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Contemporary and Future Secondary Copper Reserves of Vietnam

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Abstract: As ASEAN countries, including Vietnam, approach the living standards of developed countries, their copper demand is set to rise. This study investigates Vietnam's copper stock and flow from 1995 to 2050, employing dynamic material flow analysis and five socioeconomic pathway scenarios (SSPs). Based on this, the secondary copper reserves of Vietnam were assessed. The results showed that the domestic copper demand is expected to grow to 526–1062 kt, resulting in a rapid increase in scrap generation. In 2022, Vietnam's secondary copper reserves stood at 2.2 Mt and are projected to reach 6.8–8.6 Mt by 2050 under the SSP2 scenario. This corresponds to 3.6–4.6 times the 1.8 Mt primary copper reserve of Vietnam. However, these primary and secondary reserves cannot meet the cumulated demand by 2050. On the other hand, a large amount of copper, 8.9 Mt to 10 Mt, will become difficult-to-recover resources, such as waste in landfill sites, dissipated materials, or mixed metal loss. To promote the sustainable use of copper in Vietnam, we recommend increased geological expedition and mining investment, and improved waste management systems related to secondary resources.

Keywords: dynamic material flow analysis; in-use stock; metal scrap; secondary resource classification; Shared Socioeconomic Pathways (SSPs)

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Citation: Le, T.V.; Yamamoto, R.; Dente, S.M.R.; Hashimoto, S. Contemporary and Future Secondary Copper Reserves of Vietnam. *Resources* **2024**, *13*, 82. https://doi.org/10.3390/resources13060082

Academic Editor: Jun Liu

Received: 7 May 2024
Revised: 30 May 2024
Accepted: 10 June 2024
Published: 14 June 2024

1. Introduction

Copper, the third most produced metal after iron and aluminum [1], is essential for industrial and economic development and remains irreplaceable in the electronic components market thanks to its good conductivity and reasonable price [2]. The world's copper demand has increased considerably throughout the twentieth century [3] and is projected to grow by 275–350% by 2050 compared to its level in 2010 (approximately 20 Tg of copper) [4], driven by the world population reaching nine billion by 2050 [5] and the rising of living standards in developing countries. Schipper et al. [3] reports a rise to 3–21 times of the world copper demand in 2100 compared to 2010, whereas Dong et al. [6] expects the 2050 copper demand in China to be six times the 2005 level (around 4 Tg). Nishiyama et al. [7] indicates that other Asian countries' copper consumption (India, Indonesia, Thailand, and Vietnam) will continue to grow at a high rate, while Nguyen et al. [8] emphasizes the importance of economic expansion, industrialization, urbanization, and rising living standards to explain the consumption growth in Vietnam. Vietnam has indeed experienced a rapid economic reformation, with its Gross National Income rising from USD 80/person in 1986 to USD 1962/person in 2015 [9], representing an average annual rate of economic growth of 5–6% [10]. This increase is coupled with a doubling of the urban population, from 16.9 million in 1996 to 32.1 million in 2016 [5].

However, the increase in demand for copper will impose constraints on the global and Vietnamese copper supply chains. First, the decrease in high-grade copper deposits is expected to lead to the closing of large copper mines worldwide (Escondida, Chile; Collahuasi, Chile; Morenci, the USA; Antamina, Peru.) before 2050 [11], thereby restraining access to primary copper. Second, the extraction of copper ore requires huge amounts of water, land, and power resources [12,13], and is responsible for the emissions of greenhouse gases [14], sulfur dioxide, and large quantities of hazardous compounds, as demonstrated by the heavy metal contamination near copper mines [15]. This situation may worsen as the extraction of lower grade ore poses challenges to the metallurgical and waste management processes [16]. To remediate this, developed countries are bound to set stricter economic and socio-environmental regulations that might engender longer delays in discovering accessible new deposits than in the past [17], and therefore reduce global copper ore availability.

In this context, the development of secondary copper production is essential. Indeed, secondary production has less environmental impact than primary production [18] and may save 85% of the energy resources and reduce the greenhouse gas emissions by 65% [19,20]. The key question is, however, to know where and when the secondary copper is available. This is particularly important for Vietnam, whose economy is still oriented towards the use of low-skilled labor and the export of natural resources [8,21], despite being the third-largest producer of minerals in Southeast Asia [20]. From that perspective, Hashimoto et al. [22] proposed a framework for classifying secondary resources based on the primary resource classification [23]. Maung et al. [24] applied this framework to copper and assessed the secondary copper reserves and resources in 2010 for China and main copper consumers among developed countries.

The present work aims to assess the future availability of secondary copper for the Vietnamese economy. For this purpose, copper stock and associated secondary reserves up to 2050 were calculated in two steps. First, we developed a material flow analysis until 2022 using historical statistical data. Second, we modeled the evolution of copper stocks and flows after 2022 using social economic pathway scenarios (SSPs) [25,26]. Third, we applied the secondary resource classification framework [22] to secondary copper resources. Finally, the results are discussed to shape resource policy recommendation for Vietnam during its modernization and industrialization process.

2. Methodology

2.1. Estimation of Copper Stocks, Demand, and End of Life Scrap

Stock results from the cumulative difference between the copper consumption of finished products (inflow) and the copper scrap arising from the end of life products (outflow) [27].

For historical calculations (1995–2022), we conducted a material flow analysis to estimate copper consumption and used a lifetime function to estimate copper stocks:

$$C(t') = SPC(t') \times FE(t') + (IFP(t') - EFP(t')) \quad (1)$$

$$S(t) = \sum_{t'=1995}^{t} C(t') \times (1 - DpR)^{(t-t')} \times SR(t - t') \quad (2)$$

wherein $C(t')$ represents the copper consumption for finished products in year t'; $SPC(t')$ stands for the semi-finished product consumption in year t'; $FE(t')$ denotes the fabrication efficiency for finished products in year t' (%); and $EFP(t')$ and $IFP(t')$, respectively, represent the exported and imported finished products in year t'. Furthermore, $S(t)$ is copper stock in year y; DpR represents the in-use dissipation rate; and $SR(t–t')$ denotes the survival ratio of the finished product after $t–t'$ years.

For the 2022–2050 period, the future in-use stock is estimated using the S-shape curve or logistic function [28]. The core idea is that, as the per-capita income grows, copper demand increases before reaching a saturation level [29,30]. For this study, copper stocks of

2022–2050 were estimated using the approach reported by Hatayama et al. [29], as shown in Equation (3).

$$S(t) = P(t) \times Spc(t) = P(t) \times \frac{S_{sat}}{1 + exp(\alpha - \beta \times GDPpc(t))} \quad (3)$$

In that equation, P(t) is population in year t; Spc(t) is per-capita copper stock in year t; Ssat stands for the saturation value of per-capita copper stock; GDPpc(t) denotes per-capita GDP in year t; and α and β are logistic function parameters.

Finally, the copper consumption (C(t)) is iteratively calculated until 2050 as presented in Equations (4) and (5):

$$C(t) = S(t) - S(t-1) + EoLS(t) + DM(t) \quad (4)$$

$$EoLS(t) = \sum_{t'=1995}^{t} C(t') \times (1 - DpR)^{(t-t')} \times DR(t-t') \quad (5)$$

$$DM(t) = \sum_{t'=1995}^{t} DpR \times C(t') \times (1 - DpR)^{(t-t'-1)} \times SR(t-t') \quad (6)$$

wherein EoLS(t) is the end-of-life scrap generated in year t; DM(t) is dissipated material in year t; and DR(t–t′) is the discard ratio of finished products after y years.

2.2. Classification of Secondary Copper Resources

Hashimoto et al. [22] proposed the system presented in Table 1 for categorizing secondary resources. The vertical orientation represents the potential for reusing secondary resources depending on various levels of profitability, whereas the horizontal orientation represents the existing knowledge related to secondary resources. Different degrees of profitability were used, such as economic (the normal recovery rate conditions technologically and economically feasible at the time of estimation), marginally economic (the best recovery rate technologically and economically feasible at the time of estimation), and subeconomic (the amount not recoverable due to technological, economic, and other pertinent reasons at the time of estimation). If recycling is not economical, then secondary resources cannot be expected to be collected and recovered. Regarding knowledge, human society in general is more knowledgeable about "items in use or after use" than about "wastes in managed landfill sites" or "dissipated materials". The amounts of waste or secondary resources generated in a year are also better known than the "final products in/after use", which are stocked in society. Information about stocked materials is important because such materials can be expected to appear in future economies as waste or as secondary resources. This classification table presents an idea of the amounts of secondary resources available for use in an economy as well as fundamental knowledge about the dissipated materials to support analyses of the related environmental impacts and resource losses.

The copper stock in year t (S(t)) either emerges during the following year or in subsequent years as end-of-life scrap (EoLS(t)) or dissipated materials (DM(t)). Table 1 shows that the secondary reserves in year t (SR(t)) correspond to the technologically and economically recoverable share of the stock. For this purpose, the secondary reserve ratio in year t (SRR(t)), corresponding to the fraction of in-use copper stocks that is technologically and economically recoverable, is introduced in Equation (7) following the approach used by Maung et al. [24]. Marginal economic is presented in Equation (10) considering the best recovery rate (SRR(t_{high})). In those equations, e and n denote emerging in a year and not emerging in a year.

$$SR(t) = S(t) \times SRR(t) \quad (7)$$

$$SRe(t) = EoLS(t) \times SRR(t) \quad (8)$$

$$SRn(t) = SR(t) - SRe(t) \tag{9}$$

Table 1. Classification framework of secondary resources (adapted from [22]).

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 **(SSURMw)**	Subeconomic secondary resources and unrecoverable materials - Dissipation **(SSURMd)**
	Subeconomic secondary resources and unrecoverable materials - Mixed metal loss **(SSURMm)**			

These recoverable amounts can be extended by considering the highest secondary reserve ratio in year thigh, i.e., the best technological and economic situation for material recovery in the past. The marginal secondary reserve is then defined as in Equations (10)–(12):

$$MSR(t) = S(t) \times \left(SRR\left(t_{high}\right) - SRR(t)\right) \tag{10}$$

$$MSRe(t) = EoLS(t) \times \left(SRR\left(t_{high}\right) - SRR(t)\right) \tag{11}$$

$$MSRn(t) = MSR(t) - MSRe(t) \tag{12}$$

wherein MSR(t) represents the marginal secondary reserves and $SRR(t_{high})$ is the secondary reserve ratio in a year thigh, which is the year recording the highest secondary reserve ratio.

The subeconomic secondary resources and unrecoverable materials (*SSRUM*) corresponds to the part of the stock which is not recoverable economically and technologically. It includes dissipated materials and the end-of-life scrap which are not part of the secondary reserves.

$$SSRUMe(t) = DM(t) + EoLS(t) - (SRe(t) + MSRe(t)) \tag{13}$$

$$SSRUMn(t) = S(t) - SR(t) - MSR(t) - SSURMe(t) \tag{14}$$

Considering $C(t')$ as the copper consumption for finished products in year t′, the cumulative consumption in year t ($CC(t)$) is the sum of the stock in year t and cumulative dissipation and end-of-life scrap.

$$CC(t) = \sum_{t'=1995}^{t} C(t') = S(t) + \sum_{t'=1995}^{t-1} D(t') + \sum_{t'=1995}^{t} EoLS(t') \tag{15}$$

As shown in Equations (16)–(18), the landfill ratio (LFR(t′)) and mixed metal loss ratio (MMLR(t′)) are then applied to complete the calculation of Table 1. In which, w, m and d are wastes in managed landfill sites, mixed metal loss, and dissipated material, respectively.

$$SSURM_w(t) = \sum_{t'=1995}^{t} EoLS(t') \times LFR(t') \tag{16}$$

$$SSURM_m(t) = \sum_{t'=1995}^{t} EoLS(t') \times MMLR(t') \tag{17}$$

$$SSURM_d(t) = \sum_{t'=1995}^{t-1} DM(t') \tag{18}$$

2.3. Data and Scenarios

2.3.1. Data

For the historical material flow analysis, we collected data from the World Bureau of Metal Statistics, the International Copper Study Group, and the UN COMTRADE database to determine the semi-finished product consumption ($SPC(t)$), and the exported ($EFP(t)$) and imported finished products ($IFP(t)$). The copper contents of copper-containing products are taken from the data compilation made by [24] from various sources [30–35]. These data are presented in Table S1. Fabrication efficiency ($FE(t)$) is set constant at 0.84 as a weighted average of the fabrication efficiencies [36] and the global market share [37] of end-use sectors (see Table S2). The dissipation ratio (DpR) is 0.02% during their whole life [38].

The survival ratio ($SR(t)$) and discard ratio ($DR(t)$) are Weibull functions with an average mean lifetime of 21.9 years calculated from [39], as detailed in Table S4. In addition, three scenarios of stock saturation (minimum, average, and maximum values) were considered based on developed countries' estimates: 178.3 kg/cap, 210.9 kg/cap, and 234.1 kg/cap, respectively. These values, as well as the parameters for logistic curve function, are shown in Table S5.

Based on a global average end-of-life recycling ratio of 40–50% [40], we set $SRR(t)$ to 0.4 and $SRR(t_{high})$ to 0.5 for all years. The landfill ratio ($LFR(t')$) and mixed metal loss ratio ($MMLR(t')$) are assumed to be constant and the LFR:MMLR ratio is set to 82:18, following Maung et al. [24].

2.3.2. GDP and Population Scenarios

"Shared Socioeconomic Pathways" (SSPs) were used for GDP and population scenarios. SSPs are a set of scenarios developed by the Intergovernmental Panel on Climate Change as part of their Fifth Assessment Report in 2014. These scenarios are used to explore how various combinations of socioeconomic development and policy choices might influence future greenhouse gas emissions, as well as their impacts on climate change and adaptation [41,42]. They include:

SSP1: "Sustainability"—Concentrated on sustainability and fairness, SSP1 depicts steady economic expansion and balanced population growth. There is a notable rise in GDP per capita alongside a stable increase in population, following a sustainable development trajectory.

SSP2: "Middle of the Road"—Positioned as a "moderate" scenario, SSP2 reflects economic and demographic trends that largely mirror historical patterns. Both GDP per capita and population show gradual and consistent growth.

SSP3: "Regional Rivalry"—Characterized by societal fragmentation and a resurgence of nationalist sentiments, SSP3 experiences the most rapid population growth among the scenarios. However, economic progress might face challenges due to political and social unrest.

SSP4: "Inequality"—Illustrating a world marked by widening wealth disparities, SSP4 displays relatively high GDP per capita but with significant social class discrepancies. Population growth occurs but at a slower pace compared to other scenarios.

SSP5: "Fossil-fueled Development"—Portrayed as a realm of swift economic expansion and heightened energy consumption, SSP5 boasts the highest GDP per capita and the fastest population growth rate among the scenarios. This growth is accompanied by a substantial surge in energy and resource usage.

In this study, we used the growth data of GDP per capita and population through 2050 (see Figures S2 and S3) for Equation (3). Figure 1 illustrates the differences in population and GDP per capita among the 5 SSP scenarios. Specifically, SSP1 and SSP5 demonstrate significant economic growth, while SSP3 and SSP2 exhibit the fastest population growth compared to the other scenarios.

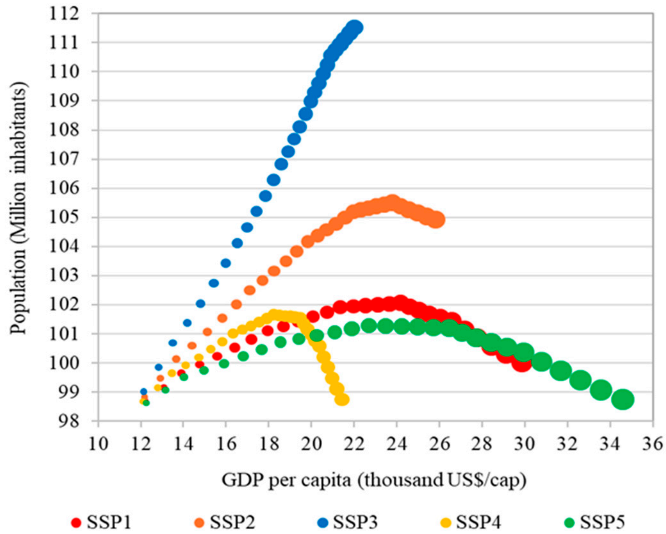

Figure 1. Vietnam per-capita GDP and population during 2023–2050 according to SSP scenarios (our calculation based on the SSP Database [43]).

3. Results

3.1. Evolution of Copper Stocks during 1995–2050

Figure 2 presents the estimated total copper stocks during 1995–2050. Copper stocks increased from 1.7 kt in 1995 to 4.4 Mt in 2022. After 2022, for all three stock saturation values, SSP4 and SSP3 scenarios exhibit the slowest accumulation in total stock, ranging from 10 Mt to 12 Mt for SSP4 and 12 Mt to 15 Mt for SSP3. Throughout the period, SSP1 and SSP5 demonstrate superiority in total copper stocks, with ranges of approximately 15–19 Mt and 16–21 Mt, respectively.

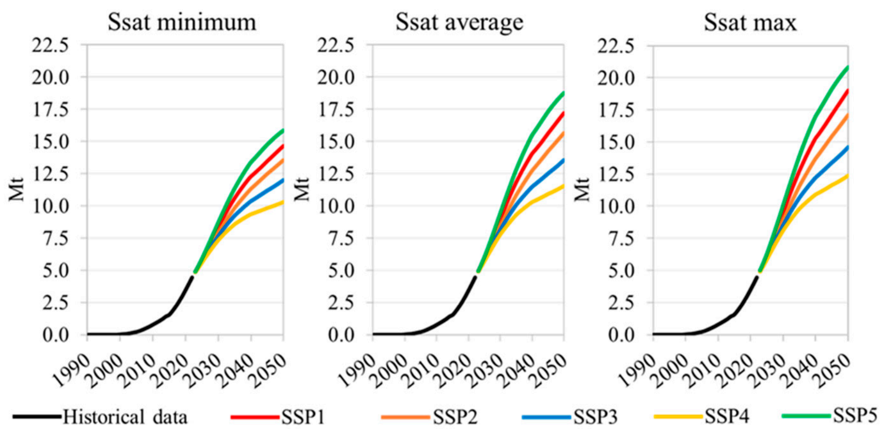

Figure 2. Total copper stocks during 1995–2050.

Figure 3 presents the estimated per-capita copper stocks during 1995–2050. The per-capita copper stock in 2022 was about 45 kg, reaching, respectively, 30%, 22% and 16% of the three stock saturation values. On the other hand, all six SSP1 and SSP5 scenarios reach over 90% of copper stock saturations in 2050, while nine other SSP scenarios exhibit lower than 90%. SSP1 and SSP5 demonstrate robust economic growth, leading to a rapid accumulation of copper in society.

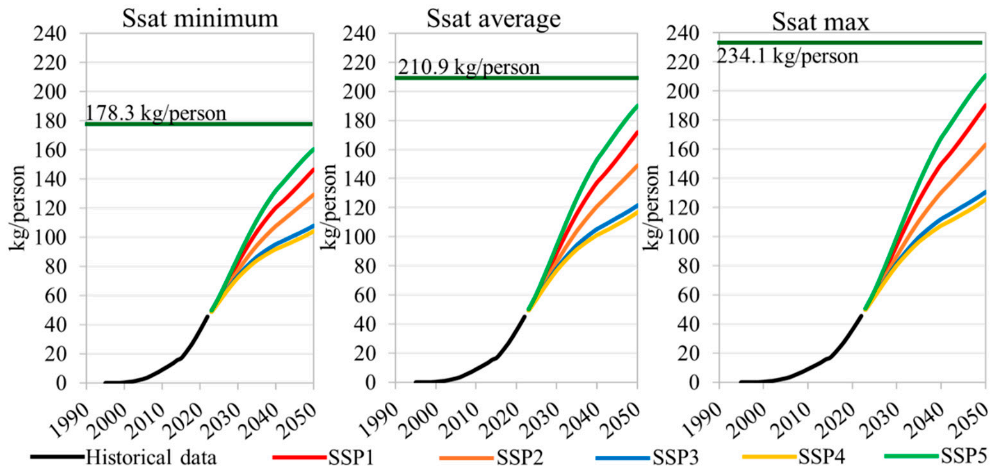

Figure 3. Per-capita copper stocks during 1995–2050.

3.2. Evolution of Copper Demand and Scrap during 1995–2050

Figure 4 portrays the copper demand during 1995–2050. The Vietnam finished consumption level evolved from 1.7 kt in 1995 to 571 kt in 2022. In 2050, like stock level, consumption ranges are distinguishable by saturation level, per-capita GDP, and population factors. In general, the demand for copper in SSP4 and SSP3 scenarios is low, ranging from 526 kt to 814 kt, while SSP1 and SSP5 depict the higher copper demand, ranging from 719 kt to 1062 kt. We did not connect the stock saturation values with the storylines of SSP scenarios; however, this high demand for SSP1-Ssat max can be interpreted as the results of the demand for energy transition—"Sustainability", while the high demand for SSP5-Ssat max can be understood as the results of the adoption of resource- and energy-intensive lifestyles—"Fossil-fueled Development".

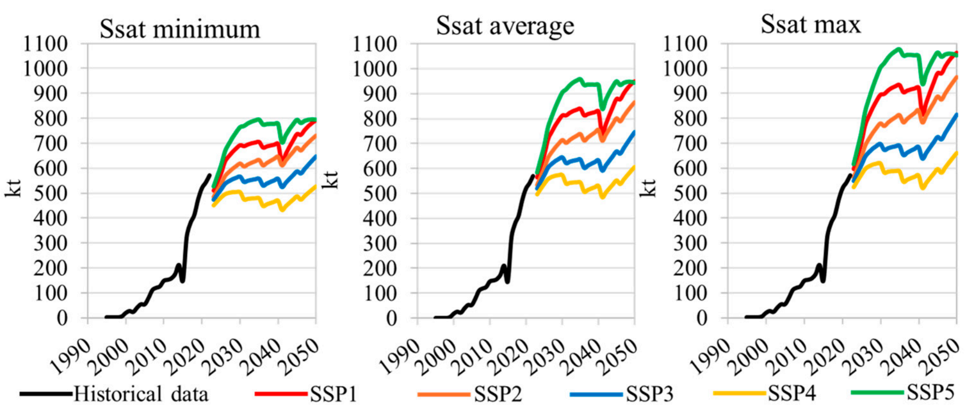

Figure 4. Copper demand during 1995–2050.

Figure 5 shows the generated copper scraps during 1995–2050. The end-of-life copper scrap is increasing all along the period, reaching its maximum value in 2050. The ranges for minimum, average and maximum saturation values are, respectively, 420 kt (SSP4)–600 kt (SSP5), 460 kt (SSP4)–690 kt (SSP5), and 490 kt (SSP4)–760 kt (SSP5) in 2050. Considering an assumed secondary reserve ratio of 50% ($SRR(t_{high})$) and a generated scrap value of 70 kt in 2022 for a demand of 571 kt, the capacity of Vietnam to fulfill its consumption in 2022 is only 6%. In 2050, for the minimum, average and maximum saturation scenarios, this capacity rises, respectively, to 38–40%, 37–38%, and 36–37%. Overall, across all scenarios, Vietnam will not be able to fulfill its demand from secondary resources only, and will therefore have to rely on domestic primary resources or imported copper, or need to enhance copper recycling.

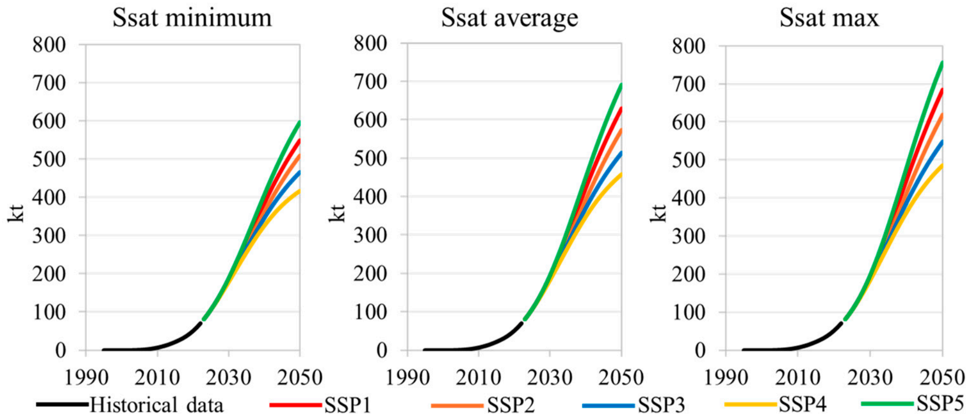

Figure 5. Generated copper scrap during 1995–2050.

3.3. Secondary Copper Reserves in 2022 and 2050

Table 2 presents the classification of secondary copper resources in 2022. The cumulated finished consumption during 1995–2022 amounts to 4.9 Mt (4882 kt in Table 2), of which 8.8% (430 kt) has already left the system, either as waste in managed landfill sites (342 kt), dissipated materials (13 kt) or mixed metal loss (75 kt). The remaining 4.5 Mt corresponds to the stock, of which 72 kt (1.6%) will be released in 2022, with half of it (35 kt) constituting the secondary reserves, including economic (28 kt) and marginally economic (7 kt). The total secondary reserves, including those not emerging in a year, are estimated to be 2.2 Mt, which is comparable with the Vietnamese copper reserves of 1.9 Mt [44].

Table 2. Classification of secondary copper resources in 2022.

Total 4882 kt (100%)	Final Products in/after Use		Wastes in Managed Landfill Sites	Dissipated Materials
	Emerging in a Year	Not Emerging in a Year		
Economic	28 kt (0.6%)	1753 kt (35.9%)		
Marginally economic	7 kt (0.1%)	438 kt (8.9%)		
Subeconomic and Other	37 kt (0.8%)	2189 kt (44.8%)	342 kt (7.0%)	13 kt (0.3%)
	75 kt (1.5%)			

Table 3 presents the classification of secondary copper resources in 2050. Here, three SSP2 scenarios corresponding to three stock saturation values (*Ssat*) were chosen as an intermediate scenario to present the outlook for Vietnam's secondary resources in 2050.

The cumulated finished consumption during 1995–2050 will reach 22 Mt to 27 Mt (22,420 kt to 27,173 kt in Table 3), which are 4.6 and 5.6 times the 2022 level, respectively. The cumulative amount of copper as waste in landfill sites, dissipated materials, or mixed metal loss has increased rapidly from about 8.8% in 2022 to approximately 37–40% in 2050. The cumulated waste in landfill sites, accounting for 7.0% in 2022, will quickly increase to around 30–32% of the cumulated consumption, whereas dissipated materials and mixed metal loss will rise to 0.6–0.7% and 6.5–7.0%, respectively. In total, a large amount of copper, 8.9 Mt to 10 Mt, will become difficult-to-recover resources by 2050.

In 2050, approximately 515–627 kt of copper scrap will be generated, with half of this assumed to be recycled, including economic (203–247 kt) and marginally economic (51–62 kt). However, compared to Vietnam's copper demand in 2050, the amount of recycled copper only meets 35% (SSP2—Ssat min), 33% (SSP2—Ssat average), and 32% (SSP2—Ssat max) of the demand.

The secondary copper reserves will reach 6.8 Mt to 8.6 Mt. This corresponds to 3.6–4.6 times of Vietnamese copper reserves of 1.9 Mt [44], indicating the importance of the effective use of secondary reserves.

Table 3. Classification of secondary copper resources in 2050 for SSP2 scenarios (top: Ssat min; middle: Ssat average; bottom: Ssat max).

Total 22,420 kt 25,232 kt 27,173 kt (100%)	**Final Products in/after Use**		**Wastes in Managed Landfill Sites**	**Dissipated Materials**
	Emerging in a Year	**Not Emerging in a Year**		
Economic	203 kt (0.9%) 203 kt (0.9%) 247 kt (0.9%)	5212 kt (23.2%) 6030 kt (23.9%) 6601 kt (24.3%)		
Marginally economic	51 kt (0.2%) 57 kt (0.2%) 62 kt (0.2%)	1303 kt (5.8%) 1508 kt (5.9%) 1650 kt (6.1%)		
Subeconomic and Other	261 kt (1.2%) 295 kt (1.2%) 318 kt (1.2%)	6509 kt (29.0%) 7530 kt (29.8%) 8243 kt (30.3%)	7161 kt (31.9%) 7725 kt (30.6%) 8102 kt (29.8%)	147 kt (0.7%) 161 kt (0.6%) 171 kt (0.6%)
	1572 kt (7.0%) 1696 kt (6.7%) 1779 kt (6.5%)			

4. Discussion

4.1. Result Validation

Gerst and Graedel [45] reported the global per-capita copper stocks as 35–55 kg. This value, for more-developed countries such as Australia, Canada, the European Union EU15, Sweden, Switzerland, Japan, New Zealand, and the US, was about 140–300 kg. Maung et al. [24] also reported similar findings, indicating that the per-capita copper stock in 2010 for countries such as Germany, Japan, South Korea, and Spain ranged from 140 to 300 kg. Our result of Vietnamese per-capita copper stock of 45 kg in 2022 is in the range of the global per-capita copper stocks of 35–55 kg. It is comparable to the value reported for China in 2010 by Maung et al. [24], However, it remains significantly lower compared to the level of developed countries [24].

The ability to fulfill copper demand by recycled copper in 2022 is very low (6%). However, our projection of 36–40% of the demand in 2050 being potentially met by recycled copper is comparable with the 2010 values for Spain (40%), South Korea (43%) and Italy (55%) reported by Maung et al. [24].

4.2. Policy Recommendations

4.2.1. Increasing the Geological Expeditions and Mining Investment

Vietnam's domestic copper consumption in 2022 is 571 kt, and this figure is projected to increase to approximately around 732–964 kt in 2050 under SSP2 scenarios. Correspondingly, the cumulated demand for SSP2 is estimated to be 17–22 Mt in the next 25 years. However, the estimated reserves in domestic mines are 1.9 Mt of copper [44]. Therefore, the domestic resources are not sufficient to meet domestic demand.

In this study, we assumed the maximum recycling rate for Vietnam is 50%. Thus, the secondary copper reserves are estimated to be 6.8–8.6 Mt. Even if both primary and secondary reserves are combined, they still cannot meet the domestic demand. If the recycling rate increased up to 100%, the secondary reserves would be 13.5–17.2 Mt. These values are comparable with cumulative demand (17–22 Mt), but still somehow lower.

Statistics on Vietnam's copper product trade indicate that imports have consistently exceeded exports during 1995–2022, with this disparity tending to increase in recent years. However, the reliance on imported resources highlights the risks related to supply chain disruptions. Therefore, in order to reduce Vietnam's dependence on imported copper in the future, our first proposal is to increase geological expeditions and mining investment, to locate copper ore resources and to develop copper mines.

Nowadays, the main deposits in Vietnam are the western Red River, between Lao Cai and the Chinese border, the Luc Ngan River basin in the northeast, and the Son La–Son Da rivers area in the northwest. The largest copper deposit, which was found in the 1960s, is in the Lao Cai area [46]. Nevertheless, these copper mines have lower grade ore than those in other countries in Asia, such as China and Laos [47]. The exploration and evaluation of mineral reserves in Vietnam have remained inadequate because of the use of outdated and inefficient traditional methods [48]. To address this issue, new technologies for evaluating mineral deposits need to be applied. However, the current level of research and development capacity for new technology indicates that the Vietnamese enterprises have yet to respond to the high technological requirements for mining exploitation [49]. Vietnam's government project to increase its mining capacity to 255 kt in 2030, and 330 kt in 2035 [44], has approved seven projects for exploring new copper mines with reserves of approximately 421 kt until 2025 [44]. Additionally, they aim to expand by another 3 to 5 exploration projects to discover approximately 20 kt of copper reserves from 2026 to 2035 [44]. Despite the government's initiatives, the estimated copper reserves at the existing mines up to the present and forecasted for the future still do not meet domestic demand. Therefore, the combination of other policies is necessary, as described below.

4.2.2. Improving the Management System Related to Secondary Resources

As stated above, in any scenario of assumed recycling rates (including 100%), Vietnam's secondary reserves still cannot meet domestic demand. However, the higher the amount of copper recovered from waste, the less demand there will be for primary resources and imported resources. Developing the appropriate waste management systems and increasing the recycling rates will contribute to reducing environmental burdens and resource loss. The estimates in this study indicate that from 342 kt in 2022 (Table 1), the accumulated copper in landfills has increased by approximately 21 to 24 times in just nearly 30 years, with the highest volume reaching 8.1 Mt (Table 2). If Vietnam maintains its current status quo in waste management, these estimations are likely to materialize. Several solutions to increase recycling can be implemented, including:

(1) Encouraging the sorting of solid waste (especially copper-containing products) at its source is essential to enhance and improve recycling. In Vietnam, scavengers or waste-pickers play a key role in waste collection and recycling. However, the current practice of manual sorting by scavengers or waste-pickers lacks technology and efficiency, resulting in significant resource loss and deposition into landfills. Therefore, implementing source segregation and resource recovery at the point of waste generation can help reduce the workload for subsequent processing steps and increase the amount of recycled materials. Additionally, expanding the network for solid waste collection by increasing the coverage area, adding more collection points, and improving logistical efficiency is crucial for ensuring comprehensive and timely waste collection services, thus contributing to high-efficiency waste management. Regulations related to waste collection and sorting remain nevertheless insufficiently strict in economically developing countries [50], particularly in Vietnam. Furthermore, the lack of awareness of users has been reported as an important reason for ineffective waste management [51].

(2) Encouraging the establishment and adoption of a comprehensive system for initiatives for reuse, recycling, and the appropriate treatment of waste materials is also important.

In recent years, refined copper production has continued to develop, but the activities of refined copper production from recycled copper have been limited, particularly addressing E-waste [52,53] and vehicles [54]. This limitation stems from small-scale operations, obsolete technologies, and a limited capacity for cleaner technology investment and waste treatment facilities [52,55]. Vietnam has approximately 1450 craft villages, characterized by small-sized and fragmented operations. The use of obsolete and manual technologies in these villages results in significant emissions of heavy metals and gaseous chemicals during the metal recycling process [56]. With the aim of maximizing the benefits derived from waste materials and limiting the emissions of pollutants and toxins into the environment, strategic planning in the recycling industries and the improvement of the machinery and equipment used in recycling facilities are important requirements. Although secondary production presents fewer negative effects on the environment than primary extraction, it still generates wastewater, solid waste, and toxic gases during the smelting and refining processes. Traditional recycling methods (such as incineration [57], hydraulic shaking bed separation [58], and acid leaching process [59]) are applied, while the use of more advanced techniques (like mild extracting technology [60], electrochemical technology [61], supercritical technology [62], and vacuum metallurgical technology [63]) is quite limited [64]. However, the application of advanced recycling technologies is expected for future perspectives. The Vietnamese government should establish clear and sustainable directions for these activities.

(3) Mining landfill sites is another potential approach for future mining strategies. According to the Ministry of Construction of the Socialist Republic of Vietnam, there were about 660 landfill sites with a total area around 4900 hectares in 2015 [65]; among these landfill sites, only approximately 31% are sanitary landfills. Due to urbanization, economic growth, and population growth leading to an ever-growing amount of waste, the quantity of solid waste generated has doubled in recent years. The number of landfill sites also increased to 904 by the year 2020 [66]. There are two common approaches to resource extraction from landfills: in-situ and ex-situ. Among them, the ex-situ method focuses on material resource recovery by partially or fully excavating the waste materials for further treatment [67]. For developing countries, especially the case of Vietnam, investing in resource recovery technologies from landfills is highly costly and demands high expertise in equipment installation and operation [68]. With the current amount of copper in landfills being relatively small (around 342 kt), extracting them would not yield significant economic and environmental benefits. Therefore, implementing an efficient recycling industry should be the priority, as technology implementation would cost less and the copper content of the end-of-life materials is higher than in landfill. However, as shown by our research, if no improvement in the recycling rates is carried out by 2050, the copper in landfill may reach as much as 7000–8000 kt, ten times the annual copper demand in Vietnam.

5. Conclusions

In this paper, we estimated the copper stocks, demand, scrap, and secondary reserves for Vietnam during 1995–2050. The key findings of the study are presented below.

(1) Copper consumption rose from 1.7 kt in 1995 to 571 kt in 2022. The estimated copper demand in 2050 varied from 526 kt to 1062 kt depending on the future scenarios of per-capita GDP and population, and the assumption of copper stock saturation values. Estimated copper scrap in 2050 ranges from 420 kt to 760 kt. The amounts of recycled copper correspond to 36–40% of the demand, assuming a secondary reserve ratio of 50%.

(2) Vietnam had 2.2 Mt of secondary copper reserves in 2022, whereas this number is expected to reach 6.8–8.6 Mt in 2050 under the SSP2 scenario. It corresponds to 3.6–4.6 times of Vietnamese copper reserves of 1.8 Mt. However, these reserves cannot meet the cumulated demand by 2050. On the other hand, a large amount of copper, 8.9 Mt to 10 Mt, will become difficult-to-recover resources, such as waste in landfill sites, dissipated materials, or mixed metal loss.

(3) Increasing the geological expeditions and mining investment and improving the waste management systems related to secondary resources were discussed from the viewpoint of Vietnam.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources13060082/s1, Table S1: Copper contents of copper-containing products (as reported by [24]); Table S2: Fabrication efficiency FE(t); Table S3: Determining the mean lifetime of copper products; Table S4: Saturation value of the per-capita copper stock (Ssat); Table S5: α and β; Figure S1: Survival ratio SR(t) and discard ratio DR(t); Figure S2: Per-capita GDP, GDP(t) (constant 2017 $) (our calculation based on [43]); Figure S3: Population, POP(t) (our calculation based on [43]).

Author Contributions: Conceptualization, T.V.L., S.M.R.D. and S.H.; methodology, T.V.L., R.Y., S.M.R.D. and S.H.; validation, S.M.R.D. and S.H.; resources, S.M.R.D. and S.H.; data curation, T.V.L., R.Y. and S.M.R.D.; investigation, T.V.L., R.Y., S.M.R.D. and S.H.; writing—original draft preparation, T.V.L.; writing—review and editing, T.V.L., R.Y., S.M.R.D. and S.H.; visualization, T.V.L., S.M.R.D. and S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by (i) the Environment Research and Technology Development Fund (JPMEERF20S20604) of the Environmental Restoration and Conservation Agency provided by the Ministry of Environment of Japan (ii) JSPS KAKENHI grant numbers P19H04329 and JP23K25059, and (iii) Ritsumeikan Global Innovation Research Organization (R-GIRO).

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.

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