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Contemporary and Future Secondary Copper Reserves of Southeast Asian Countries

Thi Van Le [1], Sebastien Michael Rene Dente [2,*] and Seiji Hashimoto [3]

[1] Graduate School of Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan; gr0500rs@ed.ritsumei.ac.jp
[2] Ritsumeikan Global Innovation Research Organization, Ritsumeikan University, Kusatsu 525-8577, Japan
[3] College of Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan; shashimo@fc.ritsumei.ac.jp
* Correspondence: sdente@fc.ritsumei.ac.jp

Abstract: This study employed dynamic material flow analysis (MFA) and mass balance principles to examine copper flows in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam from 1960 to 2020, with projections extending to 2050 using five shared socioeconomic pathway (SSP) scenarios. We applied the secondary resources classification framework to assess secondary copper resources and their recoverability in these countries. The results indicated that total copper stocks across these countries would continue to rise, with Indonesia's copper stock projected to reach around 5000–12,000 kt by 2050, the highest among the five nations. In 2022, Malaysia had the highest per capita copper stock at 100 kg/person, although all countries were expected to remain below the per capita stock levels seen in major copper-consuming developed countries by 2050. Copper demand was projected to increase by 118–238 kt annually from 2023 to 2050, leading to a significant rise in end-of-life copper scrap. By 2050, secondary copper reserves in Indonesia were estimated to reach 4096 kt, with similar growth trends observed in other countries (3898 kt in Thailand, 3290 kt in Vietnam, 3096 kt in Malaysia, and 2564 kt in the Philippines). This highlights both the potential for resource recovery and the need for improved waste management. If recycling rates increase to 80–90%, secondary reserves could meet up to 42–65% of the copper demand in 2050. However, current recycling rates remain well below this potential, underscoring the urgent need for better waste management systems. This study emphasizes the balance between economic development and resource sustainability, offering critical insights for policymakers to improve recycling efficiency and reduce reliance on primary copper sources.

Keywords: dynamic material flow analysis; in-use stock; metal scrap; secondary resource classification; Southeast Asia

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1. Introduction

Modern society depends on major metals like iron, aluminum, and copper for infrastructure and services like transportation, housing, and communication [1]. Metal demand has surged in middle- and high-income countries, while low-income nations are rapidly increasing their mineral consumption as they undergo development [2]. These long-term trends in resource consumption raise concerns about resource scarcity, environmental degradation, and social conflict, potentially hindering future economic growth [3,4].

Copper, in particular, plays a crucial role in global industries due to its corrosion resistance, ductility, and superior conductivity [5]. Global copper demand has continuously increased throughout the 20th century and shows no signs of abating as low- and middle-income countries continue their economic expansion [6]. However, declining ore grades and predictions of copper reserve exhaustion within the next 50 years present a serious threat to global copper supply [7–9].

To address these challenges, attention has increasingly shifted toward secondary copper—copper that is already circulating in society. Recycling secondary copper reduces dependence on primary extraction, conserves natural resources, and minimizes environmental impacts, consuming up to 85% less energy and cutting greenhouse gas emissions by 65% compared with primary production [10]. However, despite improvements in recycling efforts, copper recycling has not reached its full potential, and many countries remain highly dependent on primary copper sources.

Numerous studies have analyzed copper flows and stocks across different scales. For instance, Spatari et al. (2005) [11] analyzed the copper lifecycle in North America, identifying significant losses of copper to landfills and reservoirs, highlighting the potential for copper recovery through landfill mining. Kapur et al. (2003) [12] examined copper flows in Asia, noting substantial accumulations of in-use copper that remain underutilized for recycling. Ciacci et al. (2020) [9] focused on Europe, where only 40% of copper demand is met by secondary sources despite advances in recycling technology. In China, Dong et al. (2019) [13] projected that copper demand will triple by 2050, emphasizing the need for a circular economy approach to mitigate resource scarcity. Other studies at the country and city levels have revealed similar trends: Daigo et al. (2009) [14] identified challenges in recovering copper alloys in Japan, while Gorman and Dzombak (2020) [15] demonstrated that large amounts of copper remain locked in U.S. infrastructure, hampering efficient end-of-life recovery. Drakonakis et al. (2007) [16] and Van Beers et al. (2007) [17] explored urban mining potential in cities like New Haven and Sydney, using GIS to map in-use copper stocks in buildings and infrastructure.

While these studies offer comprehensive assessments of copper flows, they often lack a clear and consistent classification of the secondary copper resources available in society. To fully utilize the potential of secondary metals, it is crucial to understand their distribution throughout their lifecycle—specifically, where metals are used, accumulated, and lost and their recycling potential. Hashimoto et al. (2008) [18] proposed a classification framework for secondary resources based on the McKelvey resource classification system for primary resources. This framework tracks cumulative metal consumption and classifies in-use stock and others based on its economic recovery potential, making it an essential tool for managing secondary metal reserves. Maung et al. (2017) [19] applied Hashimoto et al.'s (2008) [18] framework to major copper-consuming countries such as Japan, Germany, South Korea, and the U.S. However, no equivalent studies have been conducted for developing regions, including Southeast Asia. Also, no studies have been done for future secondary reserves, despite the region's growing importance in global copper consumption.

Over the past few decades, Southeast Asia has become increasingly interconnected and urbanized, with its economies tightly linked through trade, investment, and migration flows [20]. The region has experienced robust economic growth, with an average GDP per capita increase of 3.5% per year from 1960 to 2018 [21], and projections suggest that this growth will continue around 1.5% to 3.7% annually until 2050 [22]. The population in Southeast Asia is also rapidly expanding, rising from 612 million in 2000 to 671 million in 2022, and is expected to reach approximately 680–745 million by 2050 [22]. Urbanization has further accelerated, with 51% of the population now living in urban areas, up from 37% in 2000 [23]. These trends are driving a substantial increase in copper demand across the region [24]. Despite being rich in mineral resources such as gold, epithermal deposits, and porphyry copper, the uneven distribution of these resources, coupled with the region's complex geological structure, poses challenges for sustainable copper supply.

This research aimed to address this gap by (1) estimating contemporary copper in-use stocks and demand through material flow analysis based on historical data, (2) projecting future copper stocks and flows until 2050 using shared socioeconomic pathways (SSPs), and (3) applying a secondary resource classification framework to assess secondary copper reserves and their recoverability in Southeast Asian countries.

2. Methodology

2.1. Target Countries

This study focused on contemporary copper usage in Southeast Asia (SA), selecting the top five copper-consuming countries based on criteria adapted from Kapur et al. (2003) [12] and Maung et al. (2017) [19]. The selection process identified the top five countries according to (1) a population of at least 50 million in 2023, (2) the total refined copper consumption in 2023, (3) the per capita refined copper consumption in 2023, and (4) the cumulative refined copper consumption from 1962 to 2023 (see Table A1 in Appendix A). Figure 1 illustrates the geographic locations of the five countries included in this study [25].



Figure 1. Geographical location of the selected Southeast Asian countries [25].

2.2. Estimation of Copper Stocks, Demand, and End-of-Life Scraps

The copper lifecycle in our study consisted of five key stages [19]: (1) copper mine production, (2) fabrication of semi-finished products, (3) manufacturing of finished products, (4) in-use stocks, and (5) waste management (see Figure A1 in Appendix A). Historical in-use stock was calculated from 1960 to 2022 using material flow analysis to estimate annual copper consumption (C). A Weibull lifetime function, incorporating a dissipation ratio (Dpr), was applied to calculate the in-use stock (S(c,t)), generated end-of-life scrap (EoL(c,t)), and dissipated copper (DM(c,t)) for each year t and country c (see Table A2 and Figure A2 in Appendix A).

To project future copper stocks, per capita stock was hypothesized to follow an S-shaped logistic growth curve [26]. The main concept is that as per capita income rises, copper stock grows until it hits a saturation point. The saturation point is based on the historical trends of developed nations taken from previous research. Three stock saturation levels (Ssat_min, Ssat_av, and Ssat_max) were defined using data from five developed countries as detailed in Table A2 in Appendix A. For the period 2024–2050, copper stock was calculated annually by calibrating logistic curve parameters (a_i, b_i) and using the five "shared socioeconomic pathways" (SSPs) for projected per capita GDP and population data (POP) (Equation (1)) (see Figure A3 in Appendix A). Copper demand (C_(i,j) (c,t)) was calculated for each of the 15 scenarios using Equation (2).

$$S_{i,j}(c,t) = \frac{SSat_i}{1+\exp(a_i - b_{i,} \times GDP_j(c,t))} \times POP_j(c,t) \quad (1)$$

$$C_{i,j}(c,t) = S_{i,j}(c,t+1) - S(c,t) + DM_{i,j}(c,t) + EOL_{i,j}(c,t) \quad (2)$$

Therein, $S_{i,j}(c,t)$ is the total amount of in-use stock of finished products in country c in year t; Ssati denotes the per capita stock saturation corresponding to the i value (min, average, max); and $POP_j(c,t)$ and $GDP_j(c,t)$ are the estimated total population and GDP per capita in country c in year t, following the SSPj scenario, respectively.

2.3. Development of Secondary Copper Resource Framework

The secondary reserve classification framework, adapted from Hashimoto et al. (2008) [19], provided a comprehensive snapshot of **cumulative copper consumption (CC)** for any selected year. Copper consumption was categorized into four key components: **in-use stock (S)**, **cumulative waste in landfills (CWL), cumulative in-use dissipated metal (CDM), and mixed metal loss (CML)**, as shown in Equation (3).

$$CC(c,t) = S(c,t) + CWL(c,t) + CDM(c,t) + CML(c,t) \quad (3)$$

The vertical axis of the classification table (Figure 2) represents the economic profitability of the resource. The **secondary reserve (SR)** refers to the recoverable portion of the in-use stock under current technological and economic conditions. In contrast, the **marginal secondary reserve (MSR)** accounts for the additional recoverable share under optimal conditions. These conditions are defined by the **secondary reserve ratio (SRR)** and the **marginal secondary reserve ratio (SSR(t_{high})),** as shown in Equations (4) and (5).

$$SR(c,t) = S(c,t) \times SRR(t) \quad (4)$$

$$MSR(c,t) = S(c,t) \times \left(SRR\left(t_{high}\right) - SRR(t)\right) \quad (5)$$

Knowledge ↑

Profitability ↑

	Final products in and after use		**Wastes in managed landfill sites**	**Dissipated materials**
	Emerging in a year	Not emerging in a year		
Economic	Secondary reserves in a year **(SRe)**	Secondary reserves in future **(SRn)**		
Marginally economic	Marginal secondary reserves in a year **(MSRe)**	Marginal secondary reserves in future **(MSRn)**		
Subeconomic and Other	Subeconomic secondary resources and unrecoverable materials in a year **(SSRUMe)**	Subeconomic secondary resources and unrecoverable materials in future **(SSRUMn)**	Subeconomic secondary resources and unrecoverable materials - Landfilled waste **(SSRUMw - CWL)**	Subeconomic secondary resources and unrecoverable materials – Dissipation **(CDM)**
	(SSRUMm - CML) Subeconomic secondary resources and unrecoverable materials - Mixed metal loss			

Figure 2. Classification of secondary copper resources (adapted from Hashimoto et al., 2008 [19]).

Resources deemed **subeconomic secondary resources and unrecoverable materials (SSRUM)** were not recoverable under current technological and economic conditions. These included CWL, CDM, and the portion of in-use stock that remained unrecoverable $(S - SR - MSR)$. Additionally, the framework accounted for the timing of stock release. End-of-life scrap (EoLS) generated in the following year was categorized into the secondary reserve (SRe), marginal secondary reserve (MSRe), and subeconomic resource and unrecoverable materials (SSRUMe), as calculated in Equations (6)–(9).

$$EoLS(c,t) = SRe(c,t) + MSRe(c,t) + SSRUMe(c,t) \quad (6)$$

$$\text{where } SRe(c,t) = EoLS(c,t) \times SRR(t) \quad (7)$$

$$MSRe(c,t) = EoLS(c,t) \times \left(SRR\left(t_{high}\right) - SRR(t)\right) \quad (8)$$

$$SSRUMe(c,t) = EoLS(c,t) \times \left(1 - SRR\left(t_{high}\right)\right) \quad (9)$$

The release of copper stocks in future years was derived by calculating the difference between current stock levels and the amount of reserves depleted in the following year:

$$SRn = SR - SRe\,;\; MSRn = MSR - MSRe\,; SSRUMe = S - SR - MSR - SSRUMe \quad (10)$$

Finally, the framework distinguished between copper lost to other metal cycles and copper waste sent to landfills. These losses were quantified using **the landfill ratio (LFR)** and **mixed metal loss ratio (MMLR)**, as shown in Equations (11) and (12):

$$SSURM_w(c,t) = CWL(c,t) = \left(1 - SRR\left(t_{high}\right)\right) \times CEOL(c,t) \times LFR \quad (11)$$

$$SSURM_m(c,t) = CML(c,t) = \left(1 - SRR\left(t_{high}\right)\right) \times CEOL(c,t) \times MMLR \quad (12)$$

2.4. Data and Scenarios

Historical population data from 1960 to 2023 were collected from the World Bank [27]. Production and consumption data for ore and refined copper were sourced from the World Bureau of Metal Statistics (WBMS) [28] and the International Copper Study Group (ICSG) [29]. United Nations Commodity Trade statistics (UN Comtrade) [30] provided information on imports and exports of semi-finished and finished products. The copper content data for traded commodities from various sources [31–36] is detailed in Table A3. Table 1 summarizes the parameters used for analysis. For the 2023–2050 analysis, this study used the GDP per capita growth and population projections of each country as developed in the shared socioeconomic pathways (SSPs). SSPS are scenarios created by the Intergovernmental Panel on Climate Change to assess how different socioeconomic developments and policy decisions might affect future greenhouse gas emissions and their impacts on climate change and adaptation [37,38]. Figure 3 illustrates the socio-economic challenges of mitigation and adaptation across the five SSP scenarios [38].

Table 1. Details of the parameters applied in the analysis.

	Data	Unit	References
Dissipation ratio (*DpR*)	0.02	%	[9]
Secondary reserve ratio (*SRR*(*t*))	40	%	[39]
Highest secondary reserve ratio *SRR*(t_{high})	50	%	
Landfill ratio (*LFR*)/mixed metal loss ratio (*MMLR*)	82:18	%:%	[19]

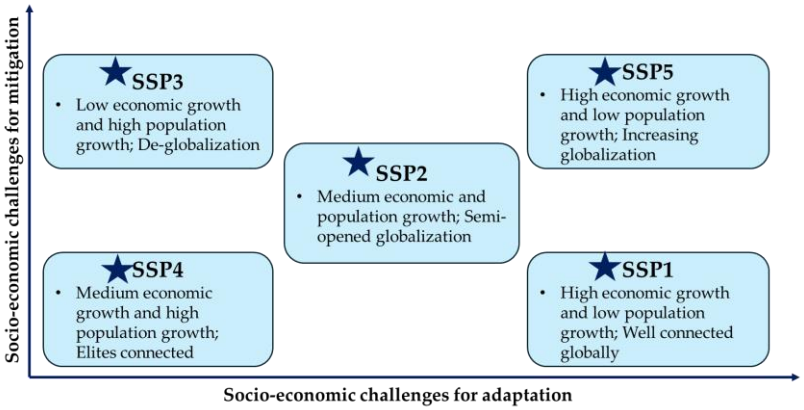


Figure 3. Five SSPs illustrate various combinations of challenges related to both mitigation and adaptation [38].

In these SSP scenarios, SSP1 focuses on renewable energy, reducing fossil fuel reliance, and improving efficiency. Achieving SSP1 requires overcoming financial and technological challenges. SSP5 maintains fossil fuel dependence, leading to higher emissions and delayed clean energy transition, but may support short-term economic growth [38]. Detailed descriptions of GDP per capita and population projection for Southeast Asian countries [22] based on SSPs are available in Figure A3 in Appendix A.

3. Results

3.1. Copper Stock and Copper Stock per Capita from 1960 to 2050

Figure 4 illustrates the evolution of total copper stocks (a) and per capita stocks (b) between 1960 and 2022, with projections for future trends from 2023 to 2050. Copper stocks have rapidly increased since the 1990s in most countries, with the exception of Vietnam, which experienced approximately a 10-year delay in growth. Among the five countries, Thailand maintained the largest total copper stock throughout the historical period, followed by Malaysia, Indonesia, Vietnam, and the Philippines. By 2050, copper stock is projected to continue increasing in all five countries across all scenario pathways. This period is expected to see rapid copper accumulation, driven by population growth and economic expansion, with Indonesia anticipated to show the highest accumulation across multiple scenarios (SSP1, SSP2, SSP3, and SSP5). In contrast, Malaysia, the Philippines, and Vietnam are predicted to accumulate smaller amounts of copper stocks. These trends align with the rapid economic development seen across Southeast Asian countries in recent decades.

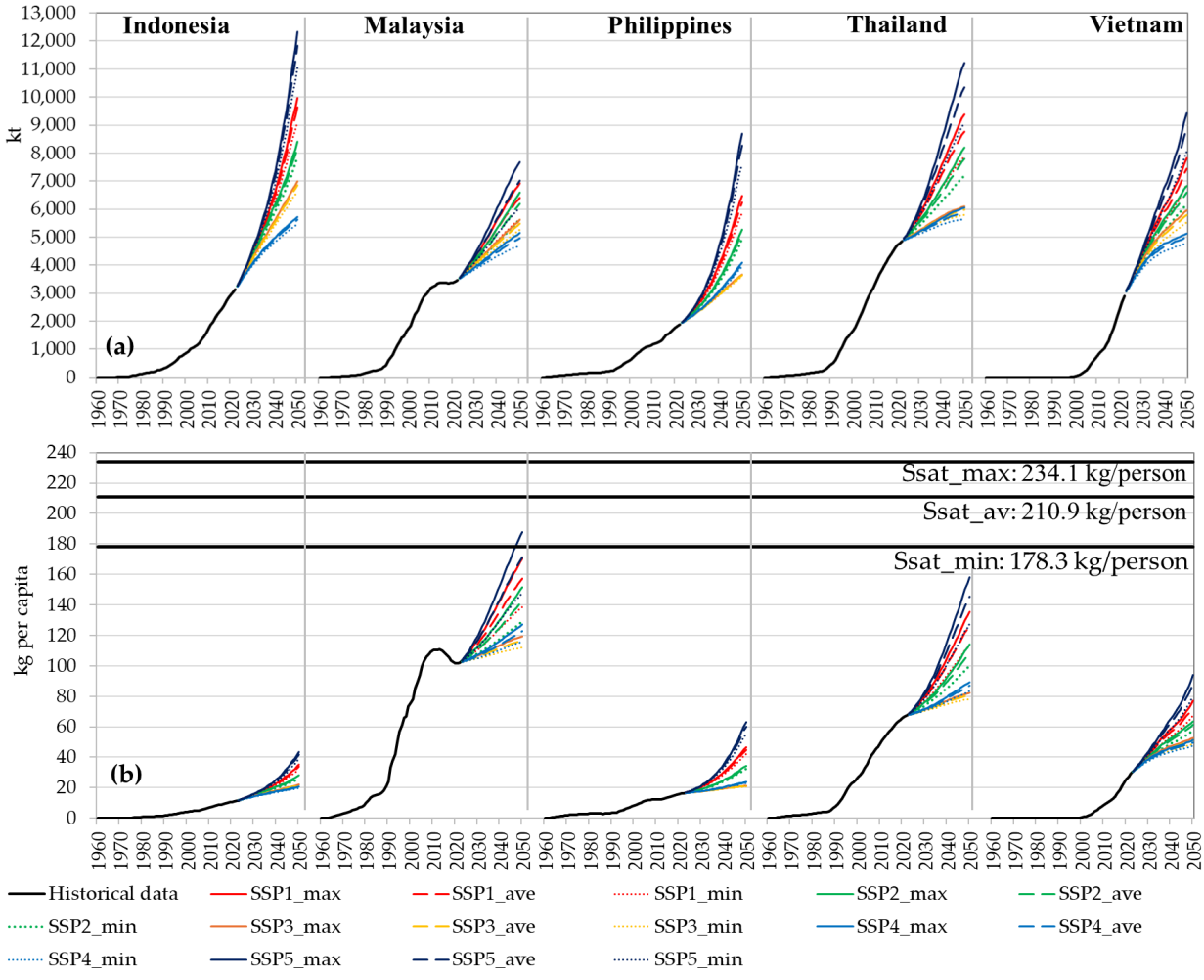


Figure 4. Estimated total copper stocks (**a**) and stocks per capita (**b**) of finished products in use.

From a per capita stock perspective, Malaysia currently holds the highest stock, estimated at approximately 100 kg/person in 2022. Thailand ranks second, with around 15 kg/person less than Malaysia. Vietnam, the Philippines, and Indonesia follow with significantly lower figures of 31 kg/person, 16 kg/person, and 11 kg/person, respectively. This ranking is expected to remain consistent until 2050, with projections indicating that Malaysia will have between 112 and 188 kg/person, Thailand between 78 and 158 kg/person, Vietnam between 48 and 94 kg/person, the Philippines between 21 and 63 kg/person, and Indonesia between 20 and 44 kg/person, depending on the scenario and stock saturation levels (Ssat). Notably, SSP1 and SSP5 show the highest values for per capita stocks, while SSP3 and SSP4 exhibit the lowest. However, none of these countries are predicted to reach per capita stock saturation by 2050, even across the 15 future scenarios.

3.2. Copper Demand from 1960 to 2050

Copper demand has surged significantly since the 1990s, as depicted in Figure 5. Estimates derived from dynamic material flow analysis show that by 2022, demand in Indonesia reached 193 kt, Malaysia 199 kt, the Philippines 124 kt, Thailand 220 kt, and Vietnam 290 kt. While four of the countries—Indonesia, Malaysia, Thailand, and the Philippines—experienced substantial growth in copper consumption since the 1990s, Vietnam's growth lagged by approximately a decade due to political and economic factors, including the U.S. embargo, which was lifted in 1994 [40]. Global economic crises, such as those in 1997 and 2008, caused temporary declines in copper consumption across the region. Nevertheless, economic structural shifts, characterized by a reduced share of agriculture and a growing industrial and services sector, have driven copper consumption upward. For instance, in Malaysia, the share of agriculture in the economy has decreased significantly, from 21% in 1980 to 6.9% in 2022, and mining has also declined, from 12.1% to 6.5% during the same period. In contrast, the construction, manufacturing, and services sectors have grown, with services increasing from 43.1% in 1980 to 58.3% in 2022 [23], contributing to a corresponding rise in copper consumption.

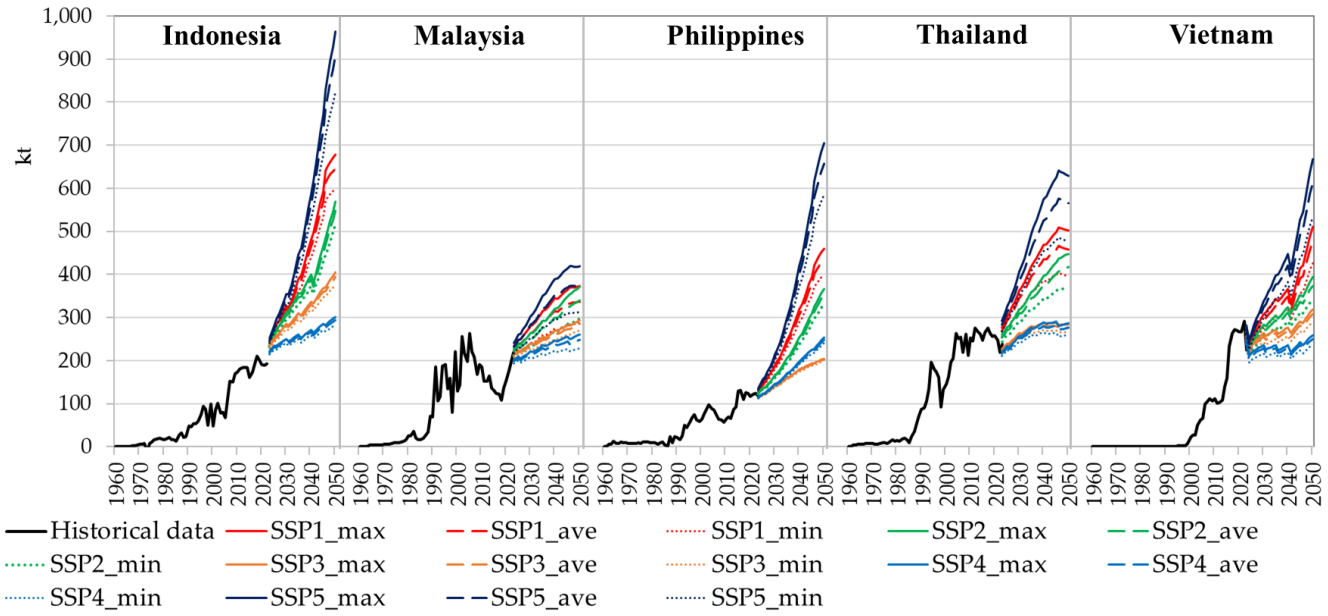


Figure 5. Estimated copper demand.

Future copper demand from 2023 to 2050 is expected to increase significantly, as illustrated in Figure 5. Total demand is projected to rise by 1.8–4.7 times in Indonesia, 1.2–2.1 times in Malaysia, 1.6–5.6 times in the Philippines, 1.2–2.6 times in Thailand, and 0.8–2.6 times in Vietnam compared with 2022 levels. This growth in demand is driven by

population and economic growth, the two parameters describing SSP scenarios as described in the methodology section and Figure A3.

The economic factor potentially includes the following.

- **Urbanization and Infrastructure Development**: Rapid urbanization is leading to an increase in infrastructure projects, including the construction of buildings, roads, and transportation networks. Copper demand is projected to increase by up to 58% by 2050, specifically for the building and construction sector [41]. This copper is accumulated in buildings to meet the housing needs of the population, especially during rapid urbanization.
- **Industrialization**: As these countries continue to industrialize, copper demand is increasing across various sectors, including manufacturing, electronics, and automotive industries. The estimated global copper demand for electric vehicle production is expected to rise from about 400 million tons in 2015 to approximately 700 million tons by 2035 (baseline scenario), as reported in Habib's study [42]. This demonstrates the impact of industrial growth on global copper demand, a similar effect also examined in this study.
- **Electrification and Renewable Energy**: The push for electrification in rural areas and the global shift toward renewable energy sources (e.g., solar and wind power) require significant copper resources for infrastructure development. Seck's research [43] on the impact of low-carbon energy transition processes indicates substantial growth in copper demand, especially in the renewable energy sector (including wind and solar power), which is expected to account for 35% by 2050 to limit global warming to 4 °C and up to 69% in a more ambitious scenario, aiming to limit warming to 2 °C.

3.3. Copper Waste Generation from 1960 to 2050

Estimating copper waste generation is crucial for developing efficient recycling and waste management strategies. Figure 6 shows copper waste flows from 1960 to 2022, with projections through 2050. In 2022, copper scrap generation was estimated at 168 kt in Thailand, 141 kt in Malaysia, 94 kt in Indonesia, 60 kt in the Philippines, and 55 kt in Vietnam. Projections indicate that copper waste generation will continue to rise by 2050, with Thailand expected to generate between 254 and 392 kt, Malaysia between 205 and 276 kt, Indonesia between 221 and 359 kt, the Philippines between 143 and 236 kt, and Vietnam between 208 and 313 kt, depending on stock saturation levels and scenario pathways.

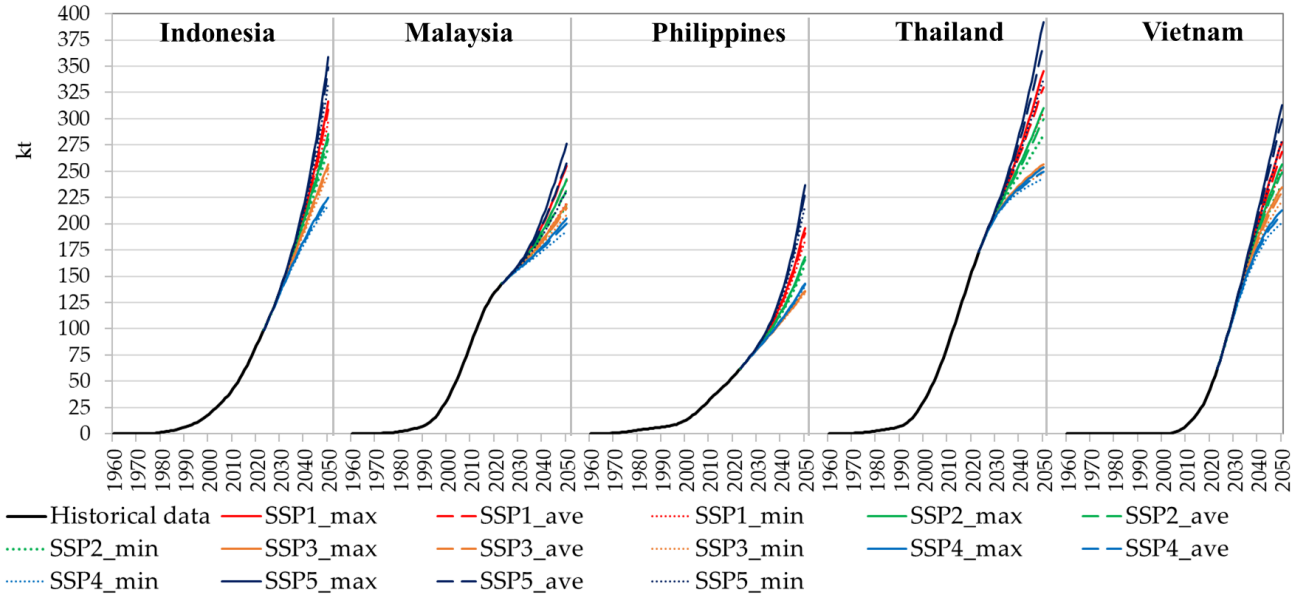


Figure 6. Estimated copper scraps.

The increasing volume of copper waste presents opportunities for resource recovery, but it also highlights the environmental pressures these countries face. Waste management systems in Southeast Asian countries remain underdeveloped, with landfilling as the primary method of disposal. Non-compliant landfills contribute to environmental degradation, signaling the need for improved recycling infrastructure to mitigate the impact of rising copper waste.

3.4. The Classification of Secondary Copper Resources in 2020 and 2050

The classified secondary copper resources in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam in 2020 and 2050 are presented in Figure 7 (more detail are provided in Tables A4 and A5 in Appendix A). In 2020, these countries had the following secondary copper reserves (including marginal reserves): Indonesia, 1464 kt; Malaysia, 1687 kt; the Philippines, 882 kt; Thailand, 2356 kt; and Vietnam, 1217 kt. By 2050, the total secondary copper reserves are projected to increase substantially, with Indonesia reaching 4096 kt, Malaysia reaching 3096 kt, the Philippines reaching 2564 kt, Thailand reaching 3898 kt, and Vietnam reaching 3290 kt. However, the amount of secondary reserves emerging in 2020 from Indonesia (42 kt), Malaysia (68 kt), the Philippines (27 kt), Thailand (141 kt), and Vietnam (40 kt) can meet 22%, 44%, 23%, 30%, and 8% of the copper consumption, respectively, in the same year, 2020.

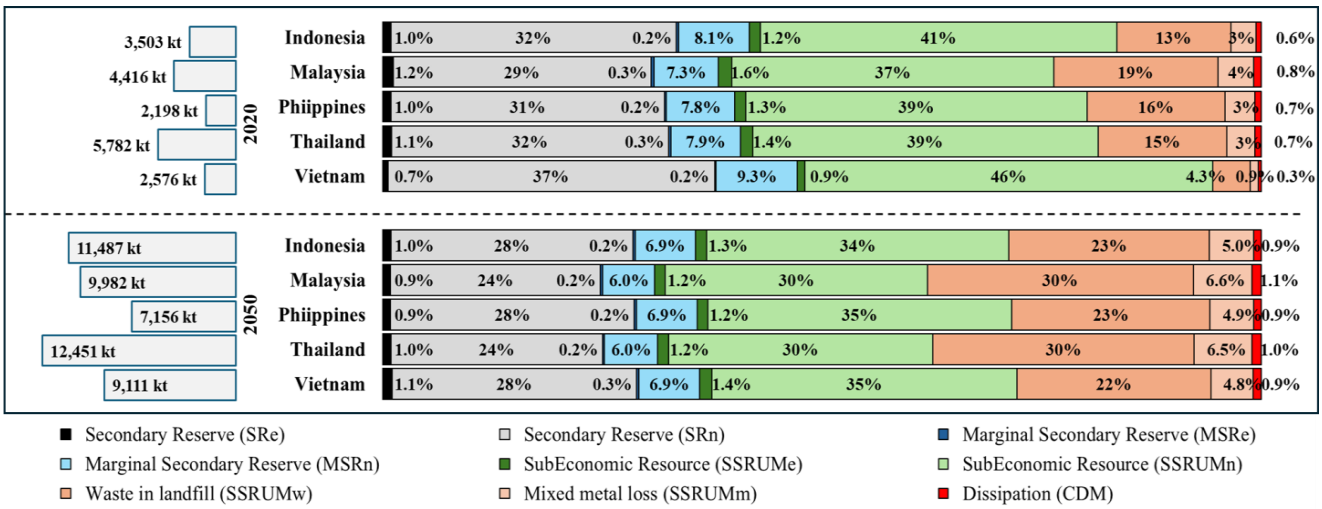


Figure 7. Total secondary copper resources (**left**) and classification of secondary copper resources (**right**) in 2020 and 2050.

The secondary copper reserves, including marginally economic copper, accounted for 38% (Malaysia) to 47% (Vietnam) of the total secondary resources in 2020. This proportion is projected to decrease to 31% (Malaysia and Thailand) to 36% (three other countries) by 2050. However, annually available secondary copper (both economically and marginally recoverable) represents only around 1% of the total copper resources in these countries.

Special attention should be paid to the accumulation of secondary copper as waste in managed landfill sites. In 2020, Indonesia had 454 kt of copper waste in landfills (13% of its total secondary copper), Malaysia had 824 kt (19%), the Philippines had 344 kt (16%), Thailand had 845 kt (15%), and Vietnam had 110 kt (4%). These amounts are projected to increase significantly by 2050, with Indonesia's landfill copper increasing by approximately 5.8 times, Malaysia's by 3.7 times, the Philippines by 4.7 times, Thailand's by 4.4 times, and Vietnam's by an alarming 18.3 times. As noted in Le et al.'s [10] report, recovering copper from landfills is particularly challenging for developing countries due to the high costs associated with resource recovery technologies. To prevent the accumulation of difficult-to-recover copper in landfills, it is essential to minimize the flow of copper waste into these sites and focus on enhancing recycling efforts and resource recovery technologies.

4. Discussion

4.1. Comparison with Previous Studies

Our study projected that by 2050, Malaysia would have a per capita copper stock of 112–188 kg/person, with Thailand reaching 78–158 kg/person. In contrast, significantly lower levels are expected for Vietnam (48–94 kg/person), the Philippines (21–63 kg/person), and Indonesia (20–44 kg/person). These projections differ substantially from those of Watari et al. [44], who estimated per capita copper stocks of 66 kg/person for upper-middle-income countries like Malaysia and Thailand, and 42 kg/person for lower-middle-income countries, including Indonesia, Vietnam, and the Philippines. The difference can be attributed to several factors. First, Watari et al. [44] relied on historical data up to 2010, while our analysis integrated more recent data (up to 2022), capturing the accelerated industrialization and urbanization of the past decade. Additionally, Watari et al. [44] employed a global material flow analysis (MFA) model that grouped Southeast Asian countries into broader income categories, potentially oversimplifying country-specific developments and diluting the precision of per capita estimates.

Countries like Malaysia and Thailand have made strides in deploying modern renewable energy technologies, while still relying on fossil fuels, particularly coal and oil, to meet their growing energy demands [45]. Investments in green technologies, such as solar panels and electric vehicles, which require significant amounts of copper [46], may explain the higher copper stock observed for these countries in our study.

In contrast, Vietnam, Indonesia, and the Philippines appear to be more reliant on traditional biomass and fossil fuels, which, combined with slower industrialization and limited renewable energy infrastructure, contributes to their lower copper stock projections. Both Gorman and Dzombak (2020) [15] and Glöser et al. (2013) [47] note that countries with underdeveloped industrial infrastructure and slower technological advancement accumulate copper at a much lower rate as they rely less on copper-intensive technologies.

4.2. Primary vs. Secondary Copper Reserves

Among the five Southeast Asian countries studied, only the Philippines and Indonesia possess significant primary copper reserves, with 165,978 kt [48] and 19,936 kt [49] of copper metal, respectively. In comparison, Malaysia holds around 9640 kt [50], Thailand has 965 kt [51], and Vietnam has only 441 kt [52]. The Philippines, Indonesia, and Malaysia show considerably higher primary reserves than their secondary reserves for both 2020 and 2050, while Thailand and Vietnam exhibit the opposite pattern (see Figure 8). This imbalance in reserves indicates that Thailand and Vietnam will likely face long-term challenges in meeting their copper demands, making effective management of their secondary copper reserves essential.

Without the discovery of new deposits, depletion of primary copper reserves is likely to occur in Thailand and Vietnam sooner than in other countries, particularly as domestic demand rises. In such a scenario, these nations may become increasingly reliant on imported copper resources or recycled scrap materials from other regions, potentially raising concerns about dependency and the risk of becoming dumping grounds for global copper waste. Although environmentally unsustainable, investment in domestic exploration and mining activities could address short-term demand but is not a viable long-term solution. For the Philippines, Indonesia, and Malaysia, the wealth in primary copper reserves offers greater flexibility in planning for future supply stability, not only to meet domestic needs but also from a geopolitical standpoint, potentially influencing their relationships with neighboring countries.

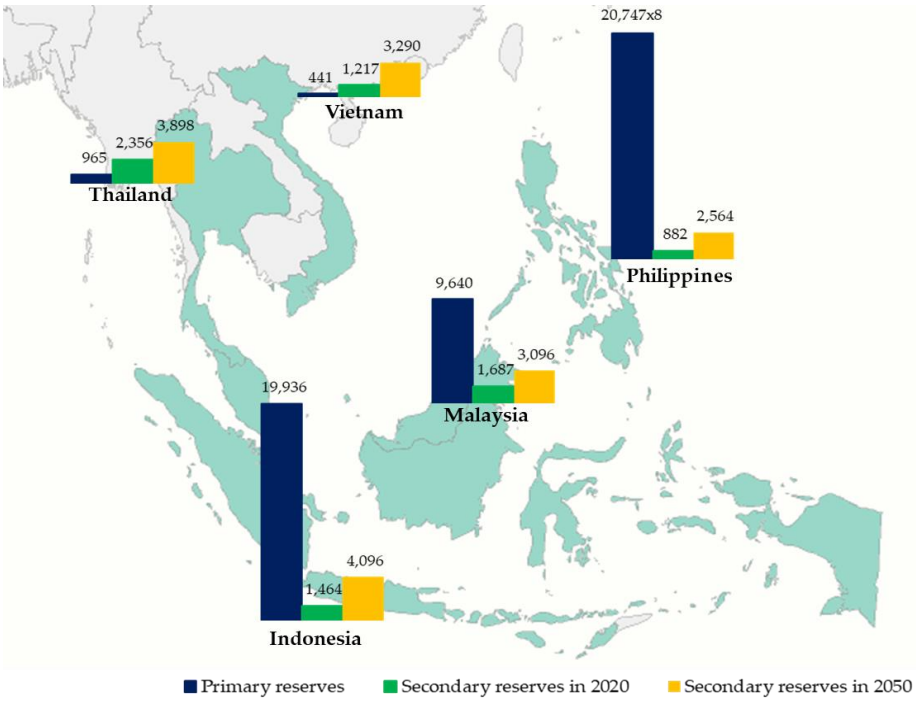


Figure 8. Primary and secondary copper reserve distribution in Southeast Asian countries.

4.3. The Effect of Recycling Rates

Although copper has a theoretical recycling potential of up to 95% [9], practical recycling rates are significantly lower, ranging between 26 and 82% [53] depending on the type of scrap, location, and available technology. In this study, we assumed an average recycling rate of 40% and a maximum rate of 50%. Our analysis revealed that substantial volumes of copper were accumulating in landfills, highlighting the need to enhance recycling practices.

If recycling rates were improved to reach 80–90% across the studied countries, the secondary reserves under the SSP2 scenario (average stock saturation) appearing in 2050 would increase significantly: 140 kt (Indonesia), 150 kt (Thailand), 124 kt (Vietnam), 116 kt (Malaysia), and 83 kt (the Philippines). At these levels, secondary reserves could meet approximately 36% for Thailand, 34% for Malaysia, 33% for Vietnam, 26% for Indonesia, and 24% for the Philippines of copper demand in 2050. This demonstrates a strong correlation between higher recycling rates and the ability to meet future consumption demands.

Increasing recycling rates also mean less waste present in landfills. For the SSP2 scenario, if the recycling rate were to increase to 80–90%, the amount of copper accumulated in landfills would decrease by 2097 kt in Indonesia, 2418 kt in Malaysia, 1290 kt in the Philippines, 2968 kt in Thailand, and 1607 kt in Vietnam. This could, in turn, reduce the rate at which landfills are filled and improve their efficiency in use.

However, increasing recycling rates in Southeast Asia poses significant challenges due to limited financial and technological investments in recycling infrastructure. Common issues such as inefficient sorting and collection practices further exacerbate this problem. Therefore, improving recycling rates requires the development of comprehensive waste management systems that mandate proper sorting, collection, and recycling processes. Government policies and regulations will be critical in driving this change. Furthermore, aside from Indonesia and the Philippines, most countries in the region face limitations in their primary copper resources. Increasing recycling rates could help reintroduce more copper waste into the economy, alleviating some of the dependency on primary reserves. Over the long term, higher recycling rates would conserve natural resources, reduce dependence on imported copper, and contribute to environmental protection by mitigating the impact of mining and extraction activities.

4.4. Energy Planning and Sustainable Development Pathways

Energy planning is crucial for Southeast Asia's development, directly shaping its sustainability pathways. This study used shared socioeconomic pathways (SSP) to explore two potential futures: SSP1 and SSP5. These scenarios highlight sharply contrasting directions for energy usage and environmental impact.

SSP1 focuses on transitioning to renewable energy, reducing fossil fuel dependence, and improving energy efficiency. This would decrease greenhouse gas emissions and overall energy consumption, aligning with global climate goals. However, renewable energy technologies like solar panels and wind turbines require up to four times more copper than conventional systems [46], leading to a significant rise in copper demand. To pursue SSP1, Southeast Asian countries must overcome substantial financial, infrastructural, and technological challenges.

SSP5, by contrast, assumes continued reliance on fossil fuels and minimal investment in renewables, resulting in higher emissions and a delayed shift to cleaner energy. Currently, the region still heavily depends on coal and oil despite efforts to adopt modern renewables [45]. While SSP5 may foster short-term economic growth by supporting conventional energy infrastructure, it risks undermining environmental sustainability.

Developed nations, having already invested in energy infrastructure, can focus on advancing clean energy technologies and reducing their reliance on copper-intensive systems. Southeast Asian countries, still building their energy systems, face the challenge of balancing rapid economic development with resource conservation and emissions reduction. Achieving this balance requires long-term policies that promote both economic growth and environmental protection. Although SSP1 offers long-term sustainability, SSP5 allows for immediate growth. The most effective strategy may involve blending both approaches (similar to the assumptions in the SSP2 scenario, which combines elements of both sustainable and unsustainable development), tailoring energy policies to meet both development and sustainability goals.

5. Conclusions

This study estimated copper stocks, demand, and secondary reserves for five Southeast Asian countries—Indonesia, Malaysia, the Philippines, Thailand, and Vietnam—from 1960 to 2050. The key findings are summarized as follows:

(1) **Copper Stocks and Demand**: Copper stocks have surged since the 1990s in most countries, with Thailand consistently holding the largest total copper stock, although Indonesia is expected to surpass it by 2050. On a per capita basis, Malaysia currently has the highest copper stock, a trend that will likely continue. None of the countries are projected to reach per capita copper saturation by 2050. Copper demand has also grown rapidly, driven by urbanization, industrialization, and the increasing need for renewable energy technologies. By 2050, copper demand is expected to rise significantly across all countries, while increasing copper waste will demand more effective management.

(2) **Copper Waste and Secondary Resources:** Waste flows are set to rise sharply by 2050, presenting both opportunities for resource recovery and challenges for countries with underdeveloped waste management systems. In 2020, secondary copper reserves across the five countries ranged from 882 kt to 2356 kt, with projections showing continued growth. By 2050, Indonesia is expected to have the largest secondary copper reserves (4096 kt), followed by Thailand, Vietnam, Malaysia, and the Philippines. Without improved recycling and reduced landfill use, waste volumes are projected to increase between 3.7 to 18.3 times by 2050, underscoring the urgent need for more sustainable waste management practices.

(3) **Recycling and Future Resource Management**: Secondary copper reserves released in 2020 meet 8–44% of the demand, in that year, but without substantial improvements in recycling, reliance on primary resources will rise by 2050. Indonesia and the Philippines are the only countries with significant primary copper reserves, and

resource depletion is a real threat if new discoveries are not made. Increasing recycling rates from their current levels to 80–90% could allow secondary reserves to meet up to 42–65% of copper demand in 2050. This shift would require comprehensive waste management systems, along with strong regulatory frameworks for sorting, collection, and recycling. Enhancing recycling rates would not only conserve natural resources but also reduce dependency on imports and minimize environmental impacts.

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Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Top five copper-using countries.

	1	2	3	4	5
POP in 2023 (million people) [27]	Indonesia 277.53	The Philippines 117.34	Vietnam 98.86	Thailand 71.80	Myanmar 54.58
Refined copper usage in 2023 (kt) [29]	Thailand 331.97	Vietnam 326.8	Malaysia 255.16	Indonesia 197.04	The Philippines 37.31
Refined copper usage per capita in 2023 (kg/cap) [29]	Malaysia 7.44	Thailand 4.62	Vietnam 3.31	Indonesia 0.71	The Philippines 0.32
Cumulative refined copper usage during 1962–2023 (kt) [28,29]	Thailand 7631.2	Malaysia 6142.7	Indonesia 5365.6	Vietnam 3408.8	The Philippines 1425.2

Table A2. Saturation value of the per capita copper stock.

Stock Saturation (kg/person)		Country	α	β	A1 (kg/cap; USD)	A2 (kg/cap; USD)
Minimum	178.25	Indonesia	3.29	0.15	(11.34; 4074)	(160.4; 37,000)
		Malaysia	0.24	0.05	(102.2; 11,399)	(160.4; 52,000)
		The Philippines	2.91	0.18	(16.37; 3528)	(160.4; 29,000)
		Thailand	1.08	0.09	(67.58; 6276)	(160.4; 35,000)
		Vietnam	2.32	0.19	(29.39; 3659)	(160.4; 23,686)
Average	210.94	Indonesia	3.49	0.15	(11.34; 4074)	(189.8; 37,000)
		Malaysia	0.70	0.06	(102.2; 11,399)	(189.8; 52,000)
		The Philippines	3.12	0.18	(16.37; 3528)	(189.8; 29,000)
		Thailand	1.40	0.10	(67.58; 6.276)	(189.8; 35,000)
		Vietnam	2.55	0.20	(29.39; 3659)	(189.8; 23,686)
Maximum	234.21	Indonesia	3.62	0.16	(11.34; 4074)	(210.8; 37,000)
		Malaysia	0.94	0.06	(102.2; 11,399)	(210.8; 52,000)
		The Philippines	3.25	0.19	(16.37; 3528)	(210.8; 29,000)
		Thailand	1.58	0.11	(67.58; 6.276)	(210.8; 35,000)
		Vietnam	2.70	0.21	(29.39; 3659)	(210.8; 23,686)

We used the historical statistical data for five developed countries including Japan, Korea, Germany, Spain, and the USA to determine the copper stock saturation. Minimum and maximum stock saturation correspond to Spain and Korea. Average stock saturation corresponds to the average logistic regression of these countries.

The logistic coefficients (α, β) were determined by selecting two key points, A1 (copper stock per capita and GDP per capita in 2022 of the studied country) and A2 (90% of copper stock saturation and the corresponding GDP per capita at that level).

Table A3. Copper contents in commercial products.

SITC Rev.1	Items	Unit	Copper Content	References
28,311	Ores and concentrates of copper	t/t	0.272	AUDM, 1996 [31]
28,312	Copper matte	t/t	0.625	NIRS, 2010 [32]
28,402	Copper waste and scrap	t/t	0.750	METI, 2015 [33]
68,211	Blister copper and other unrefined copper	t/t	0.9850	NIRS, 2010 [32]
68,212	Refined copper including remelted	t/t	0.9999	
68,213	Master alloys of copper	t/t	0.9999	
68,221	Bars, rods, angles, shapes, and wire of copper	t/t	0.9999	
68,222	Plates, sheets, and strips of copper	t/t	0.9999	
68,223	Copper foil	t/t	0.9999	
68,224	Copper powders and flakes	t/t	0.9999	
68,225	Tubes, pipes and blanks, and hollow bars of copper	t/t	0.9999	
68,226	Tube and pipe fittings of copper	t/t	0.650	RIETI, 1955 [34]
69,212	Refined copper including remelted	t/t	0.9999	NIRS, 2010 [32]
69,312	Wire, cables, ropes, etc., not insulated of copper	t/t	0.9999	
69,332	Gauze, netting, grill, and fencing wire of copper	t/t	0.9999	
69,342	Expanded metal of copper	t/t	0.9999	
69,412	Nails, tacks, staples, spikes, etc., of copper	t/t	0.65	RIETI, 1955 [34]
69,422	Nuts, bolts, screws, rivets, and washers of copper	t/t	0.65	
695	Tools of use in the hand or in machines	t/MY	0.006	NIES, 2000 [35]
696	Cutlery	t/MY	0.003	
69,712	Domestic stoves, etc., of copper	t/t	0	METI, 2008 [36]
69,722	Domestic utensils of copper	t/t	0.9999	NIRS, 2010 [32]
6979	Other household equipment of base metals	t/MY	0.002	NIES, 2000 [35]
6981	Locksmith wares	t/MY	0.003	
69,862	Springs and leaves for springs of copper	t/t	0.9999	NIRS, 2010 [32]
6988	Miscell. articles of base metal	t/MY	0.004	NIES, 2000 [35]
69,892	Articles of copper, n.e.s.	t/t	0.9999	NIRS, 2010 [32]
71	Machinery, other than electric	t/MY	0.006	NIES, 2000 [35]
72	Electrical machinery, apparatus, and appliances	t/MY	0.008	
73	Transport equipment	t/MY	0.009	
81	Sanitary, plumbing, heating, and light fixtures	t/MY	0.012	
82	Furniture	t/MY	0.001	
86	Scientif and control instrum, photogr gds, and clocks	t/MY	0.002	
89	Miscellaneous manufactured articles, n.e.s.	t/MY	0.004	
95	Firearms of war and ammunition therefor	t/MY	0.020	

Table A4. Classification of secondary copper resources in 2020.

Year: 2020 Unit: kt	Final Products in/After Use				Wastes in Managed Landfill Sites				Dissipated Materials		Total (100%)	
	In a Year		In Future		Cumulated Waste		Mixed Metal Loss					
Secondary reserve	IDN	34 (0.8%)	IDN	1138 (28.0%)								
	MYS	54 (1.0%)	MYS	1296 (23.9%)								
	PHL	22 (0.8%)	PHL	684 (26.1%)								
	THA	62 (0.9%)	THA	1823 (26.8%)								
	VNM	17 (0.6%)	VNM	957 (35.3%)								
Marginal secondary reserve	IDN	8 (0.2%)	IDN	284 (7.0%)								
	MYS	14 (0.3%)	MYS	324 (5.9%)								
	PHL	5 (0.2%)	PHL	171 (6.5%)								
	THA	15 (0.2%)	THA	456 (6.7%)								
	VNM	4 (0.2%)	VNM	239 (8.8%)								
Subeconomic reserve	IDN	43 (1.1%)	IDN	1421 (35.0%)	IDN	454 (22.4%)	IDN	100 (4.9%)	IDN	21 (0.5%)	IDN	3503
	MYS	69 (1.3%)	MYS	1618 (29.8%)	MYS	824 (30.4%)	MYS	181 (6.6%)	MYS	62 (0.7%)	MYS	4416
	PHL	28 (1.1%)	PHL	854 (32.6%)	PHL	344 (26.3%)	PHL	75 (5.8%)	PHL	15 (0.6%)	PHL	2198
	THA	80 (1.2%)	THA	2276 (33.4%)	THA	845 (24.8%)	THA	186 (5.4%)	THA	39 (0.6%)	THA	5782
	VNM	22 (0.8%)	VNM	1195 (44.1%)	VNM	110 (8.1%)	VNM	24 (1.8%)	VNM	8 (0.3%)	VNM	2576

(IDN, Indonesia; MYS, Malaysia; PHL, the Philippines; THA, Thailand; VNM, Vietnam.)

Table A5. Classification of Secondary Copper Resources in 2050, SSP2-Ssat average.

Year: 2050 Unit: kt	Final Products in/After Use				Cumulative Waste				Cumulative Dissipation		Total (100%)	
	In a Year		In Future		Cumulated Waste		Mixed Metal Loss					
Secondary reserve	IDN	112 (0.8%)	IDN	3165 (21.6%)								
	MYS	93 (0.7%)	MYS	2384 (17.4%)								
	PHL	66 (0.7%)	PHL	1985 (21.8%)								
	THA	120 (0.7%)	THA	2999 (17.7%)								
	VNM	100 (0.9%)	VNM	2533 (21.9%)								
Marginal secondary reserve	IDN	28 (0.2%)	IDN	791 (5.4%)								
	MYS	23 (0.2%)	MYS	596 (4.4%)								
	PHL	17 (0.2%)	PHL	496 (5.4%)								
	THA	30 (0.2%)	THA	750 (4.4%)								
	VNM	25 (0.2%)	VNM	633 (5.5%)								
Subeconomic reserve	IDN	144 (1.0%)	IDN	3952 (26.9%)	IDN	2621 (35.7%)	IDN	575 (7.8%)	IDN	99 (0.7%)	11,487	
	MYS	119 (0.9%)	MYS	2977 (21.8%)	MYS	3022 (44.2%)	MYS	663 (9.7%)	MYS	105 (0.8%)	9982	
	PHL	85 (0.9%)	PHL	2497 (27.2%)	PHL	1613 (35.4%)	PHL	354 (7.8%)	PHL	61 (0.7%)	7156	
	THA	154 (0.9%)	THA	3744 (22.1%)	THA	3710 (43.7%)	THA	814 (9.6%)	THA	130 (0.8%)	12,451	
	VNM	128 (1.1%)	VNM	3163 (27.4%)	VNM	2009 (34.8%)	VNM	441 (7.6%)	VNM	79 (0.7%)	9111	

(IDN, Indonesia; MYS, Malaysia; PHL, the Philippines; THA, Thailand; VNM, Vietnam.)

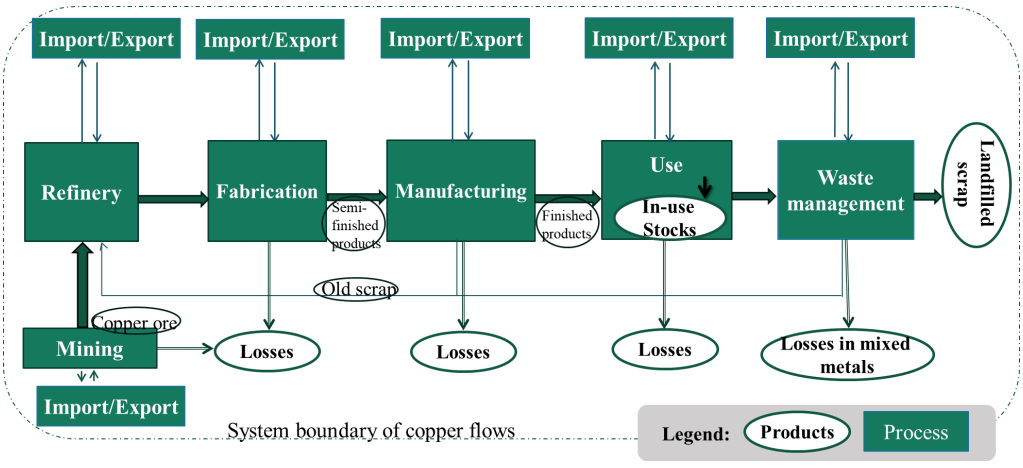


Figure A1. Copper flows and stocks model [19].

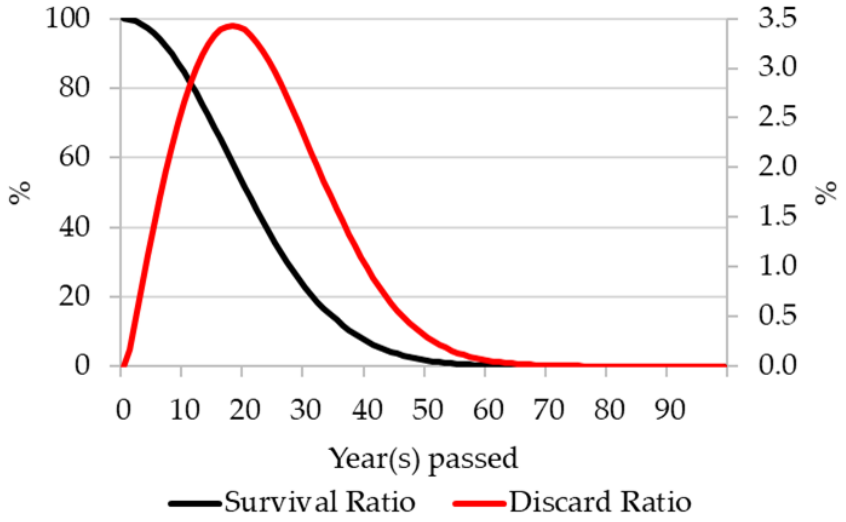


Figure A2. Survival ratio and discard ratio based on the average mean lifetime.

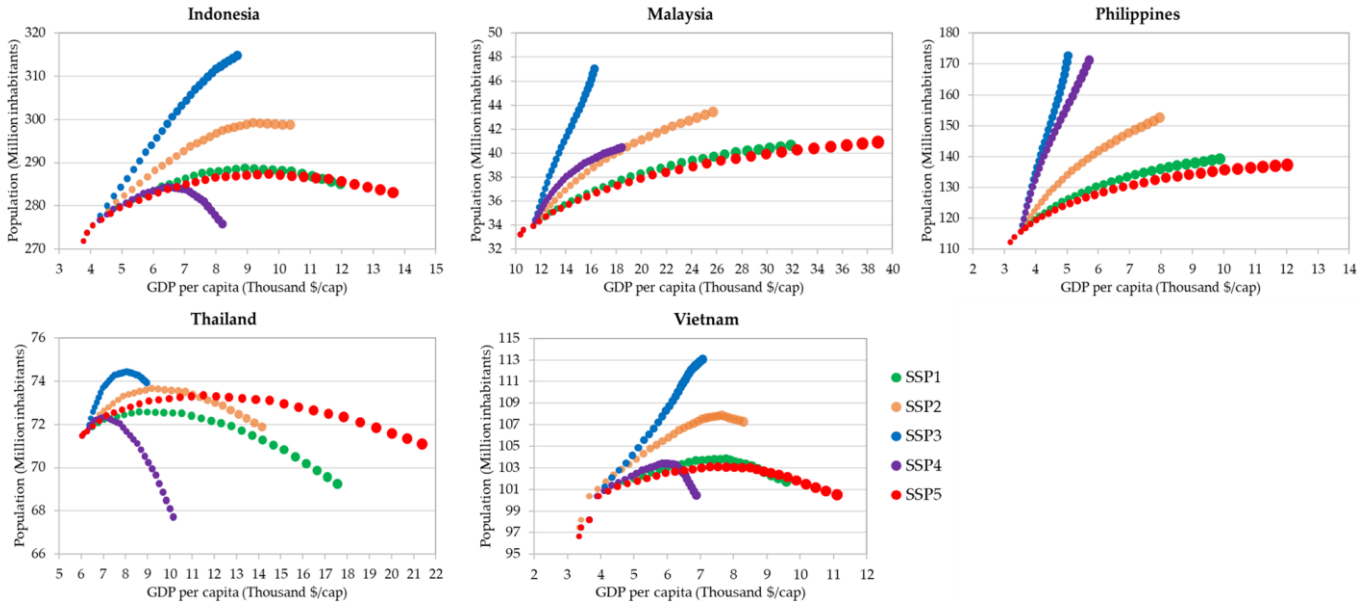


Figure A3. The estimated population (POP) and projected GDP per capita, PPP (GDP) of the five Southeast Asian countries based on SSP scenarios by 2050 (constants 2015 USD) [38].

Note A1. *Calculation method of copper consumption, stocks, and stocks per capita*

$$C(c,t') = SPC(c,t') \times FE(t') + \left(IFP(c,t') - EFP(c,t')\right) \quad \text{(A1)}$$

$$S(c,t) = \sum_{t'=1960}^{t} C(c,t') \times (1 - DpR)^{(t-t')} \times SR(t-t') \quad \text{(A2)}$$

Here, $C(c,t')$ is the finished product consumption in country c in year t'; $SPC(c,t')$ is the copper consumption for semi-finished product in country c in year t'; $FE(t')$ stands for the fabrication efficiency for finished products in year t' (%); and $EFP(c,t')$ and $IFP(c,t')$ denote the exported and imported finished products, respectively, in country c in year t'. $S(c,t)$ represents the copper stock in country c in year t, DpR is the in-use dissipation rate, and $SR(t-t')$ denotes the survival ratio of finished product after $t-t'$ years. For future projection, the hypothesis posits that copper stock per capita will increase before reaching a saturation point to economic growth. Forecasts of copper in-use stock for each country are

derived by fitting a logistic function to the assumed relationship between per capita in-use stocks and per capita GDP, as presented in the following equation:

$$S(c,t) = P(c,t) \times \frac{S_{sat}}{1 + exp(\alpha - \beta \times GDPpc(c,t))} \quad \text{(A3)}$$

$$C(c,t) = S(c,t) - S(c,t-1) + EoLS(c,t) + DM(c,t) \quad \text{(A4)}$$

$$EoLS(c,t) = \sum_{t'=1960}^{t} C(c,t') \times (1 - DpR)^{(t-t')} \times DR(t-t') \quad \text{(A5)}$$

$$DM(c,t) = \sum_{t'=1960}^{t} DpR \times C(c,t') \times (1 - DpR)^{(t-t'-1)} \times SR(t-t') \quad \text{(A6)}$$

Therein, $P(c,t)$ stands for the number of populations in country c in year t, $Ssat$ is the saturation value of copper stock per capita, $GDPpc(c,t)$ is GDP per capita in country c in year t, and α and β are logistic function parameters. The finished product consumption in country c in year t' ($C(c,t)$) is calculated by using the total copper stock in county c in year t ($S(c,t)$), the total copper stock in county c in year $t-1$ ($S(c,t-1)$), the end-of-life scrap generated in country c in year t ($EoLS(c,t)$), and the amount of dissipated copper in country c in year t ($DM(c,t)$). $DR(t-t')$ is the discard ratio of finished products after $t-t'$ years.

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