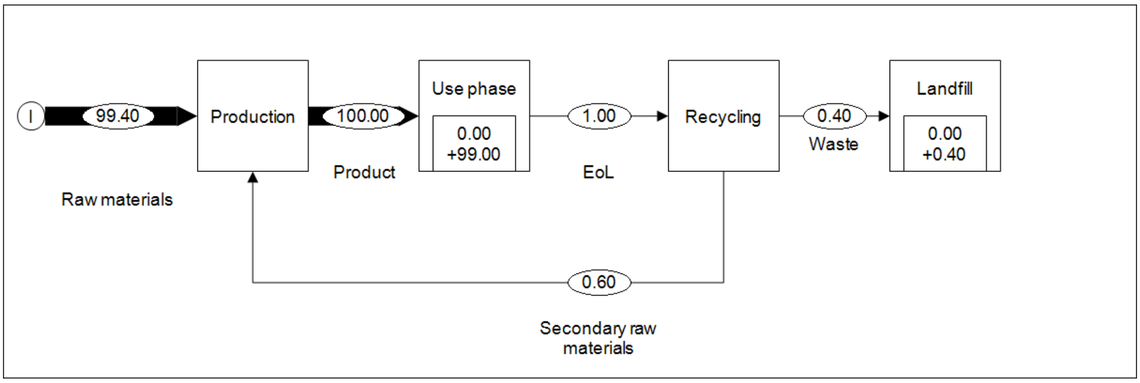

Figure 1 Outline of the material flow system and relations between the different life stages of the product (numbers are illustrative and indicate the material flows after 1 year assuming a recycling rate of 60%).

Three important parameters were varied to assess the need for raw materials over a period of 100 years:

- **Growth in production**: growth rates of 1% and 3% per year were used for the model calculations. The production growth rate of an important product (or good) as steel is around 3% per year, based on the long term average. The more conservative growth rate of 1% was taken as a reference.
- **Product lifetime**: in one case, the product lifetime was assumed to be 5 years. This example could be relevant for consumer products like laptops, cloths, et cetera. The disposal rate of the product was assumed to be 10%, 20%, 30%, 30% and 10% from year 1 to year 5 respectively. Another scenario assumed a product lifetime of 20 years with a disposal rate according to Figure 2. This example would more represent products like cars or construction materials although the disposal rate was purely chosen as an example. When data of certain products is available, the model can be easily adapted to take the real-world data into account.
- **Recycling rate**: the recycling rate of the product is varied from 1%, 60% and 99% to study the whole range of possible recycling scenarios.

The raw material need is calculated for every combination of variables, resulting in 12 different scenarios.

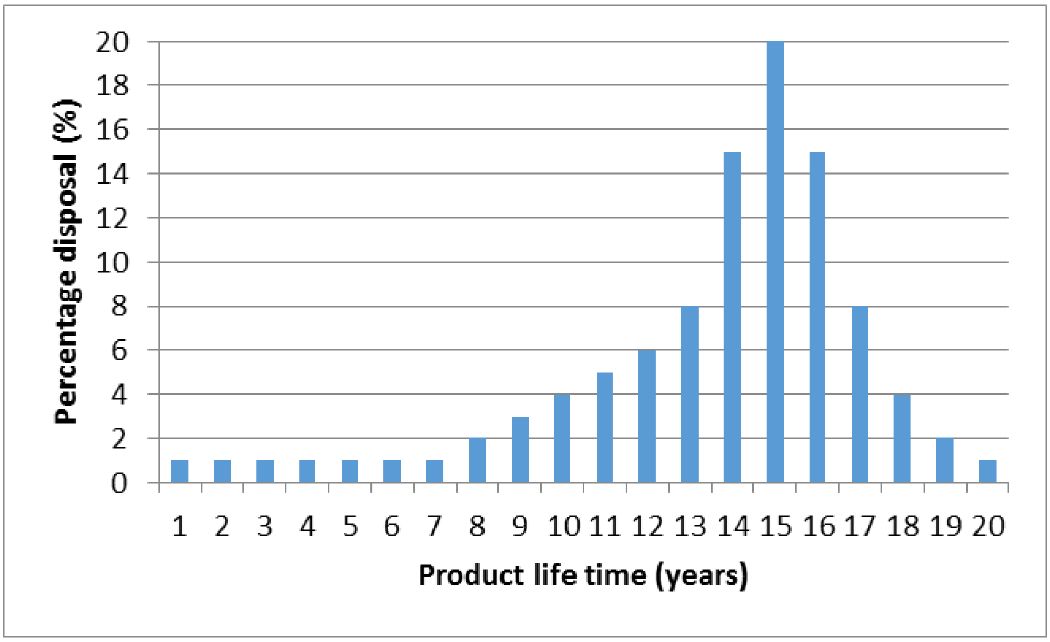

Figure 2 Disposal rate for products with a total lifetime of 20 years (examples could be cars or construction materials).

4. Results and discussion

The results of the calculated material flows for the different scenarios are discussed here in terms of the raw material needs (input to the system) and the amounts of waste produced (outflow to landfill). The aim of this study is to assess the importance of recycling under several assumptions on recycling rates and production growth demands for products with a specified lifetime. The secondary material quality and environmental impacts of recycling and landfilling are not discussed in detail.

The material flows depend on the process variables that were assumed in the modelling, that is the yearly growth rate in production, the time that products are used (use phase) and the recycling rates at the end of life phase. The results for the scenarios with products having a lifetime of five or 20 years are discussed separately and cannot be compared readily. The main reason why these scenarios cannot be compared is because products with a lifetime of 5 years generally use different (combinations of) materials for a specific purpose (for example laptops, cloths, telephones etc.) compared to products with a lifetime of 20 years (for instance cars, buildings, roads, et cetera).

4.1 Scenarios for products with a lifetime of 5 years

Figure 3 and Figure 4 show the modelling results of the raw material needs and the waste produced over a total period of 100 years for a product with a given lifetime of 5 years (for example plastic parts or metals used in electronic goods). The graphs on the left hand side illustrate the scenarios for which a yearly growth rate of 1% in production was assumed, while the right hand graphs show the results for a growth rate of 3%. The top graphs zoom in on the effects of the raw material needs in the first 5 years; bottom graphs show the long-term effects over a period of 100 years. The coloured lines show the results of different recycling rates (1, 60 or 99%) for the end of life phase.

Several interesting observations can be made from Figure 3. When comparing the raw material need for different recycling rates in a scenario with 1% growth, the increased recycling rates contribute substantially to a lowered need for raw materials with a strong decrease in the first 5 years. The products reach their end of life phase within 5 years and will become increasingly available for the recycling market. Hence, the decrease in raw materials becomes almost proportionally greater with higher recycling rates.

After 5 years, the outflow of end of life materials reaches a steady state with a constant (relative) contribution to the materials needed for production (that is the sum of raw materials and secondary raw materials). The left graph also indicates that when using a recycling rate of 60% or more, the yearly amount of raw materials needed, is substantially lower than the start of the production (year 2000) and only approaches the starting yearly raw material need after at least 100 years.

The same generic effects are visible for the scenario with a growth rate of 3% in production (note the different Y-axis scales of the graphs). Again, there is a decrease in raw materials need in the first 5 years before there is a steady state in materials coming from recycling and the raw materials needed for production.

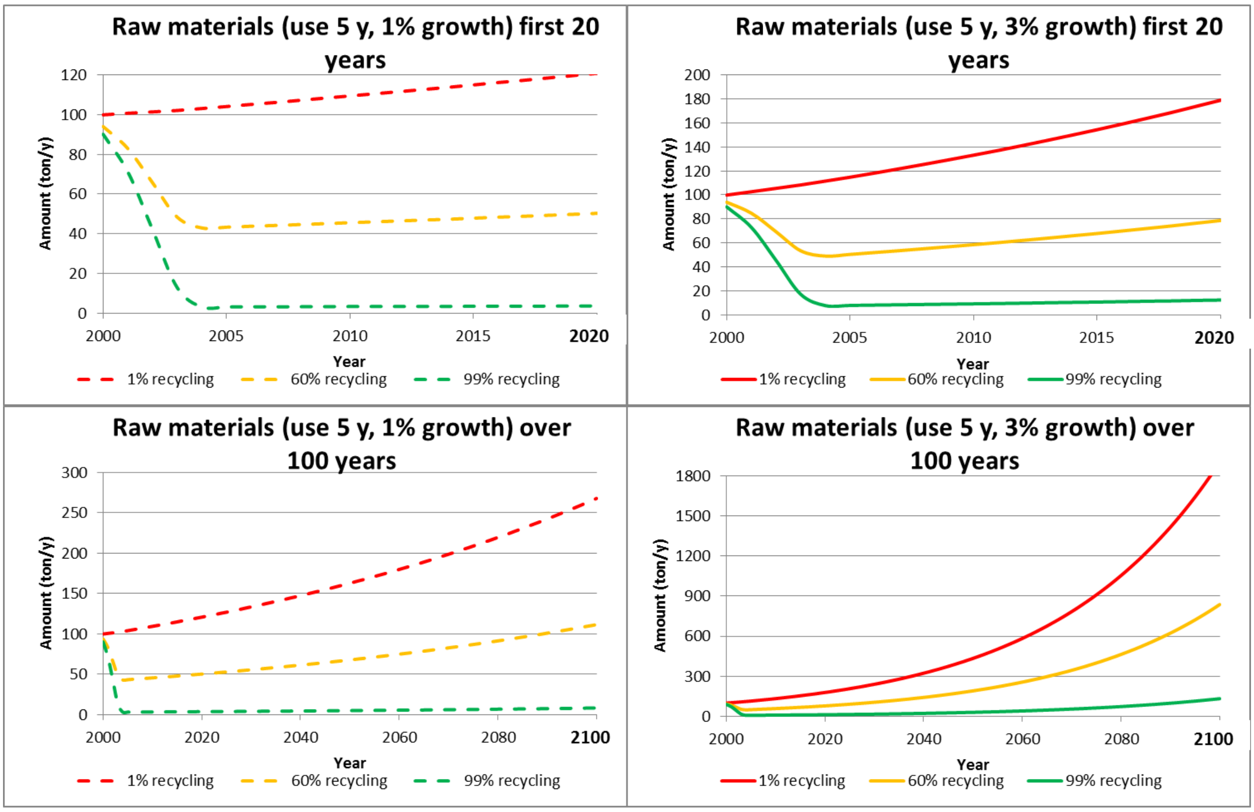

Figure 3 Scenario calculations for the raw materials demand as a function of time assuming a use phase period of 5 years and different recycling and growth rates (left graphs 1%, right graphs 3%). The top graphs zoom in on the effects of the raw material needs in the first 20 years, bottom graphs show the long-term effects over a period of 100 years.

However, the 3% growth rate scenario has a more pronounced exponential effect on the raw material needs on the longer term in comparison with the 1% growth rate scenario (compare bottom left and right graphs). In the extreme case of only 1% recycling and a growth rate of 3%, the yearly raw material need would grow a factor 18 over a time period of 100 years. The scenario with a 1% growth rate and 1% recycling leads to a factor of 2.5 more raw materials need over 100 years.

When the growth rate is 1% and the recycling rate is 60%, the raw material need would effectively not grow over a period of 100 years (bottom left graph). When a production growth rate of 3% is assumed with a recycling rate of 60%, the yearly raw material need would grow with a factor 9 more than the starting amount to keep up with the production growth rate of 3%. Similar observations have been made for a number of commodity products (aggregates, iron, steel, aluminium, plastics and paper) where it was found that the waste generation (even at substantial recycling rates) is often far lower than the demand for materials in production and the material stocks in products (Fellner et al., 2017).

Only when a recycling rate of 99% is assumed in combination with a 1% production growth rate, the yearly raw material need would drop to around 10% of the starting amount. This ideal case would substantially lower the materials needed for production. From a materials point of view, this situation could be seen as a sustainable production and use scenario. However, it is important to note that these calculations do not take the environmental impacts into account. For example, it can be imagined that there will be a clear environmental benefit from a lower raw material consumption because less raw materials need to be mined and refined. But the environmental burdens of obtaining a recycling rate of 99% could be substantially higher in comparison to a more conservative (and possibly more realistic) recycling rate of for instance 60%. Probably the energy and water use could be unacceptably high to obtain an almost complete recycling rate of 99%.

The scenario with a growth rate of 3% and 99% recycling would imply that about 30% more raw materials are needed after 100 years in comparison to the starting amount. However, the same considerations with regard to the environmental impact as described above would apply.

When the produced waste amounts are assessed (Figure 4), the same observations can be made as described for the raw materials need, although obviously the trends in the graphs develop exactly opposite from the raw materials. The steep increase in waste production mainly occurs during the first 5 years and will then be a function of the growth rate and the recycling rate of the system. In general, a high production growth rate in combination with a low recycling rate leads to substantial amounts of waste to be produced on the long term. Recycling percentages of well over 60% would be needed to substantially avoid waste production on the long term at the given production growth rates.

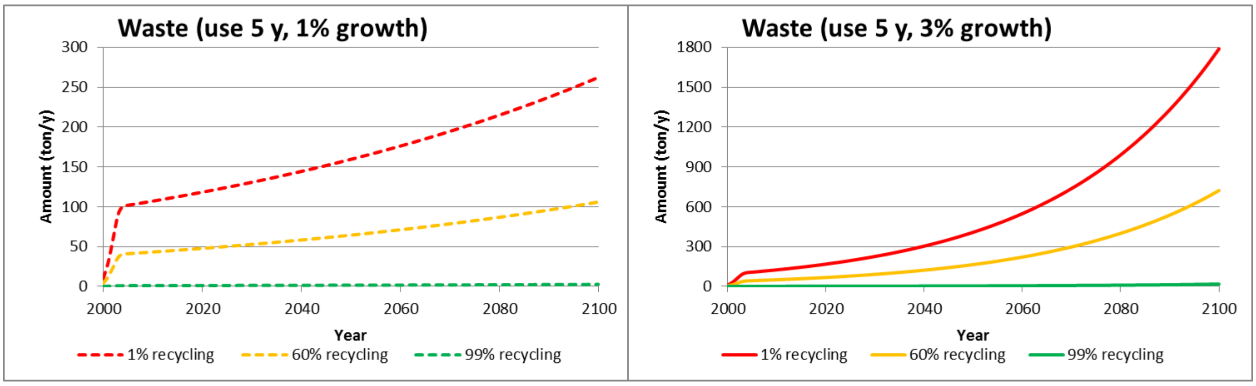

Figure 4 Scenario calculations for the production of waste going to landfill as a function of time assuming a use phase period of 5 years and different recycling and growth rates (left graph 1%, right graph 3%).

4.2 Scenarios for products with a lifetime of 20 years

Figure 5 and Figure 6 show the modelling results of the raw material needs and the waste produced for a product with a given lifetime of 20 years (for example cars or construction products). The graphs on the left hand side illustrate the scenarios for which a yearly growth rate of 1% in production was assumed, while the right hand graphs show the results for a growth rate of 3%. The coloured lines show the results of different recycling rates (1, 60 or 99%) for the end of life phase.

Again, a strong decrease in the yearly raw material need is observed for both growth rate scenarios in the first 20 years. After 20 years, the yearly raw material need increases defined by the recycling rate for both 1% and 3% growth.

The left graph also indicates that when using a recycling rate of 60% and more, the yearly raw material need would effectively not grow (or be limited to 25% for 60% recycling) over a period of 100 years. With the extreme case of 99% recycling, far less raw materials would be needed to keep up with the production growth rate of 1%. Also in these scenarios, it is questionable whether an almost complete recycling rate would be beneficial from an environmental point of view (for instance due to unacceptably high energy and water use to obtain such high recycling rates).

Again, the graphs for products with a lifetime of 5 and 20 years cannot be compared directly. The main reason why these two scenarios cannot be compared is because products with a lifetime of 5 years generally use different (combinations of) materials for a specific purpose (for example laptops, cloths, telephones, et cetera) compared to products with a lifetime of 20 years (for example cars, buildings, roads, et cetera).

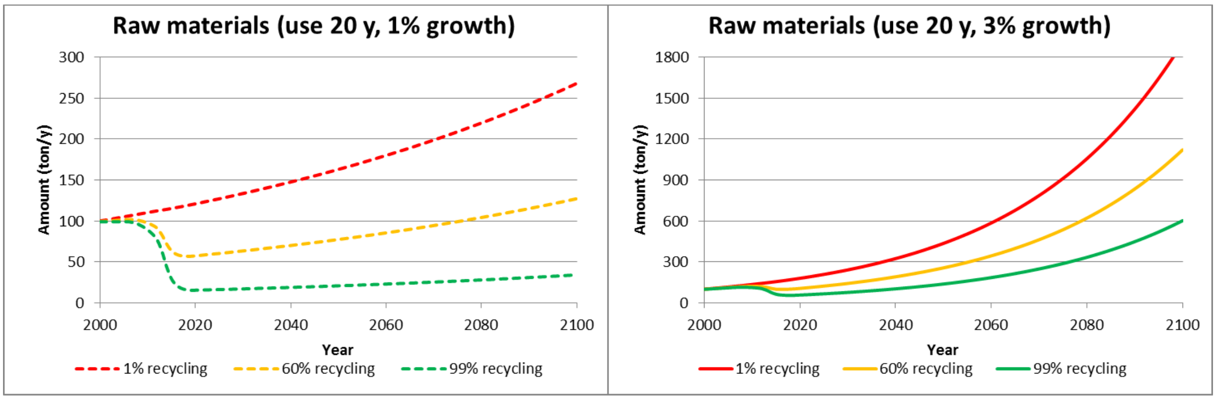

Figure 5 Scenario calculations for the raw materials demand as a function of time assuming a use phase period of 20 years and different recycling and growth rates (left graph 1%, right graph 3%).

When the produced waste amounts are assessed (Figure 6), the same observations can be made as described for the raw materials need albeit that in this case a low recycling rate implies more waste to be produced. The steep increase in waste production mainly occurs during the first 20 years and will then be a function of the growth rate and the recycling rate of the system. In general, a high growth rate in combination with a low recycling rate leads to substantial amounts of waste to be produced on the long term. Recycling percentages of well over 60% would be needed to substantially avoid waste production on the long term at the given production growth rates.

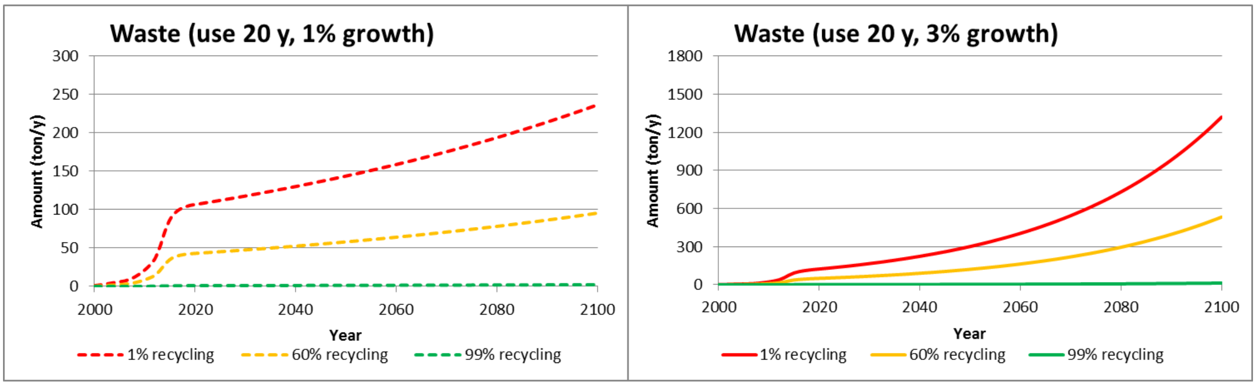

Figure 6 Scenario calculations for the production of waste going to landfill as a function of time assuming a use phase period of 20 years and different recycling and growth rates (left graph 1%, right graph 3%).

4.3 Raw material need and long term availability

There is an increasing focus on the long term availability of raw materials (resources) to make the products that society needs. These discussions started already in the 1970s regarding the long term availability of our fossil fuels both in absolute amounts as well as the geopolitical sensitivity of these resources. Nowadays, many more raw materials have been identified as being critical with regard to their availability (Moss et al., 2011). Without reviewing the literature on this subject, the results of our material flow analyses can be linked to assumed resource availabilities to put the discussion in broader perspective.

Figure 3, Figure 4, Figure 5 and Figure 6 all show the yearly needed amounts of materials or the yearly produced waste amounts (ton/year). The total cumulative amounts of raw materials needed over a period of 100 years (product lifetime of 20 years) were calculated and are plotted in Figure 7. Quite similar observations were made for the scenarios with 5 years lifetime and, therefore, these data are not shown. The total amount of raw materials needed with a 3% growth rate is a factor 4-6 higher in comparison to the amount needed in the 1% growth rate scenarios. This difference is larger than a factor 3 (that is direct comparison of 1% and 3% growth) and is caused by the exponential growth of raw materials over the longer term.

The MFA modelling results can also be used to make estimations on the expected time frame at which the raw material stock becomes depleted and/or exhausted. When the total amount of raw materials available would be for example 20.000 ton (blue line in Figure 7), it can be seen that the supply would be sufficient for at least 100 years for a growth rate scenario of 1% and only 1% recycling. With higher recycling rates, the availability of materials would be sufficient for hundreds of years.

However, when a growth rate of 3% is assumed (and the total availability of materials is 20.000 tons) the raw materials would be exhausted after 65, 80 or 100 years depending on the recycling rate.

The results show that recycling can substantially contribute to resource efficiency on the long term when recycling rates of >60% can be achieved. Recycling lowers the total amount of raw materials needed for production and can, therefore, postpone the moment of material exhaustion. In real life, also other factors can positively influence the long term material availability, that is prolonging the lifetime of products, repairing products or re-using the products. These factors have not yet been quantitatively assessed.

The results also show that the importance of recycling on the long term material availability becomes smaller when the production growth rate increases (for instance compare the material need for the 1% and 3% growth rate scenarios). If the hypothetical example in Figure 7 would represent a real case scenario, the results show that a recycling rate of 60% would postpone the material exhaustion with approximately 15 years in comparison to the 1% recycling scenario. Similar results have been obtained by Grosse (2010). More detailed analyses of real-world cases would be needed to quantify such scenarios. Material flow analyses can help to quantify these effects for different production chains.

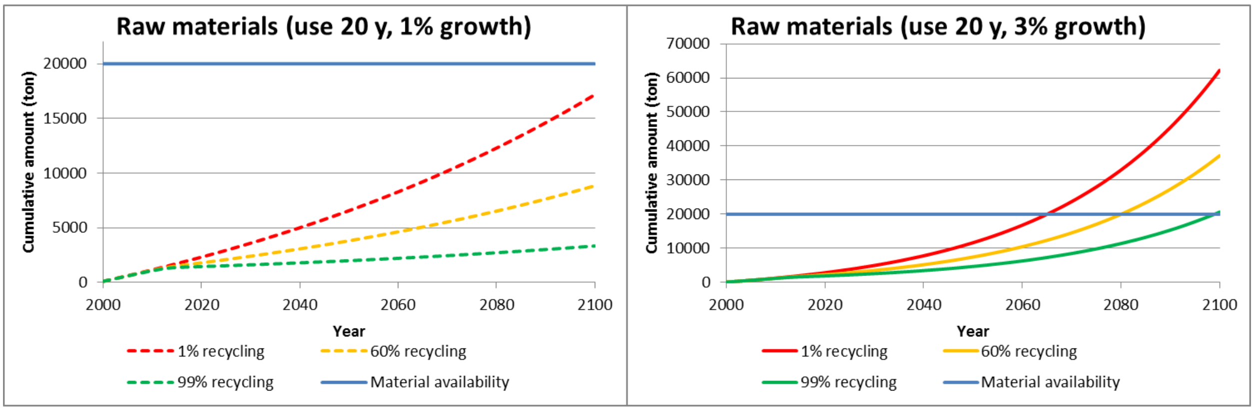

Figure 7 Scenario calculations for the total raw materials demand as a function of time assuming a use phase period of 20 years and different recycling and growth rates (left graph 1%, right graph 3%). The blue line represents a hypothetical availability of raw materials.

5. Conclusions and recommendations

In this study, a first attempt was made to quantify effects of recycling on the long term supply of raw materials. The research question was: how important is the role of recycling for a sustainable use of materials in a production chain? Important variables in this production and recycling chain are the growth rate in the production of goods, the lifetime of products in the use phase and the percentage of waste that can be effectively recycled. Material flow analyses was performed using the software STAN 2.5, developed at the TUW.

The MFA models provide insight in effects of policy choices on the whole chain from production to the waste management phase and can be applied for scenario calculations. The developments and results reported here can be seen as a first step towards application to real-world scenarios. However, the outcome of this study already provides insight in the main mechanisms that influence the long-term raw materials need and waste production: production growth rate, recycling rate and the product lifetime.

The results show that the recycling rate, product lifetime and the production growth rate are important factors that determine the long term waste production and the raw material need for production. In summary, when a production growth rate of 3% is assumed with a recycling rate of 60%, the yearly raw material need would grow with a factor 9 over a period of 100 years compared to the starting amount to keep up with the production growth rate of 3%. In other words, recycling alone would not be enough to prevent the use of primary raw materials. When the production growth rate is 1% and the recycling rate is 60%, the raw material need would effectively not grow over a period of 100 years. Such a scenario would lead to a more sustainable and circular production chain.

Only when a recycling rate of 99% is assumed in combination with a 1% production growth rate, the yearly raw material need would drop to around 10% of the starting amount. In that case, a substantial reduction of the primary raw material amounts is realised and the products would in the longer term consist largely of secondary raw materials. However, it is important to note that these calculations do not take the environmental impacts into account that are needed for a 99% recycling rate, such as the energy and water use that could be unacceptably high.

The MFA modelling results were also used to make estimations on the expected time frame at which the raw material stock becomes depleted and/or exhausted. Results showed that recycling lowers the total amount of raw materials needed for production and can, therefore, postpone the moment of material exhaustion. Depending on the assumed scenario, the material exhaustion could be postponed for periods in the order of a century or only by one or several decades. These results were also consistent with findings from other authors. In real life, also other factors can positively influence the long term material availability, that is prolonging the lifetime of products, repairing products or re-using products. More detailed analyses of real-world cases would be needed to quantify such scenarios. Material flow analyses can help to quantify these effects for different production chains.

In addition, the results of the study obviously indicate that substantial amounts of waste (that cannot be recycled) will continue to be generated over the long term when realistic recycling rates (±60%) are achieved. These observations do also provide useful input for the long term policy decisions on waste management.

An interesting and so far quite unexplored area is the assessment of the optimum recycling rate for several waste materials. It is likely that a recycling rate of nearly 100% is often not feasible from an economic point of view and also not from an ecological point of view. Research indicates that an optimum has to be found for the technical, economic and ecological aspects of recycling and this optimum might be substantially lower than 100% (Staubli et al., 2016).

5.1 Recommendations

Future work should focus on the further development of the MFA model and the collection of more real-world data for specific production chains. Examples of research questions that can possibly be addressed using the MFA approach are:

- Effects of increased recycling rates for specific waste materials in relation to the targets of the Circular Economy Package from the Commission.
- Effects of introducing alternative (for example bio-based) raw materials on the production chain to make the same products.
- More quantitative effects of the production growth rate on the resource availability (especially but not limited to scarce metals).
- More quantitative assessment of the lifetime of products in relation to the raw materials need: assess one production chain and specifically study effects of longer product life due to for instance repairability on the raw material need and the waste generation.

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