Enhancing Resource Efficiency and Reducing Metal Loss: A System Dynamic Approach to EU Mobile Phone Recycling and EoL Management

ABSTRACT.

This study investigates the recycling potential, both economically and logistically, of discarded mobile phones within the European Union (EU), focusing on their content of precious metals and rare earth elements. With the production of Waste Electric and Electronic Equipment (WEEE) rapidly increasing at an annual rate of 3%-5%, mobile phones emerge as a significant contributor to the EU's fastest-growing waste stream, primarily due to low recycling rates exacerbated by exports, disposal, and consumer neglect. Through a comprehensive analysis spanning from 1988 to 2050, this research explores the dynamics of the EU mobile phone market, end-of-life (EoL) management practices, resource recovery rates, and the economic viability of recycling processes. Employing a system dynamic modelling approach, we developed the MObile PHOne DYNamics in the EU (MOPHODYN/EU) model, which utilizes Causal Loop Diagrams (CLDs) for initial development before transitioning to a numerical simulation within the STELLA software. This model, parameterized based on extensive literature review and validated through comparison with historical World Bank data, showcases a high degree of accuracy. Our findings reveal that despite the exponential growth of mobile phone use until 2008 and a subsequent stabilization, a decline is anticipated post-2024 due to demographic shifts. In 2018 alone, approximately 316 million mobile phones reached EoL, with a mere 10% undergoing proper recycling. The study identifies significant resource recovery opportunities, noting that only a fraction of the metals used in mobile phones are currently recycled within the EU. However, recycling remains profitable, presenting an opportunity to mitigate resource loss and reduce the environmental impact of primary mining. By conducting a sensitivity analysis, we pinpointed key drivers for more sustainable resource use. Scenario analysis revealed that an export ban combined with enhanced recycling rates and financial incentives for EoL phone returns significantly increases resource efficiency. The optimal scenario suggests that targeted interventions could reduce loop leakage by 40% and improve loop efficiency by 45% by 2050, compared to a business-as-usual approach. This research underscores the potential for policy and practice changes to significantly enhance the sustainability of the EU's mobile phone ecosystem, emphasizing the need for concerted efforts to improve recycling rates and resource management.

KEYWORDS

Resource Scarcity, Recycling and Reuse, Rare Earth Elements, Environmental Sustainability, System Dynamics, Waste Electric and Electronic Equipment (WEEE)

1 INTRODUCTION

There has been an ongoing public debate on future resource scarcity since the publication of Limits to Growth (Meadows and Meadows, 1972). The topic of resource scarcity and "peak resources" is both relevant and to some degree controversial. Recently the notion that the global human population will be facing major environmental problems and resource scarcity in the very near future has been put forward in a special issue of Geochemical perspectives (Sverdrup and Ragnarsdóttir, 2014). For instance, several strategic metals and elements will become scarce in the coming decades (Sverdrup, Ragnarsdottir and Koca, 2017). The studies of Sverdrup, Koca and Ragnarsdóttir, 2013, show that scarcity may lead to concurrent peak wealth, peak population, peak waste and peak civilization. In order to prevent acute resource scarcity from happening or reduce its impact, drastic countermeasures need to be undertaken. Many of the metals and materials which have become essential for the functioning of the modern society may, in practical terms, become unavailable on a global scale or simply too expensive to extract. At current consumption rates, the supply of critical resources appears to be unsustainable, and recycling is becoming more and more critical for our society. Conventional (primary) mining comes with an enormous environmental cost and high pollution, while reuse and recycling, can offer a more sustainable solution to close the material cycles (Sverdrup, Koca and Ragnarsdóttir, 2013). The European Union consumes about 25% to 30% of the annual global consumed metal but accounts only for 3% of the annual global production (Wilson *et al.*, 2017). Critical resources are mainly produced outside the European Union, this is particularly critical when it comes to rare earth elements with a near monopoly on production hold by China. China, which is the leading producer of rare earth elements (95%) decided to reduce its exports in recent years. For Western countries, such domination of strategic resources becomes impossible to ignore. The reduced export rate forced the governments of Europe, the U.S and Japan to act and ensure their continuous supply with these strategic resources. Since China's export reduction interrupts manufacturing in the US, Europe and Japan, it will be necessary to reopen local production to feed the hunger of the global supply chain. As rare earth minerals are needed for green energy solution, high tech devices (laptop, phones and tablets) and military devices , resources become a security issue for the EU. Since there is a lack of production in the EU, recycling of discarded or obsolete electronic equipment is a major opportunity to ensure that at least a part of the resource demand can be met. Also, recycling will prevent that precious metals and rare earth elements will be lost. Instead, they can be recovered and used for a new generation of products. Furthermore, recycling offers, in comparison to conventional mining, benefits regarding energy consumption, water usage and pollution. (Cui and Forssberg, 2003)

This study has been conducted to determine the recycling potential (economically and logistically) in the European Union of mobile phones, which contain several precious metals and rare earth elements. The global production of **Waste Electric and Electronic Equipment** (**WEEE**) will increase as economies grow and technologies develop. For any given country, the total amount of WEEE is strongly correlated to the country's GDP (Robinson, 2009). This relationship along with an ever- decreasing lifespan of (**Electric and Electronic Equipment – EEE**) products has increased WEEE. According to (Eurostat, 2016) WEEE is the fastest growing waste stream with an annual growth of 3-5 % in the EU. WEEE causes several environmental issues as the EEE contain hazardous contaminants. Several countries have drafted national legislation in order to improve the management of WEEE primarily by improvement of reuse, recycling or other forms of waste recovery. One example of international legislation is the Basel Convention, which forbids the export of WEEE from developed countries to developing countries. The European Union drafted several directives to control e-waste and implemented guidelines for disposal and recycling rates. Recycling of WEEE is an important subject not only regarding waste management and prevention of environmental hazards but also for the recovery of valuable materials such as precious metals and rare earth minerals (Cui and Forssberg, 2003). Despite the reasonable overall situation in the recycling of old electrical appliances in the EU, the environmentally sound disposal of some equipment groups needs to be improved. Mobile Phones are one example of the equipment groups that could still be improved in recycling and return since most devices are either exported, disposed or hibernating in consumer households.

2 HYPOTHESIS AND AIM

The recycling of mobile phones and mobile phone batteries is economically viable and could help to reduce the dependency on resource import and support the EU's resource security.

Aims

The studies aim is to gather knowledge about the lifetime and recycling circle of mobile phones in the context of the extractable minerals and their economic value. Many studies indicate that a significant percentage of mobile phones never enter the recycling circle and therefore substantial amounts of minerals and metals is lost. The goal is to:

- Get a clear picture of the number of mobile phones on the EU market and what percentage of mobile phones end up being recycled. Further, to identify the drivers that could improve recycling and therefore support the resource security.
- Calculate the amount of resources (precious metals and rare earth elements) which are recovered and recoverable by recycling mobile phones as well as their economic value

- Test different scenarios to test different potential policy responses to improve metal recovery from mobile phone recycling which would be beneficial for resource security.
- Propose a future optimized case based on identified drivers meeting the concept of the circular economy cycle and provide a suggestion for policy measures that could lead to an implementation of the optimized case in a real-world scenario.

3 BACKGROUND

3.1 Metals and Rare Earth Elements

Metals are foundational to our modern society, integral from the structural steel in our buildings to the copper in computers and power lines, the lithium in batteries, and rare earth elements like neodymium and tantalum in green energy technologies and mobile phones. Their ubiquity in contemporary electronic products has made them critical to the functioning of our society. Despite the essential nature of these metals, their continued availability is becoming increasingly uncertain. The study by Sverdrup, Ragnarsdottir, and Koca (2017) forecasts critical shortages for several metals crucial to our electronics industry and, by extension, our way of life, within the next four decades. The indispensable nature of these electronics, paired with the relative scarcity of some metals, has led to the designation of certain metals as critical (Bollinger, 2010). Elements such as tellurium, indium, gallium, rare earth elements, lithium, tantalum, palladium, platinum, ruthenium, germanium, and cobalt are identified as scarce or likely to become scarce by 2050 (Buchert, Schüler, and Bleher, 2009). From 1900 to 2010, the extraction and consumption of metals have risen continuously, with the output of the world's mines growing exponentially (Sverdrup, Koca, and Ragnarsdóttir, 2013). This increase in consumption now surpasses sustainable production rates, effectively borrowing from future supplies. As the extraction of these resources continues to grow, the availability of relatively cheap, high-grade ore is diminishing. Future mining of less rich ore bodies will necessitate more expensive extraction processes and result in higher environmental costs. If the design of electronics does not fundamentally shift, manufacturers may face future constraints on metal availability as the demand for new technology, particularly for rare earth metals with unique properties, continues to escalate (Gordon, Bertram, and Graedel, 2006). The global population is projected to grow at least until 2050, thereby increasing the consumption of resources. According to Gordon et al. (2006), this growth, especially in developing countries, will cause the demand for metals like copper and zinc to exceed the supply held in natural deposits. Without significant countermeasures, our future resource supply is unsustainable (Sverdrup, Koca, and Ragnarsdóttir, 2013; Sverdrup and Ragnarsdóttir, 2014; Sverdrup, Ragnarsdottir, and Koca, 2017). The depletion of natural resource stocks makes recycling a critical strategy to close the material loop and recover metals. The anthropogenic stock is increasing as more products and metals are in use, with the anthropogenic stock of some metals already exceeding the amounts held in natural deposits. Effective resource management becomes crucial for sustainability. The concentration of gold per ton of mobile phones, for instance, exceeds that in natural ore by 200 times (Takahashi et al., 2009), highlighting the importance of recycling. Despite the challenges in collecting end-of-life products and the need for highly specialized recycling facilities, which require substantial upfront investments, recycling remains a key component in addressing the complex issue of metal recovery and sustainability.

3.2 Political Issues Regarding Resources

There are several political issues connected to metals and other resources. Several different metals are mined under inhumane conditions. Other metals face supply risks simply because they are mined in limited geographical regions.

3.2.1 Rare Earth Elements

Until 1990, the USA led in rare earth element (REE) production but was overtaken by China in the mid-1990s due to lower operational costs, leading to the closure of US mines (Ortiz and Viana Júnior, 2014). Global REE production fell from 134,000 tons in 2010 to 110,000 tons in 2012, significantly impacted by China's reduced output from 130,000 to 100,000 tons, given China's 95% share in global production

(Cordier, Daniel, 2012; Gambogi, 2013; Ortiz and Viana Júnior, 2014). China dominates heavy REE production, with a slow diversification of sources (Liedtke and Elsner, 2009). China imposed export limits in 2010 and 2011, restricting light REEs and banning heavy REE exports, affecting global demand for green technologies, defence, and other advanced technologies (Tse, 2011). This led to tighter supplies and higher prices internationally, prompting countries to reconsider mining operations to reduce dependence on Chinese REEs (Tse, 2011). The USA, the EU, and Japan disputed China's export restrictions at the WTO, arguing they violated trading laws. The WTO ruled in favour of the complainants in 2015, forcing China to lift the restrictions. The case centred on China's justification of environmental protection for its export limits, highlighting the environmental and health damages from REE mining, such as acid use, sludge impoundments, and radioactive waste risks. However, the WTO found the restrictions were discriminatory, not primarily aimed at protecting health or the environment. This dispute underscored the global vulnerability to China's REE monopoly, sparking initiatives for resource recovery from waste and diversifying supply sources beyond China.

3.2.2 Precious Metals and Conflict Resources

Conflict minerals, specifically gold, tungsten, tantalum, and tin (3Tgs), are sourced from conflict or high-risk areas, often lacking stable governance, such as the Democratic Republic of Congo (DRC). The DRC, plagued by armed conflicts and political instability, heavily relies on these minerals, crucial for manufacturing modern technology devices like mobile phones and laptops. The surge in global demand for these consumer products has inadvertently bolstered revenues for armed groups in the region, exacerbating conflicts. The eastern DRC, rife with rebel activity and continuous conflict, suffers significantly from the exploitation of 3Tgs. Smuggling activities by neighbouring countries complicate the traceability of these minerals, entangling foreign smelters and manufacturers in the conflict supply chain, often unbeknownst to consumers who use devices made from these minerals. Mining in these areas not only perpetuates violence and human rights abuses but also poses severe environmental and health risks due to unregulated operations. Workers face dangerous conditions with little or no pay, while local communities endure violence and repression. In response, the last decade has seen policy efforts, such as the Dodd-Frank Act and the European Union Directive 2017/281, aimed at curtailing the use of conflict minerals. Additionally, the OECD's 'Due Diligence Guidance for Responsible Supply Chains from Conflict-Affected and High-Risk Areas' offers recommendations for handling 3Tgs, developed in collaboration with developed countries, industry stakeholders, and civil society (OECD, 2013), aiming to mitigate the trade of conflict minerals.

3.3 Electric and Electronic Equipment Waste (WEEE)

The global volume of waste electrical and electronic equipment (WEEE) is increasing, with estimates showing a rise from 43.9 million tonnes in 2014 to 50 million tonnes in 2018 (Baldé et al., 2015). Factors contributing to this growth include new technologies, lower equipment prices, global population growth, and rising GDPs across countries. This leads to a projected annual growth rate of e-waste between 3% and 5%, significantly outpacing other waste streams (Cucchiella et al., 2015; Singh, Li, and Zeng, 2016). In 2005, the European Union produced 9 million tonnes of WEEE, expected to reach 12 million tonnes by 2020, with each citizen contributing an average of 17 kg annually (Huisman et al., 2007). Developing countries currently produce around 1 kg of WEEE per capita annually, but this is anticipated to increase dramatically. The disposal of WEEE alongside municipal waste is problematic due to the hazardous substances it contains, leading to environmental and health risks from heavy metal leakage. WEEE is a valuable source of copper, aluminium, ferrous metals, precious metals, and rare earth metals, all of which are recoverable through recycling (Chancerel and Rotter, 2009). Recycling not only conserves these non-renewable resources but also reduces the need for primary metal mining, thereby mitigating environmental damage and making countries less dependent on resource imports (Prakash and Manhart, 2010). As of 2018, only one-third of WEEE in the EU is processed through official collection schemes. The remainder is either handled by unregistered parties, disposed of in landfills, or incinerated (Eurostat, 2018). The collection rate for officially processed WEEE was set at a minimum of 45% in 2016, based on the total weight of products entering the market over the past three years, with an increase to 65% by 2019 (Eurostat, 2018).

3.3.1 s-WEEE (Mobile Phones)

Since 2003, the European Union (EU) has enforced laws to enhance the collection and recycling of waste electrical and electronic equipment (WEEE), although the effectiveness of these regulations for small WEEE (s-WEEE) like mobile phones has been limited (Polák and Drápalová, 2012). Larger WEEE items tend to have higher return rates due to spatial constraints at home, but mobile phones, in particular, show exceptionally low return rates for recycling. Research indicates that a majority of consumers either dispose of, sell, or store their old phones, with only about 15% reporting recycling at proper facilities (Ylä-Mella, Keiski, and Pongrácz, 2015). Mobile phones are notably valuable for recycling, capable of yielding up to 17 different metals, including precious ones and those likely to become scarce (Hagelüken, 2007). This study aims to analyse the mobile phone lifecycle, estimate the potential for resource recovery in the EU,

3.3.2 Lifespan and estimated number of mobile phones available in the EU

Polák and Drápalová (2012) estimate that within the next decade, the EU could have 1.3 billion mobile phones available for recycling, encompassing approximately 31 tonnes of gold and 325 tonnes of silver, alongside significant amounts of copper and rare earth minerals. Their study in the Czech Republic found that mobile phones have an average lifespan of 7.99 years, with 4.35 years spent unused in storage. Contrarily, other research suggests mobile phones have a much shorter active use phase of 1-2 years before entering a hibernation period (Wilson et al., 2017; Robinson, 2009; Sinha et al., 2016), accelerated by rapid technological advancements (Laurenti et al., 2015). The mobile phone recycling rate in the Czech Republic was reported at a mere 3-6% in 2010 (Polák and Drápalová, 2012). In Finland, Ylä-Mella, Keiski, and Pongrácz (2015) found that 55% of consumers have unused phones at home, but only 15% recycled them, often due to lack of recycling opportunities or awareness, with many keeping a phone as a backup. These findings highlight a significant potential for recycling mobile phones in the EU, driven by the valuable metals they contain and the growing number of end-of-life (EoL) devices.

3.3.3 Material Composition of mobile phones

Over the past two decades, despite a reduction in the amount of precious metals per mobile phone, the overall number has risen significantly. Mobile phones are composed of over 40 different elements, including recyclable metals like copper, gold, palladium, and silver, which constitute 13.2% of a phone's weight (UNEP, 2009; OECD, 2010; Yu, Williams, and Ju, 2010). Notably, the gold content in a phone, at 0.04% or 44mg, is 200 times more concentrated than in gold ore, allowing for the extraction of 300g-350g of gold per tonne of phones compared to just 5 grams per tonne of ore (Takahashi et al., 2009; Namias, 2013). Gold drives recycling efforts, comprising 80% of the economic value from recycled materials, with palladium (10%), silver (7%), and other metals (3%) making up the rest (Valero Navazo, Villalba Méndez, and Talens Peiró, 2014a). While the recovery of other metals is currently economically viable only alongside gold, silver, and palladium, rising prices and scarcity may change this. Mobile phones also include rare earths and other critical metals like gallium and antimony, essential for technology development but at risk of supply disruptions (Buchert, Schüler, and Bleher, 2009; European Commission, 2010; British Geological Survey, 2012).

Table 1: Presents the materials concentration (in grams) in cell phones vs smartphones (Cucchiella et al., 2015)

Metal	Cell phones	Smartphones
Aluminum	12	2.9
Antimony		0.084
Beryllium		0.003
Cobalt	3.8	6.3
Copper	26	14
Glass		10.6
Gold	0.024	0,038
Lead	1	0.6
Mercury	1	
Neodymium		0,5
Nickel	1	1.5
Palladium	0.009	0.015
Plastic	63	60
Platinum		0.004
Praseodymium		0.01
Silicon	5	
Silver	1	0.244
Steel	11	8
Tin	1	1

The metal content varies by phone model and age, with differences in construction materials and functionalities affecting the composition. For instance, a touchscreen phone requires different metals compared to a standard screen. Umicore, a leading recycler, reports the ability to recover 17 different metals from mobile phones (Hagelüken, 2007), highlighting the significant recycling potential and the importance of mobile phones as a source of valuable materials.

3.3.4 End of Life Streams of Mobile Phones in the EU

The study of Baldé et al. (2015) outlines four main destinations for end-of-life (EoL) mobile phones: landfill disposal, official take-back systems, unofficial collection, and informal recycling, with a notable amount also stored unused by consumers.

1. **Landfill Disposal:** Many EoL mobile phones are discarded with household waste, leading to environmental hazards from heavy metal leaching in landfills and harmful emissions if incinerated. It's estimated that e-waste contributes to 70% of heavy metal content in landfills (Mundada et al., 2004; Widmer et al., 2005), with disposal rates varying widely in literature from 1% to 90% (Wilhelm et al., 1999; Silveira and Chang, 2010; Herat and Agamuthu, 2012; Peng and Su, 2014; Wilson et al., 2017).
2. **Official Take-Back Systems:** EU regulations mandate municipal and retailer collection points for e-waste, including mobile phones. However, less than 20% of e-waste reaches these official systems in developed countries, with mobile phones often overlooked due to their small size and consumer unawareness (Panambunan-Ferse and Breiter, 2013; Umair et al., 2013).
3. **Unofficial Collection:** E-waste, including mobile phones, is often collected by waste dealers or small companies for reuse or recycling, particularly in developing countries. This practice concerns high-end and middle-class devices that are refurbished and resold, while older or broken devices are often illegally shipped to developing countries for dismantling or resale, violating the Basel Convention (Cucchiella et al., 2015; Basel Convention, 2009).

4. **Consumer Storage:** A significant number of EoL mobile phones are kept in drawers by consumers, either as backup phones or due to personal attachment, rendering them inaccessible for recycling (Ylä-Mella, Keiski, and Pongrácz, 2015; Wilson et al., 2017).

The overall recycling rate for mobile phones in the EU is estimated between 2.5% to 20%, with reuse rates ranging from 10% to 25% of EoL phones (Hagelüken and Buchert 2008; Silveira and Chang, 2010; Wilhelm et al., 2011; Herat and Agamuthu, 2012; Shakila Umair, Anna Björklund, 2013; Ylä-Mella, Keiski and Pongrácz, 2015; Kang T., 2018

3.3.5 Economic Aspects

Mobile phone sales often involve contracts that spread the cost over time, encouraging frequent upgrades every two years due to new technologies and features. The mobile phone market ranges from basic models at €20 to high-end devices at €800-€1000, with a significant mid-range segment. Consumer preferences largely favour new over refurbished phones, the latter's market driven by the device's age and condition, with older models often exported for reuse or informal recycling abroad (Ylä-Mella, Keiski, and Pongrácz, 2015). Global demand for metals in electronics, including tin, silver, and copper, increased from 2005-2014, while gold demand remained stable, underscoring the importance of recycling e-waste, which contains up to 40 different materials including valuable metals (OECD, 2010; Golev et al., 2016). In 2015, the global value of WEEE was estimated at €48 billion, with printed circuit boards, prevalent in mobile phones and laptops, representing the most valuable part due to high metal concentrations (Balde et al., 2015; Cuchiella et al. 2015). However, recycling's main cost lies in reverse logistics, with collection costs often rendering recycling unprofitable unless subsidized by collection fees from consumers or producers (Hainault et al., 2000; Geyer and Blass, 2010). Despite decreasing precious metal content in mobile phones reducing potential profits (Geyer and Blass, 2010), the increasing volume of devices and higher future metal demands due to declining global ore grades (Lebre and Corder, 2015) and growing REE demands (Dutta et al., 2016; Sverdrup, Ragnarsdottir, and Koca, 2017) suggest recycling will become more economically viable, necessitating more investment in the recycling sector to alleviate the strain on primary mining resources.

3.4 The Urban Mining Concept

Urban mining, defined as reclaiming elements from human-made stocks such as infrastructure, industry, and products, aims to sustain production activities for human comfort and minimize waste discharge by promoting resource recovery (Brunner, 2011; Baccini and Brunner, 2012). It addresses the challenge of resource scarcity and environmental protection by recycling electronic waste, a rich source of precious metals and rare earth elements (REES) (Cossu, 2013; Cossu and Williams, 2015). As global consumption of non-renewable resources increases, leading to potential shortages and growing waste disposal needs, urban mining supports the transition towards a circular economy, emphasizing waste volume reduction, pollution control, and changing societal attitudes towards waste management. The recovery of REEs and precious metals from end-of-life (EoL) products like mobile phones is increasingly vital for reducing import dependency and enhancing the EU's security and independence. While urban mining cannot fully replace traditional mining, it offers a significant reduction in resource extraction (Namias, 2013). Globally, four major smelters - Boliden (Sweden), Umicore (Belgium), Aurubis (Germany), and Xstrata Copper (Canada) - lead in recovering metals from WEEE through smelting and refining, receiving e-waste worldwide. Smaller e-scrap smelters also operate in Japan and South Korea. Recognizing the growing e-waste challenge, these smelters have expanded their capacities, with Boliden notably tripling its capacity from 45,000 metric tons in 2008 to 120,000 tons in 2012 (Namias, 2013), illustrating the scaling efforts to accommodate increasing e-waste volumes.

3.5 Different Recycling Methods

This chapter outlines WEEE recycling methods, distinguishing between pre-processing (dismantling, shredding, separation) and end-processing (metal recovery) phases, as described by Kumar, Holuszko, and Espinosa (2017). **Pre-processing** includes manual/automatic disassembly and separation into material streams, also addressing battery disposal due to its unique process. Shredding and material separation follow, employing magnetic or gravity techniques (Kumar, Holuszko, and Espinosa, 2017; Namias,2013). **Dismantling**, especially manual for large devices, facilitates material segregation, offering benefits like reduced dust and higher material quality but facing challenges with technological advancements and labour costs. **Shredding**, contrasting dismantling, provides quicker processing and greater throughput but at the expense of metal quality and increased dust, emphasizing the need for effective dust management and highlighting high capital costs for shredding facilities (Namias, 2013). **Mechanical separation** post-shredding uses magnetic and other methods to sort metals, with innovations in sensor technology improving efficiency and reducing environmental impacts, despite the high investment required and challenges like dust generation and moisture management in wet processes (Das et al., 2009; Duan et al., 2009; Veit et al., 2014; Kellner, 2008). **End-processing** aims to recover and purify metals through pyrometallurgy, hydrometallurgy, and bio-metallurgy, each with distinct advantages and drawbacks in efficiency, energy consumption, and environmental impact (Namias, 2013). **Pyrometallurgy**, preferred for certain metals, is fast but energy-intensive and environmentally challenging, whereas **hydrometallurgy** offers a controlled, less energy-demanding alternative, suitable for smaller-scale operations despite its slower pace and costliness (Namias, 2013; Khaliq et al., 2014; Veit et al., 2014; Hagelüken, 2007; Valero Navazo, Villalba Méndez, and Talens Peiró, 2014a). **Bio-metallurgy** uses microbes like bacteria and algae to extract metals from e-waste, offering an eco-friendly alternative. Thiobacillus ferrooxidans, an acidophilic bacterium, is notably effective for leaching gold and copper. This method is less costly and uses fewer chemicals but is slow and not suitable for all metals, requiring more research for broader application (Bosecker, 1997; Namias, 2013). In **plastic recycling**, e-waste plastics are utilized as a substitute for coke in pyrometallurgy, reducing energy needs and landfill waste (Hagelüken, 2007). However, only 10% of the annually produced 280 million tons of polymers are recycled. Efficient recycling involves separation by plastic properties, with solvent dissolution shown as an effective method for recycling polycarbonate from e-waste like cell phone cases. Yet, this approach lacks industrial scale adoption due to economic factors and the small volume of products like cell phones (Chandrasekaran et al., 2018). **Battery recycling**, particularly for Lithium-ion batteries in mobile phones, necessitates a dedicated process involving discharging, dismantling, and material separation, followed by leaching to extract valuable metals. This comprehensive process is outlined by Chagnes and Pospiech (2013), emphasizing the need for specialized facilities for safe and effective recycling.

3.6 Regulatory Perspectives of the European Union on Metal Flows

Regulatory frameworks for metal flows and WEEE recycling differ globally. The Basel Convention aims to regulate hazardous waste transport, including WEEE, to prevent dumping in developing countries, but lacks specific definitions for hazardous WEEE, leading to its misuse under the guise of reuse (Peiry, 2010). The Mobile Phone Partnership Initiative (MPPI), involving 12 manufacturers and the Basel Convention, seeks to improve sustainable end-of-use mobile phone management, despite enforcement challenges (Bollinger, 2010). The EU Directive 2002/96/EC encourages WEEE recycling, imposing resource recovery targets and manufacturer responsibility for product lifecycle costs (Magalini et al., 2015). Despite its aims, it struggles with enforcing a 65% recovery rate for mobile phones, suggesting the need for broader recovery strategies beyond metal extraction. The RoHS Directive (2002/95/EC) limits hazardous substances in electronics, promoting safer recycling practices. Recent EU legislation and the Dodd-Frank Act in the US address conflict minerals (tantalum, tin, gold, tungsten) extraction, which finances armed conflict in the Democratic Republic of Congo (DRC) and neighbouring regions. The Dodd-Frank Act requires US-listed companies to disclose conflict mineral use, aiming to reduce armed group financing (Dodd-Frank Wall Street Reform and Consumer Protection Act, 2010). The EU's 2017 regulation seeks to halt conflict mineral imports and ensure responsible sourcing, with compliance required by 2021 (European Union, Directive, 2017/281). Projects like the Critical Raw Materials (CRM) recovery initiative and Remanence focus on increasing WEEE recycling rates and recovering rare earth elements, respectively, to reduce EU dependency on imports and enhance resource security. CoLaBATS aims to advance battery recycling technologies for critical materials, supporting sustainable consumer product and electric vehicle development. These efforts highlight the EU's commitment to circular economy principles and reducing environmental impact.

3.7 Environmental Issues

This section contrasts the environmental impacts of primary mining versus secondary mining, and the recycling practices in developing countries. **Primary vs. Secondary Mining:** Recycling e-waste can significantly reduce the need for primary metal extraction, lowering greenhouse gas emissions and energy consumption (Cui and Forssberg, 2003; Valero Navazo, Villalba Méndez, and Talens Peiró, 2014b). Recycling materials like iron and steel can save 74% of energy, reduce air and water pollution by 86% and 76% respectively, and decrease mining wastes by 97% (Cui and Forssberg, 2003). Smartphones, for example, contain gold at concentrations 25-30 times higher than the richest primary ores, offering an 80% CO2 reduction per unit of gold recovered (Baldé et al., 2017). Urban mining in developed regions, subject to stricter environmental regulations, helps minimize waste and environmental damage, contrasting with primary mining often conducted under less stringent standards. **Recycling in Developing Countries:** A significant portion of EoL mobile phones from the EU is exported to developing countries for reuse or recycling. Despite the Basel Convention's efforts to regulate non-functional e-waste exports, enforcement challenges persist, leading to environmental and health issues in informal recycling sectors (Sthiannopkao and Hung, 2013). Informal recycling processes are inefficient and harmful, with metal recovery rates substantially lower than in formal facilities (Hagelüken, 2007). Developing countries, reliant on the income from informal recycling, face severe environmental damage and health risks from improper handling and processing of e-waste (Annamalai, 2015). Overall, while secondary mining presents a sustainable alternative to conventional extraction, improving recycling practices globally, especially in developing countries, is crucial to addressing the environmental and health impacts associated with e-waste.

4 MATERIAL AND METHODS

This chapter gives a brief introduction to the methodological approach chosen, conceptual modelling using causal loop diagrams. Any complex system like the mobile phone market and their EoL streams needs to be simplified for analysis. Consequently, one has to balance the simplification necessary against the detail needed to represent the system and it's dynamics while also taking data availability into account in order to produce a functioning numerical model. The **Mo**bile **Pho**ne **Dyn**amics model developed for the **EU** (MOPHODYN/EU-model) is based on literature research and calibrated based on data found in the literature.

4.1 Systems analysis and systems dynamics

In this study, we employed systems analysis and dynamics to map out and understand the intricacies of the EU mobile phone market, particularly focusing on the recycling potential of discarded mobile phones. The primary tool for our analysis was the MObile PHOne DYNamics in the EU (MOPHODYN/EU) model, designed to predict aspects such as supply, resource recovery, and the economic impacts of recycling within the timeframe of 1988 to 2050. This model was meticulously developed using Causal Loop Diagrams (CLDs) to identify feedback loops, then further elaborated into a numerical simulation using the STELLA® software platform, drawing on foundational concepts from notable sources in systems dynamics (Forrester, 1971; Meadows et al., 1972, 1992, 2005; Senge, 1990; Sterman, 2000; McGarvey and Hannon, 2004; Senge et al., 2008; Sverdrup et al., 2014a,b).The creation of MOPHODYN/EU was grounded in a comprehensive literature review, ensuring its parameters closely mirrored real-world data and trends. Validation against historical data from the World Bank confirmed the model's robustness and accuracy. Utilizing both numerical modelling and CLDs, we were able to dissect the system's structure, pinpointing critical intervention points for policy suggestions and assessing their potential success This methodological approach, while demanding in terms of insight and parameterization, enabled a nuanced understanding of system properties and the identification of effective strategies for enhancing EU mobile phone recycling efforts. A detailed description of the CLD's, the Stella model can be found in the supplementary material.

4.2 Indicators for the Evaluation of Model Results

To measure the effects and the outcome of different scenarios compared to the BAU case, I defined specific indicators. The indicators should help to understand the results of the MOPHODYNE-EU model and also serve as a tool to test the effects of potential policy measures. Further, they should help to improve the current handling of EoL management of mobile phones in the EU.

4.2.1 The total amount of metal (gold) recovered in tons

The total amount of recovered gold (metal) in tons is used to compare recovery in different scenarios and to calculate the amount of recovered resources in the BAU case. Specific model settings limit the use of this indicator. For example, if mobile phones get used longer, fewer metals will be recycled from phones, because fewer phones will enter the market so less metal will be recovered. When the recovered metal amount is high, it doesn't mean necessarily that is an improvement in recycling it could also just mean that more phones enter the market and therefore more metal got recovered. It has to be discussed in the context of other indicators. The following Eq.1. describes how the total amount of metal (gold) is calculated:

(1)

$$T_m(t) = \sum_{t=0}^{t} T_m$$

The total amount recovered metals (T_m) with metal m at the time t; $\sum_{t=0}^{t} T_m$ is the cumulative mass of metal recovered at the time t. The metal amount recovered will be presented in graphs and tables in the result section. This indicator must be discussed together with the recycling indicator and the available amount of end-of-life phones.

4.2.2 Phone Recycling indicator

In the literature, different recycling percentages are discussed. The literature mentions recycling rate in relation to mobile phones in use at that time and others mention the recycling rate in relation to the EoL mobile phones which would be potentially available for recycling. After testing both methods to determine the recycling rate, I decided to use the phones getting recycled in relation to the EoL phones available is more appropriate to measure the recycling rate. The reasoning behind this is that the recycling rate in relation to the total mobile phones in use is depending on the phone use time and is, for example, decreasing when the mobile phones are used longer. If the total EoL mobile phones moving to storage is put into relation to recycled phones, the recycling rate is not depending on the phone use time. The following Eq. (2) will describe the recycling indicator:

(2) Percentage of EoL phones being recycled (t) =

$$\frac{\text{phones getting recycled (t)}}{(\text{Eol phones moving to storage(t)} + \text{reused phones moving to storage (t)} + \text{Dzf})} * 100$$

The recycling indicator appears to be lower for the model run time from 1988 until 2020 as it actually is. Due to the fast increase of mobile phone entering the market in this time period and also more phones become obsolescent. The ratio of EoL phones moving to storage and phones getting recycled is affected by a system delay which occurs in the MOPHODYNE-EU model and in the real world. Mobile phones remain in the mobile phone system for a couple of years before they enter recycling. To indicate the correct recycling rate for every time step EoL phones were moving to storage in must be compared with phones getting recycled several years later. I decided to compare the EOL phones moving storage with the EoL phones recycled in the same year to include the system delay in my analysis.

4.*2.3* Metal (gold) recovery Indicator

The metal recovery indicator M_{RP} at the time (t) is used to determine the percentage of metal recovered in comparison to the amount of metal entering the system due to sales of new mobile phones. This indicator is used to understand and study the efficiency of the MOPHODYNE-EU model in terms of metal recycling. The following Eq. (3) is used for the calculation:

(3)

$$\text{metal(gold) recovery indicator } M_{RP}\ (t) = \frac{\text{metal (gold) needed for mobile phones (t)}}{\text{metal (gold) recovered from recycling(t)} + \text{Dzf)}} * 100$$

Metal (gold) needed for mobile phones at the time t is calculated from the flow sale of new phones to consumer and metal (gold) per phone. The metal recovered from recycling is calculated from the metal recovery per year flows at the time t.

4.2.4 The energy used in conventional copper mining vs. copper refining from mobile phones

This Indicator shows how much energy is needed in MJ to refine the same amount of copper. Urban mining and conventional mining are put in perspective to each other. The following Eq. 4 describes the total energy needed for conventional mining (Enc) and the total energy needed for copper refining from mobile phones:

(4)

$$\text{Enc (t)} = \sum_{t=0}^{t} E_{nc}$$

$$\text{Erm(t)} = \sum_{t=0}^{t} E_{rm}$$

The energy needed for conventional mining (Enc) in MJ at the time t; $\sum_{t=0}^{t} E_{nc}$ is the cumulative amount of energy needed in MJ for conventional mining at the time t; energy reqiurement for refining copper from mobile phones Erm in MJ at the time t; $\sum_{t=0}^{t} E_{rm}$ is the cumulative amount of energy needed for copper refining copper from mobile phones at the time t. Similar to the total energy used for conventional mining and urban mining of copper. The waste produced by refining the same amount of copper from conventional copper mining in tons is compared to waste produced by refining copper from mobile phones in tons. The total mining waste produced will also be included in the analysis.

Additionally, the profit will serve as an indicator of success since the results of profit are needed to answer the research question. It has to be mentioned that the profit must be discussed together with the recycling rate and the number of available EoL phones, because the profit is depending on the number of mobile phones entering the end of the life process of recycling.

4.2.5 Loop efficiency and Loop leakage

The evaluate the different scenarios compared to the BAU case two circularity indicators, loop leakage by the Ellen Mac Arthur Foundation (2015) and loop efficiency produced by Bollinger (2010) were implemented. In the study from (Sinha *et al.*, 2016) these indicators were used to determine how efficiently gold (metals) are used and preserved in a global mobile phone product SD model. The loop leakage indicator shows the metal fraction leaving the product system and is based on the linear flow index by Ellen MacArthur Foundation (2015). It is an indicator of how sound metals are preserved in the mobile phones system and to what extent the loop is closed (Sinha *et al.*, 2016). To measure the efficiency the loop efficiency indicator which is based on the cradle to cradle indicator (C2CI) developed by Bollinger (2010) got implemented. The indicator indicates how well metals are used practical and effective in the mobile phone system. In the case of the MOPHODYN-EU, it shows how efficient metals are used without hibernating resources (Sinha *et al.*, 2016). To apply these indicators on the MOPHODYN-EU model, I adapted the equations from (Bollinger ,2010) and (Sinha *et al.*, 2016) and modified them . The Eq. (5) illustrates the quantification of loop leakage (l_m) and loop efficiency (e_m) in the MOPHODYNE-EU model.

(5)

$$l_m\ (t) = \frac{\sum_{t=0}^{t} m_d + \sum_{t=0}^{t} m_{dr} + \sum_{t=0}^{t} m_{ex} + \sum_{t=0}^{t} m_{un}}{\sum_{t=0}^{t} m_m(Dzf)}$$

$$e_m(t) = 1- \frac{\sum_{t=0}^{t} m_d+\sum_{t=0}^{t} m_{dr}+\sum_{t=0}^{t} m_{ex}+\sum_{t=0}^{t} m_{rh}+m_h(t)}{(\sum_{t=0}^{t} m_m+Dzf)}$$

Dzf= Division by zero factor= 0,001

The value for loop leakage (lm) is determined by metal m at time t; loop efficiency (em) it is metal m at time t; $\sum_{t=0}^{t} m_d$ is the cumulative mass of metal disposed by consumer through phone disposal at the time t; $\sum_{t=0}^{t} m_{dr}$ is the cumulative mass of metal getting disposed or lost through phone recycling at the time t, $\sum_{t=0}^{t} m_{ex}$ is the cumulative mass of metal getting lost because of export at the time t; $\sum_{t=0}^{t} m_{rh}$ is the cumulative amount of metal from phones remaining in hibernation through phones getting forgotten at the time t; $\sum_{t=0}^{t} m_m$ is the cumulative amount of metal that is needed to manufacture the phones at the time t and m_h (t) is the amount of metal m in hibernating phones (new and reused) at time t.

Both indicators were applied to gold. They could be used for any of the metals tracked in the MOPHODYNE-EU model, but since the behaviour of the indicators is likely to be similar for the other metals, I decided to present and use the indicators for gold only.

4.3 Assumptions and limitations

The MOPHODYN-EU model, covering 1988-2050, validates mobile phone usage against World Bank historical data (2016), assuming subscription numbers reflect actual usage. Future EU population projections are based on a moderate scenario from the European Environmental Agency (2018), considering stable or declining birthrates (Hoßmann et al., 2008). Phone per capita usage in the EU, drawn from World Bank data (2016), is projected to peak at 1.3 by 2022, up from the current 1.24, based on a decade-long stability at around 1.2. Recycling costs exclude collection expenses due to established municipal and private schemes, with a conversion of Geyer and Blass's (2010) cost estimate to Euros using the 2018 exchange rate (XE: Convert USD/EUR, 2018).

The model focuses on recycling precious metals (gold, copper, silver, palladium) due to their high economic value and recyclability, alongside lithium and cobalt, considering their future demand and conflict zone sourcing issues (Azevedo et al., 2018). It assumes whole-phone recycling post-battery removal, mirroring practices like Umicore's, to avoid metal loss. This approach contrasts with conventional copper mining, highlighting recycling's energy and waste advantages. A critical model limitation is treating exported phones as lost resources, ignoring their potential recovery in informal recycling sectors of developing countries. This assumption simplifies the EU's resource potential estimation by considering only domestically recycled metals, overlooking the lower recovery rates in informal recycling and the necessity of metal re-importation (Peiry, 2010; Tischner and Hora, 2012; Navazo et al., 2014; Geyer and Blass, 2010; Azevedo et al., 2018).

4.4 Detailed Model description, Parametrization, Scenarios development, sensitivity analysis and model testing

For comprehensive insights into the methodologies applied, including the model description, the parametrization, scenario development, sensitivity analysis, and model testing, readers are directed to the supplementary material accompanying this article. This additional documentation provides an in-depth exploration of the techniques and approaches utilized in our study, offering a valuable resource for those interested in the finer details of our research process.

5 RESULTS

The MOPHODYNE/EU model is able to reproduce historical dynamics with a high degree of precision and accuracy. As such it provides a good tool for assessing various scenarios for resource policy and consumer action.

The MOPHODYNE/EU model is able to produce a wide range of results for the scenario analysis since the model allows analysis of a large number of parameters (more than used in this study) for each model run. This study is primarily interested in understanding the current mobile phone system in the EU in terms of a number of phones on the market, market development, end of life processes, metal recovery and their economic value. Additionally, the study is directed to identify if there are environmental benefits in resource recovery of mobile phones in terms of energy required and waste produced as compared to primary mining. Further, the model is designed to identify the main driver of the system and to test different scenarios which are evaluated against the BAU case. The results of the scenarios should help to discuss different policy measures that could lead to the more sustainable use of resources and aid to reduce the loss of metals.

5.1 Results of the Business-as-Usual Case (BAU)

5.1.1 BAU Case Model Results for the Number of Mobile Phones in Use Between 1988 to 2050

The business as usual (BAU) represents the base case, the parameter values in this model are chosen by the best estimates from the literature. Fig 11. shows the total number of mobile phones in use in the EU from 1988 until 2050. In the beginning of the model run time from 1988 until 2008 the number of mobile phones in use is growing exponentially until the market is nearly saturated. From 2008 to 2025 the marked is still growing, but not nearly at the same speed as before. In 2016 the model calculated the number of phone users to be around 625 million, according to the World Bank (2016) 630 million mobile phones subscribers exist in the EU by 2016. According to the model, the number of mobile phones in use is increasing until the year 2025. In the year 2025, the number of phones in use reaches its maximum with 662 million phones in use and afterwards the number of mobile phones in use is staying stable until the year 2033. In the year 2033, the number of mobile phones in use starts to decrease slowly. The reason for the decrease in a number of mobile phones in use is the expected population decrease of the EU population according to (EEA, 2016) along with the decreasing population the number of potential phone users is decreasing. According to the EU mobile phones model, the total number of new mobile phones sold in the EU market from 1988 until 2050 is around ~15 *billion phones*.

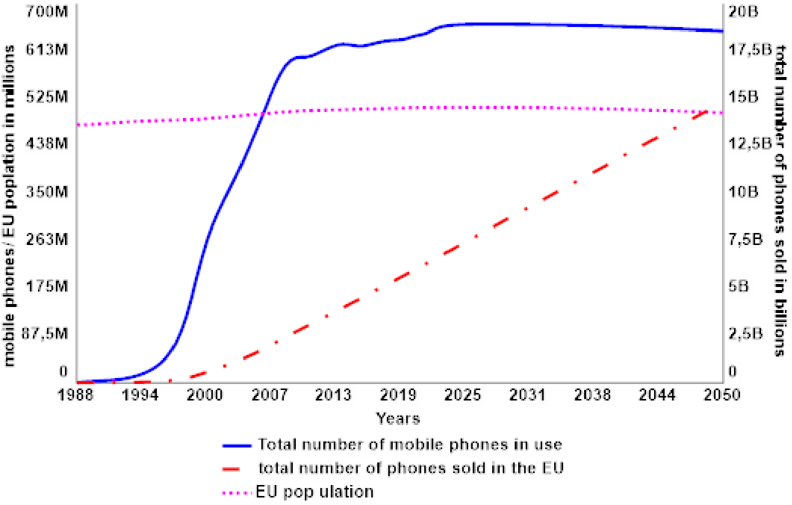

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Figure 11: Shows the results for BAU case in terms of the total number of phones in use, EU population (based on EEA 2016) and the total number of phones sold in the EU between 1988 to 2050

5.1.2 The Result of the BAU Case for the Total Number of EoL Phones Available and the Management of EoL Devices from 1988 until 2050

The result of the BAU case model run in Fig.12. shows the number of new and reused EoL phones moving to storage in the EU per year and the management of EoL devices, from 1988 until 2050. Between 2010 and 2050 there are around 300 to 330 million EoL phones entering the storage each year, in the same time 141 to 165 million phones per year, around half, of the EOL phones which are entering the storage are forgotten and remain in consumers drawers. The other half of the EoL phones is leaving the storage and end up at a different end of life processes. Between 2010 to 2050 an average of ~32 million phones are disposed by the consumer, ~66 million phones get exported, ~31 million are entering recycling, and ~29 million get resold for reuse each year.

The percentage of mobile phones entering the recycling compared to the EoL phones moving to storage per year (recycling indicator) is presented (green solid line) in Fig. 12. The recycling rate remains unchanged in the business as usual with a set rate of 0,25 of the collected phones being recycled (similar for new and reused phones), the results show a lower percentage for the recycling indicator for the year 1988 until 2014-2015, this is caused by the system delay and the fast growth of the mobile phone market caused by phones entering the EU market via sales of new phones. It takes a while until the EoL devices enter the recycling stream due to hibernation in consumers drawers and overall system delays. In 2008, there are around 303 million EoL phones moving into storage per year while only 25 million units are entering the recycling stream in the same year. That accounts for 8.5% per cent of EoL mobile phones which are entering the recycling. Further testing of policy measures and system changes in terms of scenarios will be analysed for the model runtime 2010 to 2050. The scenarios will be introduced in 2018. That time frame is more interesting for the analysis since it is in the future, and it is easier to see when and how the measure will interact on the system because the market is not growing exponentially at that point.

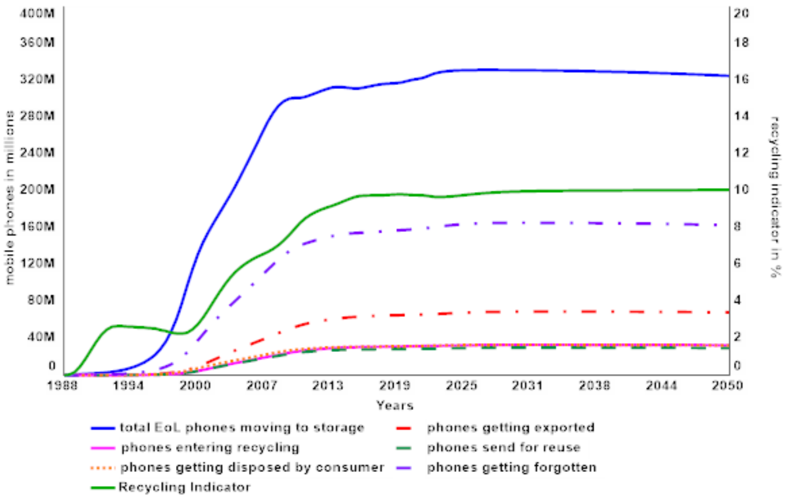


Figure 12: shows the result of the BAU case for the total number of EoL phones available and the management of EoL devices from 1988 until 2050.

5.1.3 *Amount of Metals (t) Used, Potentially Available and Recovered in the BAU Case and Their Economic Value*

Table 13 shows how much gold (Au), Palladium (Pd), silver (Ag), lithium (Li), cobalt (Co) and copper (Cu) is entering the EU mobile phones system calculated from the amount of metals needed for mobile phones entering the system via sales of new phones to consumer until 2050. The maximum amount of metals which are potentially available for recovery with the current state of the art recycling technics and the results for the amount of recycled metals in the BAU case are presented in Table 13. The metal recovery indicator shows the percentage of metals recovered entering the MOPHODYNE/EU model. Results of metal recovery indicator MRP differ for different metals since each metal has a different recovery rate. Gold, for example, has the highest MRP since gold also has the highest recovery rate with 97%. The metal recovery indicator shows that only 7,2% up to 9,3% depending on the metal is recovered. The result for the max. amount of metals available for recovery clearly indicate that vast amounts of metals are lost and not recovered in the MOPHODYNE/EU model.

Table 13: The cumulative amount of metals used for mobile phones entering the system, max. available amount for recovery under the current state of the art recycling, metal recovered in the BAU case until 2050 (ton and % respectively).

Metals analyzed	Tons used in mobile phones by 2050	Max. amount of metal in tons available for recovery by 2050	Total amount of meta Recovered in the BAU case by 2050	Metal recovery percentage (MRP)
Au	444.5	431.2	41.3	9.3
Pd	666.8	613.5	58.8	8.8
Ag	7557.1	6952.5	666.1	8.8
Li	35562.8	26672,1	2555,4	7.2
Co	93352.0	82149.8	7870.0	8.4
Cu	222267.0	195595.0	18740.0	8.4

5.1.4 Average Yearly Recovery of Metals and Their Economic Value in the BAU Case Between 2010 to 2050

The table 14. shows the results of the BAU case in terms of average yearly recovery of Au, Pd, Ag, Li Co and Cu in tons and their economic value. The table also shows the average total economic value of the recovered metals per year calculated with the current metal prices. It is important to state that the economic value is not the profit since the profit is including the recycling costs per phone and /or the recycling costs per battery. The total average economic value of ~89 € million per year between 2010 to 2050 indicates that the EoL mobile phones have a high value in terms of the resources they hold. The recovered amounts of metals per year clearly indicate that recycling has the potential to reduce the need for primary mining or resource import. With an average profit of approx. ~70 million Euros per year in BAU case between 2010 to 2050, mobile phones recycling seems to be economically viable. On the other hand, the recycling of mobile phone batteries is not profitable. The average profit in the BAU case between 2010 to 2050 for battery recycling is negative with around -~48 million Euros per year. With the current state of art recycling technics, the recycling of mobile phone Li-batteries is not economically viable. To calculate the profit the recycling costs per phone or the recycling costs per battery is included in the calculation and subtracted from the economic value of the recovered metals. The costs of recycling per phone are excluding the costs for collection and transport of each phone since the European Countries have implemented municipality collection station where consumers can bring their WEEE waste and pay for the amount of the delivered EoL products or the taxes cover the costs end of life management. There are also plenty of private collection schemes, and it would exceed the limitations of this study to include them all.

Table 14: Results of the BAU case for the average amount of metals recovered per year and the aver- age economic value of the recovered metals per year.

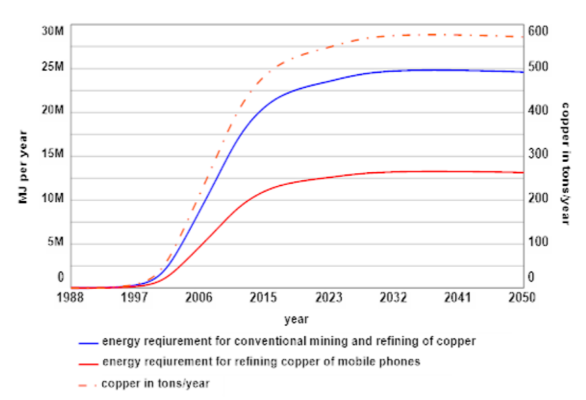
Metals analyzed	The average amount of metals recovered between 2010-2050 in tons each year in BAU case	An average Economic value between 2010-2050 of recovered metals in a million Euros per year
Au	0.93	~32 *million* €
Pd	1.3	~35 *millio ton* €
Ag	15.0	~7.5 *million* €
Li	57.7	~0,84 *million* €
Co	177	~11 *million* €
Cu	421.3	~2.5 *million* €
Total		~88.8 *million* €

5.1.5 Energy in Copper Refining: Phones vs. Mined Ore

Figure 13 shows the results for the energy consumption in MJ/year for the pyrometallurgy process of refining the same amount of copper, using conventional mined copper ore vs mobile phone as a copper source. The results indicate the energy consumption in the same process for the same amount of copper is nearly twice as high for conventional mined ore compared to mobile phones as a copper source.

5.1.6 Waste Comparison: Urban vs. Conventional Copper Mining

The difference in waste produced during conventional primary mining compared to secondary mining is presented in Fig. 14. This analysis includes the amount of mining waste produced to produce copper, and the amount of slag produced during the pyrometallurgy process for conventional mined copper ore and the use of mobile phones as a resource for the production of the same amount of copper. By 2050 around 20000 tons of copper will be recovered due to mobile phone recycling in the BAU case, which will lead to approx. 7400 tons of slag waste in the pyrometallurgy process. If the same amount of copper was to be produced and refined from conventionally mined copper ore approx. 55000 tons of slag waste and around 5 million tons of mining waste will be produced.



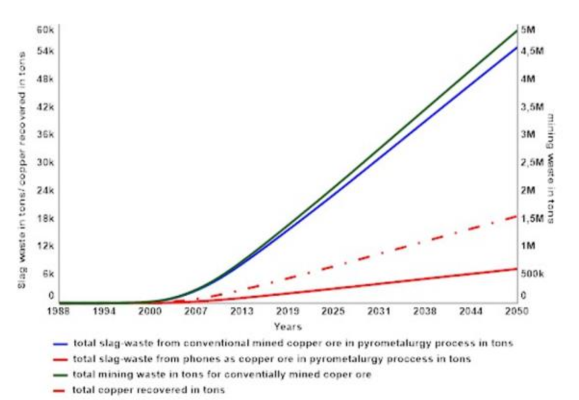


Figure 13 left: Energy consumption (MJ/year) for copper refining in the pyrometallurgy process for Urban mining vs conventional mining for the same amount of copper (tons/year) Figure 14 right: Total waste produced for the same amount of copper refined: Urban mining vs conventional mining

5.2Results of the Business-as-Usual Case Compared to the Scenarios 1 to 5

5.2.1Results of Scenario 2 Monetary Incentives vs BAU Case

Figure 15 shows of the results for the scenario 2 to 2.5 compared to the BAU case scenario for loop efficiency values. The results for loop leakage and total gold recovered showed also improved results with higher incentives and can be found in the appendix C. With higher incentives more phones are returned which triggers the improvement in the loop leakage, loop efficiency and total gold recovered since the number of mobile phones getting forgotten in consumers drawers is reducing the higher the incentive is. The highest results are reached in scenario 2.5 which has the highest monetary incentives with 30 € for returning a mobile phone. In addition, the scenario 2.5 effects the collection rate positively and decreases the disposal rate. For the following analysis, the result of the scenario 2.4 are used since the base for that scenario is the highest monetary incentive with 20 Euro mentioned in the inter- view of (Ylä-Mella, Keiski and Pongrácz, 2015)

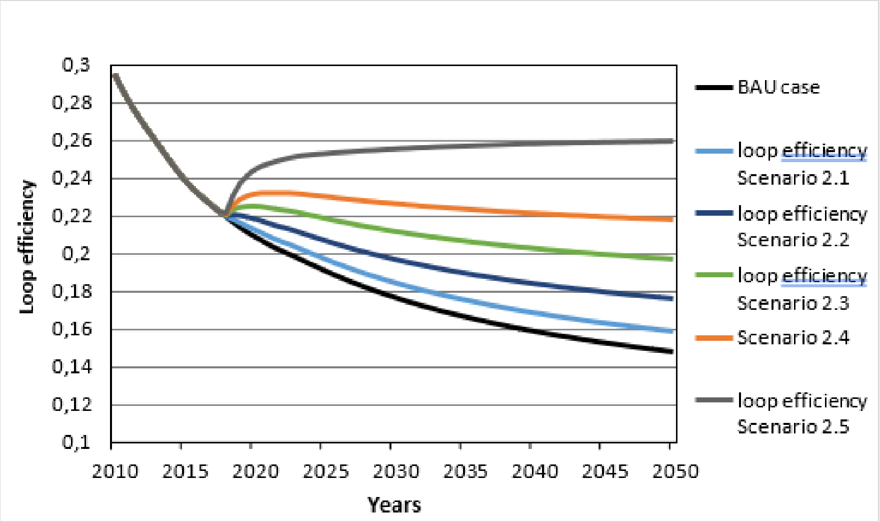
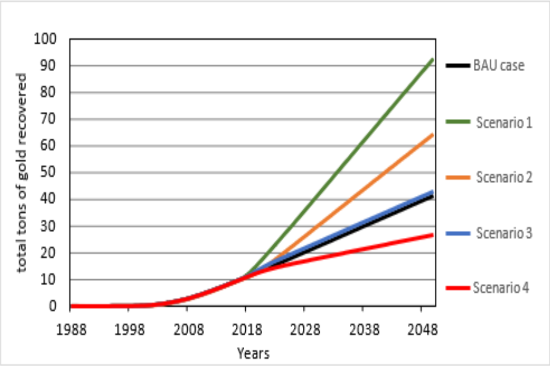


Figure 15: Loop efficiency of scenario 2 vs BAU case

5.2.2 Results for the Total Amount of Gold Recovered, Scenario 1 to 4 vs BAU Case; Scenarios Starting in 2018

Differences in the total amount of gold recovered for the BAU case and for Scenario 1 to 4 are presented in Fig. 16. The total amount of gold recovered in the modelled system is predictably the lowest for the Scenario 4, given that the phones use time is changing from 2 years to 4,5 years, which results in fewer phones entering the market and therefore fewer phones will be available for recycling. Scenario 1 has the highest amount of total gold recovered, which could be expected since the scenario 1 is affecting the export rate negatively and the recycling rate positively, resulting in more phones getting recycled and therefore for more gold recovered (metals). The second highest gold recovery is reached in scenario 2. The monetary incentives have a positive effect on the variable rate of EoL moving out of storage and a negative effect on the rate of phones getting forgotten, with increasing numbers of EoL mobile phones leaving the storage more mobile phones will end up being collected and therefore more will be recycled. The BAU case results and the results of scenario 3 are close together. Scenario 3 shows a slightly higher gold amounts recovered because the hibernation time is changing directly from 2 years to 0,5 years in 2018 which results in a high number of mobile phones leaving the hibernation stock in a short time until the stock normalized to the lower hibernation time. It can be expected that the scenarios will have a similar effect on the other metals studied in MOPHODYNE/EU model.



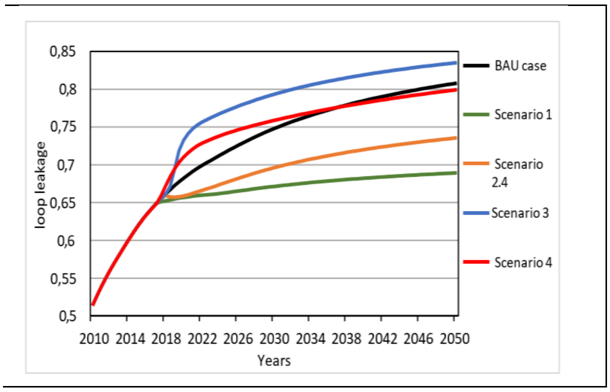


Figure 16 left: Total gold (metal) recovered in BAU case vs Scenario 1-4. Figure 17 right: Loop leakage of gold: BAU case vs Scenario 1-4

5.2.3 Results for the Loop Leakage, Scenario 1 to 4 vs BAU Case; Scenarios Starting in 2018

The loop leakage indicates the fraction of gold (metal) that is leaving the EU mobile phones system, i.e. it indicates to what extent the mobile phone system loop is closed and how well the gold (metal) is preserved in the system. A higher loop leakage values are meaning that more gold (metals) is leaving the EU mobile phone system and is therefore lost for recovery. Figure 17 shows the result of the different scenarios on the loop leakage. The lowest loop leakage is reached in scenario 1 with a loop leakage value of around 68.9 % by 2050. Second lowest loop leakage is reached in scenario 2.4 with a loop leakage value of around 73.5% by 2050.The result of the loop leakage values for the scenario 4 and the business as usual case are close together with 79.9% and 80.8% , with slightly lower values reached in scenario 4 by 2050. Shortly after the implementation, scenarios 4 results in a higher loop leakage than the business-as-usual case, this is due to the reduction of gold (metals) entering the market caused by a longer phone use time and therefore lower sales of new phones. The highest loop leakage occurs in scenario 3 with 83.4% by 2050, which is caused by the shorter hibernation time. Therefore, more phones are reaching the end-of-life process in a shorter time which triggers a higher loss of gold (metals), since no change of the EoL management of phones is occurring in this scenarios. A similar impact of the scenarios can be accepted for the other metals researched in the MOPHO- DYNE/EU model.

5.2.4 Results for the Loop Efficiency, Scenario 1 to 4 vs BAU Case; with the Scenarios Starting in 2018

Loop efficiency is describing how efficiently resources in, this case gold, is utilized in the MOPHO-DYNE/EU model without hibernation. Figure 18 shows the impact of the different scenarios on the loop efficiency with the scenarios starting at 2018. The highest loop efficiency value with 26,6 % by 2050 is reached in scenario 1. Second highest results in the loop efficiency are reached in scenario 2 with a loop efficiency value of 21,8 % by 2050. The results of scenario 3 show that there is a short peak in loop efficiency between 2018 to 2022, caused by a shorter hibernation time resulting in a high number of mobile phones leaving the stock “phones in hibernation” in a short time period. By 2050 the loop efficiency values for the BAU case and scenario 3 are close together with 14,7% and 15,1 %. The third highest efficiency is reached in scenario 4, with 16,8 % by 2050 which can be explained by the lower amount of metals getting lost in the system, because mobile phones will have a longer phone use time starting 2018 Therefore the amount of metals entering the MOPHODYNE/EU model will be lower.

5.2.5 Results of the Optimal Case Scenario on the Loop Leakage and Loop Efficiency vs BAU-Case

Figure 19 shows the impact of the optimal case scenario on the loop leakage and loop efficiency with the optimal case scenario starting in 2018. The loop leakage and loop efficiency both show improved results in the optimal case scenario compared to the BAU case. By 2050 the optimal case scenario improved the loop efficiency to around 60% (BAU case approx. 22 % at, 2017 and around 15% by 2050). The result for loop leakage with 40 % leakage by 2050 (BAU case approx. 65% at 2017 and 80% at 2050) indicate that the optimal scenario is helping to reduce the loss of metals in MOPHO- DYNE/EU model.

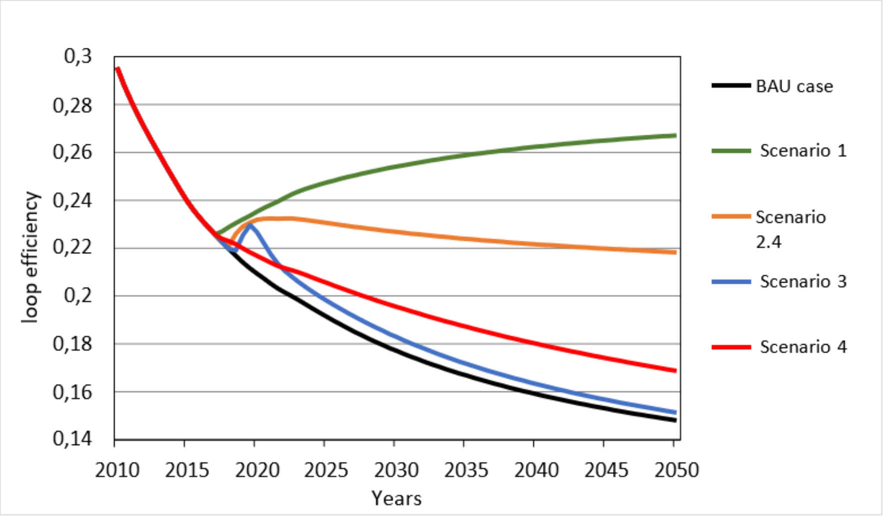


Figure 18: Loop efficiency of gold: BAU case vs Scenario 1-4

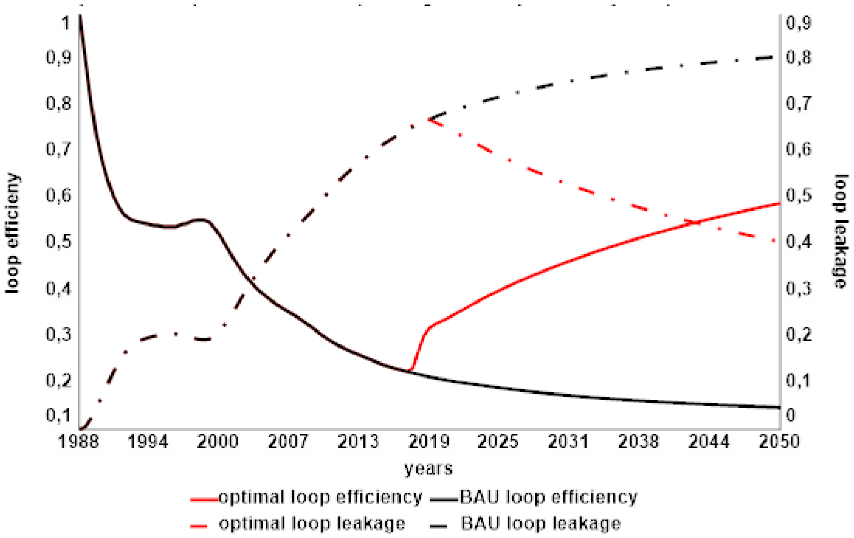


Figure 19: *Impact of the optimal case on loop leakage and loop efficiency vs BAU case*

6. DISCUSSION

The MOPHODYNE/EU model developed for this study is a useful tool to understand the mobile phone lifecycle and the end-of-life processes of mobile phones in the EU. The model is designed to deliver answers for the research questions and is specific for the system as modelled and is highly depending on the quality of the input data. The model is thoroughly tested with historical data, structure behavior and structure assessment test and is suitable for the purpose of this study. System dynamic models like the one developed and used for this study are not intended to simulate a precise replication of the real-world environments since simplification are always necessary in order to create a functional and understandable, i.e. useful, model. A reduction of complexity to the main drivers of a system is always the aim and essential to create a useful model. The results of the MOPHODYNE/EU model should not be over interpreted. They do, however, strongly improve our understand of the dynamics of the mobile phone resource system and help to assess the effect of different potential policy options that may be chosen in order to effect changes to further a more circular resource use.

6.1 The BAU Case

The results of the BAU case represent the past and the current development of the EU mobile phone market, including the future assuming no changes in current practices are made. In the BAU case, Fig. 11, the EU mobile phone marketed was growing exponentially between 1988 to 2008, from 2008 until 2024 the numbers of phones in use is still rising but at a much slower rate. From 2024 to 2050 the number of the phone in use will decrease slowly due to the predicted reduction in population size in the EU. Currently, there are 631 million mobile phones in use in the European Union. The BAU results for the market development conforms with the published data for mobile phone subscribers from the (Worldbank, 2016). Current trends also indicate that the EU phone market is saturated, the growth is declining as most people already own phones and are not replacing them on a yearly basis (Jansen, 2018).

The results of the BAU case shown in Fig. 12. Indicate that around half of the end-of-life phones, each year end up being forgotten in consumers drawers and therefore remain inaccessible for recycling and metal recovery. Devices which leave the hibernation stage and are not forgotten end up in four different end of life processes: disposal by the consumer, send to export, send for reuse and send to recycle. Between 2010-2050 around 10% of EoL phones get recycled, ~ 20% get exported, ~10% get reused, and ~10% are disposed of each year. Observed results for the EoL management in the BAU case fall within the range of the published field data for the EoL management. But since there is a range of values published it is difficult to confirm the calculated quantities with certainty. According to the model there is a demand for around 300 million devices which are getting sold each year in the EU. Further the results reveal that most of the EoL devices never end up in proper recycling facilities. Therefore over 90% of the metals which are used to manufacture the mobile phones which are sold in the EU are lost and not available for recovery. One of the major losses in the system is caused by consumers since they don’t return their EoL mobile phones back into the system and rather store them instead in their drawers. The underlying problem for this behavior is the lack of awareness of recycling possibilities, forgetting of devices, keeping phones as a spare, emotional attachment to previous devices, security issues regarding the data and misconceptions of the resource value contained by these devices. A more detailed approach to understanding the underlying problems can be found in the studies of (Jang and Kim, 2010; Wilhelm, Yankov and Magee, 2011; Yin, Gao and Xu, 2014; Ylä-Mella, Keiski and Pongrácz, 2015;Wilson *et al.*, 2017). Further, the export and disposal of devices can be identified as a problem which has a negative effect on the recycling of mobile phones. Between 2010 to 2050 around ~90 million devices per year end up being exported or disposed by the consumers.

Also, here the underlying problems are beyond the scope of this study and are more to be seen as a mix of social, financial and legislative problems. Consumers dispose of their mobile phones since they are not aware of the environmental problems that occur by disposing of the devices, further they are not aware of recycling opportunities, and it is more convenient to throw mobile phones into the general waste. When it comes to export of mobile phones there is a lack of enforcement of the current legislation (Basel convention, 2009) and it simply cheaper or more lucrative to export devices than to recycle them when they can’t be resold on the EU market. Many unofficial ‘’waste recyclers’’ claim to recycle the EoL devices, but in fact, devices are exported and resold to developing countries. The problems that can be identified is that often functional and non-functional devices are exported together. Additionally, the reselling of devices to developing countries is not problematic in itself, it is rather environmentally beneficial to reuse devices instead of manufacturing new ones. The problem occurs when exported devices reach the end-of-life phase since most countries outside the EU lack specialized facilities for recycling and EoL devices end up being informally recycled or landfilled which leads to huge environmental damage and health problems for the population and nature where it takes place. In terms of resource security and metal recovery perspective for the EU, the export has the negative effect that all the metals contained by mobile phones are lost and not accessible for recovery. If the de- vices would be treated and recycled in the EU, the resources remain in the EU and could be resold to the manufacturers, resold to manufactures inside the EU or reduce the need for import of resources. Further the recovered metals could be used to create a resource depot as a security stock for crisis since the European Union uses approximately around 25-30% of the globally produced metal while only 3% of the global production takes place in the EU, which result in an increasing dependence on resource imports (Department for Environment Food and Rural Affairs, 2012). The results are shown in Fig. 12. also reveals that the reuse rate of mobile phones is quite low. The study from (Ylä-Mella, Keiski and

Pongrácz, 2015) reveal that consumer prefers to buy a new device over the purchase of second-hand devices, which is due to lack of trust in second-hand devices and missing guarantees. It is reported that the reuse market is growing especially for high-end devices, which show a longer lifetime due to better repair options and availability of spare parts. A growing reuse market enables the change to release some pressure on the manufacturing sector and reduces the need for resource extraction, since the devices are already manufactured. A growing trend of repair opportunities can be observed in current market development. For the manufactures, on the other hand, it is more interesting to sell new devices cause they offer a higher profit margin. In the past several years manufactures got accused of building their devices with planned obsolescence, which is causing planned fallouts of devices and is shortening the mobile phone lifetime.

There is a need for a shift in manufacturing practices and legislation forbidding that practices. The model results for the number and percentage of phones entering the recycling clearly indicate that there is room for improvement. Between 2010-2050 only around one out of ten EoL phones which is moving to storage end up in a proper recycling facility. The calculated percentage of around 10% for recycling between 2010 2050 is in the range of values published in the literature. The result presented in Table 13 and 14 shows the amount of resources used for manufacturing mobile phones for the EU until 2050, the amount of resources which are potentially available for recovery with current state of art recycling by 2050 and the amount a resources recovered by 2050 in the business as usual case, further the metal recovery percentage is given for each researched metal. The result indicates that the mass of mobile phones used during the model run time holds quite a significant amount of resources which could be recovered. The recovery is quite low in the BAU case due to the above-discussed problems of phones not entering the recycling and is further limited by the metal recovery rate of cur- rent recycling practices. Considering the result of Tab. 14. which shows the results for average metal recovery per year between 2010-2050 in the BAU case it becomes clear that metal recovery of mobile phones has the potential to reduce the pressure on primary resource extraction, even though the recovered amounts are marginal compared to the global production of each metal. If we look at the estimated average economic value per year, for the same time frame, of each metal it becomes obvious that EoL devices have non negligible economic value. Considering that the estimation is calculated based on current metal prices and not accounting for price developments in the future, it has to be kept in mind that the economic value might even rise further. The predicted future scarcity of re- sources (Sverdrup, Koca and Ragnarsdóttir, 2013; Sverdrup, Ragnarsdottir and Koca, 2017), might lead to increased demand and rising metal prices which could result in an increased economic value of the researched resources. In fact, the prices for lithium (Martin *et al.*, 2017) and cobalt are already rising due to the change to electric vehicles and the ongoing increase in demand for lithium batteries. According to the calculation of the model the recycling of mobile phones is profitable with an average annual profit of 70 € million per year between 2010- 2050. The increased investments of several smelters like Boliden and Umicore indicates that the e-waste recycling is a profitable business. However, the recycling of Li-batteries is not to be found profitable with average costs of -48€ million per year between 2010- 2050. Currently, the recycling of Li-Batteries is subsidized, and there is a need for developing more cost-effective and efficient recycling methods to make the process profitable. It is necessary to mention that the calculations are excluding collection and transporting cost and that further research is needed to include these. The costs were excluded based on the assumption that waste col- lection and transportation in the EU is covered by taxes or costs for transport, collection and recycling are transferred and paid by the consumer.

All rates used in the MOPHODYNE/EU model like collection rate, disposal etc. are outside variables and are chosen by best estimates from the literature, further research is needed to understand the social aspects and gather knowledge, which is required to improve the consumer's behavior, and manufacturing practices towards improved collection and recycling behavior.

6.2 Discussion on Copper Refining: Slag/Waste and Energy from Ore vs. Mobile Phones

Results of MOPHODYNE/EU model illustrates that the recovery of copper from mobile phones is less energy demanding than the refining of copper from conventionally mined copper ore. It is important to note that the calculation of the energy requirement is conservative as it only takes the pyrometallurgy process into account; it is excluding the energy required for transport and other processes. The results clearly indicate that the recovery from e-waste, in this study from mobile phones, has environmental benefits since only around half the energy is required for the refining process compared to the conventional mined copper ore. Also, in terms of waste production, recycling is a more environmentally friendly way to produce and refine copper. The model result in Fig. 14. clearly indicate that the use of mobile phones as a copper ore is producing less waste in the recovery and refining process than conventional mined copper ore. Additionally, the slag waste from refining copper from mobile phones is sold as a construction material for road construction and can therefore not be seen as waste. On the other hand, the slag-waste from conventionally mined copper ore is usually landfilled. If the mining waste produced per ton of copper is included in the analysis, it becomes even more apparent that the recovery of copper from mobile phones is beneficial in terms of waste reduction and therefore is able to reduce the environmental pressure of primary resource production. Furthermore, the recycling from mobile phones is not nearly covering the demand of copper, but an increase of recycling in general, would aid the reduce the primary copper mining and refining and therefore reduce the environmental damage related to it, including a reduction of GHG emission associated with mining. There is additional benefits of recycling mobile phones over using conventionally mined copper ore since a mobile phone contains various precious metals and can be seen as a more diverse source for resources. In the same process of copper refining from mobile phones other metals can be recovered which makes the environmental benefit even more evident. The study of (Valero Navazo, Villalba Méndez and Talens Peiró, 2014b) shows that the energy required for extraction and production of other metals contained in mobile phones likewise is very high. The energy and waste savings by recycling also other metals used in mobile phones is excluded in this study but would, obviously, be similar to copper. '

6.3 Discussion of the Scenario Results

This chapter will discuss the effect of the scenarios on the loop leakage, loop efficiency and the total gold recovered, the result will be compared to the results reached in the business-as-usual case. The Figures 16,17 and 18 show the scenario results.

6.3.1 Discussion of Scenario 1 Export of Functional and non-Functional Phones is Forbidden

The strongest impact compared to the BAU case could be observed for scenario 1. The result for recovered gold, loss of gold measured with the loop leakage and efficient use of gold measured with the loop efficiency where positively affected in scenarios 1. The base for scenario 1 is the implementation of an export ban for functional devices and stronger enforcement of the current export ban for non-functional devices. The implementation of scenario 1 under real world conditions is problematic. Enforcement of the current export bans of non-functional devices under the Basel convention is not working mainly owing to lack of control. It is possible for waste shippers and processors to declare the e-waste as used goods which are not covered by the Basel convention (Sthiannopkao and Hung, 2013). The export of functional devices for reuse is not that problematic itself; the problematic part is the management of EoL devices in the countries where mobile phones get exported to. One way of tackling this problem could be the implementation of proper recycling facilities in the developing countries, but since the initial investment needed is quite high, it is not a viable option for most developing countries due to lack of funds. Further, an option could be that devices which got exported for reuse get imported again when they reach their end-of-life phase (Watson *et al.*, 2017). By doing so, it is ensured that recycling is done in its most efficient and environmentally friendly way and the recovery of metals would remain high. Currently, the startup ‘’closing the loop’’ is buying back buying back previously exported phones which reached the EoL phase in five developing countries and deliver them to Umicore to ensure proper recycling. However, the reverse logistics of importing previously exported devices seems to be quite difficult and requires capital. Another way to implement scenario 1 could be the implementation of new legislation which regulates export stronger and forbids the export of functional and non-functional EoL devices. To ensure such an implementation can work, stronger enforcement and controls are needed to guarantee the illegal exports would be reported and punished on an international level. Another approach to reducing the export of devices can be reached by supporting the domestic reuse market for example by reducing VAT tax for repair and second-hand phones sales (Watson *et al.*, 2017), an implementation of legislation to ensure the access to original spare parts, information about the environmental impact of smartphones inform of informational campaigns and by strengthening the guarantee rights for repaired and/or second hand phones. In the case of a growing market for reused phones inside the EU, the export would shrink since it is probably more profitable to sell used phones inside the EU than exporting them to developing countries.

6.3.2 Discussion of Scenario 2 Monetary Incentives for Recycling Mobile Phones

Scenario 2 is reaching the second-best performance for loop leakage, loop efficiency and total gold (metal) recovered compared to the other scenarios and the BAU case. The base for scenario 2 is a financial incentive to motivate consumers to return their phones back into the system and decreasing the amounts of mobile phones being forgotten. According to the MOPHODYNE/EU model, 50% per cent of the EoL mobile phones remain forgotten in consumers drawers and are therefore inaccessible for collection and recycling. This scenario discovers the effect of the implementation of a monetary take back incentive to increase the number of mobile phones being returned and is based on interview answers of the studies from (Ylä-Mella, Keiski and Pongrácz, 2015) and the author's assumptions. Fig 15. Shows the effect of the different incentive amounts on the loop efficiency compared to the BAU case. Higher incentives improved the results of the loop efficiency due to the increasing positive effect on the rate of mobile phones leaving the storage and the decreasing effect of the rate of mobile phones getting forgotten. The highest results for loop efficiency were reached with the 30 Euro incentive, for the following analysis shown in Fig 16,17,18 the 20 Euro incentive is used because it is the highest mentioned amount in the interviews. To understand when and how incentives could work, more research is needed, since the assumption that a higher incentive would motivate consumers more to return their devices can be problematic, since it is also important how incentives are implemented and under what circumstance the financial reward is paid to the consumer for the return of old devices. To implement this scenario successfully in the realty more understanding of the consumer's behavior towards returning devices is needed. Nevertheless, there are several possible ways how the realization of this scenario can be transferred into the real world. For example, the implementation of a deposit system for mobile phones with an initial amount paid by the customers when they are purchasing a phone that will be returned when their devices reach the EoL state and are handed over to a collection point could be a possible way. Educational campaigns could aid to increase the consumer's awareness for the resource potential of mobile phones and educate them about the mobile phone deposit system. Also, it is necessary to increase the awareness and accessibility for return points, since many mobile phones owners answered in several studies (Ylä-Mella, Keiski and Pongrácz, 2015; Wilson *et al.,* 2017) that they are not aware of the location of collection stations and that they don’t know about recycling options for mobile phones. In several EU countries a deposit system for single-use plastic bottles and cans got introduced which is leading to higher return rates. To create a functional deposit system for mobile phones an increase in collection points and the right amount of incentive is needed. Another way to implement the scenario could be the implementation of leasing business model instead of ownership of mobile phones, where manufacturing companies remain the owners of the phones, and the replacement of non-functional phones requires the returning of the old devices.

6.3.3 Discussion of Scenario 3 Reduced Hibernation Time

The results of scenario 3 in terms of loop leakage show higher results compared to the BAU case; this is due to the change of in hibernation time, which results in mobile phones being faster accessible for the end-of-life processes. Since the scenarios do not involve changes for handling end of life phones more phones and the gold, they contain become lost in a shorter time period. On the other hand, the result for loop efficiency and total gold recovered show higher values compared to the BAU case since the reduction in hibernation time also leads to a higher number of the phones being accessible for recycling due to the reduction of the number of phones which are stuck in consumers drawers. Shorter hibernation time is beneficial in several ways that do not resemble MOPHODYNE/EU model. A shorter hibernation time would result in a decrease of phones in hibernation and increase the number of phones that are moving forward to the collection phones per year. It is likely that a shorter hibernation time would also lead to fewer phones being forgotten since consumers might be still aware of the existence and the value of their old phones, which is not implemented in the model. One could argue that a shorter hibernation period might also increase the chance for reuse since the phone models that reach the collection would be more recent models. According to the study of Wilson *et al.*, 2017 the value of hibernating phones is decreasing and the costs for reuse, recovery, refurbishment, and recycling is increasing with longer hibernation times. The implementation of incentives informs of discounts for returning old devices while purchasing new devices could increase the return rate of EoL phones. The study of Wilson *et al*., 2017 also observed that many consumers are not aware of the value of mobile phones as a resource and in addition many consumers reported to be unaware of the returning options. In the same study consumers reported that they keep their old phones as a spare in case their current devices break or for an occasion where they fear their current devices could break (festivals, outdoor activities). This is a business opportunity for a circular business model where primarily used and retired phones are returned and replaced with durable less valuable second-hand devices to satisfy the need for a secondary phone. In addition, educational programmes and an increase in collection points could aid to reduce the hibernation time.

6.3.4 Discussion of Scenario 4 Longer Phone Lifetime

In scenario 4 the amount of recovered gold is the lowest compared to the results of other scenarios and the BAU case, this is due to the change in phone use time. In scenario 4 the phones use times changes in the year 2018 from 2 years to 4,5 years, with a more extended phone use time the number of new mobile phones entering the EU market is decreasing. The results for the loop leakage indicate that the amount of metals which are lost during the model runtime is just a little bit lower than the results of the BAU case by 2050. On the other hand, the results for scenario 4 show positive improvement in terms of loop efficiency.

Mobile phones have a potential lifespan of 5 to 10 years (Mitchel, 2017), but most consumers use mobile phones only between 12-24 months. The reason behind this behavior is the high penetration of advertisement and the market flooding with technical marginal improved devices on a yearly bases. Consumers are misled by advertising which promises an experience rather than a product which leads to early replacement sales, even though up to 90 per cent of the end-of-life devices are still functional. Fast replacement fuels further production of new phones and has a huge environmental implication since only a small portion of the retired devices end up in proper recycling. Even if all recycled phones would end up being recycled, the fast replacement would still result in higher manufacturing numbers and therefore trigger unnecessary resource use. The circle of production and replacement gets further strengthened by manufactures which build devices with planned obsolescence, non-replaceable parts, and non-durable screens. Even often updates are designed to be incompatible with existing Application or simply to slow down the installed operating system. The manufacturing process of one mobile phone generates waste which accounts for 200X the weight of a phone (Mitchel, 2017). A change in the mobile phone use time towards a longer phone use time has mainly the positive effect that resources would be used more efficiently. With longer phone use time the need for the production of mobile phones and therefore the demand for resources used in the manufacturing process would decrease. Additionally, the number of EoL devices is decreasing, and with it the amount of e-waste improperly handled. As a result, a longer phone use times could reduce the pressure on the primary mining, reduce the environmental harm from e-waste and reduce health problems occurring from e- waste.

There are several ways to reach a longer phone use time. Manufacturers should start to consider and measure their innovation, not in marginal technical improvements, but should instead try to invent more durable and more sustainable devices, where spare parts are easily replaceable. Currently, there are two companies with (Fairphone and Shiftphone) that implemented a modular phone design and working towards these goals. The further political legislation is needed to forbid for example build in batteries and planned obsolescence, preventing manufactures triggering a fast replacement by build-in defaults. In addition, a political measure should be taken to guarantee that old devices will be still constantly provided with software updates from the manufactures. Also, consumers should question their consumption behavior regarding the replacement of mobile phones, to reach a higher awareness educational campaign could aid to improve the environmental consciousness of consumers. Furthermore small phone repair businesses could be strengthened by tax reductions and by ensuring the accessibility for original spare parts. Also, a warranty guaranty for repaired phones would strengthen the consumer's trust in repair shops and could lead to longer phone use times.

6.3.5 Discussion of the Optimal Case Scenario 5

The optimal case scenario indicates, Fig. 19, that a change towards this scenario is reducing the loop leakage and increases the values reached for loop efficiency. A reduction of the loop leakage means that less gold (metals) would be lost during the model run. While an increase in loop efficiency means that the gold (metals) are used more efficiently, the difference in results between the optimal case scenario and the BAU case is quite high compared to the other scenarios. The optimal case scenario resamples a change in all drivers that were identified to create a more sustainable use of metals and reduce the fraction of metals getting lost during the process. To implement the optimal case scenarios a combination of policy measures, consumer behavior change, change manufacturing processes, and an increase of awareness of consumers and businesses is necessary. To work towards a more sustainable mobile phone market and better recycling rates of EoL mobile phones in the EU, a combination of the previously discussed scenarios and the implementation of the underlying policy recommendation, operational changes and educational programmes is necessary. The results of the previous scenarios indicate that the most significant problems for reaching better collection and recycling of mobile phones are the storing behavior of consumers, the export of mobile phones to developing countries and the general low recycling rates. Altogether these practices result in a high amount of metals remaining inaccessible for recyclers or in loss of metals since the mobile phones are leaving the EU. To tackle these issues the previous discussed measures like the export ban, import of EoL nonfunctional devices from developing countries, mobile phones deposit system, leasing business model for mobile phones, educational programs aiming to create awareness for mobile phones as a resource source and implementation of laws that would strengthen the repair/reuse market might be helpful. Further, the mobile phones use time was identified to have a significant impact on the number of metals that are used in the manufacturing process. From an environmental perspective, it is beneficial when mobile phones are getting used longer to decrease the pressure on primary resource production and to create more efficient use of resources. To reach the goal of a more sustainable mobile phone system changes in product design where manufacturers are focusing more on the sustainable aspects like recycled resources, durability and repairability of mobile phones and modular phone design must be made. Additionally, educational programs about the environmental impact of manufacturing electronic devices might help to create a change into consumer's behavior towards a more sustainable phone use time.

6.4 General Discussion of the MOPHODYNE/EU Model and the Used Data

The model results of the MOPHODYNE/EU model was tested against historical data of mobile phone subscribers from 1988 until 2016 (Worldbank,2016) and showed a very high correlation with the results of mobile phones in use between 1988 until 2016. It is, for obvious reasons, not possible to validate the future development of the EU mobile phone market since there was no data available, but current trends point out that the exponential growth for EU mobile phone market is over (Jansen, 2018). There is uncertainty in the chosen parameter values for the rate of phones moving out of storage, phones getting forgotten in storage, collection rate, recycling rate, a fraction of getting reused and recycling rate and export rate. This is due to the vast amount of values for different percentages that can be found in the scientific literature, which are based on different estimation methods and which were carried out in different countries. Another problem that increases the uncertainty for the chosen parameter values is the complexity of the EoL management system and the lack of reliable data sets about the EoL management. One example for the complexity is the diverse options for collection schemes, every EU country has different operators involved, and it is impossible to track where the mobile phones end up after their collection. For that reason, a simplification of the system is used in the MOPHODYNE/EU model to try to estimate the number of collected phones in some form as realistic as possible. In addition, the parameter values previously named are influenced by economics, consumer behavior, trends, market developments and other outside factors which are not represented in the MOPHODYNE/EU model and could be included in the future to get a better system understanding. To improve the model results better data sets are necessary which requires a stronger control of the e-waste stream in particular for small devices like mobile phones. One solution could be an EU wide documentation of the e-waste stream particularly focused on small devices. One way to reach that would be the online platform for the

European Union where every device has to be registered when it is sold to a consumer and when the EoL stage is reached the collection operators, resell businesses, exporters and recyclers have to report about the whereabouts of these devices.

The reader has to keep in mind that the profit from mobile phone recycling and battery recycling, as well as the economic value of the recovered resources, might change in the future owing to different price development for each metal. The calculations in the MOPHODYNE/EU model are based on the current metal prices, which are, in the long-term, likely to rise caused be scarcity and increased demand for some metals like lithium and cobalt. There is also the possibility that mobile phones will contain less of the researched metals since there is a trend for the replacement of precious metals with cheaper substitutes with similar physical and chemical properties. This could lead to a decrease in the profitability of mobile phone recycling.

The model has two issues that need to be discussed. The first problem is relating to the CLD and the STELLA model and is regarding the phones in hibernation stock, the mobile phones getting forgotten flow and the hibernation time. In the CLD and the STELLA model the hibernation time has a negative relationship to the flow phones getting forgotten in hibernation, so if the hibernation time is long, fewer phones will be forgotten. In reality, it is more likely that the number of mobile phones that get forgotten is smaller when the hibernation time is shorter. The second problem with the MOPHO- DYNE/EU model concerns the collection rate and the disposal rate for EoL phones and for reused phones. The collection rate has a negative relation to the disposal rate, so when the collection rate is high the disposal rate is low, but the is feedback missing. With an increase in the disposal rate there should be a decrease in the collection rate.

The MOPHODYNE/EU model has proven to a be useful tool to analysis the mobile phone market and the EoL management, with adjustments and parametrization, it could be used for other regions than the EU or single EU countries. This would be interesting as differences in regional context may affect policy appropriateness and efficiency.

7 CONCLUSIONS

A sophisticated model capturing the EU mobile phone market's historical dynamics was developed, achieving high accuracy in reflecting past trends. This model highlighted a critical issue: only about 10% of end-of-life (EoL) phones in the EU are properly recycled, with the majority either lying unused in drawers, disposed of, or exported. Such practices lead to considerable losses of valuable metals. The study delved into the market from 1988 to 2050, aiming to quantify incoming phones and their ultimate fate upon reaching EoL. It raised pivotal questions about the viability of recycling and its potential to mitigate primary mining pressures while assessing the resource content and recycling rates of mobile phones. This research sought to pinpoint drivers within the EU mobile phone system that could significantly reduce metal loss and enhance metal usage efficiency. By testing various scenarios, the study evaluated their impact on improving loop efficiency, reducing leakage, and enhancing total metal recovery, focusing on gold as a key indicator. Historical examination and scenario analysis were underpinned by previous research, which either focused narrowly on specific countries or lacked dynamic, system-wide perspectives. In contrast, this study utilized a system dynamics (SD) model for a comprehensive analysis of the EU market and EoL management. Validated against scientific literature, this model proved suitable for exploring the study's objectives. The model's results revealed exponential growth in mobile phone usage until 2008, with a subsequent period of slower growth until 2024. A gradual decline in usage is anticipated post-2024, attributed to expected population decreases in the EU. With 631 million mobile phones currently in use and an average of 296 million new phones entering the market annually between 2010 and 2050, mobile phone recycling emerged as potentially profitable, promising an average annual profit of approximately 70 million Euros. However, the study found recycling lithium batteries from mobile phones to be unprofitable, incurring average annual costs of about 48 million Euros. Key drivers for improving the EU mobile phone system included limiting exports, enhancing collection systems, extending phone usage, and reducing hibernation periods. Scenario analyses demonstrated the potential of specific policy measures and changes to positively influence the system and EoL management. Notably, the implementation of a stronger export ban, improved collection systems through monetary incentives, educational programs to raise collection awareness, and extensions in phone usage time showed promise in increasing resource efficiency and recovery.

An optimal scenario, incorporating a blend of these measures, showcased a considerable improvement in loop efficiency and metal loss reduction by 2050 compared to the baseline (BAU) case. This scenario suggests that strategic adjustments can significantly benefit the sustainable management of mobile phone lifecycles in the EU, emphasizing the study's contribution to understanding and addressing the challenges within the EU mobile phone market and its EoL management.

AUTHORS CONTRIBUTIONS

First Author: Conceptualization; Software; Methodology; Writing – Original Draft; Visualization; Validation; Investigation and Review & Editing.

Second and Third Author; Review of the Draft; Discussions and Input during model Development, Investigation and Editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data used for this study was gathered from open sources and scientific literature. The authors may not publish the data independently because data will be made accessible on the together with the Article. The model description and the used data can be found in the supplementary materials.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT 4 from Open Ai in order to perform grammar and spelling checks and text editing/shortening for readability and comprehension, since the Authors first languages is not English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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