National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

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Towards a safe circular economy

RIVM letter report 2021-0009

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Colophon

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Synopsis

An inventory of innovation in recycling waste streams with substances of concern

Many initiatives and developments are already ongoing, both in terms of policy and practice, to recycle waste (part of a circular economy). But waste can contain substances of concern that are not allowed to be present in the new materials or products. Examples are hazardous chemicals, medicine residues or pathogens. To ensure safe reuse of waste, the substances of concern have to be removed as much as possible.

The RIVM performed an inventory for which waste streams the substances of concern pose the highest (potential) risk. It also identified the areas where recycling can deliver the most benefits. Finally, it also determined where new technology is already under development to remove these substances. Taking all these aspects into account, seven waste streams can be considered of highest priority. Those are textile, plastics and rubber, batteries, sewage sludge, construction and demolition waste, tires and electronic waste. In follow-up research, RIVM will analyse three topics in more depth: radiation in construction materials, cellulose recovered from waste water and chemical recycling of plastics.

The inventory also revealed that the possibilities for recycling increase by applying additional sorting after collecting the waste streams. This is already a focus in the development of new technology and is particularly useful for heterogeneous waste streams, such as construction and demolition waste.

This report is in English as the RIVM wants to share the insights and relevant findings with respect to the national legislation and substances of concern with other countries. The main reason for doing so is that waste and the processing of waste does not stop at the border.

In the Netherlands, the attention given to substances of concern by waste processors seems of low priority, although the situation is improving. Financial incentives to sell the waste often seem to prevail above safety considerations. That is also why RIVM wishes to focus attention on safety considerations in combination with other sustainability aspects.

Keywords: waste, substances of concern, recycling, LAP3

Publiekssamenvatting

Een inventarisatie van innovatie in recycling van afvalstromen met zorgstoffen

Om afval opnieuw te kunnen gebruiken (onderdeel van circulaire economie) zijn al veel maatregelen genomen, zowel beleidsmatig als in de praktijk. Afval kan zorgwekkende stoffen bevatten die niet in nieuwe materialen of producten mogen komen. Voorbeelden zijn schadelijke chemische stoffen, medicijnresten of ziekteverwekkende stoffen. Voor een veilig hergebruik van afval moeten de zorgwekkende stoffen hier zo veel mogelijk worden uitgehaald.

Het RIVM heeft op een rij gezet welk afval waar zorgwekkende stoffen in zitten, op grond van wat nu bekend is, het meest een probleem vormt. Ook is gekeken welk afval slechts beperkt gerecycled wordt en waar mogelijk veel meer materialen kunnen worden gerecycled. Tot slot is gekeken welke vernieuwende technologie al wordt ontwikkeld om zorgwekkende stoffen uit het afval te te halen.

Zeven soorten afval scoren het hoogst op deze punten en zouden volgens het RIVM verder moeten worden uitgediept. Dat zijn textiel, plastic en rubber, batterijen, rioolwaterzuiveringsslib, bouw- en sloopafval, banden en elektronische apparatuur. Het RIVM werkt in een vervolgonderzoek drie onderwerpen uit: straling in bouwmaterialen, cellulose terugwinnen uit afvalwater en chemische recycling van plastics.

De inventarisatie heeft verder duidelijk gemaakt dat afval meer kan worden gerecycled als het uitgebreider wordt gesorteerd nadat het is ingezameld. Hier is veel aandacht voor bij de ontwikkeling van nieuwe technieken. Dat is vooral nuttig voor afval waarvan de samenstelling niet altijd hetzelfde is, zoals bij bouw- en sloopafval.

Met dit rapport wil het RIVM de Nederlandse inzichten en informatie over de nationale wetgeving en zorgwekkende stoffen delen met het buitenland. Onder andere omdat afval en de verwerking daarvan niet bij de grens ophouden. Om die reden is het rapport in het Engels geschreven.

In Nederland lijken afvalverwerkers nog niet veel aandacht te hebben voor zorgwekkende stoffen, al groeit het besef. Financiële prikkels om het afval te verkopen lijken vaak zwaarder te wegen dan veiligheid. Daarnaast raakt veel informatie over de aanwezigheid van zorgstoffen in de keten en daarmee in het afval verloren. Ook daarom wil het RIVM meer aandacht voor veiligheid vragen, in combinatie met andere duurzaamheidsoverwegingen. Een belangrijke voorwaarde hiervoor is dat in de keten meer informatie wordt gedeeld over de aanwezigheid van zorgwekkende stoffen.

Kernwoorden: afval, zorgwekkende stoffen, recycling, LAP3

Contents

Summary

The presence of substances of concern (SoC) in waste poses a threat to the safe transition to a circular economy, for example, when these waste streams are recycled. In this report we assess for which waste streams the effort for innovation on removal of SoC will be most beneficial in achieving more circularity. To do this we examine current recycling and removal technologies and developments and innovations in this field by completing a desktop study and holding stakeholder interviews. The inventory's structure is based on the existing 85 sector plans defined in the Dutch Waste Management Plan (LAP3). Thirty-two of these sector plans were deemed most relevant for explicitly addressing SoC during recycling.

We have prioritised the sector plans based on several factors: the volume and SoC content of the waste stream, the estimated risks, the effort and efficiency of the recycling with SoC removal, and the availability of innovative technologies. This resulted in seven of the 32 most relevant sector plans being prioritised. These seven offer the highest potential of benefitting from innovations made in the recycling technologies to address SoC.

We have also screened the literature on risk policy and legislation for SoC in waste streams. Some recent literature has been summarised in order to identify the main policy issues, challenges and barriers in relation to SoC and recycling. For example the limited availability of information on the SoC content of waste. The main findings from scrutiny of the legislation issues recommend that the current risk-based approaches should be implemented and harmonised at European level. Furthermore, an integrated assessment should be applied for determining recycling options, for example, including criteria for raw materials scarcity and carbon emission reduction.

1 Recycling of waste containing Substances of Concern in a circular economy

1.1 Introduction

In order to realise a circular economy, the recovery of materials from current day to day waste and residual flows is needed. Recycling such material flows, and thereby reducing consumption of primary raw materials, generally reduces our impact on this earth; for example, by reducing material-bound CO_2 emissions. However, some materials contain Substances of Concern (SoC). Substances are classified as SoC if they meet certain hazard criteria impacting on human and/or environmental health (see Section 2.1). Keeping materials that contain SoC in the loop by recycling may create unwanted side effects. Additional material cycles can increase SoC concentrations, and new applications can result in increased and new routes of exposure to SoC (Beekman et al., 2020). In addition, the presence of SoC in waste can also hamper high-quality recycling. High-quality processing is the preferred waste treatment option and is assessed by taking sustainability and circularity aspects into account (CE Delft, 2016 [*in Dutch]*).

Materials to be re-used or recycled which contain SoC will hamper any transition towards a safe circular economy. Therefore, there is a need for innovation to be made in the green transition of the chemical industry (EU, 2013). The European Chemicals Strategy for Sustainability (EC, 2020) works towards a zero pollution ambition for a toxic-free environment as part of the European Green Deal (EC, 2019).

Recycling of materials containing SoC may require specific or innovative sorting and recycling methods. While innovative technologies can contribute to a safe circular economy, legislation on waste treatment and SoC, or its absence, can create uncertainty for the recycling business and for legislative authorities. Challenges and barriers caused by legislation have to be overcome to enable the safe recycling of waste streams containing SoC.

Goal of the study
The aim of this research is a first exploration to determine the waste streams whose high quality and efficient recycling is hampered by SoC. The central research question is:

The recycling of which waste streams is currently hampered by SoC and would benefit from the development of innovative technologies?

To answer this main research question there are several subquestions:
1. In which waste streams do SoC mainly occur?
2. How are waste streams containing SoC currently recycled or treated in general?
3. Are there developments in the recycling technologies to deal with the SoC in waste streams?

4. Is adjustment of legislation needed to enhance recycling of waste streams containing SoC?

The results of this research will be used for an initial, and general, prioritisation of relevant waste streams which will act as a starting point for the transition towards a safe and sustainable circular economy from the perspective of SoC.

Context
This research is part of the project RENEW (REcycling technNologies for Existing Waste). This project is part of the RIVM (Dutch National Institute for Public Health and the Environment) Strategic Program (SPR), which was initiated to gain more insight into the circular economy transition. The aim of RENEW is to further develop a method to assess the sustainability and safety of the recycling of waste streams. We emphasise that recycling alone is not enough to achieve a circular economy, and the broader transition strategy is discussed in Section 1.2. However, both RENEW and this report focus on the recycling strategy. An overview of the context and research questions is given in Figure 1. The outcome of the study will be used to select relevant case studies for the RENEW project. However, the results may also be useful for policymakers, authorities and recyclers within the Netherlands and abroad and could, for example, be employed to initiate and prioritise developments and legislative issues regarding waste streams containing SoC.

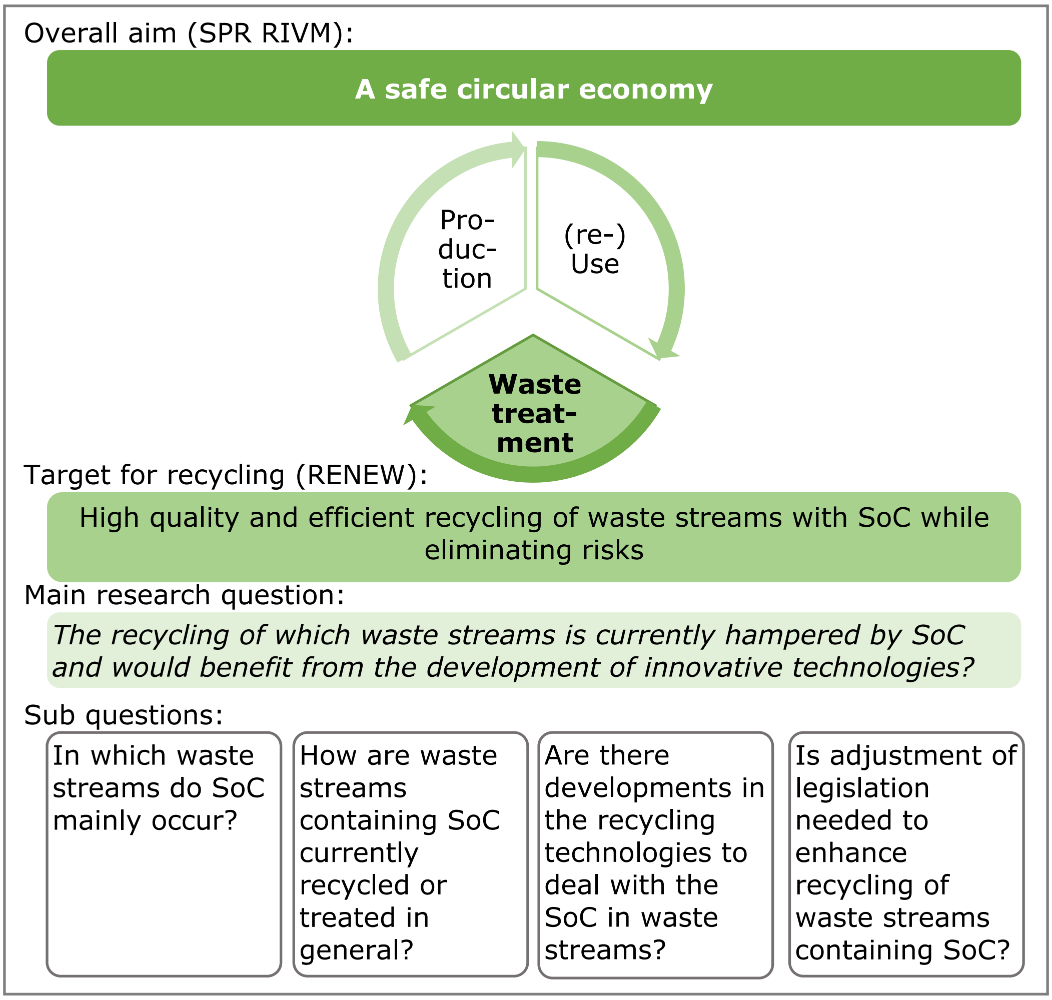

Figure 1 Overview of the context of the study and the research questions

1.2 Towards a Circular Economy

In 2016, the Dutch Cabinet published a government-wide Circular Economy Programme (Ministry for the Environment and Ministry of Economic Affairs, 2016). A 'circular economy' (CE) was defined in the programme as follows:

"In 2050, raw materials will be used and cycled efficiently, without harmful emissions to the environment. To the extent that new raw materials are needed, they are extracted in sustainable ways and further damage to the social and physical environment and to health is prevented. Products and materials are designed in such a way that they can be re-used/cycled with minimal loss of value and no harmful emissions to the environment."

The Dutch government-wide Circular Economy Programme lists the ambitions, stating broad objectives for the short term, for 2030 and for 2050. In 2050, all raw materials will be used and re-used or recycled efficiently, with no harmful emissions that affect humans or the environment. An interim target has been set for 2030: a 50% reduction in the use of primary raw materials (mineral, fossil and metal). The European Commission also published a chemicals strategy for sustainability on 14 October 2020 which is part of the EU's zero pollution ambition, a key commitment of the European Green Deal.

Figure 2 shows material flows in the Netherlands for 2014-2016 (van Berkel et al., CBS – 2019 *in Dutch*). A considerable amount is still incinerated or disposed of. From all the materials that entered the Dutch economy in 2014, about 9% was recycled.[1] The re-use and useful application of waste on the other hand is about 80%. This makes the Netherlands score highly in European recycling indices.

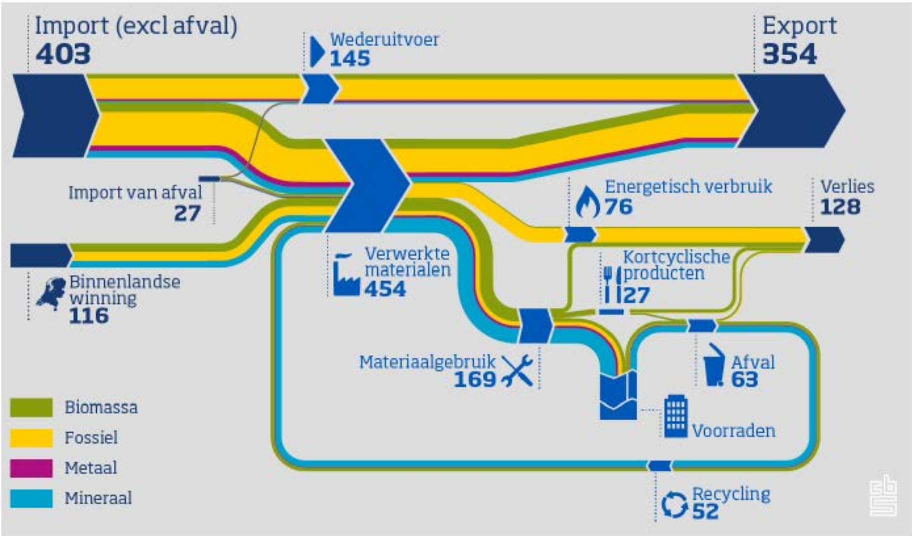

Figure 2 Material streams in the Netherlands in billion tons (van Berkel et al. 2019).

In the traditional, linear economy, a typical product chain usually has three phases: production, use and waste. For a circular economy, a transition has to take place into production (preferably free of SoC), use and safe cycling (including recycling into raw materials for new products) (Ministry of Infrastructure and Environment and Ministry of Economic Affairs, 2016).

No circular economy exists at this point of time. The current situation can better be described as a linear economy in which material cycling takes place on an ever-increasing scale, but in which there is also still large-scale new use of raw materials, net imports of products and materials, and removal or contamination as waste: a partial re-use economy (Figure 3).

It is not realistic to make a transformation to an economy in which products and production processes are fully safe and circular from one moment to the next. In addition, the world contains many products that are already in circulation and are not designed to be re-used or recycled (safely). Creating a safe circular economy on a large scale requires innovation and change in the field of technology as well as in business models. The period in which the linear practice gradually turns into a

[1] https://www.cbs.nl/nl-nl/nieuws/2018/15/via-recycling-9-procent-van-materialen-weer-in-economie

situation in which materials are safely re-used or recycled on a large scale is referred to as ‘the transition to a circular economy’.

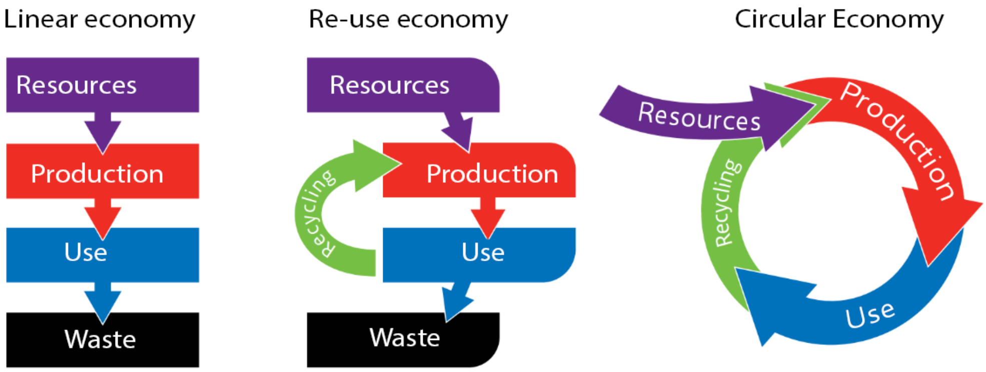

Figure 3 Visual presentation of the transition from a linear to a circular economy. Translated by RIVM (Ministry of Infrastructure and Environment and Ministry of Economic Affairs, 2016).

R-strategies
R-strategies (Figure 4) provide a system that divides the circular economy into a hierarchical ladder with different steps for more efficient use of raw materials. As a rule of thumb higher R-strategies are preferred, because they have a lower environmental impact and higher value retention of materials. Recycling has an important role in this system, but should not be focussed on solely.

Within the R-strategies, Steps R3-R7 are particularly applicable to products using raw materials that do not wear out or are hardly consumed during use. These products can be kept in circulation as is shown in Figure 4, for instance by applying a service-based business model (e.g. car rental) or by mechanical processing of products.

However, not all material stays in these material loops. Some products or parts of products are consumed, wear out or deteriorate significantly as a result of their application. Or material can be littered. Such materials can eventually end up in the environment, including the SoC present in those products. This includes, for example, cleaning agents, cosmetics, fertilisers and crop protection products. Some of these products will pass a sewage treatment plant, some will be released directly into the environment, which is, for instance, the case for debris from the outer layer of car tyres.[2] These type of products should be designed in such a way that degrading material during use is safe in biological systems. If this does not happen, these systems will be contaminated, disturbed or even hampered. Strategies R1-R2 are especially applicable in this context.

R8 and R9 are particularly relevant for all the products that end up in waste streams known as the LAP3 sector plans (Section 4.3). This report aims to create an inventory of technologies that contribute to R8 within the context of SoC containing waste streams.

[2] https://www.theguardian.com/environment/2020/dec/03/coho-salmon-pollution-car-tires-die-off

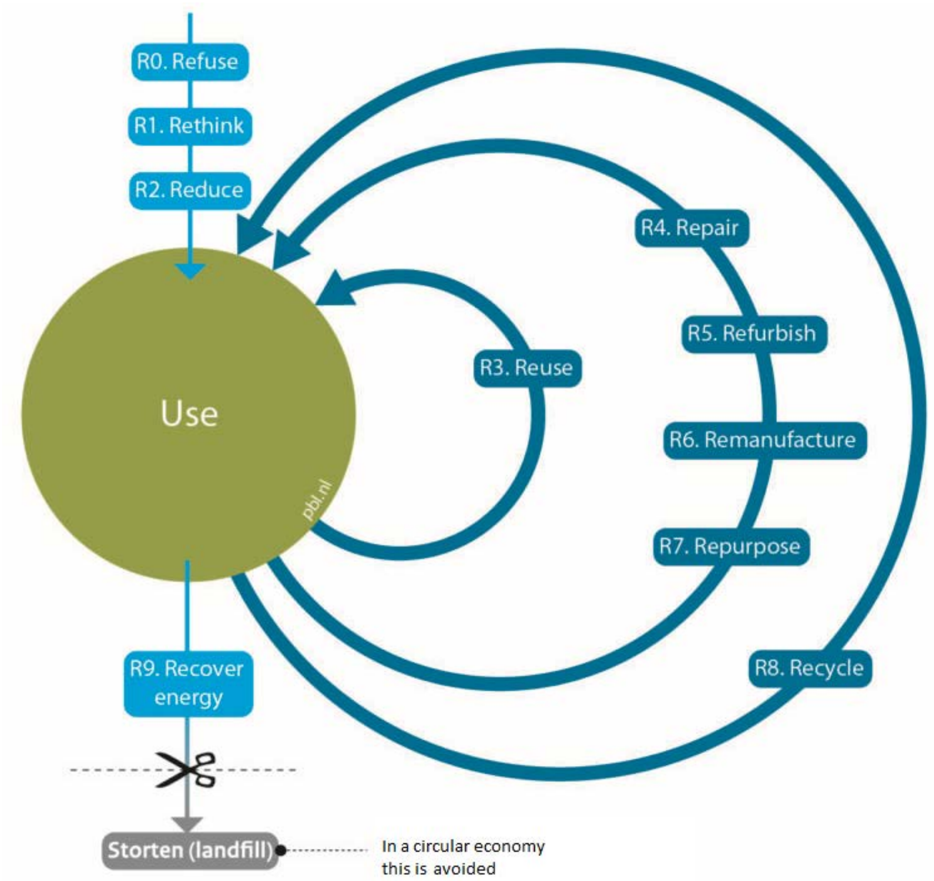

Figure 4 R-strategies for material cycling (Potting et al., 2018)

1.3 Set up of report

In Chapter 2 background information on the concept of SoC, LAP3 and legislation issues is provided. This serves as the point of departure. In Chapter 3 the approach of the inventory is described. To allocate the findings, all the information gathered is listed in a background table. In Chapter 4 the main findings with respect to the inventory are summarised, followed by considerations and interpretation in Chapter 5. In Chapter 6 some general conclusions and recommendations are given.

2 Background information and scope

This inventory is a general exploration to find the waste streams whose high quality and efficient recycling is hampered the most by the presence of SoC. However, to be able to answer the research questions we have to explain the main aspects - SoC, waste streams and recycling – in greater detail. In this chapter we provide background information on the (legislative) context of these aspects and illustrate how these aspects are taken into consideration.

To increase the usefulness of the outcomes of this research, we take current practice as our starting point. Therefore, we use the same division of waste steams which is used in the Dutch waste legislation, known as the LAP3 sector plans. More information on LAP3 and the sector plans is given in Section 2.1.

The scope of SoC in LAP3 is on a specific group of hazardous chemicals (‘ZZS’, see Section 2.2). These are mainly present in the technical cycle of a circular economy, as shown by the well-known butterfly-diagram devised by the Ellen MacArthur foundation.[3] As a result, the biotic cycle is not covered as much in this report.

Although this report focusses on waste streams in the Netherlands, dealing with waste at national level is related to European and even global material flows (see Section 2.1). The Dutch legislation on how to deal with ZZS in waste is briefly described in Section 2.3, international legislation issues will be covered later on in this report.

2.1 Legislation on (the recycling of) waste

The legislation and regulations in several countries across the world affects or prescribes the way that waste should be handled, an overview of which is presented in the report ‘Recommendations for waste legislation and regulations and their implementation towards a circular economy’ (Taskforce herijking afvalstoffen, 2019) (*in Dutch*). The Waste Framework Directive (2008/98/EC) of the European Parliament states that member states must establish a national waste management plan and waste prevention programs. In the Netherlands this was implemented in the third National Waste Management Plan, called LAP3 (Rijkswaterstaat, 2020).

2.1.1 Waste streams and sector plans

In LAP3 the management of waste streams is divided into so-called sector plans. These were developed for 85 different waste streams, which can either be collected separately or separated after collection. The sector plans include information on the waste stream, the recycling methods that are permitted, and whether the waste stream may contain ZZS (see Section 2.1). It should be noted that these 85 waste streams differ from the European waste codes (51 waste categories)[4] and those

[3] https://www.ellenmacarthurfoundation.org/circular-economy/concept/infographic
[4] https://ec.europa.eu/eurostat/documents/3859598/5915865/KS-RA-10-011-EN.PDF/39cda22f-3449-4cf6-98a6-280193bf770c

listed in the Basel Convention.[5] The general prioritisation of relevant waste streams which can act as a starting point for the transition towards a safe and sustainable circular economy from the perspective of SoC, as has been done in this report, cannot be linked to the EU waste codes, given the dissenting classification. More information on the recycling strategies covered in the Dutch Waste Management Plan is given in the next section.

2.1.2 *Minimum standard and recycling options*

For many waste streams a 'minimum standard' has been specified in the LAP3 sector plans. The 'minimum standard' gives an indication of how a specific waste material may be processed. With a permit system, the minimum standard ensures that waste is not processed at a lower standard than is desirable. The competent authority has to base their reviews of applications or initiatives for waste processing primarily on the minimum standard from the corresponding sector plan. The LAP3 differentiates several processing options, which are described below.

In LAP3 a hierarchy of waste management options (Figure 5) is defined on the basis of the 'Ladder van Lansink', which is related to the R-strategies described in Section 1.2. The waste hierarchy gives preference (as far as possible) to how a waste stream is to be processed. In principle, high-quality processing is preferable. The prevention of waste (Figure 4: R0-R7) is preferred over recycling (R8), which is then preferred over recovery (R9), which is then preferred over disposal by incineration or landfill.

Waste hierarchy

a. Prevention;
b. preparation for re-use;
c1. recycling the original functional material in an identical or comparable application; (*)
c2. recycling the original functional material in a different or non-comparable application; (*)
c3. chemical recycling; (*)
d. other recovery options, including energy recovery;
e1. incineration as a form of disposal;
e2. landfilling or dumping.

(*) In addition to these forms of recycling, the LAP also includes the term 'preferred recycling'. This form generally falls under c1, c2, or c3 [or comprised of a combination thereof], but that is explicitly designated as preferred recycling in the corresponding sector plan. The consequences of designating a form of processing as preferred recycling is discussed in more depth in Section A.4.2.2 and Chapter D.2 'Minimum standard'.

Figure 5 The waste hierarchy as defined in LAP36

Differentiation is made between various types of waste treatment and recycling. Forms of recycling that keep materials in the loop ('high value' recycling) are preferable to recycling applications which degrade

[5] http://www.basel.int/portals/4/basel%20convention/docs/text/baselconventiontext-e.pdf
[6] https://lap3.nl/beleidskader/deel-a-algemeen/a4-algemene/

material quickly and lead to 'downcycling'. In addition to conserving raw materials, other factors play a role such as costs, energy consumption, reprocessing emissions, pollutants present, etc. LAP3, therefore, identifies different forms of recycling, in which recycling of the original material is preferred over chemical recycling.
As a result, LAP3 uses both the general term 'recycling' and specific forms of recycling in its minimum standards. This is further explained below.

The recycling of waste streams requires financial investment. Recycling is the golden standard but not regardless the costs. LAP3 introduces a standard price of €205 euro per ton above which the high-quality processing of waste (including recycling) is considered to be too expensive. This standard price is generic and does not specifically reflect waste streams containing ZZS. Given the fact that waste containing ZZS forms a burden for society, it seems logical that a (much) higher standard price should be considered. In addition, the guidance on performing a risk analysis of ZZS in waste, which was drawn up by Rijkswaterstaat (2018) prescribes that if the ZZS can be removed from, or destroyed in, the waste stream (if this is considered technically and economically feasible), then this should be done.

2.1.2.1 Different recycling options under LAP3

The general term, recycling, is used for recovery processes through which waste streams are reprocessed into products, materials or substances. These can be used for re-use in their original purpose or for any other purpose. This includes the reprocessing of organic waste, but excludes energy recovery and reprocessing into materials that are intended to be used as fuels or filling material.

If the umbrella term 'recycling' is used in LAP3, this includes all forms of recycling that fall under c1, c2 and c3. In addition to these three forms of recycling, LAP3 also uses the term 'preferred recycling'. All four terms are described below (Rijkswaterstaat, 2020).

Preferred recycling
In the LAP3 sector plans a specific recycling option can be designated as the preferred recycling option for a specific waste stream. But this is not always the case. A recycling option is designated as a preferred recycling option if it is determined that it is significantly better. This can be established using the Life Cycle Analysis methodology that is included in Annex 9 of LAP3.

In practice, preferred recycling options can be either material recycling or chemical recycling. Preferred recycling is only applicable if a recycling process is explicitly designated as such in the LAP sector plans. Applying other forms of, or lower quality, recycling once a form of recycling is designated as 'preferred recycling' in a sector plan is no longer permitted.

Recycling the original functional material in an identical or comparable application (c1)
C1 level recycling involves forms of recycling in which the functional material is recovered in a similar quality as was used in the previous

application ('high value' recycling). Examples include: recovering glass packaging to be used in new package production, recovering PET (Polyethylene Terephthalate) from packaging to be used to create new PET bottles and reusing bitumen from roofing as usable bitumen.

This means that the most important factor is the quality of the material and not whether it was used in the original application. So, a different application requiring the same quality is also possible. A less obvious example of this is converting biodegradable material into usable compost, which is also considered c1 level recycling.

Recycling the original functional material in an application that is not identical or comparable (c2)
C2 level recycling includes all forms of recycling that are **not** deemed 'preferred recycling', 'recycling of the original functional material in an identical or comparable application (c1)', or 'chemical recycling (c3)'. This includes all forms of recycling in which the material is used to replace other primary raw materials but is not recovered in its pure form. Thus, the raw materials which are replaced do not need to be identical to the material to be recycled. Examples include using PET waste to replace wood in a mixed plastic fraction, or glass used as a construction material in the form of mixed granulate.

Chemical recycling (c3)
Chemical recycling is the process by which waste is broken down into smaller units at molecular level with the aim of using these for the production of new materials. This is regardless of whether the materials from which the waste originates are comparable, but does not include fuels. An example of chemical recycling is the breaking down of polymers into the original monomers by depolymerisation.

As shown in Figure 5, chemical recycling is currently considered less desirable than mechanical recycling. This is usually due to high costs and high energy consumption. In specific cases however, the contribution made to the transition toward a circular economy may be such that a chemical recycling option can still be deemed as preferred recycling, as stated in the relevant LAP3 sector plans.

Policy makers in the Netherlands have already stated that, in 2023, LAP3 is going to bereplaced by a Circular Material Plan (CMP1). LAP3 focusses on the end of the chain: waste treatment. With CMP, the scope has to be expanded to include high value recycling in order to challenge companies to achieve circular economy innovation and to bettern the prescribed minimum standard. In April 2020 it was already stated that LAP3 will be updated to align it more closely to the Waste Framework Directive and the Environmental Law [Omgevingswet].

2.2 Substances of Concern (SoC) and ZZS

The main focus of this report is on SoC. However, the results are mainly covered by a group of SoC which, in the Netherlands, is classified as ZZS: 'zeer zorgwekkende stoffen' (Van Herwijnen, 2013 and Poorter en van Leeuwen, 2016). The direct English translation of the term ZZS is 'substances of high concern'. But the substance list of ZZS does *not* contain the same set of substances as the European/REACH list of substances of very high concern (SVHC) does. So to avoid confusion the Dutch term of ZZS is left untranslated in this report. This is illustrated in Figure 6.

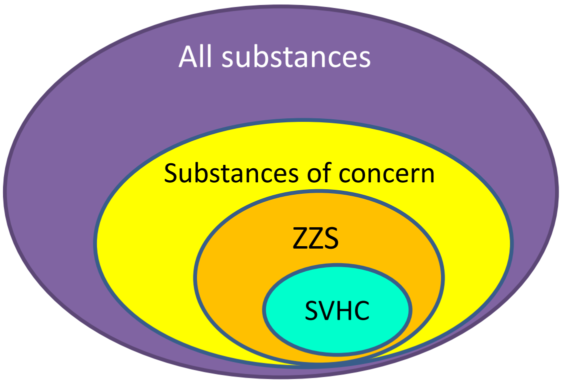

Figure 6 Illustration of the chemical subsets 'Substances of Concern' (SoC), ZZS as defined in the Netherlands (substances fulfilling the criteria of REACH Article 57) and SVHC identified under REACH. By January 2021 1564 substances had been classified as ZZS (RIVM), of which 211 were also SVHC (ECHA).

The concept of ZZS is used in the Netherlands in a national context. Substances fulfilling at least one of the hazard criteria of REACH Article 57 are included:

- Carcinogenic category 1A or 1B according to Regulation 1272/2008/EC.
- Mutagenic category 1A or 1B according to Regulation 1272/2008/EC.
- Toxic for reproduction category 1A or 1B according to Regulation 1272/2008/EC.
- Persistent, Bioaccumulative and Toxic in accordance with the criteria set out in REACH Annex XIII.
- Very Persistent and Very Bioaccumulative in accordance with the criteria set out in REACH Annex XIII.
- Substances for which there is scientific evidence of probable serious effects on human health or the environment which give rise to a level of concern equivalent to the criteria listed above.

Substances fulfilling these criteria are regulated by specific chemical legislations of different forms. The RIVM compiles a non-limitative list[7] of these substances which is updated twice a year, the ZZS-list. By January 2021 this list contains 1564 substances.[8] The sources of the ZZS-list are in particular:

- Substances on the so-called Candidate list; these substances have been identified as Substances of Very High Concern (SVHC) and are candidates for authorisation (REACH Annex XIV).
- Substances in Annex XVII of REACH that are restricted due to their ZZS properties as listed above.
- Substances listed in Annex IV the POP Regulation 850/2004/EC.
- Priority Hazardous Substances according to the Water Framework Directive 2000/60/EC.
- The OSPAR list of substances for priority action.
- CLP annex VI.

[7] https://rvs.rivm.nl/stoffenlijsten/Zeer-Zorgwekkende-Stoffen
[8] https://rvszoeksysteem.rivm.nl/ZZSlijst/TotaleLijst

Note that the first sources for the ZZS-list are the SVHC, shown in Figure 6. By using these sources the international chemicals policy is connected with regulations for industrial emissions.

Next to the main focus on ZZS, the broader area of SoC have also been included in the inventory. SoC is an overlapping group containing ZZS and (EU) SVHC, as illustrated in Figure 6. Pharmaceutical residues, pesticides and pathogens are examples of SoC.

The Dutch ZZS policy focuses on the minimisation of emissions of ZZS. This can be done by minimising or preventing emissions or by their substitution with less harmful alternatives.

The information on the occurance of ZZS in waste streams is rather scarce and still under development (Wassenaar et al., 2017). Furthermore, in the context of LAP3, a useful inventory was made of ZZS that may be present in each type of waste stream (Hofstra, 2019). As well as the dearth of information about the presence of ZZS in waste streams, there is also hardly any information available about the content of the ZZS, although this information is required for the LAP3 prescribed risk analysis (see Section 2.3).

Some general information can be found on presence of SVHC in articles[9] on the ECHA website. In addition, in January 2021, the SCIP database hosted by ECHA became operational. This is a database of the SVHC content of articles above 0.1% (w/w) which has to be submitted by suppliers of those articles (as prescribed by the Waste Framework Directive 2008/98/EC Amendment 2018/851). This SCIP database[10] has to ensure that information on SVHC is available throughout the whole lifecycle of products and materials, including at the waste stage. It is stated on the ECHA website that the information in the database will be made available to waste operators and consumers.[11]

As mentioned earlier, in addition to ZZS, other substances can also be of concern. For instance, environmental quality standards have been set for metals such as zinc or copper. These metals can be relevant for assessing waste treatment options. However, they do not fulfil the criteria of REACH Article 57 and are not included in the ZZS list. However these are included in the SoC subset of chemicals. The same applies to other types of SoC not on the ZZS-list, like pharmaceutical residues or pesticides.

2.3 Legislation on the handling of SoC in waste streams

LAP3 uses a risk-based approach to determine the cases in which recovery and re-use or recycling of waste containing ZZS may be permitted. However, if ZZS can be removed from a waste stream this should always be done. LAP3 compares the objectives of policies on ZZS and waste management in a circular economy and concluded that:
"a balance must be found between promoting recycling on the one hand and reducing the amount of hazardous substances in the economy on

[9] https://echa.europa.eu/information-on-chemicals/candidate-list-substances-in-articles-table
[10] https://echa.europa.eu/scip
[11] https://echa.europa.eu/nl/scip#:~:text=SCIP%20is%20the%20database%20for%20information%20on%20Substances,articles%20to%20ECHA,%20as%20from%205%20January%202021.

the other. In the European discussion on recycling of materials containing ZZS, the Netherlands believes that a methodology must be formulated at the European level to determine the best option.[12]"

The LAP3 addresses the handling of waste streams containing ZZS in Section B14 and Annex F11 and provides guidance on how to deal with ZZS content in waste or material streams that are recycled. The LAP3 states that a risk analysis should be performed if ZZS are present in waste streams above the generic limit concentration value of 0.1%, or above the specific limit values provided by the specific framework for the new foreseen application. By performing the risk analysis it should become clear whether or not the ZZS would hamper the granting of a permit for the foreseen new application. Or whether an experimentation phase could resolve the remaining uncertainty. This provides the recycler with the possibility of overcoming any ambiguity in the outcome of the risk assessment by performing a chemical analysis and taking measurements both during and after the production process. The experimentation phase should become part of the permit granted by the license officer. If the measurements indicate that the risks are not acceptable, the permit is revoked and the recycled materials or products have to be destroyed.

A guidance document on the risk analysis for ZZS in waste has been developed by Rijkswaterstaat (2018) and is based on an advisory report on this subject published by the RIVM (Zweers et al., 2018). The methodology of this advisory report has also been included in the Safe and Sustainable Material Loops (SSML) framework (Quik et al., 2018). However, in the SSML framework, other types of SoC as well as ZZS are included. More information on the SSML framework is given in Appendix 1.

[12] https://lap3.nl/beleidskader/deel-b-afvalbeheer/b14-zeer/

3 Method

3.1 Approach

To answer the research questions we made a general inventory based on the waste streams defined by LAP3. In the inventory we:

- Created an overview of the size;
- Created an overview of the likelihood of ZZS occurance as an indicator of the presence of SoC;
- Listed the minimum standard and current practice of recycling;
- Explored the developments in recycling technologies to overcome the potential problem of SoC content.

Furthermore we discussed legislation challenges and barriers hindering the recycling of waste streams containing SoC.

4. Data collection and analysis

	Desktop study	Stakeholder consultation
§4.1 Waste streams containing SoC	- Number of ZZS per waste stream (SP): *> 3* - Mass of waste streams (SP): *>25 kton*	- High risk waste streams (inc. (potential) exposure)
§4.2 Current recycling of relevant waste streams containing SoC (outcome 1)	- Minimum standard per waste stream (SP): *extensiveness* - Mass of waste streams (SP) per recycling option: *<90 %*	- Current practice of recycling waste streams with SoC: *qualitative results*
§4.3 Developments in recycling of waste streams containing SoC	- Internet search hits on recycling technologies for handling SoC per waste stream: *qualitative results*	- Developments in recycling technologies for handling SoC per waste stream: *mentioned*
§4.4 Legislation challenges on waste streams containing SoC	- White papers on policy and legislation issues concerning recycling: *featured issues*	- Expert views on policy and legislation issues concerning recycling: *featured issues*

5. Interpretation and selection

Data interpretation on:

Potential risk by SoC, using potential exposure	Effort and efficiency of removal	General lessons on the developments in recycling technologies

Priority waste streams:

- Mass of waste stream
- Number of ZZS
- Minimum standard
- Additional relevant aspects

Figure 7 Overview of the methods and set up of the report

The data collection was set up using two approaches; desktop study and stakeholder consultation. The collected data on volumes of waste streams, the occurance of ZZS, the minimum standard, relevant waste treatment options, developments in recycling technologies and relevant stakeholders is combined in the general inventory. The method is described in Section 3.2.

This inventory was also used for priority setting to select the most relevant waste streams. This was done by data analysis (method described in Section 3.3) and interpretation of the data using different points of view (method described in Section 3.4).

3.2 Data collection

3.2.1 Desktop study

The desktop study was performed to retrieve quantitative data on the occurance of SoC in waste streams and information about the current recycling practices of these waste streams. Furthermore, via desktop study, the developments in recycling technologies and legislation issues were explored.

SoC and volume of waste streams
To gain insight into the relevant waste streams with respect to SoC, two main data sources were used. Firstly, the SGS-Intron report on ZZS in waste streams (Hofstra, 2019) was examined to find out how many, and which, ZZS could be expected in a waste stream. The number of ZZS as analysed by Hofstra (2019) were summarised as an indicator to establish whether the ZZS are relevant for the respective waste stream.

Secondly, a database from Rijkswaterstaat containing information on the tonnage of waste streams (sector plans) was used to determine the relative size of waste streams. The database is based on data from 2016, when the former version of the LAP was in use: LAP2. Where applicable, the volumes of the waste streams from the former sector plans were transposed to the new sector plans. Rijkswaterstaat stressed that the provided information on tonnage could only be used as an indicative criterion. This was done by listing tonnage as one of the parameters and as a percentage of the total waste mass.

Current practice
In the LAP3 sector plans, a limited or more detailed minimum standard for the waste treatment is prescribed, which roughly reflects the current practice of recycling. The minimum standards can prescribe recycling but also incineration or landfilling of waste streams. For every sector plan, the mass percentages, according to the data of Rijkswaterstaat (2016), of the different recycling options stated in the minimum standard are listed.

Developments in recycling technologies
An internet search was conducted to obtain information on developments in recycling technologies. For every sector plan a limited search was performed using the name or the related terms of the sector plan and terms concerning innovative technologies, recycling and SoC.

Besides providing insight into the developments, the seach was also used to find and select relevant parties for the stakeholder consultation.

Legislation challenges
An explorative literature study of the legislation challenges and barriers hindering the recycling of waste streams containing SoC was performed. The selected literature consisted mainly of white papers published by governmental or non-governmental organisations.

3.2.2 *Stakeholder consultation*

Some of the information about the current recycling of waste streams containing SoC and developments in recycling technologies was obtained by interviewing stakeholders. These interviews were conducted in two phases:

- Phase 1 focussed on the current recycling of waste streams containing SoC in the Netherlands in general; and
- Phase 2 focussed on developments in recycling technologies relating to the presence of SoC in specific waste streams.

A total of eleven different parties were consulted. A diverse group of stakeholders was consulted, as (obviously) not all stakeholders involved in the treatment of waste containing SoC could be interviewed. The organisations were selected on relevance, the waste stream (to cover the broad field of the waste-landscape) and those who had general knowledge about recycling. These include companies, trade associations, universities, research institutes, governmental institutes and consultants.

Stakeholder consultations were conducted as qualitative research in the form of semi-structured interviews. This is an approach taken from the social sciences, and enables a framework of themes to be explored. Compared to the fixed set of questions from a structured interview, a semi-structured interview allows for a more open, flexible and conversational style of interviewing (Wholey et al., 2015). Because of the variety of knowledge and expertise held by the consulted stakeholders, the questions were adapted and made specific to the interviewed party by selection from a standard list (see Appendix 2 [*in Dutch*]).

SoC and volume of waste streams and Current practice
In Phase 1 interviews were conducted with six parties who were selected to cover a broad and general perspective of the waste sector. Interviewees included a university professor on resources and technical change (and energy), several trade associations (e.g. plastics, waste) and a governmental organisation (Rijkswaterstaat). General insights from these interviews were noted, as well as specific insights on material streams containing SoC.

Developments in recycling technologies
The second phase focussed on innovative technologies related to the treatment of SoC. The parties who were selected were, in part, chosen as a result of the findings of Phase 1. Insights from the desktop study were also used to make the selection. Five different parties were consulted: a large waste-collector and recycler, a large technical

consultancy, an innovative waste-water treatment facility, a professor of waste technology and a metal processing company. General insights were also noted at this stage, as well as any specific insights gained into innovative technologies on the treatment of SoC in waste streams.

Legislation challenges
During both phases of the interviews legislation challenges and barriers were discussed and general insights were noted and used.

3.3 Data analysis

SoC and the volume of waste streams
During the data collection both qualitative and quantitative data on waste streams and the occurance of SoC were obtained. To select the most relevant waste streams containing SoC for this reseach a list was compiled of the waste streams with waste masses of above 25 ktons, or which werereported as potentially containing four or more ZZS, or were explicitly mentioned by the stakeholders in this regard.
The chosen thresholds for the quantitive aspects were not based on limit values or legislation. Because of the lack of information on the concentration of ZZS in the waste streams it was not possible to use relevant limit values from legislation. The thresholds were chosen in a way that ensured that a broad, but representative, selection of waste streams was made.

Current practice
The current practice of the recycling of waste streams containing SoC is based on two aspects; the current recycling percentage (Rijkswaterstaat, 2016) and the LAP3 prescribed minimum standard of waste treatment. Waste streams with recycling rates below 90% are considered to still have sufficient potential to contribute to the transition towards a (more) circular economy.

The minimum standard of the waste streams is scored. If the description is very brief and/or recycling is not specified in the minimum standard, it is considered to be more relevant for higher quality recycling and contributing to the circular economy.

Developments in recycling technologies
Information on innovative technologies for recycling of waste streams containing SoC was obtained via an internet search and a number of interviews. For the results of the internet search, the quality of the findings was verified by the outcomes of the interviews. The findings were qualitatively summarised.

The information in the summary can only be used indicatively. The study did not aim to provide a complete overview of all developments in the recycling industry or all recycling technologies but focussed on general developments in the recycling of waste streams containing SoC and was strictly explorative. However, when specific technologies or research papers were mentioned these were included.

Legislation challenges
To determine some of the central issues underpinning the legislation challenges, the main conclusions from recent 'position' papers on waste treatment and circularity in relation to SoC were examined and summarised. This was not a complete review, but provided a quick 'feel' for the field. Next to challenges and barriers, solutions were also suggested to resolve the issues at stake. A subdivision was made on general EU-wide papers and a more so-to-speak national scope for the Netherlands.

3.4 Interpretation and selection of priority waste streams

The aim of the data collection and analysis was to create a general overview of the available information relevant tor the research questions.

The next step was the selection of the most challenging or promising waste streams on the criteria of high quality and efficient recycling of SoC. This is done based on three different perspectives:

1. The (potential) risk of SoC in a waste stream and recycling: (potential) hazard and (potential) exposure;
2. The current effort and efficiency of the recycling of the waste streams;
3. The developments in recycling technologies.

3.4.1 Interpretation

The (potential) risk of SoC in a waste stream and recycling
Risks arise from exposure to hazardous substances. For SoC in recycling, it is assumed that the potential hazard can be derived from the SoC content (both type and amount) and the size and heterogeneity of the waste streams.

Larger volumes of waste streams, and higher SoC content, are considered to increase the potential risk of a waste stream; high volumes also indicate a high potential for increased recycling rates, which in turn contributes to the transition towards a circular economy. Therefore the SoC content of waste and the high volumes increase the relevance for overcoming recycling issues and limitations to achieving a safer circular economy. However, relatively small waste streams can also still be of interest for recycling, for instance from the perspective of the scarcity of elements or the high environmental impact of the mining of scarce elements. The data retrieved on the number of ZZS in waste streams was considered to be indicative of the total amount of ZZS and SoC in the absence of data about the content. Of course, there are other important issues that should preferably be taken into account to assess the potential hazard, but, because of the absence of data, these were not considered. Factors that were of interest were: the harmfulness of the specific ZZS, or the SoC, in the respective waste streams, and concentrations of the SoC.

If SoC are present in waste streams this can lead to exposure and risks during the recycling phase, but this could also apply in regard to new, anticipated applications or products. The guidance on risk analysis of ZZS in waste by Rijkswaterstaat (2018) contains several aspects for assessing whether the recycling of a ZZS containing waste stream is allowed. A rule of thumb is: if the ZZS can be removed from, or destroyed in, the waste stream (if this is considered technically and economically feasible), then this should be done. If this is not possible a risk analysis should be performed.

The first aspect states that the ZZS content should be determined, and compared to the general (0.1% w/w) or substance specific standard values. If specific standard values are not available for new, anticipated application and the ZZS content does not meet the general standard value, then additional aspects need to be considered.

Two other aspects are related to determining the potential exposure during the use of the waste stream in the new anticipated application(s) and at the end of the life cycle. These aspects address the extent to which the ZZS will, or could be released during and after the service life by wearing off and migration from the material. If there are migration limit values applicable then a straightforward outcome can be derived. But in most of the cases this will not be the case and an assessment will have to be made on the containment and the potential of release of the ZZS.

Other general aspects to be considered during (the LAP3) risk analysis are whether the volume of the ZZS containing waste stream is being increased and whether the new ZZS containing material is being applied in a wide spread, both of which are not allowed. Instead the preferred approach is to sort out and to concentrate the ZZS containing material. In such a case the concentration of the ZZS in the remaining waste stream will increase, which potentially hampers recycling.

In general, consumer applications are considered to be wide spread and critical in terms of exposure as the vulnerable population (i.e. children, elderly and people with disorders) is exposed too. SoC from waste streams could also end up in the environment, for example, because of poor waste policy or the lack of it. This can result in indirect human exposure via air, drinking water or food.

As mentioned above, from the guidance on the risk analysis of ZZS in waste by Rijkswaterstaat (2018) a priority for risk perspective can be derived. Based on qualitative expert judgement, a quick assessment of the relevant waste streams is performed which includes:

- Potential of the release of SoC during the use-phase and end-of-life treatment (are the SoC in general expected to be released during and after the life-cycle? This will depend on the level of containment of the SoC.)
- Potential for consumer exposure (are consumer applications expected in a new, similar, or alternative life-cycle?)
- Wide spread use/ diffuse use of applications (is the SoC containing waste stream in a new, similar, or alternative life-cycle expected to be used or released widely [at numerous sites or more site-specific?])

The waste streams are scored on risk aspects, such as: not likely (-), possible or potential (+/-) or applicable (+). This rough scoring is considered justifiable based on the limited assessment, but also adequate for the aim of the assessment.

The current effort and efficiency of the recycling of waste streams
The most suitable waste streams for recycling are those that are homogeneous and clean or just slightly contaminated. Furthermore, recycling is enhanced when a suitable infrastructure is in place and technologies for efficient removal are available to make recycling possible. For waste streams containing SoC, the type and concentration of the SoC should be known, and preferably be of rather consistent composition.

These qualitative aspects, as well as current recycling rates and the minimum standards (see data analysis), were used to select waste streams that are relevant from a recycling effort and efficiency point of view.

This is considered a priority criterion for assigning the waste streams which can profit the most in terms of higher processing quality. It is assumed that it provides a first indication of where development of innovative recycling technologies are needed the most to obtain higher value recyling of waste streams containing SoC.

The developments in the recycling technologies
The information in the summary of developments in recycling technologies for removal of SoC is indicative, as the desktop study (a quick google search with a limited number of terms) is only explorative. In addition, findings from interviews were summarised. To select the most challenging waste streams in regard to high quality and efficient recycling of SoC in general, lessons from the explorative study were used. Ongoing developments, if any, were considered indicative for the potential improvement of high quality and efficient recycling.

3.4.2 Selection of priority waste streams
Based on the considerations and qualitative criteria in the data interpretation, the waste streams where a focus on SoC could enhance material circularity the most, were selected. This was done based on the mass of the waste stream, the incidence of ZZS, the current recycling rate and additional considerations from the data interpretation.

4 Results of the data collection and analysis

As shown in Figure 8, data collection was divided into four categories:

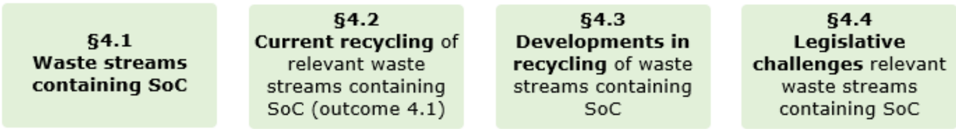

Figure 8 Overview of the methods and set up of the report

The results and analysis of this data are reported in this chapter.

4.1 Waste streams containing SoC

Several indicators can be taken into account when prioritising waste streams' potential safety issues from SoC such as the waste stream's volume or mass and the SoC content and containment (incidence, concentration and type of matrix). The data collection provided only quantitative data on the mass of the waste streams and the incidence of ZZS in the streams. Data on the total mass of the ZZS per waste stream is lacking. Qualitative information in the form of expert judgement on the relevant SoC was derived during the stakeholder interviews.

The relevance of waste streams, therefore, was primarily based on the mass of the waste stream and the number of ZZS that were identified in the waste streams, and secondly the interview results. This information provided an indication as to which waste streams couldt create safety concerns during, or after, recycling and hence, potentially obstruct the transition to a safe circular economy.

Appendix 3 shows a table with information on the occurrence of ZZS (one type of SoC) and relative mass flow for 2016 of waste streams according to the LAP2 (the former version of LAP3) sector plans (Rijkswaterstaat, 2016).

The waste stream with the largest mass is sludge from dredging (SP40, about 67% of total mass of waste streams) and from waste water treatment (SP16, 1%) (Rijkswaterstaat, 2016). There are also large (semi-)organic streams e.g. uncontaminated soil -(SP39, 3%), wood (SP36, 1%) and organic waste (SP8, 1%). Other larger waste streams come from construction and demolition (mixed (SP28, 2%) and stone-like materials (SP29, 8%). Residual domestic waste (SP1, 3%) and industrial waste (SP3, 4%) are also important streams in terms of quantity. The waste streams with the largest masses can in general be characterised by their broad definition and heterogeneity in composition. Given the huge volumes, these waste streams are in fact collections of smaller streams from different origins from a wide range of locations. The diverse composition of these waste streams complicate the circularity issues at stake, one of which is safety with respect to SoC content.

Based on the analyses by Hofstra et al. (2019), of the 85 sector plans, 59 deal with contamination with ZZS (see Appendix 2). Higher incidences of ZZS are observed in relatively homogeneous and clearly defined waste streams, including waste streams from consumer products (Table 1). Examples are plastic and rubber (SP11, 92 ZZS), textiles (SP5, 44 ZZS) and electrical and electronic waste (SP71, 31 ZZS). Furthermore, packaging waste streams can contain large amounts of ZZS which is also determined by what they contained (packaging containing residues of paint, adhesives, sealant or resin (SP42, 71 ZZS), or packaging containing residues of hazardous substances (SP43, 26 ZZS).

Many of the above-mentioned waste streams were also discussed during the interviews. Specific waste streams that were considered relevant by the stakeholders which have not yet been mentioned are EPS (expanded polystyrene foam), specific mono-streams such as mattrasses or solar panels and contaminated soil.

When a broader perspective of SoC is considered even more waste streams are relevant. SoC could be in the form of pathogens, medicine residues and radio-active materials. Examples of relevant waste streams are residual domestic waste (SP1), sludge from waste water treatment (SP16), waste originating from human or animal health care (SP19) and residue from energy production (from biomass [SP24] or from coal [SP23]).

Some waste streams, or parts of them have to be disposed of using a method prescribed by strict legislation. Examples are PCB-containing waste (SP64) or waste from hospitals that has to be destroyed or incinerated at high temperature. Recycling is not an option for these waste streams.

Examples of waste streams with low mass, but high ZZS-content are packaging containing residues of paint, glue, sealant or resin (SP42), and packaging containing residues of hazardous substances (SP43). On the other hand, waste streams with higher mass, but low ZZS-content include uncontaminated soil (SP39), sludge from waste water treatment (SP16) and organic waste streams (SP8 and 6).

In Table 1 the waste streams containing masses above 25 ktons, an incidence of ZZS higher than 3, or which were specifically mentioned by the stakeholders are listed. A total of 32 sector plans remain. Please note, that the quantitive thresholds were selected by the authors, based on the available data. The derived selection of prioritised sector plans can only be considered as a first rough screening of the most relevant waste streams containing SoC (see Table 1).

Table 1 Waste streams (grouped according to Dutch Waste management sector plans) with >25 kton mass and a ZZS incidence >3 and/or mentioned as relevant by stakeholders during interviews

Waste stream	**ZZS [#]**	**Mass [kton]**	**Relevant** as indicated by stake-holders
1 Residual domestic waste	18	6,321	yes
3 Process-dependent industrial waste	8	9,008	
4 Separately collected paper and paperboard	11	1,904	
5 Separately collected textiles (including shoes)	44	86	yes
11 Plastic and rubber	92	231	yes
12 Metal waste	9	1,042	yes
13 Batteries and accumulators	18	106	yes
14 Paper or plastic-insulated cables and off cuts thereof	34	73	
16 Sludge from waste water treatment and purification	4	2,635	yes
20 Bottom ashes from waste incineration facilities	17	1,209	yes
21 Fly ashes and kettle ashes from waste incineration facilities	7	280	yes
28 Mixed construction and demolition waste and comparable waste	20	3,689	yes
29 Stone-like materials	10	15,923	
30 Sieve sand	8	442	
31 Gypsum	5	66	
33 Roofing waste (bituminous, containing tar, composite)	9	93	yes
34 Asphalt	8	1,603	
35 Blasting grit	9	93	yes
36 Wood	28	2,206	yes
37 Asbestos and asbestos-containing material	4	398	
38 Separately collected glass sheets	16	89	yes
39 Uncontaminated soil that has become waste	0	6850	yes*
40 Dredging sludge	7	136,780	
41 Clean packaging waste	14	1,193	
52 Tyres	10	110	yes
56 Used oil (mineral and synthetic origin)	55	52	yes
71 Discarded electrical and electronic equipment	31	210	yes
72 Sulphuric acid, acid coal tar and other sulphur-containing waste	8	561	
73 Highly contaminated wastewater streams and baths	8	41	
78 Filter cake from detoxification/neutralisation/dehydration	9	365	
84 Other mono-streams for recycling (matrasses, stone wool, carpet, artificial grass)	15	7	yes
85 EPS (polystyrene foam)	*unknown*	*unknown*	yes

* contaminated soil was mentioned in the interviews (e.g. with PFAS)

The information from Table 1 is visualised in Figure 9. From this figure a first rough separation was made between lower priority (orange) and higher priority (blue) waste streams. Sector plans with zero identified ZZS (6, 8, 9, 25, 27, 39, 44, 46, 49, 50, 51, 53, 58, 60, 64, 65, 66, 67, 68, 69, 74, 75, 76, 77, 79, 83) or <1 kton (15, 22, 45, 47, 48, 54, 57, 64, 70, 79, 81) are not plotted. Also sector plans 39, 84 and 85 are not plotted due to lack of data on volume.

Figure 9 Visualisation of information from Table 1. On the x-axis the incidence of ZZS is plotted, and on the y-axis an indication of the mass of the waste stream (in kton) is given, for the Netherlands in 2016. The squared points were mentioned by stakeholders. Note that the graph is on a log-scale.

4.2 Current practice of recycling of waste streams containing SoC

The LAP3 states a minimum standard for treatment for every sector plan (or: waste stream). In general the extensiveness of the minimum standard provides a rough indication of the current state of recycling possibilities. If the minimum standard is limited, with landfilling or incineration as the only option, an innovative recycling technology for that waste stream could result in a significant win for material conservation.

In Table 2 the percentage of recycling is indicated (Rijkswaterstaat, 2016) in combination with the extensiveness of the minimum standard for the higher priority waste streams. Low recycling percentages can indicate siginifcant material wins. It should be noted, however, that the percentage of recycling does not provide any information on the quality of the recycling. In other words, even if the recycling rate is 100%, it may be possible for a higher quality of recycling to be achieved. This is, for instance, the case for plastics. Incineration with energy recovery is **not** acknowledged as recycling. In terms of higher quality recycling, innovation in technologies are observed, primarily by involved companies. Depending on these developments the minimum standard can be revised by future LAP updates.

The scoring of the extensiveness of the sector plans was made by dividing them into three categories: an extensive descripton of the minimum standard for treatment, a very brief description, or an in-between description. This is shown in Appendix 4, which is an extract from the table with all the retrieved information. In Table 2, the minimum standard of the sector plans is scored if the description is very brief and/or recycling is not (totally) specified. These aspects are considered to provide potential for higher quality and better recycling rates thus contributing to the circular economy. The sector plans with a very brief description of the minimum standard are indicated with the symbol Δ, and the symbol o indicates that recycling is not specified. The recycling rates combined with the sector plan extensiveness are listed in Table 2.

Table 2 Percentage recycling and minimum standard for the selected sector plans (from 4.1). Percentages in the 'remark' column are mass percentages of the total waste stream.

Sector plan LAP3	**Recycling [%]**	**Remark**
1 Residual domestic waste	3	Energy recovery: 94%
3 Process-dependent industrial waste	90	Energy recovery: 7%
4 Separately collected paper and paperboard	100	
5 Separately collected textiles (including shoes)	40	Preparation for re-use: 47%
11 Plastic and rubber	89	
12 Metal waste	99	
13 Batteries and accumulators	99	
14 Paper or plastic-insulated cables and off cuts thereof	99	
16 Sludge from waste water treatment and purification	27	Incinerated: 46% Energy recovery: 20%
20 Bottom ashes from waste incineration facilities	100	Recovery: 100%
21 Fly ashes and kettle ashes from waste incineration facilities	0 Δ, o	Landfill: 56% Recovery: 35%
28 Mixed construction and demolition waste and comparable waste	89	Landfill: 6% Energy recovery: 6%
29 Stone-like materials	99	
30 Sieve sand	81	Landfill: 15%
31 Gypsum	96	
33 Roofing waste (bituminous, containing tar, composite)	99	
34 Asphalt	100	
35 Blasting grit	60	Landfill: 39%
36 Wood	33 o	Energy recovery: 66%
37 Asbestos and asbestos-containing material	15 o	Landfill: 85%
38 Separately collected glass sheets	91 Δ	Landfill: 9%
39 Uncontaminated soil that has become waste	98 o	
40 Dredging sludge	9 o	Discharge / unknown: 89%
41 Clean packaging waste	87 Δ	Energy recovery: 11%

Sector plan LAP3	Recycling [%]	Remark
52 Tyres	71 [Δ]	Preparation for re-use: 26%
56 Used oil (mineral and synthetic origin)	92 [o]	
71 Discarded electrical and electronic equipment	86	Energy recovery: 11%
72 Sulphuric acid, acid coal tar and other sulphur-containing waste	98	
73 Highly contaminated wastewater streams and baths	64 [o]	Discharge / unknown: 27%
78 Filter cake from detoxification/neutralization/dehydration	9	Landfill: 88%
84 Other mono-streams for recycling (matrasses, stone wool, carpet, artificial grass)	69	Energy recovery: 30%
85 EPS (polystyrene foam)	?	

[Δ] A very brief description of the minimum standard in LAP3
[o] Recycling not (totally) covered in minimum standard of LAP3

4.3 Developments in recycling technologies for waste streams containing SoC

Information on innovative technologies for recycling waste streams containing SoC was obtained via an internet scan and interviews. In Table 3 the findings are summarised for the 13 waste streams which were most frequently mentioned in interviews. Please note that this list is by no means exhaustive. Some references in the technology column which were retrieved via the internet scan were added to the information from the interviews. An extensive overview of the incidence of specific ZZS per waste stream is shown in Appendix 4. The corresponding sector plan(s) for each waste stream and possible SoC are included, as mentioned in the interviews. This table covers 13 of the 16 blue squares in Figure 9.

Table 3 Indication of some innovative technologies based on interviews and internet scan.

Waste stream	LAP3 sector plans	Possible SoC mentioned in interviews	Technologies
Plastics	11, 85 (EPS)	(Dependent on type of plastic); Brominated flame retardants, plasticiser (phthalates), phenols, UV blockers, etc.	*General findings:* Many initiatives of innovative technologies occur. A good overview of recent developments is provided by Vollmer et al (2020) *Specific technologies (on chemical recycling):* • PET solvolysis and depolymerisation • Solvent-based Purification of polystyrene and PVC • gasification/pyrolysis • Separation technologies: ○ Magnetic density separation (MDS)

Waste stream	LAP3 sector plans	Possible SoC mentioned in interviews	Technologies
			for household plastics ○ Near infra-red separation technology
Sludge from waste water treatment	16	Cadmium, copper, zinc, pathogens , poly- and perfluorinated substances	*General findings:* Recent innovations are operating, e.g. the extraction of biopolymer.[13] For some innovations, like cellulose extraction from waste water, the hold-up is of a mainly organizational character ("not my task") rather than any technical limitations. *Specific technologies:* • Subtraction of Vivianite ($Fe_3(PO_4)2{\cdot}8(H_2O)$) crystals for phosphate recovery • Alginic acid subtraction from waste water sludge • Subtraction of cellulose • Production of PHA (polyhydroxyalkanoate)
WEEE[14]	71	Flame retardants, metals, plastics additives	*General findings:* Few technologies mentioned *Specific technologies:* • Pyrolysis (of plastic parts) • Melting to extract precious metals
Diapers	84	Pathogens, pharmaceutical residues	*General findings:* The recycling of diapers is developing, an example is set with the 'diaperprotocol'[15] *Specific technologies:* • Recovery cellulose fibres
Batteries	13	Nickel and cobalt compounds[16]	*General findings:* No innovative recycling technologies were mentioned by the parties interviewed, but recycling is the current practice. For Li-ion "the market is not yet

[13] https://kaumera.com/
[14] Waste Electrical and Electronic Equipment
[15] https://www.rivm.nl/bibliotheek/rapporten/2019-0111.pdf
[16] https://www.rivm.nl/publicaties/zeer-zorgwekkende-stoffen-in-circulaire-maakindustrie

Waste stream	LAP3 sector plans	Possible SoC mentioned in interviews	Technologies
			large enough" to recycle in the Netherlands
Soil contami-nated with PFAS	39	PFAS	*General findings:* Promising technology was mentioned, but this is not yet fully developed (see below). *Specific technologies:* • PFAS water treatment by metal-carbon adsorption (electrocoagulation)[17] • Thermal treating[18]
Bottom ashes from waste incinera-tion facilities	20	Heavy metals (Zinc, lead, copper)	*General findings:* There are several existing technologies to deal with bottom ashes, which are laid down in the Green deal WIP
Construc-tion and demoli-tion waste	28	*Not mentioned in interviews*	*General findings:* The construction sector is a cross-over between energy-transition and materials. The fact that the current policy focus is mainly on reducing direct CO_2 emissions, rather than on the circular (sustainable) use of materials was mentioned. Although this could greatly help reducing CO_2 emissions. The same was observed for electrical mobility.
Roofing waste	33	*Not mentioned in interviews*	*General findings:* Roofing waste is granulated and used in road constructions. However specific information on SoC removal is unavailable.
Wood	36	*Not mentioned in interviews*	*General findings:* A and B wood (e.g. chipboard) and other biomass could be recycled, but is primarily used for (subsidised) energy generation. *Specific technologies:* Press-wood pallets
Glass sheets	38	*Not mentioned in interviews*	*General findings:* Separation technologies results in pure recyclable glass streams, without contaminations.

[17] https://repository.tudelft.nl/islandora/object/uuid%3A24a8cc25-2c16-4c4b-893c-5ce90660f0ee
[18] https://www.hmvt.nl/kennis/pfas-verontreiniging-in-grond-aangepakt-met-thermische-technieken/

Waste stream	LAP3 sector plans	Possible SoC mentioned in interviews	Technologies
Tyres	52	*Not mentioned in interviews*	*General findings:* Currently mainly recycled for use as rubber granulate infill in sport fields. *Specific technologies:* Pyrolysis of tyres resulting in the extraction of carbon black.

As listed in the table above, innovation in sorting methods is ongoing for several waste streams. In several interviews it was indicated that sorting techniques are considered to make a large contribution to the improvement of recyclability. Improving the sorting of materials increases the number of homogeneous material streams which are relatively easier to recycle than mixed streams. In sector plans with relatively miscellaneous materials streams (e.g. plastics) innovations in sorting technologies will have a larger impact than sector plans which are more homogeneous by definition (e.g. tyres).

Textbox 1 Example of innovation in sorting methods

Plastics

Additives are present in all plastics, some of which can be classified as SoC (Wagner, 2020). The (exact) concentration of SoC is important for risk analysis. Household plastics probably contain low levels of SoC, because of stringent food-contact regulations. Innovations are primarily focused on increasing recycling rates of plastics and much less on the removal of SoC (e.g. endocrine disrupters), although this topic is gaining more attention.

Although innovative technologies have been developed for several waste streams that to some extent deal with SoC, this is often not the primary reason for innovation. This can, in part, be attributed to the fact that, with LAP3, the ZZS legislation is rather new or information on SoC content is missing. Furthermore, SoC removal can pose technological challenges.

Textbox 2 Example of technological challenges

Non-ferro metals

In non-ferro industry, SoC like arsenic and cadmium occur. These SoC are not intentionally added, such as for example additives in plastics. In the purification of non-ferro materials, SoC like arsenic and cadmium are mixed with critical raw materials (like palladium), because of the similar intrinsic properties of these metals. Extracting all the SoC from the materials is not deemed realistic because of the intrinsic (entropic) properties of metals.

To increase the attention given to SoC in recycling a few possible solutions were mentioned during the interviews. For example, for new materials or products, the SoC should be kept within the product and traced during and after their service life. A deposit-system on products with SoC was also mentioned. Increasing awareness by education programs, and offering help in treating waste streams containing SoC (a helpdesk) were also suggested.

The interviewed parties pointed out that waste streams are related to each other; it is an entangled system. Changes in one stream could have unforeseen effects in other streams. Government policy is seen as tending to reward frontrunners; this was considered to be a good thing in that it should promote circularity. Another observation by interviewees was that there should be more attention given to viable business models for recycling initiatives, with an emphasis on re-use instead of recycling.

4.4 Legislative issues in relation tore. recycling waste streams containing SoC

In the next two sections some recent 'position' papers on waste treatment and circularity in relation to SoC are summarised.

4.4.1 General and EU-wide scope:

The RIVM has investigated what is needed to achieve the transition to a safe circular economy and has identified three challenges (Beekman et al., 2020):

1. It is essential to share information about the substances used, including substances of (high) concern, throughout the product chain;
2. All parties in the product chain must ensure that materials and products can be re-used safely. Producers should think about this at the design stage of their products. Users, (waste) processors and governments should also contribute;
3. Finally, it's important that everyone involved deals responsibly with the materials and products that contain substances of (high) concern for which there is no alternative.

Based on these three challenges the authors recommend possible actions for the short and longer term. For the short term the necessity of developing a policy vision was highlighted and of prioritising the products, materials and substances for which there is an urgent need to realise safe and circular product chains. These recommendations need to be developed further over the coming years and adapted to the rapidly changing demands for substances, created, for example, by technical innovation. Additionally, monitoring is recommended to oversee whether the re-use/recycling of substances of high concern during the transition to a circular economy is taking place safely. This aspect is taken up as part of the Dutch Integral Circular Economy Report (ICER)[19] expected in early 2021.

In November 2019 a paper was developed by Oekopol, Sofia and RPA for the CARACAL (Competent Authorities for REACH and CLP) meeting based on a feasibility study (an assignment of the European Commission) (Oekopol, 2019). In this paper a number of mechanisms for the beneficial use of targeted information on SoC during waste

[19] https://www.pbl.nl/monitoring-circulaire-economie/icer

treatment were described. Several conditions were identified as being necessary to actually change the activities in waste treatment:

- the availability of information in such a form that those accessing it are able to read and understand it easily;
- waste (collection) fractions which are sorted for, or directed to, specific treatment routes depending on their SoC content, among other properties;
- the technologies needed to sort, separate and specifically treat a (waste) product, article or material;
- a market request for secondary materials with clearly defined qualities (secondary material standards incl. SoC concentration limits).

In April 2020 ChemSec shared its view on how to deal with hazardous chemicals. It stressed that there are five important aspects that need to be included in the upcoming Chemical Strategy for Sustainability:

1. Support EU industry frontrunners;
2. Speed up the regulatory processes and avoid "paralysis by analysis";
3. Strengthen the balance between generic and specific risk assessments in all EU chemicals regulations;
4. Transparency and traceability are important for a circular economy;
5. Close existing legislative gaps.

ChemSec, therefore, calls on the Commission to present clear ambitions for real change. The strategy must include clear commitments, deadlines and deliverables as well as a more ambitious chemicals legislation (Chemsec, 2020).

4.4.2 National scope: the Netherlands

In 2017 Van der Eijk from the Dutch Waste Management Association published the article 'Striking a balance between substances of concern and the circular economy' which described how to strike a balance between SoC and the circular economy from several perspectives. The perspectives are summarised below.

The point of designating SoC and setting limit values is to reduce the risks to humans, animals and the environment. Two main approaches can be distinguished: a hazard-based approach and a risk-based approach. The EU's REACH policy takes a hazard-based approach by identifying hazardous substances and focussing on the specific properties of the substances in relation to exposure. Both the EU's waste policy and the Dutch environmental policy follow a risk-based approach for restricting the use of substances (see: Bodar et al., 2018). It is not only the properties of a substance that may make it hazardous, as in the hazard-based approach, but also whether specific uses are acceptable or not is taken into account. The risk-based approach is also applied for determining whether or not the recycling SoC containing waste streams is acceptable (LAP).

The twin ambitions of maximising recycling and minimising hazardous substances in the loop are not always compatible. Banning hazardous substances can inhibit recycling, while recycling can keep hazardous substances in the loop. The challenge is to find the right balance. The Dutch risk-based approach offers a way forward. When a compound is categorised as a ZZS, policy aims to prevent any exposure to it. This is often possible to do, but then a problem still consists with all the 'legacy' materials. What to do with all the products still in circulation? Should we stop recycling them? Also, the EU is setting higher recycling targets, but at the same the number of substances being classified as hazardous is also growing.

According to van der Eijk the focus on phasing out SoC could hamper the recycling sector. New SoC keep popping up and at even lower limit values, which is not doing the recycling sector any good. This uncertainty is making it less attractive to set up new recycling initiatives. The recycling industry argues for a broader approach than the current fixation on SoC; an approach which would take other factors into account, such as recycling, raw materials scarcity and carbon reduction. Recycling reduces carbon emissions by millions of tonnes. Such considerations should be taken into account when deciding whether to lower limit values and prevent recycling (Van der Eijk, 2017).

The report of the Dutch Taskforce Recalibration of Waste provides a thorough overview of the limitations of the current legislation on waste and recycling (*Taskforce herijking afvalstoffen,* 2019; *in Dutch*). As well as some lack of clarity in the definitions and criteria used in relevant waste legislation, it was observed by the taskforce that stricter conditions apply to recycled materials compared to virgin materials and substances. For primary (virgin) raw materials, a registration including a chemical safety assessment according to the REACH Regulation is sufficient for them to be marketed freely. While on the other hand it is more difficult to market recycled materials. First an assessment for end-of-waste has to be conducted for which additional risk assessments are requested. Like, for instance, for the residues of medicines, pathogens, potential ZZS and ZZS which are not regulated by REACH and POP. In addition, the end-of-waste part of the lifecycle has also to be assessed.

Another main finding of this Taskforce is that a small number of the limitations can be attributed to legislation and guidance, the main part of the limitations can be traced back to the execution. Rules are not always interpreted in the same way and trials for new production processes are sometimes hampered. It is observed that innovative initiatives remain low profile, contrasting with the evolution to large-scaled innovative processes which are needed nowadays. A pilot phase on waste treatment is subject to a permit. But the implementation of such a pilot phase in the permit is rather time-consuming for both the recycler and the regulator. This hampers experimentation and innovation because, without a permit, no experimentation is possible. If a successful pilot is conducted, upscaling is needed. However, although the risks of the process are established in the pilot phase, upscaling the results introduces additional and other risks. These are even more difficult to consider given the current legislation.

The Taskforce states that within Europe much heterogeneity can be observed with respect to waste treatment. There are member states where the main part of the waste is disposed of by landfilling or by incineration. In Europe the Netherlands is at the top of the league in terms of recycling and has amibitions to scale up to a circular economy. Given the huge differences in waste treatment among the members states achieving consensus within Europe on circularity is a challenge.

The start towards finding a solution for waste treatment can be differentiated based on risks. When the origin of the waste stream is disregarded, the focus should be on the new application. The current legislation provides a basis for checking the ZZS that are present. In doing so three categories can be distinguished:

1. An application with low or no risk (no or hardly any ZZS). In this case generic or specific product rules could be set;
2. Average risk: specific product rules or management conditions in LAP or in the permit;
3. High risk: identification and control of risks and possibly phasing out via LAP.

Ministries and branch organisations should cooperate to select the main waste streams, their risks and their possible applications, from the perspective of circularity. However, safety for humans and the environment should never be at stake. For the low and average risk categories, the existing possibilities should be applied more extensively, like setting limit values for secondary materials. The SSML framework (Appendix I) could be expanded for secondary materials and existing English UK Quality Protocols (which are more generic compared to Dutch jurisdictions) should be translated to the Dutch situation.

According to the VNO-NCW (Confederation of Netherlands Industry and Employers), chemical recycling should be implemented more specifically in the Dutch legislation on waste (VNO-NCW, 2019; *in Dutch*). The current framework, as specified by LAP3, provides sufficient flexibility to enable innovation in terms of chemical recycling. The general understanding is to leave the legislation as it is on this aspect. However, it is advised that only the retransition to raw chemicals should be considered as (partial) chemical recycling. The current framework is not clear enough for all entrepreneurs. Elucidation of LAP3 is needed, which could then be added to the framework or used for explanatory communication. The following issues have to be addressed:

- How to select the preferred waste treatment
- What minimum standards are applicable
- Which role plays the LCA in the consideration
- If a higher quality feedstock plays a role
- If input streams are to be considered

It is advised that the VNO-NCW and the ministries I and W (Infastructure and Water Management) and EZK (Economic Affairs and Climate Policy) cooperate to provide supplementary guidance to develop a common understanding among stakeholders on how to deal with the current regulations with respect to the mentioned elements of chemical recycling.

4.4.3 Stakeholder insights

Five of the eleven conducted interviews addressed the role of the Dutch government (including the RIVM) in the transition towards a safe circular economy. Most frequently mentioned was the development of policies geared towards the standardisation of materials (e.g. via the NEN).[20] Standardisation helps reuse and recycling, as in general the more mixed or diverse a material stream is, the more complicated it is to reuse or recycle. So standardisation improves recycling efficiency significantly. Next, the need for development of knowledge about which SoC are present in which products and/or materials is mentioned. To tackle thispolicies should be developed to regulate SoC early on in the material chain. Knowledge about the different recycling technologies to remove SoC from material flows is also considered useful.

A role attributed to the RIVM is to provide an unbiased picture of the consequences of recycling for human beings and the environment (either positive or negative). This has to be done with an integrated assessment framework. Such an analysis leads to the safest and most sustainable approach for the long-term and prevents short-sighted regrettable choices being made.

[20] http://circulaireeconomie.nen.nl/whitepaper-afspraken-voor-een-circulaire-economie/whitepaper/

5 Interpretation

In Chapter 5 a selection of the waste streams which are challenging in terms of high quality and efficient recycling in relation to SoC is made. This is done based the collected data and on three different points of view:

1. The (potential) risk of SoC in a waste stream and recycling using (potential) exposure.
2. The current effort and efficiency of the recycling of the waste streams.
3. The general developments in recycling technologies.

5.1 Most challenging waste streams to overcome current recycling issues with respect to SoC

5.1.1 The (potential) risk of SoC in a waste stream and recycling

Risks arise from the exposure to hazardous substances. The groups of ZZS present in relevant waste streams which are frequently mentioned in literature and expert interviews include flame retardants in several consumer products, as well as plasticisers (phthalates) and phenols in plastics and plastic products like packaging. Metals and PFAS contaminated waste streams from consumer products and sludge or soil are also cases which are mentioned. ZZS that are not intentionally added to materials, like polycyclic aromatic hydrocarbons (PAH), are also detected in several relevant waste streams. Looking at the broader definition of SoC, besides ZZS, there are also pathogens, medicine residues and radio-active materials which are relevant in a safe circular economy. Relevant waste streams in regard to these aspects are residual domestic waste, sludge from wastewater treatment, waste originating from human or animal health care and residue from energy production (from biomass or from coal).

Based on the data collection and analyses, several waste streams were considered more relevant, based on their volume and SoC content (see Section 4.1). This resulted in a first selection of 32 waste streams which included consumer waste or products, like household waste, textile, electronic waste and batteries. Other relevant waste streams were large material streams, including paper, plastics, glass and wood. Among the 32 waste streams 17 were considered less relevant in terms of (direct) human exposure given the nature of the waste streams. The majority of these were specific industrial or processing waste streams or were processed by specialistic companies.

In Table 4 these waste streams were scored on potential exposure aspects from the described risk analysis perspective produced by Rijkswaterstaat (2018)(see Section 3.4.1). The waste streams are scored as not likely (-), possible or potential (+/-) or likely (+). Although assessment of the ‘lifecycle related risks’ is important, because of limited data availability only a rough scoring based on the careful considerations by the authors was possible. This is considered adequate for the explorative character of this study.

Table 4 Priority from risk perspective for the most relevant sector plans. Waste streams are scored as not likely (-), possible or potential (+/-) or likely (+). Waste streams in italics are considered most relevant based on the scoring incidence of +/- and +.

Sector plan LAP3	**SoC release**	**Consumer applications**	**Wide-spread/ diffuse**
1 Residual domestic waste	+/-	+	+/-
3 Process-dependent industrial waste	+/-	-	-
4 Separately collected paper and paperboard	+/-	+	+
5 Separately collected textiles (including shoes)	+/-	+	+
11 Plastic and rubber	+/-	+/-	+
12 Metal waste	-	+/-	+/-
13 Batteries and accumulators	+/-	+/-	+/-
14 Paper or plastic-insulated cables and off cuts thereof	+/-	-	-
16 Sludge from wastewater treatment and purification	+/-	+/-	+/-
20 Bottom ashes from waste incineration facilities	-	-	+/-
21 Fly ashes and kettle ashes from waste incineration facilities	-	-	+/-
28 Mixed construction and demolition waste and comparable waste	+/-	+/-	+/-
29 Stone-like materials	-	+/-	+/-
30 Sieve sand	+/-	-	+/-
31 Gypsum	-	+/-	+/-
33 Roofing waste (bituminous, containing tar, composite)	+/-	+/-	+/-
34 Asphalt	+/-	-	+/-
36 Wood	+/-	+/-	+
37 Asbestos and asbestos-containing material	+/-	+/-	+/-
38 Separately collected glass sheets	-	-	-
39 Uncontaminated soil that has become waste: specifically containing PFAS	+/-	+/-	+/-
40 Dredging sludge	+/-	-	+/-
41 Clean packaging waste	+/-	+	+/-
52 Tyres	+/-	+/-	+/-
56 Used oil (mineral and synthetic origin)	+/-	-	+/-
71 Discarded electrical and electronic equipment	-	+/-	+/-
72 Sulphuric acid, acid coal tar and other sulphur-containing waste	+/-	-	-
73 Highly contaminated wastewater streams and baths	+/-	-	-
78 Filter cake from detoxification/neutralisation/dehydration	+/-	-	-
84 Other mono-streams for recycling (matrasses, stone wool, carpet, artificial grass): specifically diapers	+/-	+	+
85 EPS (polystyrene foam)	-	+/-	+/-

5.1.2 *The current effort and efficiency of recycling of the waste streams*

As stated in the method, the relevant aspects to consider when determining the effort and efficiency of recycling include the homogeneity of the waste stream and the availability of facilities and technologies for efficient removal. Besides these qualitative aspects, current recycling rates, and the minimum standard, are also used to select waste streams that are considered most relevant from a recycling effort and efficiency perspective. In this section we provide some qualitative considerations that currently play a role in the removal of SoC from waste streams to enable high value and safe recycling. These considerations are based on the outcomes of the stakeholder interviews and desktop study and are considered strictly indicative and illustrative.

An example of high quality recycling is the relatively homogeneous waste stream from tyres (SP52). Tyres contain both SoC (Hofstra, 2019) and valuable materials like carbon black. Innovative recycling techniques (pyrolysis) for tyres are in the scale-up phase and are used for extracting the carbon black which is brought back on the market as a resource for new tyres or paints.

A stream containing SoC for which facilities are already partly in place to improve sustainable waste management is sludge from wastewater treatment. Sludge (SP 16) is a large stream (~1% of total waste NL), which is now mostly incinerated. This is expensive and incineration is not considered as recycling. The sludge contains about 20-35% dry substance, the rest is water. It would be more efficient to dry the sludge and remove the contaminants. The (dried) sludge could then be used as, for example, soil improver. Sludge can contain heavy metals, drug residues and poly and perfluorated substances. However, valuable minerals and materials are also present. For example, sulphates which can be extracted as struvite crystals. Struvite crystals can be efficiently isolated and only require washing as a cleaning step. So relatively low effort and high efficiency can be obtained. Cellulose and biopolymers, as polyhydroxyalkanoate (PHA), are also valuable resources which can be extracted from wastewater. Limiting issues for further upgrading the sludge recycling are related to scaling up the capacity, because most of these extraction technologies for increased recycling are still under development. Use of pilot plants can help to further prove the technologies on a larger scale, and to obtain the necessary information on SoCs.

Non-ferro metals (part of SP12) already have a very high recycling rate. Specific SoC are inherently present in non-ferro material streams, like cadmium or arsenic. Cadmium, for example, can mostly be separated during the recycling process. However, due to intrinsic properties of the metal, cadmium inpurities are present in ‘pure’ batches (for example in purified zinc oxide). The separated stream of precious metals contains some arsenic because of the same reason. Also, some SoC like lead are used as extraction material and are therefore necessary to achieve sufficient high recycling rates.

Textile (SP5) is an expanding waste stream (created by fast fashion), raising concern for both human beings and the environment (EPA, 2019). Next to the presence of SoC, sustainability topics like the large water footprint, and poor working conditions are of concern (Amutha, 2017). However, technologies for the (chemical) recycling of textiles are not yet fully developed. Incineration of textile is the current practice. Recycling initiatives are in development (eg. De la Motte and Palme, 2018; Chemsec, 2020a) and, if textiles are recycled on a large scale, this could be a huge gain in terms of circularity. However, options for, and the efficiency of, removal of SoC during recycling are still unknown.

Plastics (SP 11) are also a very large and suitable waste stream for recycling, where a lot of innovation takes place nowadays. Efficiency of SoC removal depends on the separation of the various polymers. Monostreams of plastics (i.e. streams with plastics from one type of polymer) are more efficient to recycle. For example, polyesters used in clothing are a dry and relatively clean material stream that has the potential for efficient recycling by removing SoC by chemical recycling (Notman, 2020). Proper recycling also creates less littering of plastics and therefore a lower release of microplastics to the environment.

In Table 3 several other SoC relevant waste streams are listed for which the recycling rate is below 90%. A number of these waste streams have specific issues that are estimated to pose a great barrier for improving recycling rates. These are:

- SP1 Residual domestic waste: this waste stream is heterogeneous. Enhancement of recycling rates would take quite some effort.
- SP37 Asbestos and asbestos-containing material: given the restriction on asbestos, recycling of asbestos-containing materials (and removing the asbestos) is hampered.
- SP73 Highly contaminated wastewater streams: the water must be filtered.
- SP78 Filter cake from detoxification/neutralisation/dehydration: which is highly polluted.

Other waste streams with low recycling rates and for which no specific issues are known, include:

- SP28 Mixed construction and demolition waste and comparable waste
- SP29 Stone-like materials
- SP30 Sieve sand
- SP35 Blasting grit
- SP36 Wood
- SP40 Dredging sludge
- SP41 Clean packaging waste
- SP84 Other mono-streams for recycling (matrasses, stone wool, carpet, artificial grass)
- SP85 EPS (polystyrene foam)

Streams that are most challenging in regard to the removal of SoC based on effort and efficiency are of low volume and are mixed/complex. For example, small chemical waste and batteries. For these low volume streams the market seems ‘too small’ to achieve efficient recycling in the Netherlands, but recycling abroad is possible. This is also currently the case for WEEE products (SP71) like solar panels, although in future this particular stream is expected to grow substantially because of the energy transition. Other societal transitions, like digitalisation, can also change waste stream volumes and recycling needs.

To enable safe recycling, designing upfront for end-of-life scenarios should be taken into account, for example, by employing circular-by-design approaches. The effort and efficiency of SoC removal would then be considered before the life cycle had even started.

5.1.3 The developments in the recycling technologies

General lessons from the explorative study were used to select the most challenging waste streams in regard to the high quality and efficient recycling of SoC.

Innovative recycling options are under development for several waste streams. The desktop study and interviews looking at innovative recycling options with respect to SoC indicated a wide variety of development stages of recycling innovations and technologies (see Section 4.2). The development of advanced separation techniques were found for several waste streams which was often followed by the re-use or recycling of specific, separated streams. Techniques for the mining of specific components or nutrients from waste streams were also used and being developed in different sectors, like wastewater treatment, waste incineration or specific material stream, like car tyres or animal waste. For organic waste streams, like garden waste, mainly fermentation and composting techniques were used.

Some innovative techniques considering SoC are chemical recycling techniques, including depolymerisation of plastics. The techniques focussing on plastics can also be used in packaging recycling, after applying advanced separation techniques.

Some techniques do not remove the SoC from a stream, but lower the SoC content in the secondary materials, for example through advanced sorting of the waste, which concentrates polluted material streams. Another possibile way to reduce the risk of SoC is to lower the potential exposure by immobilisation. Only when SoC cannot be separated or extracted from the waste stream in terms of capacity or technical difficulty, can immobilisation be considered for waste streams, like for instance PVC or sludge.

If we focus on SoC containing waste streams it can be stated that few techniques specifically focus on the removal or handling of SoC. It seems that in most recycling sectors SoC are not (yet) a driver for innovation. It is mainly the reduction of the physical quality of materials, or regulation of the quality of secondary materials, which is important for innovative recycling techniques considering SoC. It should also be noted that the recycling of several important waste streams, like textile, does not primarily take place in the Netherlands; this results in in limited innovation locally. But if we want to increase the recycling of SoC containing waste streams substantially more emphasis should be put on cleaning up these streams to achieve a (more) circular economy.

5.2 Selection of priority waste streams

In the previous section (5.1), considerations and qualitative criteria were described to consider which waste streams could be prioritised and where the focus on SoC could enhance material circularity. Based on the analysis presented in this report, seven sectors plans have been selected which could benefit the most from having an extra focus on issues related to SoC and should be prioritised as shown in the table below. No further distinctions have been made between these seven waste streams.

Table 5 The seven prioritised waste streams with considerations

Waste stream (number)	**Volume (kton/ year)**	**ZZS identi-fied (#)**	**Minimum standard**	**Additional relevant aspects from the analysis**
Separately collected textiles, including shoes (5)	86	44	recycling or incineration	Direct human exposure (dermal), large variety in quality (e.g. legacy SoC) and high incidence of ZZS. Microplastics are being released from synthetic textiles (Zambrano 2019, De Falco, 2018).
Plastic and rubber (11)	213	92	recycling (thermo-plastics) or incineration (rest)	Huge volume, wide dispersive use, many ZZS, high relevance for society and many innovations in recycling technologies
Batteries and accumulators (13)	106	18	recycling of metals	Presence of ZZS, expected rise in volume due to the energy transition
Sludge from wastewater treatment and purification (16)	2,635	4	recycling or incineration	Incineration is current practice, while many useful substances are present in this waste stream. Besides ZZS also SoC like pathogens, medicines, pesticides etc. There are already some pilots running on recycling options.
Mixed construction and demolition waste and comparable waste and 29 Stone-like materials (28 and 29)	3,689 and 15,923	20 and 10	recycling or incineration (28) or landfilling (29)	Huge quantities, so high potential. Large variety in quality (e.g. legacy SoC). Both are combined because overlap is expected to occur at waste separators/ recyclers.
Tyres (52)	110	10	recycling or incineration	Current practice as fill-in material on artificial grass is an issue. Innovative technologies are developed, leading to removal of ZZS (PAH) from the waste stream.
Discarded electrical and electronic equipment (71)	210	31	recycling or incineration	Many ZZS, complex products, presence of critical raw materials (scarce). Growing market due to digitalisation.

6 Conclusions and recommendations

Substances of concern in waste streams can hamper recycling. This study aimed to provide some general insights into the current status and development of the recycling of waste streams containing SoC. The study provides general information which supports the answering of the question:
The recycling of which waste streams is currently hampered by SoC and would benefit from the development of innovative technologies?

A desktop study and stakeholder interviews were conducted. These focussed on the presence of SoC in waste streams, on current and innovative recycling technologies and on relevant legislation issues. This resulted in a rough inventory based on waste streams defined in the Netherlands in LAP3 with 85 sector plans. To answer this research question, the results from the data collection and analysis were interpreted in the light of: the potential risk created by SoC, the effort and efficiency of removal of SoC and some general lessons on the developments in recycling technologies.

The study revealed that data on the SoC content of waste streams is currently not adequately available to determine the risks. Only a rough estimation on which SoC might be present in waste streams can be made from the available data. The lack of information is limiting for recyclers and policymakers. From the minimum standards and interviews it became clear that waste streams containing SoC are currently often not recycled. While there are several developments in recycling technologies to increase recycling rates, the study shows that the SoC content is often not the driving force for innovation. However, certain technologies, such as chemical recycling, are promising for recycling waste streams containing SoC. At the moment chemical recycling is seen as a less desirable form of recycling in LAP3. It is recommended that this is reviewed for waste streams containing SoC. From the conclusions and recommendations concerning legislation issues, we conclude that:

- The current risk-based approach should be implemented and harmonised at European level.
- The setup of the (Dutch) waste legislation serves the purpose, but extra guidance on particular issues, such as SoC should be provided to industry and authorities.
- A broader approach to evaluating recycling options should be applied. Next to SoC other factors should also be considered in an integrated assessment, for example, raw material scarcity and carbon footprint (for example by using SSML).
- Special attention should be given to secondary materials, by assigning the main waste streams, their risks and their possible applications.

Furthermore, the waste streams containing SoC were also prioritised, based on the quantitative and qualitative results. From the 32 most relevant sector plans from the data collection and analysis, a selection of seven priority sector plans was made, as follows:

- SP5 Separately collected textiles (including shoes)
- SP11 Plastic and rubber
- SP13 Batteries and accumulators
- SP16 Sludge from wastewater treatment and purification
- SP28/29 Mixed construction and demolition waste and comparable waste in combination with stone-like materials
- SP52 Tyres
- SP71 Discarded electrical and electronic equipment

This derived selection of prioritised sector plans can only be considered as a first screening of the most relevant waste streams that contain SoC. But, in our view, these waste streams could benefit from the development of innovative recycling technologies to create a safer circular economy. The next phase of RENEW will use case studies to evaluate the SSML methodology for assessing the safe and sustainable recycling of streams containing SoC. The case studies will focus on radiation in construction materials, cellulose recovered from wastewater and the chemical recycling of plastics.

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Appendix 1: Safe and Sustainable Material Loops

If the circular economy is based on the pursuit of value retention, then downcycling (see Section 2.1.2), as frequently is the case these days, should be avoided. The Safe and Sustainable Material Loops (SSML) framework developed by the RIVM (Quik et al., 2018) takes the risk and benefit aspects of recycling in account. In this method the risk assessment of a substance is compared to the environmental benefits of its recycling or re-use.

The SSML framework is set up as an integral framework and consists currently of seven modules: Substances of concern, Pharmaceutical residues, Antibiotic Resistance, Pathogens, Pesticides, Circularity and Energy and Land Use (Figure 10).

Figure 10 Modules of the SSML framework as shown in the Material Safety and Sustainability data sheet, giving an overview of the outcome.

It depends on the particular material stream which modules of the SSML framework are applicable. To provide an indication for which waste streams the separate modules are applicable, the modules are explained hereafter with corresponding examples.

Sustainability - Environmental benefit modules

The environmental impact module is the first of two available sustainability modules. This modules uses the indicators - energy and land use - to estimate the effect in terms of environmental impact and is considered relevant for all recycling processes; energy is always consumed and released. This module is even more relevant for streams containing biomass (biomass has large impact on land use). However, if a safety concern is only addressed by e.g. replacing substance x by z, which has a similar environmental impact, then this module is less relevant. The assessment of module relevancy for a case is part of the SSML framework.

The second sustainability module, circularity, is applicable when the application of the recycled material is higher, or equal, on the LAP3 waste hierarchy compared to the current application (see Figure 5). If this is lower, circularity is not further assessed. If the outcome is equal or higher, then tier 1 follows, with a check to ascertain whether the material stream contains any of the EU critical raw materials (CRM) (EC, 2020a). This is combined with a supply check: is there a concern about material supply related to a significant increase in demand for the source material? Then tier 2 follows with an assessment of recovery efficiency, contribution (towards the new application), and recyclability of the material, as indicators for circularity.

Safety modules
Modules concerning safety are relevant if the indicated hazard is present in the material stream. The SoC module is relevant if SoC are present in the material stream to be recycled.

The module for pharmaceutical residues differentiates between human pharmaceutical residues and veterinary pharmaceutical residues. Both can be present in different waste streams and enter via human or veterinary excreta and by washing off dermal medication. Pharmaceutical residues are expected to be present in materials that originate from various streams related to waste water, manure, solid waste or other residual materials of biological origin. Examples of this are diapers or sludge from waste water treatment and purification.

The module about pesticides describes the safety assessment of waste streams that potentially contain residues of plant protection products (PPP). An extension with biocides is possible. The basis of this module lies in the existing approach to asses plant or crop-based organic waste streams that are used as fertilizer or co-digester substrate.

The pathogens module concerns microbiological hazards. In theory these can be present in, and on, all types of products, but the most likely source of any hazards are products of biological origin. Safety assessments of (recycling) material flows in the biomass and food sector should take this aspect into account.

The module for antimicrobial resistance addresses an additional concern in relation to pathogens; microbial resistance to antibiotics. This issue can play an important role in material flows where antibiotics and resistant bacteria are present, such as waste water, manure and other livestock waste flows.

Other evaluation frameworks exist to consider the recycling of materials with SoC, for instance the Clean Material Recycling (CleaR)[21] Project. CleaR focusses on the social-economic assessment (SEA), which is important to support regulators assessing the presence of SoC in

[21] https://op.europa.eu/en/publication-detail/-/publication/26e22c04-5b62-11e9-9c52-01aa75ed71a1/language-en/format-PDF

recycled materials. This methodology consists of a stepwise approach to assess whether or not a draft proposal for restriction under the REACH Regulation should include derogations (exemptions) for recycled materials under strict and exceptional conditions (De Blaeij et al., 2019). We consider this topic to be outside the scope of this report. Our focus is on the environmental aspect of sustainability and risk assessment.

Appendix 2: Standard list of questions (*in Dutch*)

Algemene vragen :

- Wat is uw beeld van de materiaal/afvalstromen binnen Nederland?
  - Typen stromen (sectorplannen) en volumes
  - Welke bevatten (relatief of absoluut veel) SoC?
  - Bent u bekend met de sectorplannen van het LAP?
    - Zo ja: is de (uitgebreide) minimumstandaard in sectorplannen toereikend?
- Bent u bekend met ontwikkelingen voor (hoogwaardige) recycling van afvalstromen met zorgstoffen?
- Bij welke sectorplannen vindt u de **prioriteit** het hoogst om tot hoogwaardiger recycling te komen?
  - grootste volume
  - grootste knelpunt vanwege aanwezige SoC
  - grootste winst te behalen
  - of juist beperkt aantal SoC aanwezig en daarmee relatief makkelijk op te schonen ("laaghangend fruit")
- Welke veranderingen of trends ziet u plaatsvinden binnen de afvalwereld?
- Heeft u een overzicht van materiaal/afvalstromen binnen Nederland?
- Toegevoegde waarde van het RIVM (advies overheid)?
- Kan het RIVM een rol of nut vervullen?
  - Zo ja, hoe ziet de geïnterviewde dat voor zich?

Specifiek:

- Hoe gaat u om met zorgstoffen (SoC) binnen uw materiaal-/afvalstromen?
- Is de minimumstandaard voor de voor u relevante sectorplannen toereikend?
- Bij welke sectorplannen ziet u de meeste ruimte voor verbetering?
- Merkt u effect van het veranderen van wetten en regels op uw organisatie?
  - Specifieke regels? Wat zijn belemmeringen? Wat zou u helpen?
- Ervaart u knelpunten voor meer hoogwaardige recycling?
  - Zo ja, wat zijn voor u de grootste knelpunten?

Slot

- Welke personen/instanties/bedrijven (liefst met overzicht) zouden we nog meer kunnen (moeten) spreken over innovatie recyclingmethoden voor afvalstromen (met ZZS)?

Appendix 3: Overview of waste streams (sector plans) with their relative masses and occurrence of ZZS based on data from 2016 in the Netherlands

Sector plan LAP3	# ZZS	% [of total waste mass]
1 Residual domestic waste	18	3.1%
2 Commercial, industrial and institutional waste, similar to household waste	14	<0.1%
3 Process-dependent industrial waste	8	4.4%
4 Separately collected paper and paperboard	11	0.9%
5 Separately collected textiles (including shoes)	44	<0.1%
6 Separately collected organic waste from household (vegetables, fruit and garden waste)	0	0.7%
7 Separately collected organic commercial, industrial, agricultural and institutional waste	6	<0.1%
8 Organic waste from maintenance of gardens, parks and forests	0	1.4%
9 Waste from maintenance of public areas	0	0.2%
10 Street litter	9	NA
11 Plastic and rubber	92	0.1%
12 Metal waste	9	0.5%
13 Batteries and accumulators	18	0.1%
14 Paper or plastic-insulated cables and off cuts thereof	34	<0.1%
15 Glass fibre cables	6	<0.1%
16 Sludge from waste water treatment and purification	4	1.3%
17 Waste from the production of drinking water	3	0.1%
18 Minor chemical waste/ minor hazardous waste and chemical packaging	2	<0.1%
19 Waste originating from human or animal health care	9	<0.1%
20 Bottom ashes from waste incineration facilities	17	0.6%
21 Fly ashes and kettle ashes from waste incineration facilities	7	0.1%
22 Ashes from sludge combustion	6	<0.1%
23 Residue of coal-fired power stations	1	0.9%
24 Residues from biomass energy production	8	NA
25 Activated carbon	0	<0.1%
26 Residue from flue gas cleaning from waste incineration factories and plants for sludge combustion of biomass energy extraction	1	<0.1%
27 Residual stream from shredding	0	<0.1%
28 Mixed construction and demolition waste and comparable waste	20	1.8%
29 Stone-like materials	10	7.8%
30 Sieve sand	8	0.2%
31 Gypsum	5	<0.1%
32 Aerated concrete	8	<0.1%
33 Roofing waste (bituminous, containing tar, composite)	9	<0.1%
34 Asphalt	8	0.8%

Sector plan LAP3	# ZZS	% [of total waste mass]
35 Blasting grit	9	<0.1%
36 Wood	28	1.1%
37 Asbestos and asbestos-containing material	4	0.2%
38 Separately collected glass sheets	16	<0.1%
39 Uncontaminated soil that has become waste	0	3.4%
40 Dredging sludge	7	67.2%
41 Clean packaging waste	14	0.6%
42 Packaging containing residues of paint, adhesives, sealant or resin	71	<0.1%
43 Packaging containing residues of hazardous substances	26	<0.1%
44 Gas cylinders and other pressurised containers	0	<0.1%
45 Fire extinguishers	2	<0.1%
46 Ammunition	0	NA
47 Fireworks	6	<0.1%
48 Explosive waste	5	<0.1%
49 Underground storage tanks	0	NA
50 Autogas pressure vessels	0	NA
51 End-of-life vehicles and motor bikes	0	0.1%
52 Tyres	10	0.1%
53 Waste from ships and vessels	0	0.2%
54 End-of-life ships and vessels	1	<0.1%
55 Oil filters	13	<0.1%
56 Used oil (mineral and synthetic origin)	55	<0.1%
57 Waste oils containing halogens	4	<0.1%
58 Oil/water mixtures and oil/water/sludge mixtures and oil-containing sludge	0	0.2%
59 Liquid fuel and oil residues	2	<0.1%
60 Oil based mud (OBM) and OBM containing cuttings	0	<0.1%
61 Oil applied in the treatment of metals (drilling, cutting, grinding and rolling)	2	<0.1%
62 Metal waste with attached oil or emulsion	6	<0.1%
63 Other oil containing waste	1	<0.1%
64 PCB-containing waste	0	<0.1%
65 Animal sourced waste	0	0.3%
66 Gas discharge lamps and fluorescence powder	0	<0.1%
67 Halogen-reduced solvents and glycols	0	<0.1%
68 Halogen-containing solvents	0	<0.1%
69 Residue from distillation activities	0	0.1%
70 Controlled substances (CFK, HCFK, halons) and fluorinated greenhouse gases (HFC, PFC, SF6)	6	<0.1%
71 Discarded electrical and electronic equipment	31	0.1%
72 Sulphuric acid, acid coal tar and other sulphur-containing waste	8	0.3%
73 Highly contaminated wastewater streams and baths	8	<0.1%
74 Precious metal containing baths	0	NA
75 Metallic wastewater containing organic contaminants	0	<0.1%
76 Other acids, alkalis and metallic wastewater	0	<0.1%
77 Aqueous waste with specific contaminants	0	0.4%
78 Filter cake from detoxification/neutralisation/ dehydration	9	0.2%

Sector plan LAP3	**# ZZS**	**% [of total waste mass]**
79 Black/white fixer, black/white developer	0	<0.1%
80 Solid photographic waste	12	<0.1%
81 Tempering salts	2	<0.1%
82 Mercury and mercury-containing waste	2	<0.1%
83 Arsenic-sulphide sludge and arsenic-sulphide filter cake	0	NA
84 Other mono-streams for recycling (matrasses, stone wool, carpet, artificial grass)	15	<0.1%
85 EPS (polystyrene foam)	NA	NA

Appendix 4: Extraction of table using results from data collection (in Dutch)

Waste streams			**Minimumstandaard**					**Recycling technologie**	
Sectorplan	**Mass**	**ZZS #**	**Uit-gebreid**	**Tussenin**	**Summier**	**Recycling?**	**Verbranding (of storten)?**	**Beschrijving**	**Bron (internet search)**
1 Residual domestic waste	6321	18	1			ja, bijv. Bij milieustraten	ja, oa voor fijn huidhoudelijk afval: sorteren etc … nuttige toepassing is toegestaan … met als beperking dat het overblijvende residu nog minimaal verbrand moet kunnen worden.	nascheiding, verbranding, fracties toepassen in funderingen.	https://www.degraafgroep.nl/afval-verwerken-recyclen/restafval-verwerking
								PMD nascheiding ipv gescheiden inzamelen	https://www.avr.nl/nl/plastic-scheiden-uit-de-grijze-vuilniszak
2 Commercial, industrial and institutional waste, similar to household waste	11	14	1			ja, alleen als overblijvende deel nog minimaal verbrand kan worden	ja	nascheiding, verbranding, fracties toepassen in funderingen.	
3 Process-dependent industrial waste	9008	8		1		ja	ja als recycling niet mogelijk of >€205,-/ton / storten		
4 Separately collected paper and paperboard	1904	11		1		ja	ja als recycling niet mogelijk of >€205,-/ton (andere toepassing, verbranding)	meubels van gerecycled papier	https://www.parool.nl/nieuws/1-2-3-4-huisje-van-papier-de-opmars-van-kartonnen-meubels~b56358d6/?referer=https%3A%2F%2Fwww.google.com%2F https://www.thekube.nl/index.php/meubels-van-papier/ http://www.jenspraet.com/shredded-series-4-low-table.html
								recycling **drankkarton**, zowel papiervezels als PE en aluminium. Papiervezels verwerkt tot wc-papier en papieren handdoekjes	https://www.hedra.nl/keten/recycling https://www.duurzaambedrijfsleven.nl/recycling/14459/recycling-innovatie-wc-papier-van-gebruikte-drankenkartons
								papierrecycling voor toiletpapier dat veilig is voor biologische systemen	https://www.wepa.nl/mvo/293/cradle-to-cradle.html https://c2cvenlo.nl/papierfabriek-van-houtum-succesvol-dankzij-duurzame-innovatie/
5 Separately collected textiles (including shoes)	86	44	1			ja	ja als recycling niet mogelijk of >€205,-/ton (andere toepassing, verbranding)	scheiden, vervezelen. Geen specifieke methodes voor detecteren/verwijderen van zorgstoffen gevonden.	
								scheiden, vermalen. Gebruikt als top/onderlaag voor tracks, kinderspeelplaatsen en sportscholen	https://www.fastfeetgrinded.eu/projects
								papier verwaarding van vezels oude spijkerbroeken	https://www.kidv.nl/8128/ambachtelijk-papier-vol-innovatieve-technologieen.html
6 Separately collected organic waste from household	1456	0		1		ja	ja, residuen verwijderen door verbranden	Vergisten (groengas; CO2) en composteren. Levert ook water en warmte op.	https://www.meerlanden.nl/circulaire-economie/groene-energiefabriek

Waste streams			**Minimumstandaard**					**Recycling technologie**	
Sectorplan	**Mass**	**ZZS #**	**Uit-gebreid**	**Tussenin**	**Summier**	**Recycling?**	**Verbranding (of storten)?**	**Beschrijving**	**Bron (internet search)**
(vegetables, fruit and garden waste)									https://www.rova.nl/leren-en-doen/pagina/1201/wat-is-gft-afval
								Substraatcompost voor potgrond (ipv normaal compost)	https://www.rvomagazines.nl/miavamil/2018/01/praktijkverhalen-attero
7 Separately collected organic commercial, industrial, agricultural and institutional waste	9	6		1		ja, composteren of vergistern	ja, residuen verwerken	Vergisten (groengas; CO2) en composteren. Levert ook water en warmte op.	zie hierboven
								cacaodoppen omzetten in hardboard, cacaothee, cacaovervanger of gebruik als vulmiddel in papier	http://www.afvalkring.nl/downloads/Bijlage%201%20Verslag%20Toekomstverkenning%20mogelijkheden%20recycling%20voedselverwerkende%20industrie.pdf https://www.wur.nl/nl/project/Ontwikkeling-van-hoogwaardige-producten-van-cacaodoppen.htm
								papier/karton verwaarding van vezels uit agrarische reststromen	https://www.schutpapier.nl/segmenten/technisch-op-maat/valorise/ https://www.ruimteinregels.nl/sites/default/files/2018-10/Tomatenstengels-fasctsheet-versie-11122017.pdf http://tulpenbollenpapier.nl/ https://paperwise.eu/ https://www.thegreenery.com/innovaties/een-kartonnen-doos-van-tomatenstengels
8 Organic waste from maintenance of gardens, parks and forests	2828	0	1			Ja	ja residuen	Bioraffinage van cultuurgras. Producten: eiwitconcentraat (=veevoer); suiker- en mineralenrijk restsap (=meststof), en grasvezel (=papierproductie).	http://grassa.nl/bioraffinage/ https://www.bnnvara.nl/vroegevogels/artikelen/grassa-eiwit-uit-gras https://www.hooglandgrasengroen.nl/wat-doen-wij/
								Eierdozen/papier uit gras	https://www.staatsbosbeheer.nl/zakendoen/inspirerende-voorbeelden/huhtamaki-graseierdozen
9 Waste from maintenance of public areas	414	0	1			(ja)	ja		
10 Street litter		9							
11 Plastic and rubber	231	92		1		ja, thermoplasten	ja, thermoharders en elastomeren	Depolymerisatie van nylon	https://www.econyl.com/the-process/
								Mechanische recycling van PE and PP	https://www.qcpolymers.com/waarom/
								Solvolyse	
								Chemolysis	2017 - Mechanical and chemical recycling of solid plastic waste - Ragaert et al
								Pyrolysis (waaronder thermisch, katalytisch, hydrolytisch kraken)	
								Gasification	
								Zie EU link voor H2020 projecten voor plastics recycling met zorgstoffen.	https://www.duurzaambedrijfsleven.nl/recycling/25543/dutch-design-week-3-keer-innovatieve-recycling https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/ce-sc5-01-2018
								Solvolyse van EPS	https://polystyreneloop.org/technology

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								Gasificatie	
								Depolymerisatie van PET	
								Depolymerisatie van PET	https://www.agro-chemie.nl/artikelen/cumapol-bouwt-pilotfabriek-voor-chemische-pet-recycling/
								Verschillende	2019 - Techniques for separation of plastic wastes - Serranti et al
								Solvolyse PVC	http://www.vinyloop.com/en/
								Gasification	https://enerkem.com/products/methanol/
								thermisch depolymeriseren van styreen	https://bmbf-plastik.de/en/joint-project/resolve
12 Metal waste	1042	9		1		Ja	ja, ook AVI, met restoffen terugwinning		https://www.basismetaal.nl/wp-content/uploads/2019/04/Presentatie-II-Hugo-Waeterschoot.pdf
								Verwerken staal-schroot tot nieuwe hoogwaardige producten	https://jansengroup.com/nl/doorbraak-in-de-recycling-van-vervuild-metaal/
13 Batteries and accumulators	106	18	1			ja	ja, alleen bakelietafval	Bestaande technieken met bijne gesloten kringloop	https://www.deingenieur.nl/artikel/batterij-recyclen-kan-veel-zuiniger
								verschillende technieken, nietin NL	https://www.nature.com/articles/s41586-019-1682-5
									https://urecycle.eu/portable-batteries/recycling-process/ https://evreporter.com/lithium-ion-battery-reuse-and-recycling/
14 Paper or plastic-insulated cables and off cuts thereof	73	34	1			ja na scheiden	ja		https://www.bodemrichtlijn.nl/Bibliotheek/bouwstoffen-en-afvalstoffen/kabels-en-draden/afvalstoffase-kabels-en-draden
15 Glass fibre cables	0	6			1	nee	ja, verbranden als vorm van verwijdering		https://www.bodemrichtlijn.nl/Bibliotheek/bouwstoffen-en-afvalstoffen/kabels-en-draden/afvalstoffase-kabels-en-draden
16 Sludge from waste water treatment and purification	2635	4	1			Ja	ja	Lokale afvalwaterzuivering voor ziekenhuizen die pathogenen en andere microverontreinigingen uit het afvalwater zuivert door middel van o.a. anaerobe digestie	https://pharmafilter.nl/en/infrastructure/the-system/pharmafilter-installation/
								gelachtige grondstof (= alginaat) die wordt gewonnen uit slibkorrels die zich vormen bij het Nereda® zuiveringsproces	https://www.efgf.nl/producten/kaumera/
								Bioplastics (PHA; polyhydroxy-alkanoaat) geproduceerd door bacterien in RWZI	http://phario.eu/ https://www.efgf.nl/producten/bioplastics/
								Cellulose winnen uit rioolwater slib	https://www.efgf.nl/producten/cellulose/
								Power-to-Protein is about closing this artificial nitrogen cycle by direct N upcycling as microbial protein from sewage water.	https://www.powertoprotein.eu/
								Controlled Struvite Precipitation	https://www.eliquo-we.com/en/airprex.html

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17 Waste from the production of drinking water	261	3	1			Ja	storten		
18 Minor chemical waste/ minor hazardous waste and chemical packaging	18	2						tot 70% kan gerecycled worden, zoals batterijen,	
19 Waste originating from human or animal health care	14	9				nee	ja, beleid is verbranden		
20 Bottom ashes from waste incineration facilities	1209	17	1			ja, green deal avi	ja, ook storten van residue	terugwinnen metalen en verontreinigingen concentreren in residu. Overig bodemas nuttig toepassen	
21 Fly ashes and kettle ashes from waste incineration facilities	280	7			1	nee	storten		https://www.nemokennislink.nl/publicaties/vliegas-uit-huisvuilverbranding-veilig-te-verwerken-tot-schuimglas/
22 Ashes from sludge combustion	1	6		1				terugwinnen fosfaat uit slibas	
23 Residue of coal-fired power stations	1925	1			1	ja			
24 Residues from biomass energy production		8			1		storten		https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-E--11-034
25 Activated carbon	7	0			1	nee	ja	Carbon Black halen uit oude banden, daarnaast komt ook energie vrij en olie. Gebeurt met verhitten zonder zuurstof, pyrolyse. Filters voor rookgassen	https://blackbearcarbon.com/
26 Residue from flue gas cleaning from waste incineration factories and plants for sludge combustion of biomass energy extraction	28	1			1		storten		
27 Residual stream from shredding	40	0		1		ja	ja, overig		
28 Mixed construction and demolition waste and comparable waste	3689	20		1		ja, met beperking dat residu nog verbrand moet kunnen worden	ja, residu		
29 Stone-like materials	15923	10	1			ja	storten		
30 Sieve sand	442	8	1			ja (pak-arm)	storten		
31 Gypsum	66	5		1		ja	storten		
32 Aerated concrete	12	8			1	nee	storten		
33 Roofing waste (bituminous, containing tar, composite)	93	9	1			ja	ja, gemengde stroom	Cryogeen (lage temperatuur) granuleren van bitumen dakbedekking voor inzet als granulaat in wegenbouw	https://www.bodemrichtlijn.nl/Bibliotheek/bouwstoffen-en-afvalstoffen/dakbedekking-dakleer-bit112885
34 Asphalt	1603	8		1		ja			
35 Blasting grit	93	9		1		ja	stort, regeling niet-reinigbaar staalgrit		
36 Wood	2206	28		1		nee (andere nuttige toepassing voor A- en B-hout)	ja + storten	pallet gemaakt van 100% post-consumer gerecyclede houtvezel	https://www.verpakkingsmanagement.nl/nieuws/presswood-pallets-100-pefc-gerecycled33054

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								verschillende processen: chemische recycling, spuitgietbaar hout, OSB platen, spaanplaat, isolatieplaten, Houtwolcementplaten, linoleum, etc. (zie bijlage 2 van TAUW rapport 2017 genaamd "Knelpuntenanalyse houtrecycling")	https://zoek.officielebekendmakingen.nl/blg-843684.pdf
37 Asbestos and asbestos-containing material	398	4		1		nee	ja		
38 Separately collected glass sheets	89	16			1	ja		magneten, zeven, cyclonen, Eddy Current-scheiders, laser- en cameratechnologie en röntgen-detectie	http://www.maltha.nl/nl-nl/holglas-vlakglas/vlakglas.aspx
39 Uncontaminated soil that has become waste	6850	0	1			nee (nuttige toepassing)	ja	Vele technieken, van in situ tot baggeren, transporteren, isoleren en meer. Zie link voor overzicht.	https://www.bodemplus.nl/onderwerpen/bodem-ondergrond/verwerking-grond/verwerkers/verwerkers-nederland/ https://www.infomil.nl/onderwerpen/duurzaamheid-energie/ippc-installaties/vragen-antwoorden/vragen-antwoorden-1/afval-recycling/vraag-antwoord/ https://www.bodemrichtlijn.nl/Bibliotheek/bodemsaneringstechnieken/a-overzichten/principe-van-saneringstechnieken
40 Dredging sludge	136780	7	1			nuttige toepassing	ja		
41 Clean packaging waste	1193	14			1	ja	hoofdgebruik brandstof als bijv. Te sterk vervuild		
42 Packaging containing residues of paint, adhesives, sealant or resin	9	71		1		ja (metalen van spuitbussen), terugwinnen metalen na verbranding	ja		
43 Packaging containing residues of hazardous substances	16	26			1	nee	ja (enige mogelijkheid)		
44 Gas cylinders and other pressurised containers	2	0		1		ja	ja (brandbare en/of (milieu)gevaarlijke gassen		https://www.linde-gas.nl/nl/products_and_supply/refrigerants/recycling-en-regeneratie/index.html
45 Fire extinguishers	1	2		1		ja	(indien recycling niet mogelijk is)		https://www.volkskrant.nl/economie/zo-wordt-van-brandbluspoeder-een-bodemverbeteraar-gemaakt~b0ab7cba/?referer=https%3A%2F%2F
46 Ammunition		0			1	nee	verbranden of detoneren		
47 Fireworks	0	6			1	nee	verbranden		
48 Explosive waste	0	5			1	nee	verbranden of detoneren		
49 Underground storage tanks		0		1		ja via ander sectorplan			
50 Autogas pressure vessels		0			1	ja			

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51 End-of-life vehicles and motor bikes	218	0			1				
52 Tyres	110	10			1	ja	ja (andere nuttige toepassing indien niet geschikt voor recycling)	Carbon black uit autobanden	https://blackbearcarbon.com/
									https://www.utwente.nl/nieuws/2018/5/32011/universiteit-twente-en-continental-ontwikkelen-nieuw-proces-voor-recycling-autobanden
53 Waste from ships and vessels	410	0			1		ja		
54 End-of-life ships and vessels	0	1		1		ja			
55 Oil filters	3	13		1		ja (ook AVI terugwinning)	ja		https://www.at-aandrijftechniek.nl/technologie/oliefilters-verwerkt-tot-waardevolle-producten/17476/
56 Used oil (mineral and synthetic origin)	52	59	1			nee	ja	opwarmen en fracties scheiden	https://wastenet.nl/recycling-afgewerkte-olie/ . https://www.recyclingplatform.nl/recycling-processen/afgewerkte-olie
57 Waste oils containing halogens	0	4							
58 Oil/water mixtures and oil/water/sludge mixtures and oil-containing sludge	341	0	1				ja		https://www.renewi.com/nl-nl/over-renewi/onze-rol/hergebruik-en-recycling/gevaarlijk-afval/olie-water-en-slib
59 Liquid fuel and oil residues	58	2		1		nee	ja (andere nuttige toepassing)		
60 Oil based mud (OBM) and OBM containing cuttings	24	0				nee	stort		
61 Oil applied in the treatment of metals (drilling, cutting, grinding and rolling)	14	2		1			ja / lozen na zuivering		https://www.omgevingsweb.nl/nieuws/minder-afvalstoffen-door-einde-afvalcriteria/
62 Metal waste with attached oil or emulsion	11	6		1		ja (metalen)			
63 Other oil containing waste	14	1			1	nee	ja		
64 PCB-containing waste	0	0	1			nee	ja		
65 Animal sourced waste	579	0		1				Eiwitten winnen uit slachtafval	https://www.dvhn.nl/groningen/Bedrijven-winnen-conserveermiddelen-uit-slachtafval-21287969.html?utm_medium=article_sharing&utm_source=email http://www.dcpingredients.com/
66 Gas discharge lamps and fluorescence powder	2	0	1			ja	stort als technisch niet mogelijk/ te duur	shredder en reinigen	https://www.lightrec.nl/producenten-/-importeurs/nieuws-producenten-en-importeurs/waar-blijven-al-die-lampen.html . https://pure.tue.nl/ws/portalfiles/portal/46815606/572137-2.pdf
67 Halogen-reduced solvents and glycols	95	0	1			ja (destilleren met het oog op recycling)	ja (niet-regenereerbaar)		
68 Halogen-containing solvents	9	0			1		ja		
69 Residue from distillation activities	131	0			1		ja		

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70 Controlled substances (CFK, HCFK, halons) and fluorinated greenhouse gases (HFC, PFC, SF6)	0	6		1		(ja, via F-gassenverordening voor HFK's PFK en SF6)	ja		
71 Discarded electrical and electronic equipment	210	31		1			ja		
72 Sulphuric acid, acid coal tar and other sulphur-containing waste	561	8		1		ja		zwavelzuur laten reageren met reactief mineraal tot nuttige en veiligere stromen	https://www.nemokennislink.nl/publicaties/recycling-op-reuzenschaal/
73 Highly contaminated wastewater streams and baths	41616	8	1			(nuttige toepassing onder blootstellingsvoorwaarden ZZS)	ja		https://www.rwbwater.nl/fysisch-chemische-zuivering/
74 Precious metal containing baths		0							
75 Metallic wastewater containing organic contaminants	2	0							
76 Other acids, alkalis and metallic wastewater	17	0							
77 Aqueous waste with specific contaminants	735	0							
78 Filter cake from detoxification/neutralization/dehydration	365	9		1		(recycling onder voorwaarden zware metalen)	storten		
79 Black/white fixer, black/white developer	1	0	1			terugwinning zilver	ja		
80 Solid photographic waste	3	12		1		ja, terugwinning zilver	ja, residu van ontzilveren		
81 Tempering salts	0	2			1		ja, storten		
82 Mercury and mercury-containing waste	4	2	1			(ja, als kwik niet diffuus wordt verspreid, zie voorwaarden)	ja, storten		https://www.recyclingplatform.nl/recycling-processen/kwikhoudende-producten
83 Arsenic-sulphide sludge and arsenic-sulphide filter cake		0		1			ja, storten		
84 Other mono-streams for recycling (matrasses, stone wool, carpet, artificial grass)	7	15		1		ja, matrassen, steenwol, tapijt(nuttige toepassing)	ja, luiers, nuttige toepassing		
85 EPS (polystyrene foam)						zie verpakkingen	ja, bouwafval		

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