Life Cycle Assessments of Selected Worst Practices in Secondary Metals Recovery and Recommendations to Move Towards Good Practices

SRI SUSTAINABLE RECYCLING INDUSTRIES

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Cover page:

Picture at the top, left: Open burning of refrigerators to extract metals

Picture at the bottom, left: Safe dismantling of refrigerators with appropriate tools in a factory

Picture at the top, in the middle: Open burning of tyres to extract metals

Picture at the bottom, in the middle: Safe metals recovery in an oven

Picture at the top, right: Open burning of cables to extract metals

Picture at the bottom, right: Mechanical striping of cables to recover metal

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Notes to the reader

The Sustainable Recycling Industries (SRI) Programme addresses the sustainability criteria in secondary resources management in developing countries. It furthermore supports the informal recyclers in their efforts to move away from 'worst practices'. The SRI programme is built on the success for more than a decade of the implementation of e-waste recycling systems in various developing countries. The programme is funded by the Swiss State Secretariat of Economic Affairs (SECO) and is implemented by the Swiss Institute for Materials Science & Technology (Empa), the World Resources Forum (WRF) and ecoinvent. To develop the Guidance Principles for Sustainable Management of Secondary Metals (ISO IWA 19:2017), in accordance with the International Workshop Agreement (IWA), the SRI Roundtable consulted key and affected stakeholders by means of workshops and local and public consultations.

To improve the understanding of the impacts of 'worst practices' identified in Annex A of the ISO IWA 19:2017 and support the implementation of 'good practices', quantitative information based on an Life Cycle Assessment (LCA) framework was identified to be most helpful for this purpose. To do so, environmental LCA will be applied. Henceforth, LCA will be understood in this report as environmental LCA.

As no LCAs of 'worst practices' for secondary metal recovery were found in the literature, LCAs of a selected sample have been developed and results are presented in this report.

This report is the result of an extensive stakeholder consultation process conducted by global experts who serve the SRI Roundtable. These individuals have also agreed to voluntarily form a dedicated work group to provide specific input (based on both their academic knowledge and practical experience) to this LCAs summary of most prevalent 'worst practices' concerning the recovery of secondary metals.

The three selected types of 'worst practices' addressed by this document are:

- Open burning of end-of-life tyres (ELT)
- Open burning of waste electrical and electronic cables
- Uncontrolled dismantling of refrigerators

The authors and contributors of this report do not claim in any way that the described 'worst practices' nor the recommended 'good practices' are comprehensive or provide full coverage of all problems caused. The authors recommend that the informative fact sheets are used as a starting point while gathering more research findings with the aim to:

- Validate the results under specific contexts and locations where the 'worst practices' take place.
- Identify alternatives that are available or better accessible in the country concerned.

This report is structured as described hereafter. The following introduction section provides the aim and scope of the report. Section 2 describes the methodology employed and the assumptions taken to estimate the impacts of 'worst practices'. Results and hotspots are discussed in Section 3. In section 4, alternative 'good practices' are presented. Finally, concluding statements close the report in section 5.

Acronyms

ALOP	Agricultural land occupation
ELT	End-of-Life Tyres
FDP	Fossil depletion potential
FEP	Freshwater Eutrophication
FETPinf	Freshwater Ecotoxicity Potential Infinite
GHG	Greenhouse Gases
GWP	Global Warming Potential
GWP100	Global Warming Potential over 100 years
IPCC	International Panel on Climate Change
IRP_HE	Ionising Radiation
HTPinf	Human Toxicity Potential Infinite
ISO	International Organization for Standards
IWA	International Workshop Agreement
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MDP	Metal Depletion
MEP	Marine Eutrophication

METPinf	Marine Ecotoxicity Potential Infinite
NLTP	Natural Land Transformation
ODPinf	Ozone Depletion Potential Infinite
PAH	Polycyclic Aromatic Hydrocarbons
PB	Polychlorinated Biphenyls
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidant Formation Potential
PPE	Personal Protective Equipment
SRI	Sustainable Recycling Industries
TAP100	Terrestrial Acidification over 100 years
TETPinf	Terrestrial Ecotoxicity Potential Infinite
ULOP	Urban Land Occupation
WEEE	Waste Electrical and Electronic Equipment
WDP	Water Depletion

1. Introduction and aim

Thousands of residents with the lowest income, mainly in developing countries, are engaged in the informal recovery of materials from waste streams for their livelihood. It is estimated that about 1 percent of the urban population in developing countries earn income by recovery of recyclables from waste streams. It is also estimated that about 95% of materials recovered in developing countries are done through informal means und in an uncontrolled way (International Organization for Standardization, [ISO] International Workshop Agreement [IWA] 19:2017). Some studies state that informal recycling recovers materials from the waste streams more efficiently than the formal counterpart (Medina, 2008). Informal waste collection and recycling can create jobs, fight and reduce poverty, and therefore contribute to economic and social development.

However, during the informal recovery processes of materials, recyclers often engage in practices that can pose severe harm to their well-being and to the environment. Such undesirable practices are commonly referred to as 'worst practices'. 'Worst practices' are defined as:

"Practices that are known or suspected to have severe (typically multiple) negative impacts on the environment, workers/community health and safety, and quality and quantity of recovered secondary metals, when applied by any Economic Operator in any of the processes concerned: with collection, manual and mechanical processing, metallurgical processing and disposal (ISO IWA 19:2017). "

Also, it is worthwhile to highlight that:

"Worst practices' are globally widespread and typically take place in economic environments and political climates that show an absence of control mechanisms—such as legislative enforcement of minimum standards to ensure the protection of both human health and environmental systems integrity (Karcher et al., 2018, p. 5)."

It is commonly understood that 'worst practices' have negative impacts on the environment and human health. However, the scale and magnitude of such impacts are yet to be quantified. (ISO IWA 19:2017)

Quantifying the environmental impacts of 'worst practices' is challenging as very little literature with measurements and estimation of emissions is available. Particularly, no Life Cycle Assessment (LCA) of 'worst practices' for secondary metal recovery is found in the literature.

A good basis to support the goal and scope definition of selected 'worst practices' is the SRI publication on 'From worst practices to 'good practices' in secondary metals recovery' (Karcher et al., 2018). This publication provides background information (without quantitative data) of most common types of 'worst practices' in recycling.

The aim of this publication is to help improving the understanding of the impacts of 'worst practices' by filling the gap in this research area through the development of Life Cycle Assessments for selected 'worst practices'.

Three types of 'worst practices' were selected in consultation with the SRI experts in countries such as Ghana, South Africa and India who contributed with information and facts on these practices in their regions:

- Open burning of end-of-life tyres (ELT)
- Open burning of waste electrical and electronic cables
- Uncontrolled dismantling of refrigerators

The criteria according to which 'worst practices' were selected include their potential magnitude of impacts, as well as the availability of sufficient reliable data to conduct the assessment.

To round off the report, examples of and steps towards 'good practices' are presented. They shall serve as potential ideas moving towards a more environmentally sound recovery of secondary metals in the informal recovery of materials.

2. Methodology

LCA was employed as the tool to quantify the environmental and health impacts of the selected 'worst practices'. Gate-to-gate life cycle models were designed to represent these practices, whereby the life cycle stage considered is the treatment of the end-of-life fridges, tyres and cables.

The ecoinvent database (Werner et al., 2016) was used as the source of background data. The models consider and report the impacts of the recycling stage, i.e. the recovery of valuable metals through exercising 'worst practices'. The upstream impacts related to production and transportation of waste inputs such as ELTs or used cables and refrigerators, as well as the fate of the recovered metals and materials (downstream impacts like wastes and by-products) are disregarded. It can be safely assumed that recovered materials are picked up and utilized by the recyclers. Figure 1 describes the system boundaries of the study.

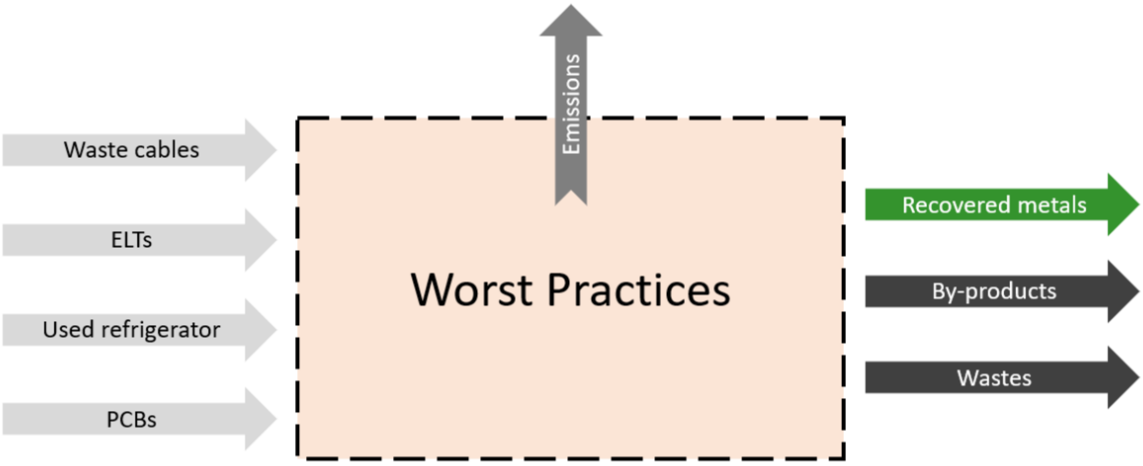

Figure 1: System boundaries of 'worst practices' for the purposes of this report.

To carry out the Life Cycle Assessment based on Life Cycle Inventory (LCI) data of the two worst practices on open burning of tyres (ELTs) and used cables, "LCI calculation tools" by Doka (2017) were employed. The tools calculate the emissions to air and soil of open, uncontrolled burning based on the composition of the waste. They do so by applying transfer coefficients of pollutants to the environment for chemical elements present in the waste.

To estimate the emissions caused by dismantling refrigerators, we constructed simplified LCI models, representing controlled and uncontrolled processes to dismantle refrigerators.

The functional units defined were one kg of recovered metal, except for the fridge, where one unit of average fridge dismantled serves as functional unit.

Data on the composition of waste inputs (ELTs, used cables and refrigerators) were taken from literature and is considered to represent the average composition of such types of waste.

Impacts from infrastructure and from fuel consumption supporting these selected 'worst practices' were considered negligible, hence, not quantified in the results.

By tracing the faith of chemical elements, LCA enables the estimation of the "average" potential impacts of the products or activities on the environment and on the 'human health' of the population.

Note that environmental LCA does not address the impacts from direct exposure to individuals, which is beyond the scope this report.

We acknowledge that recyclers directly engaging in 'worst practices' (e.g. in tyres or cables burning) are exposed to highest concentrations of emissions from recycling and there is a call for more specific assessments of impacts on workers through complementary research e.g. by applying social LCA (UNEP, 2009) and risk analysis. These workers operating without personal protective equipment (PPE) such as respiratory masks, experience the intake of toxic substances at levels that probably exceed allowed levels of exposure according to the World Health Organization.

ReCiPe (Goedkoop et al, 2008) was selected as the life cycle impact assessment (LCIA) method. In addition to mid-point categories, the LCIA results are expressed in terms of end-point categories: damage to human health, ecosystems, and resource availability.

The following section provides more details on the 'worst practices' selected, as well as the assumptions to calculate the LCI of 'worst practices'. For additional background description on the 'worst practices' selected such as steps to 'good practices', see Karcher et al. (2018).

2.1 Open burning of ELTs

A Life Cycle (LC) model was constructed, representing the activity of iron recovery through open burning of end-of-life waste pneumatic tyres. It was assumed that the iron is recovered through open-burning of ELTs without any pollution control in place, in unauthorized places. The rubber and other incinerable parts of the tyre are either completely incinerated or melted, leaving the iron exposed. The recovery rate for the iron was assumed to be 95%. The rest (5%) was assumed to be lost during the process or left behind.
The emissions were estimated based on the model by Doka (2017).
The functional unit in this case is ''one kg of recovered iron from ELTs". The composition of the waste was estimated based on typical composition of ELTs (Table 1).

Table 1: Representative Composition of ELTs used for this study (Alianpur, 2009)

Element	g/kg tyre
O	2.849E+01
H	6.121E+01
C	6.886E+02
S	1.398E+01
N	4.480E+00
Mn	1.130E+00
Zn	1.557E+01
Si	1.108E+01
Fe	1.150E+02
Ca	1.690E+00

2.2 Open burning of waste electrical and electronic cables

An LC model was constructed, which represents the recovery of copper through open-burning of waste electrical and electronic cables (WEEE) to remove the plastic insulation without any pollution control in place. Fires are manually built in open spaces and unauthorized areas. Thus, copper is exposed which allows its collection and recovery. The composition of waste cable input was compiled from literature (Table 2). No infrastructure and energy (fuel) were used.

The functional unit was selected as "one kg of recovered copper". The recovery rate of copper was assumed to be 95%, while the remaining 5% were assumed to either be lost during the process or left behind. The model accounts for the emissions to air as well as to soil. Emissions are estimated based on the models described in Doka (2017).

Table 2: Composition of waste electrical and electronic cables (Doka, 2009; Amoyaw-Osei et al., 2011) used for this study*

Element	g/kg waste cable	Element	g/kg waste cable
O	8.818E+00	**Ni**	5.590E-03
H	2.836E+01	**Pb**	6.710E-03
C	2.085E+02	**Sb**	1.260E-02
S	3.170E-01	**Se**	7.970E-04
N	4.200E-01	**Sn**	9.910E-02
Cl	1.199E+02	**V**	3.380E-01
Br	1.970E-02	**Zn**	5.560E-02
F	5.610E-03	**Be**	1.900E-04
As	7.210E-04	**Sr**	3.360E-02
Ba	7.800E-02	**Ti**	3.790E-01
Cd	4.720E-03	**Tl**	1.520E-04
Co	8.590E-03	**Fe**	1.172E+00
Cr	1.230E-02	**Ca**	3.070E-01
Cu	6.295E+02	**Al**	7.590E-02
Hg	2.310E-04	**Mg**	1.140E-02
Mn	2.480E-02	**Na**	5.560E-01

**water content used for this study: 9.780E-01 g/kg*

2.3 Dismantling of refrigerators

A large domestic refrigerator may contain more than 32 kg of metals (steel, copper, aluminium). It can, therefore, be considered as valuable resource for material recovery. Used refrigerators also contain refrigerants which have significant Global Warming Potential (GWP). The physical dismantling of refrigerators in an uncontrolled manner poses a threat to the environment as potent Greenhouse Gases (GHG) can be released to environment. Additionally, the blowing agents present in the insulation foam can escape to air which would increase the negative impacts of the process.

To assess the environmental impacts of the uncontrolled refrigerator dismantling, an LC model was constructed representing this scenario. It was assumed that the refrigerators are dismantled manually. The valuable metals are collected, and the other parts are left behind. Additionally, it was assumed that the remaining refrigerants and blowing agents present in the machines' circuits are released to environment during the process.

For comparison purposes, and to estimate the amount of emission savings, controlled dismantling was also modelled. The average amount of energy (electricity) and infrastructure (buildings) required to dismantle the refrigerators in formal recycling were taken from literature (Dayang, 2018). Other types of infrastructure and energy required, e.g. for machinery were disregarded. This was due to lack of sufficient data.

The functional unit was selected as "one fridge, dismantled". The refrigerator is modelled based on the study by Xiao et al. (2015). The type and the quantity of the remaining refrigerants and blowing agents contained within the used machines were also derived from literature (Amoyaw-Osei et al., 2011). It represents a weighted average from a sample of 6,519 used domestic refrigerators that were identified in a recycling facility. The refrigerant mix, according to the study, was modelled to contain 1,1,1,2-Tetrafluoroethane (R-134a), Isobutane (R-600a), and Dichlorodifluoromethane (R-12)[1]. Removal efficiencies of the refrigerants in the formal sector (70%) were taken from Intergovernmental Panel on Climate Change (IPCC) (Ashford et al., 2006). The rest of the refrigerant (30%) was assumed to be released to the environment during the process.

3. Results and hotspots

This section discusses the results of the LCIA of the selected 'worst practices', according to the scope and definition, and methodology described in sections 1 and 2. The LCI datasets representing the 'worst practices', including the accompanying documentation, can be found on the ecoinvent website.

3.1 Open burning of ELTs

During the open burning of ELTs to recover iron, the main sources of emissions are the direct air emissions due to the incomplete combustion of ELTs, as well as the leakage of substances to soil. In addition to GHG, other types of toxic gases, namely Polycyclic Aromatic Hydrocarbons (PAH), Polychlorinated Biphenyls (PB), formaldehyde, and very fine particles (<2.5 um) are formed and emitted. Uncontrolled burning of ELTs also causes zinc, magnesium and other types of metals present in the tyres to be leached to the soil.

Tables 3 and 4 in Appendix A provide an overview of LCIA results of incineration of waste pneumatic tyres. 1.72 kg of GHG (CO_2-eq) are emitted per kg of waste pneumatic tyres that is openly burnt. Therefore, **recovering a kg of iron from ELTs emits 17.2 kg CO_2-eq of GHG**. The emissions are mainly in the form of CO_2 (98%). The analysis also shows relatively elevated levels of human toxicity potential (2.355 human toxicity potential infinite). The emissions of zinc to air and its leachate to soil are the main causes (62%) for human toxicity, followed by emissions of formaldehyde (20%) and magnesium (12%). The emissions of zinc also lead to freshwater, marine, and terrestrial ecotoxicity impacts. The eutrophication impacts are caused by the emission of nitrogen oxides that are formed during the process. Along with sulfur dioxide, nitrogen oxide is also the main contributor to terrestrial acidification impacts.

3.2 Open burning of waste electrical and electronic cables

Similar to the open burning of tyres, the primary areas of concern regarding the open burning of waste electrical and electronic cables are the elevated levels of toxic emissions to air, as well as the emissions of metals to air and soil compartments which are identified as hotspots. Toxic emissions include dioxins, formaldehyde, as well chlorine compounds.

1.45 kg of CO_2-eq is emitted per kg of copper recovered from waste electrical and electronic cables burnt. GHG emissions are mainly in the form of carbon dioxide, which make up 80% of the total impact, but also methane (CH_4) and dinitrogen monoxide (N_2O). Cables incineration also exhibits high human toxicity potential. Dioxins are extremely toxic organic pollutants, formed during the incineration process. Leading to more than 65% of the total impact, dioxins are the main contributors to human toxicity. The emissions of vanadium, titanium, mercury, as well as formaldehyde also lead to human toxicity. These, highly toxic substances, mentioned before, have

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[1] The type of blowing agent was determined based on the refrigerant used in the refrigerator. Refrigerators with R-12 refrigerant were assumed to have R-11 as blowing agent, refrigerators with R600a were using cyclopentane as blowing agent, and R-134a is used as a refrigerator and blowing agent in the last category.

not only been proven multiple negative impacts on human health but have also been proven to cause cancer of the digestive tract, liver and skin. Table 3 in appendix A shows that incineration of cables also leads to fresh water, marine, and terrestrial ecotoxicity. Without any pollution control in place, traces of copper are emitted to air and soil compartments. The emission of coppers is the main driver of ecotoxicity impacts. The process also emits nitrogen oxides, which leads to marine eutrophication (MEP). The emission of nitrogen oxides as well as sulfur dioxide also leads to terrestrial acidification.

3.3 Dismantling of refrigerators

Since manual dismantling of refrigerators does not require any energy input (neither electricity or heat), the release of remaining refrigerants and blowing agents contained within the machines are the main sources of environmental and human-health impacts. The open venting of those gases accounts for 661 kg CO_2-eq/ refrigerator dismantled. Out of this, around 70% (450 kg) of the emissions comes from the release of blowing agent, the rest is attributed to the refrigerant. Venting of refrigerants also contributes to other types of environmental impacts, mainly to the depletion of ozone layer, and human health toxicity. The emission of R-11 and R-12 are the main causes for both these impacts. R-12 and R-11 are chlorofluorocarbon gases that were extensively used as refrigerant in cooling systems including domestic refrigerators. Their manufacture and use were banned since 1996 in compliance with the Montreal protocol. However, used domestic refrigeration systems still carry remaining substances of such refrigerants.

By employing safe and controlled dismantling practices, more than half a tonne **(0.5 tonnes) of CO_2-eq per refrigerator** dismantled can be avoided (Figure 2). Considering the number of refrigerators dismantled globally, significant quantities of GHG can be avoided by employing more controlled recycling practices. Table 3 shows that the impacts of depletion of ozone layer and human toxicity can be reduced by factors of 5 and 6, respectively, if controlled measures are employed. The slightly higher impact of controlled dismantling across other impact categories is the result of the production and consumption of electricity required for the operation, as well as the infrastructure (building construction). However, the numbers in Table 4 demonstrate that controlled dismantling of fridges exhibits 2.3 times lower impacts when comparing the end-point results.

The composition of the refrigerators such as their metal and plastic contents can change based on size and manufacture. The same holds true for removal efficiencies of machines' parts which can vary significantly based on the technologies used and skills of the personnel engaged in dismantling. The results presented here can be safely considered to be valid for other types and sizes of domestic refrigerators, as long as the composition of the refrigerants is consistent with those in this study.

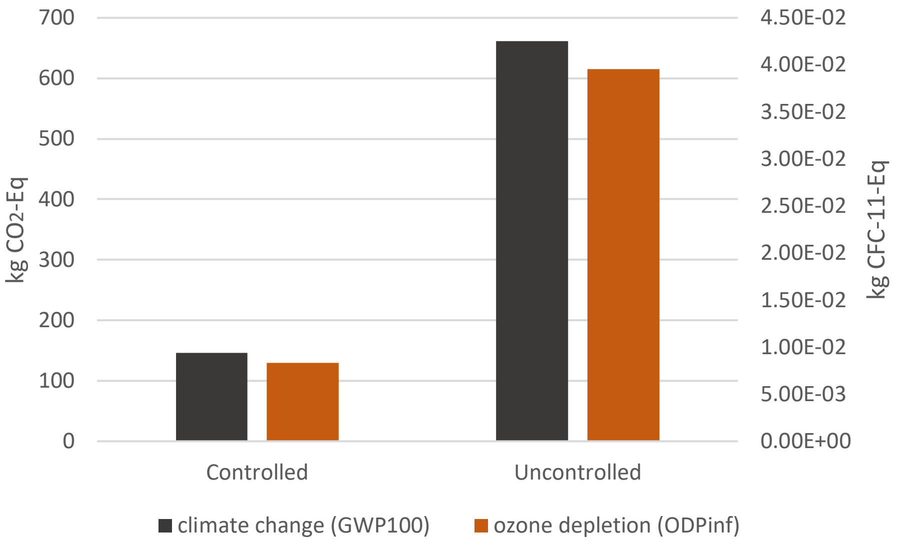

Figure 2: Controlled vs uncontrolled dismantling of refrigerators. Comparison of impacts

4. Recommendations for developing 'good practices'

This section discusses 'good practices' presenting potential ways for a more environmentally sound recovery of secondary metals. The 'good practices' presented are selected based on their practicability in the informal sector.

4.1 'Good practices' for ELT-treatment

One alternative available for responsible recycling tyres is the mechanical shredding and grinding of tyres. This technique greatly reduces the risk of any unwanted side effects regarding impacts such as GHG emissions, soil and water contamination, or human health issues, while at the same time providing optimal economic benefits. Furthermore, this 'good practice' does not require large investments and hence can be reasonably applied by micro- and small recyclers.

By mechanically shredding and grinding tyres, 'rubber crumb' is produced, which can be used for a variety of purposes, such as flooring, football pitch surfaces, as gravel substitute and footwear.

According to several studies, the net environmental benefit of burning ELT in high temperature-controlled gas kilns (1000–1200 °C) to recover the heat energy in Portland cement concrete plants, remains questionable. Hence, this option should not be considered as good practice.

The benefit of the described good practices is that by recycling tyres, the rubber and steel they contain are recovered instead of getting them lost in a landfill site. In addition, recycled rubber reduces the demand for natural and synthetic rubber, leading to a decrease of the emissions and pollution impacts linked to primary resource extraction.

4.2 Good practices for waste electrical and electronic cables treatment

Even though the type of treatment largely depends on the specifications of the cable such as diameter, copper purity and homogeneity as well as the cable volumes, the manual or mechanical processes to strip cables and wiring to recover copper are valuable alternatives to the 'worst practices' described.

The stripping method allows its application to a wide range of cables and is of relatively low cost. Another benefit of the method is that not only the copper but also the cables' plastic insulation can be recovered safely and with a minimal loss. The method, therefore does not only avoid the incineration emissions but also saves a considerable amount of raw material, which would be used to produce new plastic insulation. Another benefit is that using manual and mechanical processing, the copper recovered maintains its physical properties and composition, whereas in open burning, the surface layer of copper oxidizes. Reducing its quality leading to lower market prices compared to copper recovered via stripping.

It is worth highlighting that the method can only be considered as 'good practice' if this takes place in a safe fit-for-purpose working environment with all the activities requiring required personal protective equipment[2] and safe working precautions[3] are in place for the workers.

4.3 Good practices for dismantling of fridges

'Good practice' starts with end-of-life refrigerators being returned by the general public to authorized collection centres and facilities, and if not existing, stored in proper centres. This is of utmost importance because otherwise it would be promoting the opposite and may all the environmental gains of buying energy efficient refrigerators in the first place.

Before the fridges are treated, they need to be separated based on the type of refrigerant gases they contain. Therefore, good practice includes tools fit-for-purpose, personal protective equipment and training for workers. The proposed steps combined ensure a higher quantity and quality of metals while having less environmental impacts.

By applying 'good practice', an average recovery efficiency of 70% for the cooling system gases[4] is achieved. Similarly, the foam insulation as well as the petroleum-based lubricants can be carefully removed and re-used or disposed of properly.

In addition to the significant benefits in terms of reduced global warming GWP, responsible refrigerator recycling has a 4.7 times lower impact on stratospheric ozone depletion[5] and a 3.9 times lower impact on ecosystem quality[6] and human health.[7]

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[2] Basic PPE typically includes gloves, protective eye wear and protective clothing

[3] A safe working environment must include the provision of both sufficient lighting and ventilation

[4] Ashford et al. (2006) cited in Ecoinvent (2018). Working
Title: Life cycle inventories of Worst Practices in secondary
metals recovery. 16 pages.

[5] EDIP (2003). Stratospheric ozone depletion (ODP) total in kg CFC-11-Eq

[6] ReCiPe Endpoint (H, A), ecosystem quality based on LCA (ISO 14040) modelling and measured in points. Ecoinvent (2018)

[7] ReCiPe Endpoint (H, A), human health based on LCA (ISO 14040) modelling and measured total in points. Ecoinvent (2018)

5. Conclusions

The report provides the results of environmental assessment for three types of 'worst practices' in the recovery of secondary metals such as burning end-of-life tyres and waste cables, and dismantling end-of-life fridges. LCAs have been conducted to support these findings. The report, furthermore, shows 'good practice' alternatives moving economic operators towards a more environmentally sound secondary metal recovery.

Main impacts on the environment and the populations

The results confirm that the 'worst practices' selected are associated with several types of severe negative impacts on the environment.

During open burning of cables and ELTs, air emissions resulting from the incineration process, as well as the leakage of metals to the soil compartment were found to be the principal areas of concern. In addition to GHG, the formation and emission of chemical compounds such as dioxins and formaldehyde, as well as emissions of metals (such as mercury, vanadium, copper and zinc) to air and soil compartments have been identified, which are harmful to human health and to the environment.

To recover 1 kg of copper and 1 kg of iron through open burning, 1.45 and 17.2 kg-CO_2-Eq are released to the environment, correspondingly, while 661 kg-CO_2-Eq are emitted from fridge dismantling (without precautionary measures). These emissions can be avoided by applying 'good practices'.

National policies can benefit from these indicators to assess the national CO_2 baselines and climate change programs and include this set of activities ('worst practices') for reducing CO_2 emissions.

Research gap on health impacts on workers

One main area of concern is the direct exposure of individual recyclers to the emissions resulting from the selected 'worst practices' which was not part of the scope of this report. According the recommendations from ISO IWA 19:2017, these practices should be banned. To better address the impacts of workers operating with worst practices, complementary contextualized research in the different regions is lacking and this gap needs to be covered e.g. by applying social LCA (UNEP, 2009) and health risk analysis.

Impacts on the quality of metals recovered

In addition to severe impacts to the environment and the health of the population, there is an economic disadvantage of applying open burning-related 'worst practices'. By burning waste, valuable metals to be recovered are also heated, experiencing metallurgical changes which reduces their quality and thus their market prices as compared to applying non-thermal processes.

Feasibility of the 'good practices' presented

The good practices presented in the report are based on simple methods observed in developing countries requiring minimum additional financial resources and the use of personal protective equipment, while at the same time providing economic and environmental benefits and a healthier working environment.

Improved policies are required to support the cessation of 'worst practices'

Measuring and reducing the environmental footprint caused by the selected worst practices, combined with understanding what good practice looks like, provides a number of potential benefits, in particular for reducing harmful emissions to the atmosphere and protecting workers' health. However, this will only happen if decision-makers act to enable, enforce and improve the legal and policy frameworks to ensure responsible tyre, cable and fridge recycling. Improvements in the policy and operational spheres are needed and there is a role for all stakeholders in the recycling chain that needs to be fulfilled. Even strong regulations can only deliver benefits if there is collaboration between the public sector, private sector and civil society.

The LCI datasets (in ecoSpold, XML, and XLS format) of ‘worst practices’ are available free-of-charge on ecoinvent website.

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Appendix A

LCIA results

The appendix contains the LCIA results of the worst practices according to ReCiPe Midpoint (H) and Endpoint (H, A).

Table 3: Life Cycle Impact Assessment (LCIA) results- ReCiPe Midpoint (H)

Indicator		Unit	treatment of used domestic refrigerator, controlled dismantling	treatment of used domestic refrigerator, uncontrolled dismantling	treatment of waste, electrical and electronic cables, open burning	treatment of waste, pneumatic tyres, open burning
agricultural land occupation	ALOP	m2a	1.343E-02	0.000E+00	0.000E+00	0.000E+00
climate change	GWP100	kg CO_2-Eq	1.457E+02	6.613E+02	1.449E+00	1.722E+01
fossil depletion	FDP	kg oil-Eq	8.675E-03	0.000E+00	0.000E+00	0.000E+00
freshwater ecotoxicity	FETPinf	kg 1,4-DC.	4.977E-04	0.000E+00	1.165E-01	3.871E-02
freshwater eutrophication	FEP	kg P-Eq	1.214E-05	0.000E+00	0.000E+00	0.000E+00
human toxicity	HTPinf	kg 1,4-DC.	1.432E+00	8.013E+00	1.709E+00	2.355E+00
ionising radiation	IRP_HE	kg U235-Eq	1.897E-03	0.000E+00	0.000E+00	0.000E+00
marine ecotoxicity	METPinf	kg 1,4-DC.	4.196E-04	0.000E+00	6.577E-02	4.135E-02
marine eutrophication	MEP	kg N-Eq	4.667E-05	0.000E+00	8.598E-04	2.229E-02
metal depletion	MDP	kg Fe-Eq	5.040E-03	0.000E+00	0.000E+00	0.000E+00
natural land transformation	NLTP	m2	5.469E-06	0.000E+00	0.000E+00	0.000E+00
ozone depletion	ODPinf	kg CFC-11.	8.301E-03	3.953E-02	0.000E+00	0.000E+00
particulate matter formation	PMFP	kg PM10-Eq	1.052E-04	0.000E+00	1.561E-01	2.518E-02
photochemical oxidant formation	POFP	kg NMVOC	1.429E-04	0.000E+00	8.863E-03	9.321E-02
terrestrial acidification	TAP100	kg SO2-Eq	2.537E-04	0.000E+00	1.466E-03	8.719E-02
terrestrial ecotoxicity	TETPinf	kg 1,4-DC.	4.571E-06	0.000E+00	9.230E-01	7.368E-01
urban land occupation	ULOP	m2a	5.752E-04	0.000E+00	0.000E+00	0.000E+00
water depletion	WDP	m3	1.083E-04	0.000E+00	0.000E+00	0.000E+00

Table 4: Characterized results for all inventories and impact assessment method of ReCiPe Endpoint (H,A)

	Indicator	Unit	treatment of used domestic refrigerator, controlled dismantling	treatment of used domestic refrigerator, uncontrolled dismantling	treatment of waste, electrical and electronic cables, open burning	treatment of waste, pneumatic tyres, open burning
ecosystem quality	urban land occupation	points	2.446E-05	0.000E+00	0.000E+00	0.000E+00
	freshwater ecotoxicity	points	6.469E-07	0.000E+00	2.167E-04	7.365E-05
	natural land transformation	points	2.012E-05	0.000E+00	0.000E+00	0.000E+00
	marine ecotoxicity	points	1.085E-07	0.000E+00	2.490E-05	1.609E-05
	climate change, ecosystems	points	2.456E+00	1.159E+01	2.539E-02	3.017E-01
	terrestrial acidification	points	3.105E-06	0.000E+00	1.879E-05	1.118E-03
	terrestrial ecotoxicity	points	1.428E-06	0.000E+00	3.064E-01	2.452E-01
	agricultural land occupation	points	4.777E-04	0.000E+00	0.000E+00	0.000E+00
	freshwater eutrophication	points	1.050E-06	0.000E+00	0.000E+00	0.000E+00
	Total	points	2.456E+00	1.159E+01	3.320E-01	5.481E-01
human health	human toxicity	points	1.983E-02	1.111E-01	2.166E-02	3.264E-02
	photochemical oxidant formation	points	9.755E-06	0.000E+00	1.498E-04	3.457E-02
	ozone depletion	points	2.899E-01	1.380E+00	0.000E+00	0.000E+00
	particulate matter formation	points	5.221E-04	0.000E+00	8.038E-01	1.444E-01
	ionising radiation	points	5.766E-07	0.000E+00	0.000E+00	0.000E+00
	climate change, human health	points	3.885E+00	1.833E+01	4.017E-02	4.773E-01
	Total	points	4.196E+00	1.982E+01	8.657E-01	6.889E-01
resources	fossil depletion	points	9.704E-04	0.000E+00	0.000E+00	0.000E+00
	metal depletion	points	2.312E-04	0.000E+00	0.000E+00	0.000E+00
	Total	points	1.202E-03	0.000E+00	0.000E+00	0.000E+00
total	Total	points	6.653E+00	3.141E+01	1.198E+00	1.237E+00