Dell

Environmental Net Benefit of Gold Recycling

TRUCOST
S&P Dow Jones Indices
ESG Analysis

November 2017

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EXECUTIVE SUMMARY

The environmental impacts of recycling gold are 111-times lower than mined gold

Dell Technologies is a multinational computer technology company headquartered in the United States. Dell collects discarded computer equipment as part of the Dell Reconnect program, including components manufactured by Dell and other companies. Dell's initiative is an important step in its transition toward developing a circular business model.

Gold is used in electronic equipment in small amounts, and amongst other things, is used in contact points in printed circuit boards. This is an important function in electronic devices and gold performs well in comparison to other metals. However, tracing where mined gold comes from is a difficult task and this inhibits the assessment of environmental and social impacts and risks associated with its use.

Using recycled gold from its Reconnect program gives Dell greater transparency on the environmental and social impacts in its supply chain. Trucost and the Social Hotspots Database have thus quantified the impacts of gold produced from recycled and traditional mining methods.

An important actor in the production of recycled gold for Dell is Wistron, a company that recycles electronic equipment and recovers precious metals such as gold and silver. Wistron and Dell disclosed data on the use of chemicals and energy used in the recycling process, while data and process information on gold mining and any data gaps were filled using life cycle analysis datasets. The combination of primary and secondary information allowed for the quantification and monetization of the impacts of both processes.

The environmental net benefit of gold recycling is valued at $3.68 million for 5 pounds of gold. This translates to impacts that are 111-times lower than mined gold.

In gold mining the majority of the environmental impacts occur in the upstream phase, which includes processes such as ore extraction. The operational impacts of recycled gold mainly occur in the operations of the recycling facility. Recycled gold has a lower environmental impact in all impact categories with the exception of global warming potential. High electricity use in the gold recycling process is responsible for 81% of the global warming impact.

The impact of non-carcinogenic illnesses from gold mining is the largest among all the environmental impact categories. The value of these impacts totals $3.5 million for every five pounds of mined gold, or 95% of the total impact. The leaching of pollutants from mining waste which reach waterbodies during the ore extraction process (known as sulfudic tailings), are responsible for 95% of non-carcinogenic impacts.

Engage

Expand

Optimize

Following this analysis Dell has the opportunity to use these results by engaging with internal and external stakeholders, expand its gold recycling program, and optimize the gold recycling process.

Dell can **engage** relevant stakeholders to demonstrate the avoided impacts from its Reconnect and gold recycling programs. The results could be used to strengthen the case for using closed-loop gold and other closed-loop process in the electronics industry. The results can also demonstrate the environmental credentials of products to personal and business customers.

The net benefit results demonstrate the potential avoided impact of **expanding** Dell's recycled gold use. Dell uses only five pounds of recycled gold every month, which leaves room to scale up production to meet its 7,000 pound annual demand. Dell could explore the possibility of using the other metals recovered in similar processes, such as copper and palladium. This could deliver environmental benefits on a similar scale to those demonstrated in this report.

Dell and Wistron could consider **optimizing** the existing gold recycling process, for instance, by utilizing renewable energy in its operations. Optimization can also be achieved by avoiding electricity use during idle phases or by increasing the amount of electronic scrap that is recycled. The deployment of these types of processes could reduce costs for both Wistron and Dell.

Dell commissioned Trucost to quantify the environmental benefits of purchasing recycled gold compared to virgin gold

INTRODUCTION

Dell Technologies (hereafter Dell) is a multinational computer technology company headquartered in the United States. Dell manufactures, sells, and repairs personal computers, servers, data storage devices, network switches, and other types of electronic software and hardware.

Dell Reconnect is a recycling program run in conjunction with Goodwill Industries. Members of the public and businesses can donate old electronic equipment to the program to be reused or refurbished. If this is not possible, the items are recycled to ensure that no environmentally sensitive materials are sent to landfill. One of the providers of this service is Wistron GreenTech (hereafter Wistron) who recycle printed circuit boards (PCBs), displays, and other retired electronic devices.

The Reconnect program is an important step for Dell in its transition towards a circular business model. In this analysis, Trucost have assessed the impact of recycling gold from PCBs and other electronic items at Wistron's McKinney facility (Texas) versus the production of virgin, or mined, gold. Wistron reclaims gold using a hydrometallurgy process to a purity of 0.9997, or 24-carat gold. The recycled gold is sent to Taiwan for use in Dell's electronic manufacturing, or to Los Angeles to be used in the jewelry industry.

Tracing the impacts of gold production in the electronics industry is a challenging task. The electronics industry accounted for 5% of global gold production in 2013, making it difficult to identify sector specific impacts compared to industries such as jewelry (Gelder & Smit, 2015). Laura Gerritsen of Fairphone, a cellphone manufacturer looking to make products with positive environmental and social impacts, provides insight on the challenges of tracing gold through Chinese supply chains:

> *"Traceability of gold is a challenge as it is used in many components but in extremely small amounts… The Shanghai Gold Exchange is the agency controlling all import, export, trading of gold [in China and] is a hurdle in the attempt to trace the gold supply chain… this makes it very challenging to get a good insight in where the gold used in components comes from…"*

The most significant hubs of gold trading and refining are Switzerland, Dubai, Singapore, Shanghai, and Miami [*Ibid*]. The volume of gold transiting through these ports makes traceability difficult, which in turn limits the degree to which purchasers of gold can impact the environmental and social practices of the gold extracting sector. Procuring gold from recycled sources reduces the sourcing entity's exposure to the environmental and social impacts of virgin gold.

Dell wants to quantify the environmental and social net benefit of its gold recycling program in order to communicate the benefits to stakeholders and make the business case for its expansion.

ENVIRONMENTAL NET BENEFIT

Trucost has quantified the impacts of recycling and mining gold in seven environmental impact categories. Dell and Wistron provided data on the gold recycling process, whilst Trucost used country averages to calculate the impacts of gold mining. The resulting net benefits show the comparative performance of producing gold from cradle-to-gate. For gold mining, this includes the impacts from ore mining through to the production of gold. For gold recycling, the analysis includes the impacts from the processing of electronic waste to the production of an equal amount of gold.

FOCUS OF ANALYSIS

In order to provide the metrics needed by Dell, Trucost's assessment of the business-as-usual (BAU) scenario – purchasing virgin gold – and the alternative scenario (ALT) – recycling gold – looked to answer the following questions:

1. Is recycling gold better for the environment and society?
2. If so, how much better?
3. What are the biggest impacts from recycling gold?
4. Where do these impacts occur?

SCOPE AND BOUNDARY

The following section aims to outline the scope and boundary of the net benefit assessment.

Trucost assessed two scenarios for environmental which are summarized in Table 1. A simplified flow diagram outlining the steps analyzed in the recycled gold scenario is shown in Figure 1.

Table 2 provides further detail on the analyzed stages of each scenario.

Table 1: Scenarios analyzed in this net benefit assessment

SCENARIO	PRODUCT	GEOGRAPHY	FUNCTIONAL UNIT
BAU	Virgin, or mined, gold	Global average	1 kg of gold at 0.9999 purity
ALT	Recycled gold	United States	

Figure 1: Flow diagram of the recycled gold value chain

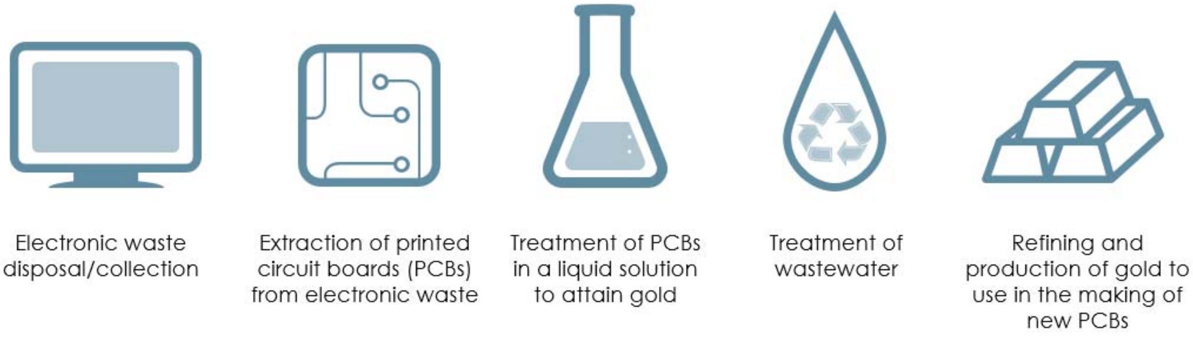

Table 2: Scope and boundaries for the net benefit assessment

VALUE CHAIN STAGE	BUSINESS AS USUAL (BAU)	ALTERNATIVE SCENARIO (ALT)
Upstream	1. Ore Exploration	1. Not applicable
	2. Mining of Ore	2. Not applicable
	4. Not applicable	4. Sorting of e-scrap
Operational	5. Removal of impurities	5. Removal of impurities
	6. Extraction of gold	6. Extraction of gold
	7. Not applicable	7. Extraction of other metals
	8. Refining of gold	8. Not applicable

The analysis excludes the following life cycle stages:

- Transport of recycled gold from Wistron's Texas facility to either Los Angeles or Taiwan
- Gold purification in Taiwan
- Disposal of the final products
- Any impacts associated with the construction and maintenance of infrastructure (such as the Wiston's recycling facility)

ENVIRONMENTAL IMPACT CATEGORIES

Trucost chose the TRACI characterization model[1] to categorize the environmental impacts arising from the two assessed scenarios. The resulting environmental impact categories group impacts according to the effect experienced either by the environment or by society. The table below lists these categories and describes the unit of measurement for each. This analysis has quantified and monetized all of these environmental categories.

Table 3: Impact categories in the TRACI characterization model

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[1] The U.S. Environmental Protection Agency developed an Impact Assessment methodology called TRACI, short for "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts". The aim is to assist in enabling Impact Assessment for sustainability, Life Cycle Assessment, industrial ecology, process design and pollution prevention. See GaBi for more information.

ENVIRONMENTAL IMPACT CATEGORY	MEASUREMENT UNIT & DESCRIPTION
Global Warming	**Carbon dioxide equivalence (CO_2 equivalence)** This measures the impact that greenhouse gases will have on the environment by quantifying global warming effects over a 100 year time horizon
Eutrophication	**Nitrogen equivalence (N equivalence)** This measures the unintended impact of nitrogen in the aquatic environment which causes the accumulation of algal biomass
Respiratory Effects	**Particulate matter 2.5 equivalence (PM2.5 equivalence)** This measures the human health impacts resulting from the inhalation of particulate matter that cause respiratory illnesses
Ecotoxicity	**Comparative toxic unit for environment (CTUe)** This measures the impact on ecosystems where 50% of a population of a species displays an adverse effect, measured as the potentially affected fraction of species (per kilogram of chemical emitted)
Carcinogenics	**Comparative toxic unit for human (CTUh)** This expresses the estimated increase in morbidity in the total human population related to carcinogenic illnesses per unit mass of a chemical emitted (in cases per kilogram)
Non-Carcinogenics	**Comparative toxic unit for human (CTUh)** This expresses the estimated increase in morbidity in the total human population related to non-carcinogenic illnesses per unit mass of a chemical emitted (in cases per kilogram)
Fossil Fuel Depletion	**Mega-joules of surplus (MJ)** This measures the depletion of fossil fuel resources
Acidification	**Sulphur dioxide equivalence (SO_2 equivalence)** This measures the impact of increasing concentrations of hydrogen ions that can cause damage to water bodies, plants, animals, and human-built structures
Photochemical Smog Formation	**Ozone equivalence (O_3 equivalence)** This measures the impact on human health through various respiratory issues caused by the formation of ground level ozone, as well as ecosystem impacts such as crop damage

METHODOLOGY

The following section briefly outlines the most important methodological considerations in this analysis. Further details on the methodology, as well as information on the monetary valuations that have been used, can be found in the Appendices.

Overview

- **Data collection:** Trucost collected primary data, such as input materials and fuel sources, for the gold recycling process from Dell and Wistron. Where needed, secondary information filled in data gaps. Sources of secondary information include Ecoinvent life cycle analysis datasets.
- **Analysis:** The environmental and social impacts were quantified using life cycle analysis (LCA) models in SimaPro, an established LCA platform.
- **Quantification**: The environmental are quantified according to the impact categories listed in Table 3. The net benefit of the gold recycling process is then calculated by subtracting impacts of the alternative scenario from the baseline scenario.
- **Monetization**: The environmental impacts and net benefits are given monetary values so that their impacts could be compared across impact categories, and to traditional financial metrics.
- **Scenario analysis**: To outline the sensitivity of the results to certain parameters, scenario analyses have been conducted. These show the change in environmental impacts that result from changing inputs such as the source of electricity.

Key Assumptions

- **Chemical usage:** Annual consumption of chemicals used in the hydrometallurgy process were extrapolated from the monthly consumption figures.
- **Electronic waste**: The total amount of electronic waste received by Wistron was assumed to feed only into the gold recycling process. In reality, electronic was received by Wistron can go into other waste and recovery streams.
- **Energy consumption:** An approximation of the amount of electricity and natural gas used for the hydrometallurgy process was taken at 40% of the plant's total consumption. This 40% was then apportioned to the gold recycled by taking into account the relative value of gold extracted compared to silver, copper, and palladium.
- **Recycled gold:** All the activities included in the modeling of the gold recycling process and supply chain are considered to occur within the United States.

Limitations

- **Dependency:** One of the fundamental methodological limitations that is faced when conducting these types of analysis is that you cannot have recycled gold without having originally mined it in the first place. Therefore there is always an impact from mining gold even when it is purchased from recycled sources. This has not been brought out in this analysis as the intention is to show the magnitude of the impacts between the recycling and mining processes.
- **Emissions disclosure:** The quantity of air, land, and water emissions along with waste generated from hydrometallurgy process could not be disclosed at this time.
- **Scope:** The cradle-to-gate analysis of mined and recycled gold does not include the further refinement of gold due to limitations in data availability.

FRAMEWORK FOR ASSESSMENT

The framework for assessment used in this study comprises three distinct analysis steps. It leverages primary data and secondary literature, and aims to understand the net benefit of recycled gold.

Quantifying Emissions and Resource Use

The first step is to quantify the emissions and resource use associated with all of the activities that fall within the scope of the net benefit. Emissions and resource use can be quantified via primary and secondary data collection. Primary data collection refers to the use of actual, measured data collected on-site at a facility. Secondary data can include LCA studies from sources such as the Ecoinvent database, academic research and input-output modelling, all of which can be used to represent activities occurring at the facility. Please refer to the Appendices for detailed information on the data points and sources used.

Measuring the Net Benefit

The second step is to understand the consequence of the impact to a specific entity, or endpoint. An endpoint is the primary receptor of the impact – society, the environment, or the business itself. Each impact can have several endpoints. For example, particulate matter can negatively impact society (endpoint 1) through increase in the number of respiratory illnesses caused from its inhalation. The environment (endpoint 2) can be impacted through decreased photosynthesis, thus affecting the availability of food for society. It can also affect business itself (endpoint 3) through increased health costs and the increased level of absence at work. Impacts are quantified in biophysical and physical terms as, demonstrated in Table 3.

Valuing Environmental Impacts in Monetary Terms

The third step involves the monetization of biophysical impacts. The monetization reflects the cost or benefit to specific endpoints. One key consideration here is that regardless of the endpoint, the monetary values are human-centric; even in the case where the endpoint is the environment. Please see the Appendices for more information on the monetary valuation approach used by Trucost in this study.

The total avoided impact of Dell purchasing five pounds of recycled gold is valued at $3.68 million

NET BENEFIT RESULTS

The results show that the net benefit of recycling five pounds of gold is valued at $3.68 million. In other words, recycled gold is 111-times better than virgin gold in terms of its environmental impact, and causes 99% less damage.

Table 4: Overall net benefit of recycling five pounds of gold versus mining virgin gold

Net Benefit	**$3.68 million**

Table 5 shows that the avoided impact of recycling five pounds of gold by impact category.

Table 5: Environmental net benefit monetary value of recycling five pounds of gold versus the use of virgin gold (per impact category)

ENVIRONMENTAL IMPACT	**IMPACT** ($ PER YEAR)		**IMPACT REDUCTION**	**NET BENEFIT RATIO**
	RECYCLED GOLD	**MINED GOLD**		
Carcinogenics	$1,140	$39,800	-97%	x35
Non-Carcinogenics	$12,550	$3,517,000	-100%	x280
Respiratory Effects	$290	$1,350	-79%	x5
Global Warming	$10,370	$4,200	146%	x2.5
Fossil Fuel Depletion	$110	$160	-34%	x1.5
Photochemical Smog Formation	$6,100	$11,270	-46%	x1.8
Acidification	$200	$1,270	-84%	x6
Eutrophication	$2,210	$86,640	-97%	x39
Ecotoxicity	$380	$56,230	-99%	x147
TOTAL	**$33,350**	**$3,718,000**	**-99%**	**x111**

The results show that recycled gold has an environmental impact that is 99% lower than virgin gold. The majority of the impacts occur in the upstream phase for mined gold, such as ore extraction, and in the operational phase for recycled gold. Recycling gold has a lower impact compared to gold mining in all impact categories, except global warming potential. In total, 81% of the global warming impact from recycling gold stems from the high electricity use in the hydrometallurgy process.

The non-carcinogenic impact of gold mining is the largest among all the impact categories, followed by eutrophication and ecotoxicity. For every five pounds of gold mined, non-carcinogenic impacts equate to $3.50 million, or 95% of the total impact. The leaching of pollutants from mining waste which reach waterbodies during the ore extraction process (known as sulfudic tailings), are responsible for 95% of non-carcinogenic impacts.

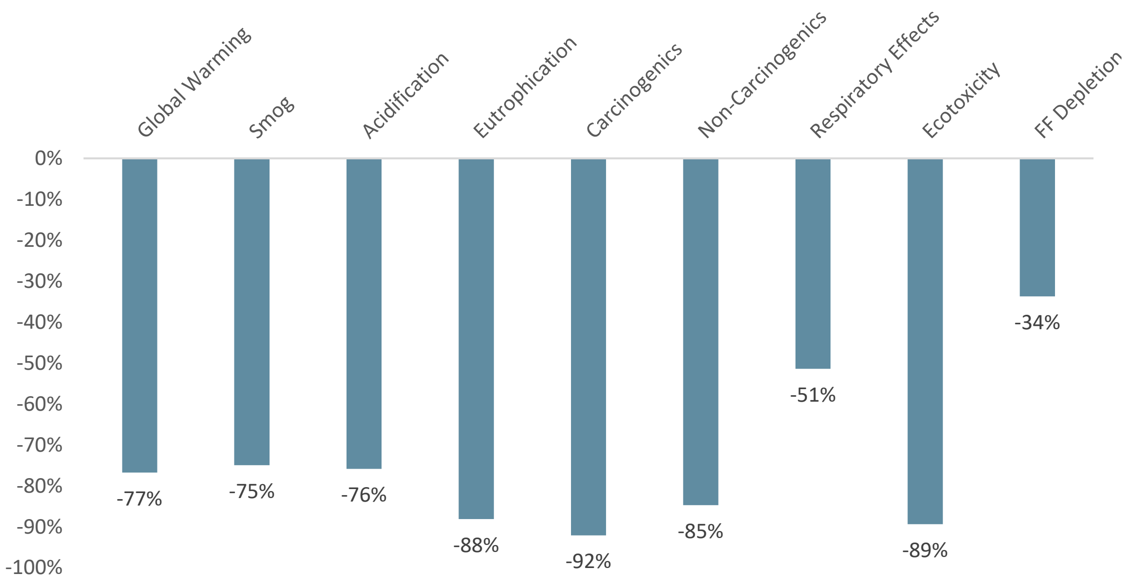
The impacts resulting from non-carcinogenics, eutrophication and ecotoxicity from gold recycling are lower than gold mining because electronic scrap replaces the mining and processing of gold ore, which are the main drivers of environmental impacts in gold mining.

Dell could increase its production or use of recycled gold, confident in the knowledge that the resultant impacts would be lower than if they purchased virgin gold.

SCENARIO ANALYSIS

More than half of the environmental impact of the gold recycling process stems from electricity use. In order to evaluate the influence of electricity as an input in the hydrometallurgy process, Figure 2 shows the effect on the environmental impact of recycling gold resulting from the use of renewable electricity, rather than electricity purchased from the national grid. This analysis excludes any impact that may occur from the construction of the renewable assets.

Figure 2: Impact reduction when sourcing renewable electricity compared to electricity from the national grid



The cumulative reduction in impacts across all impact categories is over 80%. This shows that the choice of energy sourcing can have a significant effect on the environmental impact caused during the gold recycling process.

INSIGHTS AND NEXT STEPS

ENVIRONMENTAL IMPACTS

Engage

Expand

Optimize

Engage with internal and external stakeholders

The environmental net benefit supports the business case for the continued purchase recycled gold. The avoided environmental impacts can be communicated to show the avoided health and environmental impacts that would have occurred due to the mining of virgin gold. This reinforces the earlier work completed by Dell on the benefits of its closed loop plastic, and could be used to strengthen the case for furthering Dell’s efforts in this area. For example, by including new types of materials or recycling processes.

Expand the gold recycling program

The environmental net benefit results substantiate the importance of increasing Dell’s use of recycled gold. Currently, Dell use only five pounds of recycled gold every month, which means there is significant potential to scale up this production to meet Dell’s 7,000-pound annual demand. The opportunities from the wider deployment of recycled gold within Dell’s products are highlighted by the vast environmental impact reduction shown earlier. Along with this, Dell could explore the possibility of reusing the other materials recovered similar processes, such as copper, PCBs, palladium and the like. This could deliver environmental benefits on a similar scale to those demonstrated in this report.

Optimize gold recycling processes

Dell and Wistron could consider optimizing the existing gold recycling process by utilizing renewable energy in its operations for example. Dell and Wistron can also optimize the process by avoiding wastage of power during the idle phases or by increasing the amount of electronic scrap that is being recycled. The deployment of these types of technologies could reduce costs for both Wistron and Dell. For instance, by producing its own electricity Wistron could reduce its expenditure on energy purchases.

APPENDICES

ENVIRONMENTAL IMPACTS

Detailed Methodology

The following series of tables and figures provide more detail on the methodology and data points used in the analysis. They also show the results of two further scenario analyses towards the end of the section.

Table 6: Resource inputs used to calculate the impacts of the hydrometallurgy process per kilogram of gold recycled

RESOURCE INPUT	VALUE	UNIT
Electricity	27,696	kWh
Natural gas	12,385,015	Btu
Anion polymer	25	pounds
Borax flux	0.42	pounds
EZ5050 (Nitric Acid)	714	pounds
EZ5050 (Ferric Nitrate)	714	pounds
Ferric Chloride (FeCl3)	423	pounds
Hydrochloric Acid	1,762	pounds
Nitric Acid	564	pounds
Caustic Soda	3,173	pounds
Sulphuric Acid	458	pounds
Sodium Sulfite	105	pounds
Deionized water	5,868	pounds
City water	464	liters
Sodium Hydro Sulphide	21	pounds

Table 7: Data sources used in the hydrometallurgy gold recycling process

	DESCRIPTION
Data provided by Dell	- Energy consumed at the Wistron plant - Chemicals used in the hydrometallurgy process - Water consumed in the hydrometallurgy gold recycling process
LCA data source	- Ecoinvent v3.1, 2014 in Simapro 3.0
Other data source(s)	- USD per kg values for copper, gold and silver are sourced from the World Bank. An average value from 2012 to 2016 is used in the study - USD per kg value for palladium taken from FOCUSECONOMICS. An average value from 2012 to 2016 is used in the study

	DESCRIPTION
Notes	- All the activities included in the modelling of the gold recycling process and supply chain are considered to occur within the United States - The quantity of air, land, and water emissions along with waste generated from hydrometallurgy process could not be disclosed at this time - Annual consumption of chemicals used in the hydrometallurgy process were extrapolated from the monthly consumption figures - Constituents of EZ5050 were not known and therefore 50% is apportioned to nitric acid and 50% apportioned to ferric nitrate - Polyvinylchloride production used as a proxy chemical for anion polymer in Simapro due to data unavailability - An approximation of the amount of energy used for the hydrometallurgy process was taken at 40% of the plant’s total consumption. This 40% was then apportioned to the gold recycled by taking into account the relative value of gold extracted compared to silver, copper, and palladium. This methodology is consistent with Ecoinvent guidelines of apportioning recycled gold. - This analysis represents a screening LCA for the hydrometallurgy process used in gold recycling

Table 8: Data sources used in the gold mining process

	DESCRIPTION
Data provided by Dell	- Not applicable
LCA data source	- Ecoinvent v3.1, 2014 in Simapro 8.0 - Gold-{ROW}-I production I Alloc Def, U
Other data source(s)	- Not applicable
Notes	- No primary data was used for modelling the mining process, so the results are based on secondary life cycle inventory data published on the Ecoinvent database - This analysis represents a screening LCA for gold mining

Table 9: Data sources used in the pyrometallurgy gold recycling process

	DESCRIPTION
Data provided by Dell	- Not applicable
LCA data source	- Ecoinvent v3.1, 2014 in Simapro 8.0
Other data source(s)	- Resource inputs, environmental outputs (to air, land and water), and energy used in the pyrometallurgy process have been sourced from Marianne Bigum (2012)

	DESCRIPTION
Notes	- The current record for pyrometallurgy in Ecoinvent v3.1, 2014, uses metals and synthetic materials with embodied emissions which would have been an inaccurate representation of the impacts for the gold recycling process. To accurately account for the process' inputs and outputs, we used a recent study by Marianne Bigum (2012). The study helped in deleting the unwanted inputs from the parent record. - Dataset in Ecoinvent v2.2 (Ecoinvent, 2017) for pyrometallurgy was not used to be consistent with the other records, which uses data from version 3.1. - This analysis represents a screening LCA for the pyrometallurgy process used in gold recycling

Table 10: Allocation methodology for apportioning energy use to gold in the hydrometallurgy process

METAL VALUE	VALUE[2] (USD PER KG)	CONTRIBUTION TO WEIGHT (%)	WEIGHTED AVERAGE VALUE (USD PER KG)	PORTION OF ENERGY USE (%)	SOURCE OF VALUE
Gold	43,443	12%	5,000	64%	World Bank (2017)
Copper	6.50	57%	3.73	0.05%	
Silver	687	19%	133	2%	
Palladium	22,354	12%	2,638	34%	FOCUSECONOMICS (2017)

Table 11: Monetary valuations of environmental impacts used in this analysis

ENVIRONMENTAL IMPACT CATEGORY	GLOBAL VALUATION COEFFICIENT (USD PER UNIT)	UNITED STATES VALUATION COEFFICIENT (USD PER UNIT)
Global Warming (kg CO_2 equivalence)	0.12	0.12
Eutrophication (kg N equivalence)	9.33	6.50
Respiratory Effects (kg PM2.5 equivalence)	29.41	11.03
Ecotoxicity (CTUe)	0.001	0.001
Carcinogenics (CTUh)	547,145	293,821

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[2] Values are average for the year 2012-2016.

ENVIRONMENTAL IMPACT CATEGORY	GLOBAL VALUATION COEFFICIENT (USD PER UNIT)	UNITED STATES VALUATION COEFFICIENT (USD PER UNIT)
Non-Carcinogenics (CTUh)	1,667,707	895,573
Fossil Fuel Depletion (MJ)	0.003	0.003
Acidification (kg SO_2 equivalence)	3.21	0.50
Photochemical Smog Formation (kg O_3 equivalence)	1.37	1.23

Further Results

Figure 3: Environmental net benefit of recycling five pounds of gold versus the use of virgin gold (per impact category)

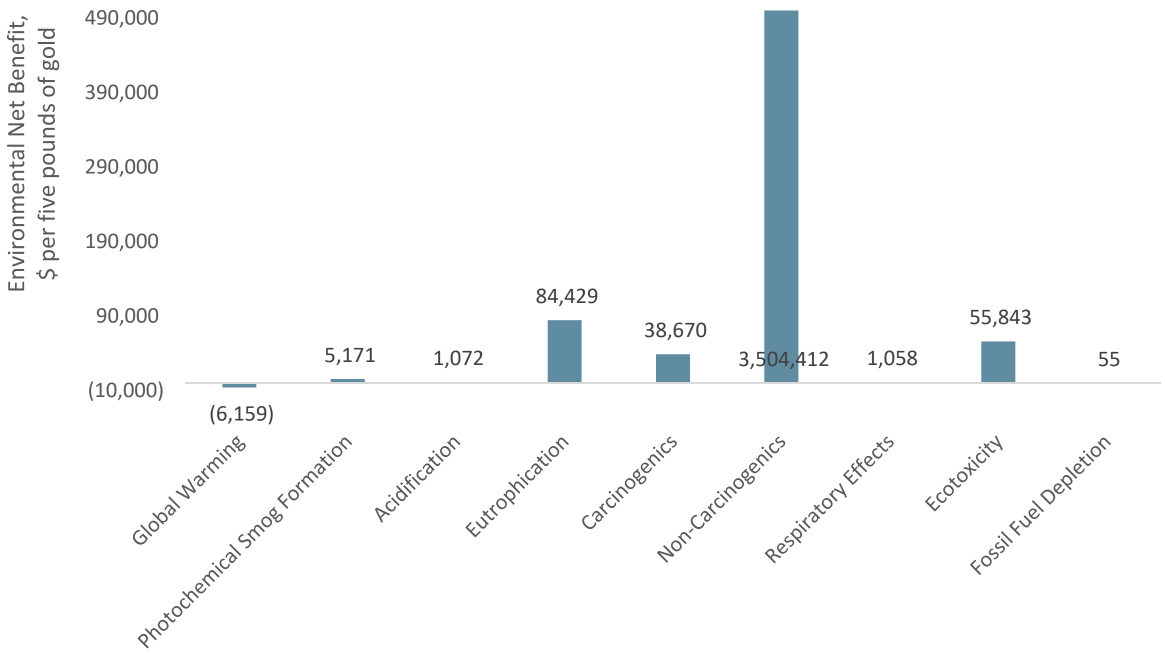


Table 12 presents the environmental impacts of each process in physical units along with the net benefit results.

Table 12: Environmental net benefit physical value of recycling 1 kilogram of gold versus the use of virgin gold (per impact category)

ENVIRONMENTAL IMPACT	UNIT	IMPACT		IMPACT REDUCTION	NET BENEFIT RATIO
		RECYCLED GOLD	MINED GOLD		
Carcinogenics	CTUh	0.00171	0.03208	-95%	x9
Non-Carcinogenics	CTUh	0.01	0.93	-99%	x93
Respiratory Effects	kg PM2.5 equivalence	12	20	-43%	x1.7
Global Warming	kg CO_2 equivalence	37,030	15,032	146%	x2.5
Fossil Fuel Depletion	MJ Surplus	14,903	20,999	-29%	x1.4
Photochemical Smog Formation	kg O_3 equivalence	2,094	3,608	-42%	x1.7
Acidification	kg SO_2 equivalence	180	175	3%	x1.0
Eutrophication	kg N equivalence	150	4,095	-96%	x27
Ecotoxicity	CTUe	154,278	22,139,602	-99%	x144

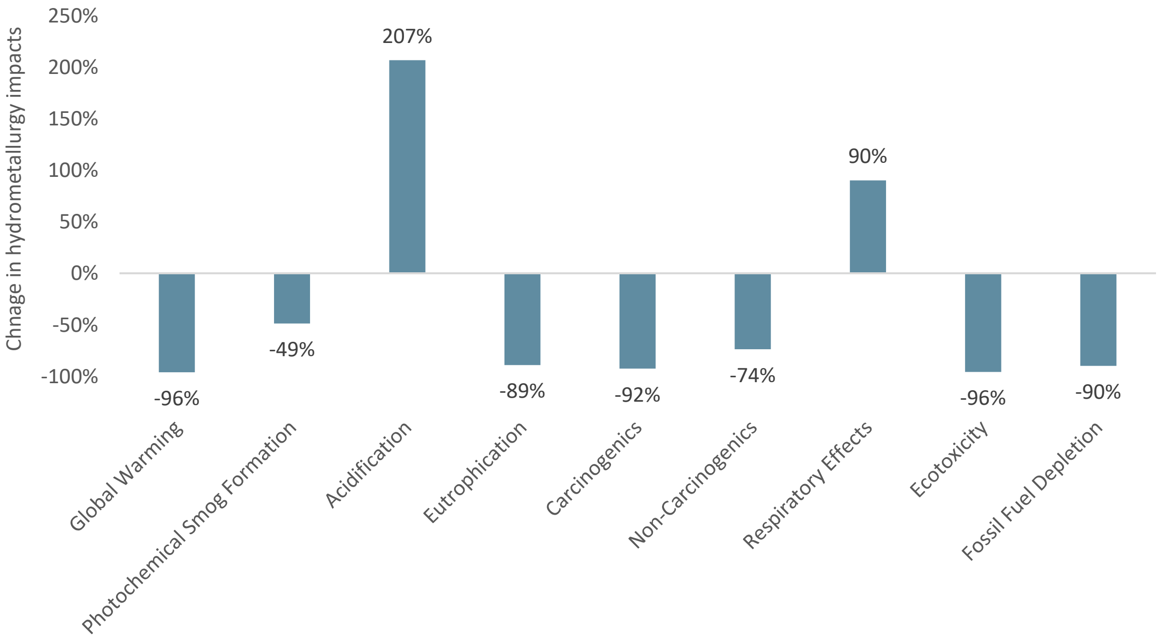
Scenario Analysis

Scenario A: Comparison of the pyrometallurgy and hydrometallurgy processes used in gold recycling

The pyrometallurgy process is a common gold recovery process that uses high temperatures to extract metals from recycled components. Hydrometallurgy is considered the greener of the two processes according to scientific literature, so a comparison of the two processes provided insightful results which were used to crosscheck the results from this analysis (Chao Li, 2014).

Figure 4 shows the difference in environmental performance of the two technologies. The percentage change is in relation to the hydrometallurgy process

Figure 4: The difference in environmental performance between hydrometallurgy and pyrometallurgy gold recycling processes

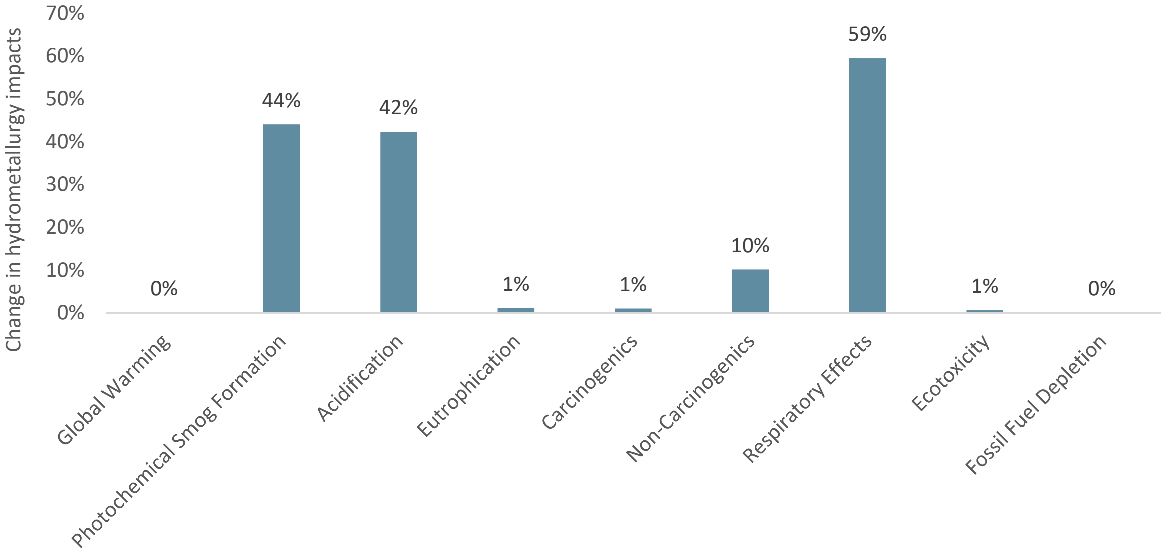


The result of the analysis tells us that the pyrometallurgy process produces recycled gold that is 75% better than that produced using hydrometallurgy. The pyrometallurgy process performs better in all impact categories except for acidification and respiratory effects. The results are driven by the high electricity requirements of the hydrometallurgy process, which uses disclosed data from Dell and Wistron.

Scenario B: The addition of air, land, and water pollution impacts that are not currently considered

Wistron could not disclose the volume of emissions to air, land, and water because the emissions currently fall below the reporting threshold for many of the pollutants. The impact of these missing outputs on the results is revealed by incorporating the emissions to air, land, and water from the pyrometallurgy record in Ecoinvent.

Figure 5: The difference in environmental performance for the hydrometallurgy process when taking into account more air, land, and water pollutant emissions



The result of this analysis tells us that the environmental impacts of recycling five pounds of gold increases from $33,352 to $37,600, an increase of 13%.

TRUCOST ENVIRONMENTAL IMPACT VALUATIONS

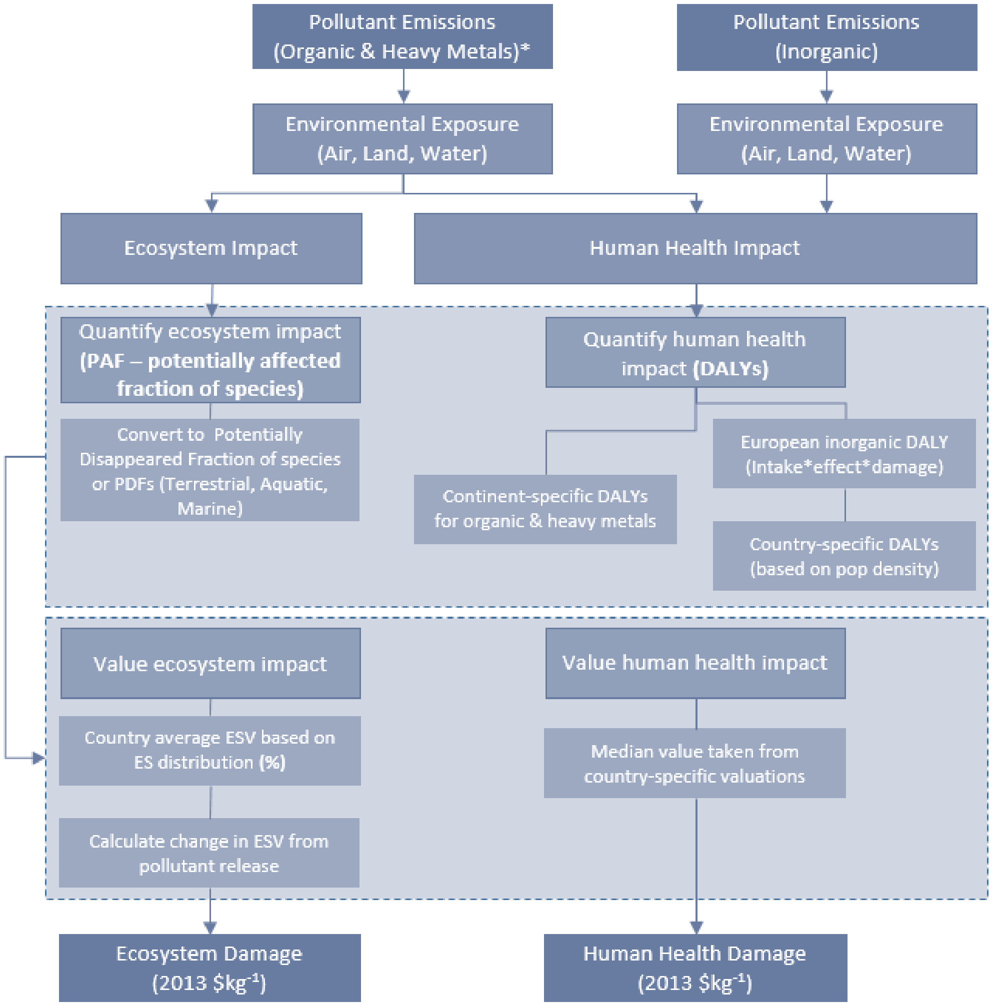
The following is an extract of Trucost's natural capital valuation methodology describing the methods underpinning the valuation of environmental costs and benefits in this study.

For more information on the methodologies summarized below, please refer to the full Trucost valuation methodology. This is available on request by emailing info@trucost.com.

AIR, LAND AND WATER POLLUTANTS

Figure 6 summarizes the overall approach used to value the emission of air, land, and water pollutants. The first shaded box indicates the steps taken to quantify the environmental impacts of these pollutants, while the second indicates the steps taken to value these impacts.

Figure 6: General overview of Trucost valuation process for Air, Land and Water Pollutants



ESV: Ecosystem Services Value

DALY: Disability Adjusted Life Years

ES: Ecosystem Services

Inorganic pollutants include carbon monoxide (CO), sulphur dioxide (SO2), nitrous oxides (NOx), ammonia (NH3), particulate matter (PM), and volatile organic compounds (VOCs)

*Organic pollutants and heavy metals are grouped together due to the similarity in methodology, not

IMPACT ON HUMAN HEALTH

BIOPHYSICAL MODELLING

Organic substances and heavy metals

Trucost uses disability adjusted life years (DALYs) as a measure of the impact on human health from environmental impacts. In order to calculate the quantity of DALYs lost due to the emission of pollutants to air, land and water, Trucost used USES-LCA2.0 (EC, 2004; National Institute of Public Health and the Environment, 2004). This model, originally developed in the context of life cycle assessment (LCA) studies, calculates the quantity of DALYs lost due to emission of over 3,300 chemicals to: freshwater and seawater; natural, agricultural and industrial soil; and rural, urban and natural air. USES-LCA2.0 takes into account the impact of cancer and non-cancer diseases caused by the ingestion of food and water, and the inhalation of chemicals.

The output of this analysis step is the number of DALYs lost due to the emission of each pollutant, to a specific media, at the continental level.

Note that organic substances and heavy metals are grouped together due to the similarity in methodology, not their chemical properties.

Sulphur dioxide, nitrogen oxide, and particulate matter (PM10)

USES-LCA2.0 does not estimate DALY impacts for common inorganic air pollutants such as sulphur dioxide, nitrogen oxide and PM10. Adaptation of USES-LCA2.0 to model these substances would result in higher than acceptable uncertainty due to the different characteristics of organic and inorganic substances. Trucost conducted a literature review to find an alternative method to quantify the DALY impact of emission of these pollutants.

ECONOMIC MODELLING

Once the quantity of DALYs lost is calculated, several valuation methods can be used to put a monetary value on a DALY, such as the cost of illness, the value of a statistical life (VSL), and the value of a statistical life year (VOLY).

Trucost decided to use the WTP technique utilized in the VOLY method to value DALYs, as it encompasses most aspects relating to illness and expresses the value of a year of life to the wider population. To value DALYs, Trucost used the results of a stated preference study conducted for the New Energy Externalities Development for Sustainability (NEEDS) project (Desaigues et al., 2006; 2011). This is a proactive cost estimate, which takes into account the perceived effects of morbidity. The value of a life year used in this methodology is just in excess of $46,500.

IMPACT ON ECOSYSTEMS

BIOPHYSICAL MODELLING

Organic substances and heavy metals

USES-LCA2.0 models the impact of polluting substances emitted to air, land and water, on terrestrial, freshwater and marine ecosystems. This model was adopted by Trucost for assessing the ecosystem damage caused by organic substances and heavy metals. It follows the same modelling steps as for human toxicity, namely exposure assessment, effect assessment, and risk characterization. USES-LCA2.0 has also been adapted to generate results at a continental level.

USES-LCA2.0 estimates the potentially affected fraction of species (PAF) due to the emission of pollutants to air, land and water. It is important to note that affected species need not disappear. Trucost adjusted the PAF results to reflect the proportion of species disappeared (PDF) using assumptions from the Eco-Indicator 99 model (Goedkoop & Spriensma, 2000). This was done to match the valuation methodology, which uses PDF (and not PAF) as an input due to data availability.

Ozone, sulphur dioxide, nitrogen oxide, and particulate matter (PM10)

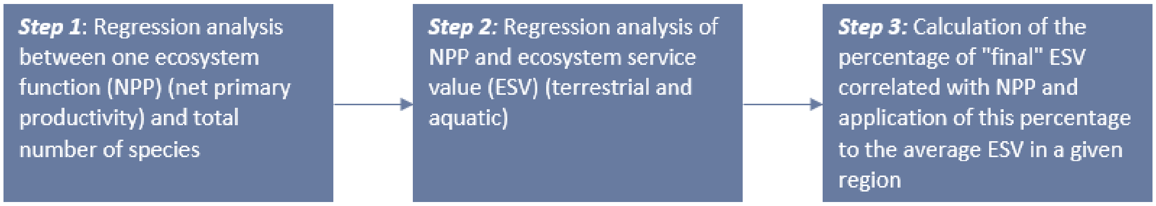
Impact on ecosystems has not been included for ozone, sulphur dioxide, nitrogen oxides and PM10.

ECONOMIC MODELLING

Valuing the impact on ecosystems in this study

Trucost's approach to valuing a change in the PDF of species follows a three-step process, as shown in Figure 7.

Figure 7: Steps for calculating the value of ecosystem services linked directly to biodiversity



In this methodology, Trucost decided to assess the link between biodiversity, measured species richness (IUCN, 2015), net primary productivity (NPP) (Costanza et al., 2007), and ecosystem service value (ESV). NPP was chosen over other ecosystem processes, such as nutrient cycling, due to data availability and its direct link with key ecosystem services. A monetary value for the provisioning, regulating and cultural services by terrestrial ecosystem type was first calculated based on the analysis of De Groot et al. (2012) using the specific ecosystem split per country (Olson et al., 2004). De Groot et al. calculate the minimum, maximum, median, average and standard deviation for each service provided by key terrestrial and aquatic ecosystems. Finally, Trucost calculated the percentage difference pre- and post-change of ESV at a country and substance level, and applied this percentage to the average value of one square meter of natural ecosystem in a given region. This aligns with the results of USES-LCA2.0, which calculates change of species richness, or PDF, at a continental level.

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GREENHOUSE GASES

Trucost values greenhouse gas (GHG) emissions using the social cost of carbon (SCC). The SCC is typically considered best practice as it reflects the full global cost of the damage generated by GHG emissions over their lifetime in the atmosphere. The SCC can be used to monetize the impact of GHG emissions globally, which is not the case when using market prices found in emissions trading schemes (ETS), nor when using the marginal abatement cost (MAC). GHG emissions are usually expressed in metric tons of carbon dioxide equivalents (CO_2e)[3].

Emission trading schemes are generally promoted for their flexibility to reduce emissions at the lowest cost for the economy, as well as their steadily increasing global reach (World Bank Group, 2014). However, traded market prices currently face a number of limitations which restrict their effectiveness in decision-making. For example, they do not reflect non-traded carbon costs nor the impact of other market-based mechanisms such as subsidies for fossil fuels or low-carbon technologies (Krukowska, 2014). Traded carbon prices have also been historically slow to come about, schemes have not been distributed equally, and they can be impacted by sudden economic changes which reduces the carbon price to levels that undermine the incentive for polluters to cut emissions (*Ibid*).

The marginal abatement cost is based on the known actual costs of existing reduction efforts. This renders it a valuable tool for informing policy discussions, prioritizing investment opportunities and driving forecasts of carbon allowance prices. Despite this, it too does not reflect non-traded carbon costs, and thus severely underestimates the true cost of GHG emissions. The MAC is highly time and geography specific with costs of reduction fluctuating over time, by sector and by geography, and estimates are influenced by fossil fuel prices, carbon prices and other policy measures.

The SCC is an estimate of the monetized damages associated with an incremental increase in GHG emissions in a given year. To estimate the SCC, Integrated Assessment Models (IAMs) are used to translate economic and population growth scenarios, and the resulting GHG emissions, into changes in atmospheric composition and global mean temperature. Trucost bases its SCC valuation on the work conducted by the Interagency Working Group on the Social Cost of Carbon. Trucost uses the values reported at the 95th percentile under a 3% discount rate, which represents higher than expected impacts from temperature change (IWGSCC, 2013). This decision has been taken to address material methodological omissions that arise due to modelling and data limitations, such as the unknown nature of resulting damages, and because the latest scientific data and methods incorporated into these models naturally lags behind the most recent research.

IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

BIOPHYSICAL & ECONOMIC MODELLING

Over 300 studies attempt to put a price on carbon, quantifying and valuing the impact of climate change on agricultural productivity, forestry, water resources, coastal zones, energy consumption, air quality, tropical and extra-tropical storms, property damages from increased flood risk and human health. The IAMs approximate the relationship between temperature changes and the economic costs of impacts. These

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[3] Carbon dioxide is only one of many GHGs, such as methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride. Carbon dioxide equivalents (CO_2e) is a measure that relates the impact of other GHGs to carbon dioxide over the same lifetime, usually 100 years.

economic costs arise from changes in energy demand, changes in agricultural and forestry output, property lost due to sea level rise, coastal storms, heat-related illnesses, and diseases such as malaria.

Out of the many studies that attempt to calculate the SCC, Trucost has chosen to use SCC estimates provided by the Interagency Working Group on the Social Cost of Carbon based in the United States (IWGSCC, 2013). The reasons for this include:

- Calculations are based on three well-established Integrated Assessment Models, which render the estimate more robust and credible than other approaches.
- The SCC takes into account the timing of emissions, which is key to the estimation of the SCC. For example, the SCC for the year 2020 represents the present value of the climate change damages that occur between the years 2020 and 2300, and are associated with the release of GHGs in 2020.
- Results are presented across multiple discount rates (2.5%, 3% and 5%) because no consensus exists on the appropriate rate to use. This allows flexibility in the choice of discount rate according to project objectives.
- The methodologies employed are continuously improved through regular feedback workshops, engagement with experts, and integrating the latest scientific evidence. As a result, the latest 2013 update provides higher values than those reported in the 2010 technical support document, and incorporates updates of the new versions of each underlying IAM.

Limitations

SCC valuations are contingent on assumptions, and in particular the discount rate chosen, the emission scenarios and equity weighting. These are highlighted briefly below.

Despite being the most complete measure of the damage caused by GHG emissions, SCC estimates have attracted criticism as they omit or poorly quantify some major risks associated with climate change. For instance, Tol's FUND model (FUND, 2015) omits social unrest, disruptions to economic growth, and ocean acidification. Other impacts that have been omitted in similar approaches include the loss of biodiversity, habitat and species extinction, and damages from Arctic sea ice loss and changing ocean circulation patterns (Howard, 2014; Kopits, 2014).

Three well-established IAMs, which form the foundation of the IWGSCC's estimates, have received most attention in the literature: DICE 2010, FUND 3.8, and PAGE09. Some of the limitations of these models are summarized below:

- Extensive experiments with DICE have shown that with small, reasonable changes to the basic data, DICE can yield very different projections.
- The FUND model was found by the Heritage Foundation's Centre for Data Analysis (CDA) to be extremely sensitive to assumptions; so sensitive that at times it even suggests net economic benefits to GHG emissions (Dayaratna and Kreutzer, 2014). According to the FUND model, change in temperature up to 3°C is contributing beneficially to the environment (IWGSCC, 2010).
- PAGE sets a relatively high temperature threshold for the onset of catastrophic damages.

SCC estimates also range from negative values up to four-figure estimates. This is mainly due to four factors that are outlined below:

- **Emissions scenarios:** The assumptions made on future emissions, the extent and pattern of warming, and other possible impacts of climate change, then deriving how these factors translate into economic impacts.
- **Equity weighting:** This refers to the spatial and temporal dimensions of climate change impacts. Some studies take account of equity weightings which adjust SCC estimates for differences in climate change impacts depending on the development and wealth of nations (Stern, 2006; Tol, 2011).
- **Uncertainties:** The variation in SCC valuations is influenced by uncertainties surrounding estimates of climate change damages and related costs.
- **Discount rate:** Higher discount rates result in lower present day values for the future damage costs of climate change. The long time horizon of climate change impacts makes the choice discount rate crucial as well as controversial (IPCC, 2014). For example, Stern (2006) uses a discount rate of 1.4% compared to a range of between 2.5% and 5% by the US EPA (2013).

Sensitivity

To illustrate the sensitivity of estimates to discount rates, discounting $1m at a rate of 1% from the year 2315 back to 2015 results in an equivalent value of $50,000 today. But if the discount rate is 5%, the current value is less than 50 cents (Burtraw and Sterner, 2009).

Arguments for not discounting future values include the ethical consideration of not equally weighting emissions that occur in the future with impacts occurring today. Discounting thus suggests that impacts on future generations are less important than those that occur on present generations. The ‘polluter pays principle’ supports this position by stating that agents causing damages should be accountable for the full extent of the impacts caused.

Consensus is also building for the use of declining discount rates (IPCC, 2014). Literature suggests that if there is a persistent element of uncertainty in the growth rate of the economy, it will result in an effective discount rate that declines over time (RFF, 2012). This approach would yield a higher present value to the long-term impacts of climate change, and thus a higher value for the SCC (Arrow et al., 2014).

The SCC used in this analysis was US$123.5 per tonne of CO_{2e} in 2016 prices

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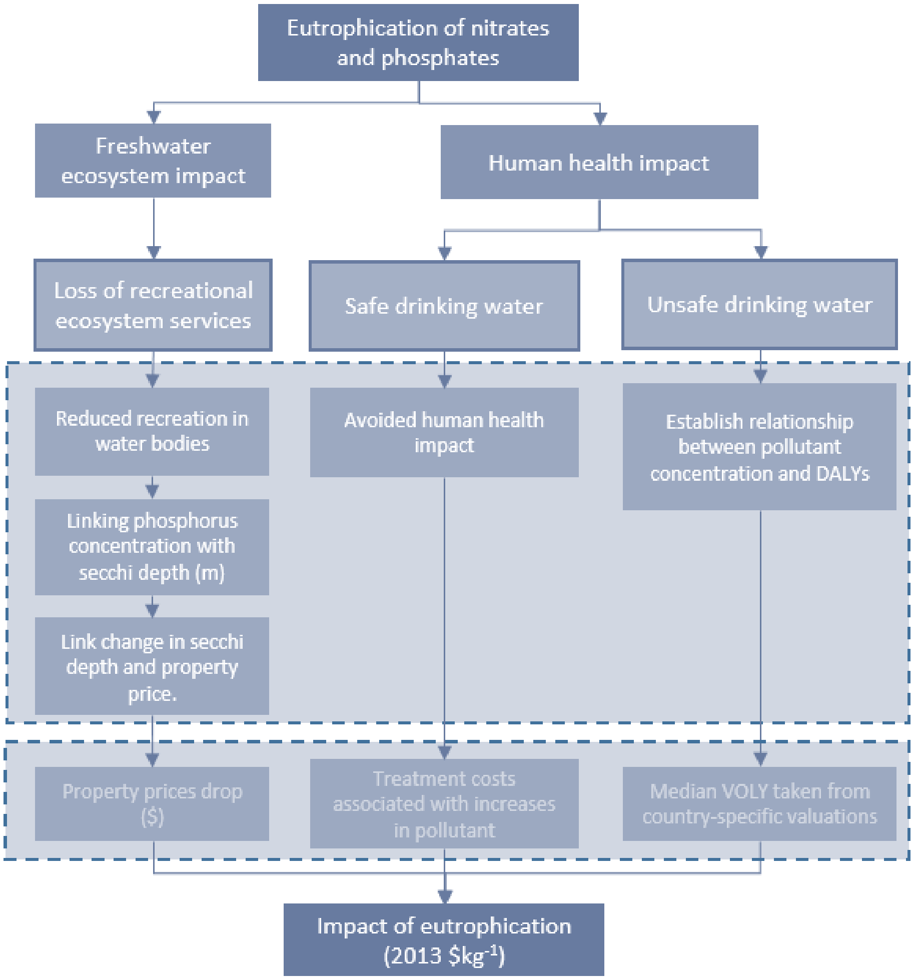
EUTROPHICATION

Figure 8 summarizes the high-level steps taken to value the impacts of eutrophication. Not all of the possible impacts have been included in the current methodology, such as the loss of fish yields in freshwater and marine ecosystems, and the loss of recreational services in marine ecosystems.

Figure 8: General overview of Trucost valuation process for Eutrophication



IMPACT ON HUMAN HEALTH

BIOPHYSICAL MODELLING

Water pollution can directly impact human health when unsafe drinking water is consumed. However, water is also treated to prevent the negative impacts of polluted water consumption and this comes with an economic cost. Therefore, to account for the true impact on human health, it is necessary to look at the economic costs of both safe and unsafe drinking water.

Unsafe drinking water

Trucost used the data from the EXIOPOL study to calculate the median years of life lost (YLL) per 100,000 males and females within a country due to the consumption of unsafe drinking water. Population data obtained from the World Bank allowed YLL to be made country-specific via adjustments for the demographic breakdown of each nation by gender. The biophysical indicator used for determining YLL was the concentration of nitrates in drinking water.

To calculate the percentage of the national population exposed to unsafe drinking water, Trucost assumed that water was taken directly from freshwater lakes. For this approach, it was necessary to estimate the catchment area from average-sized lakes within each country to determine the proportion of the national population that were most likely to be affected by drinking unsafe water caused by eutrophication. Trucost assumed a three kilometer catchment area for each national average-sized lake. This was selected from a study that found that the majority of the world's population live within three kilometers of a freshwater source (Kummu et al., 2011). The population density of each country was applied to calculate how many people live in the catchment area.

Finally, the percentage of the population with access to safe drinking water (World Bank Group, 2015) was removed from the calculation so that the valuation was only applied to those who were expected to be reliant on the consumption of unsafe drinking water.

Trucost used YLL as a proxy for DALYs as no information on the years of healthy life lost due to disability (YLD) from consuming eutrophic drinking water could be sourced.

Safe drinking water

For the proportion of water that is safe to drink, there is an economic cost associated with cleaning the water to a high enough quality. The model used in this approach requires an input of phosphorus yield in a watershed in order to calculate the cost of treating eutrophic water. Information reported by the Nature Conservancy (McDonald & Shemie, 2014) was used to determine the incremental change in phosphorus from an initial sediment yield, which could be used to calculate the biophysical metric.

ECONOMIC MODELLING

Unsafe drinking water

Once the total YLL (hence DALYs) lost is calculated, several valuation methods can be used to put a monetary value on a DALY, such as the cost of illness, the value of a statistical life (VSL), and the value of a statistical life year (VOLY).

Trucost decided to use the WTP technique utilized in the VOLY method to value DALYs, as it encompasses most aspects relating to illness and expresses the value of a year of life to the wider population. To value DALYs, Trucost used the results of a stated preference study conducted in the context of the New Energy Externalities Development for Sustainability (NEEDS) project (Desaigues et al., 2006; 2011). This is a proactive cost estimate, which takes into account the perceived effects of morbidity. The value of a life year used in this methodology is just in excess of $46,500.

Safe drinking water

With increasing sedimentation and nutrient load, the cost of removing sediments increases. A reduction in sedimentation from nutrient pollution by an average of 10% reduces treatment costs by 1.9% (McDonald & Shemie, 2014). This paper presents the relationship between phosphorus yield (tonnes of phosphorus per square kilometer of watershed) and treatment cost. The method was applied to calculate the total cost of water treatment after the unit mass of phosphorus has been applied in the watershed.

IMPACT ON ECOSYSTEMS

BIOPHYSICAL MODELLING

Trucost used the hedonic pricing approach in this methodology to quantify the impact on ecosystems, which estimates the effect of eutrophication on waterfront property prices, as these are significantly affected by water clarity (Gibbs et al., 2002). Secchi depth is the most widely used measure of water clarity, and a link between secchi depth and phosphorus level has been used to quantify the biophysical effect of eutrophication (Downing et al., 2010). This relationship has been investigated as early as the 1970s (see Canfield & Bachman, 1980).

Trucost calculated the increase in phosphorus equivalent concentration, in a national average-sized lake, associated with the use of one kilogram of nitrogen or phosphorus. Trucost calculated the marginal cost of an increase in eutrophication due to excess nutrient loading, changing the state of a lake from oligotrophic to eutrophic. The phosphorus concentration increase was calculated for an average-sized freshwater lake in a country. Using GIS data and the Global Lakes and Wetlands Database (Lehner & Döll, 2004), the median area of a lake, and the average perimeter of a median lake, was calculated for each country.

Trucost then converted the change in excess nutrient concentration into the change in secchi depth, and used the percentage change in secchi depth as the metric for valuation.

ECONOMIC MODELLING

Trucost used data from three studies (Krysel et al., 2003; Gibbs et al, 2002; Michael et al., 1996) in the US, comprising a total of 44 estimates of water frontage price decreases (per foot) due to a one meter reduction in secchi depth, and calculated the median value.

Trucost adjusted the value for each country and calculated the price per waterfront meter. Finally, the value per waterfront meter for each country was applied to the perimeter of the average-sized national lake to establish the hedonic cost of eutrophication at a country-level.

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GLOSSARY

TERM	DESCRIPTION
Natural Capital	The finite stock of natural assets (air, water, land, habitats) from which goods and services flow to benefit society and the economy. It is made up of ecosystems (providing renewable resources and services), and non-renewable deposits of fossil fuels and minerals. (NCC, 2014)
Impacts	These can be negative or positive effects that a company has on society or the environment. In places, negative impacts have been termed as costs, and positive impacts have been termed as benefits in this report
Upstream Impacts	In this analysis, upstream impacts refer to the impacts that occur before the studied process. For gold recycling, this can refer to the collection of waste electrical equipment from consumers which are used in the hydrometallurgy process – the focus of the analysis. Upstream impacts are also referred to as supply chain impacts.
Operational Impacts	In this analysis, operational impacts refer to the impacts that occur during the activities of the studied process. For gold recycling, this refers to the running of the machinery used in the hydrometallurgy process.
Downstream Impacts	In this analysis, downstream impacts refer to the impacts that occur from the further use or processing of the gold that occurs after the completion of the studied process. For gold recycling, this can refer to the further refinement of the gold in Taiwan by Dell’s manufacturing facilities.
Value Chain	This incorporates activities of a company or a process which are broken into upstream, operational, and downstream components.

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